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Water Engineering in the Ancient World

Archaeological and Climate Perspectives on Societies of Ancient South America, the Middle East, and South-East Asia

CHARLES R. ORTLOFF

WATER ENGINEERING IN THE ANCIENT WORLD

To my brother, Walter H. and parents Walter C. and Johanna E. Ortloff—your unbounded encouragement to explore man's engineering creations in my early years ultimately led to this book.

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Great Clarendon Street, Oxford OX2 6DP

Oxford University Press is a department of the University of Oxford.
It furthers the University's objective of excellence in research, scholarship,
and education by publishing worldwide in

Oxford New York

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Kuala Lumpur Madrid Melbourne Mexico City Nairobi
New Delhi Shanghai Taipei Toronto

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Argentina Austria Brazil Chile Czech Republic France Greece
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Published in the United States
by Oxford University Press Inc., New York

First published 2009

British Library Cataloguing in Publication Data
Data available

Library of Congress Cataloging in Publication Data
Data available

Typeset by SPI Publisher Services, Pondicherry, India
Printed in Great Britain
on acid free paper by
CPI Antony Rowe, Chippenham, Wiltshire

ISBN 978 0 19 923909 2

1 3 5 7 9 10 8 6 4 2

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Acknowledgements

The author wishes to thank his many colleagues who shared explorations, inspirations, ideas, and discoveries at field sites around the world to produce the narratives and conclusions interwoven into the chapters in this book. For archaeological work in Peru and Bolivia over the past 25 years, Dr Michael Moseley of the University of Florida and Dr Alan Kolata of the University of Chicago played major discovery and collaborative roles in Moche, Casma, Jequetepeque, and Moquegua Valley projects on coastal Peru and the highland altiplano site of Tiwanaku in Bolivia. Dr Ruth Shady de Solís provided site access and valuable background information for work done at Caral in Peru. Drs M. Binford and M. Brenner of the University of Florida in Gainesville provided valuable research insights related to raised field agriculture of the Tiwanaku civilization in Bolivia. Dr Adonis Kassinos of BAE Systems deserves thanks for his contributions to analysis and modelling work done on the water systems of the Jequetepeque Valley in Peru as well as the Roman siphon system located at Aspendos in Turkey. Dr P. Kessener also shared his measurement data of the Aspendos siphon, which was vital to the construction of computer models. Dr Lonnie Thompson of the Byrd Polar Research Institute at the Ohio State University provided pre-publication data relevant to Peru's long-term climate history, which proved invaluable to understand developments in Peruvian prehistory. Drs Stephan Karweise and Fritz Krinzinger, former directors of the Austrian Archaeological Institute's Ephesos project in Turkey, provided access to the site of Ephesos in Turkey as well as information regarding the site's history and excavation results. Ing. Gilbert Wiplinger of the ÖAI shared his extensive field and excavation expertise on Ephesian water systems derived from his many years of field operations at Ephesos. Ms M. Natoli provided assistance in work related to the Ephesian theatre water supply system. Dr Dora Crouch, my partner and field colleague for many years on projects in Ephesos and Priene, shared her many years of accumulated knowledge and field discoveries, and added valuable information to text material derived from her profound knowledge of historical information on Middle East sites. Drs T. Tsuk and J. Peleg provided valuable information regarding the dam system at Caesarea in Israel. Work done at Kaminal Juyu in Guatemala derived from a special project with Dr Marion Popenoe de Hatch and information sharing sessions with Dr Ed Shook in Antigua, Guatemala. For work at Petra in Jordan, Dr P. Hammond of the

University of Utah and Dr M. Joukowsky of Brown University graciously shared information regarding temple excavations in the city centre area. Further thanks to Dr Alan Kolata for introducing me to the water systems of Angkor in Cambodia and for the many years of collaborative work that lie ahead in that area to uncover the true nature of the Khmer civilization's water systems and agricultural base. Further thanks for developing many of the graphics in this book are due to Susan Dinga and Ed Bellandi (BAE Systems), who helped process and improve many of the figures found within the chapters related to South American and Middle Eastern sites.

While the many contributions to this work given by my colleagues and associates over the years are well integrated into the text, and my profound gratefulness for years of association and discovery proceeding from their contributions is hereby acknowledged, the responsibility for any oversights and errors is, of course, entirely mine.

Introduction

The purpose of this book is six-fold:

- to introduce the technical advances and historical development of selected irrigation-based, hydraulic societies of the pre-Columbian New World (Peru, Bolivia, and Guatemala) and describe their contributions to the history of the hydraulic sciences; to record the final testament from sites now destroyed by modern development or natural erosion processes that contain information on technology achievements
- to address open questions in the archaeological literature regarding hydraulic and hydrological issues for Old World, New World, and South-East Asian societies with new information and research results from computational fluid dynamics (CFD) computer modelling studies; to present findings relevant to hydraulic sciences from sites not previously reported in the literature
- to introduce new findings from analysis of selected water systems of the ancient Old World and South-East Asia (specifically Petra, Ephesos, Priene, Aspendos, Caesarea, Angkor Wat, and Bali) related to innovations in hydraulics technology
- to present mathematical models and examples of the working dynamics of New World hydraulic societies that show that their underlying actions are based on logical economic and engineering principles that maximize food resources commensurate with population growth and climatic challenges
- to show that ancient New World societies installed and managed urban and agricultural water systems based on sound engineering principles that took into account climate variations (floods and droughts) and developed defensive hydraulic strategies to combat their negative effects
- to provide insight into the thought processes of the technocrats of ancient societies responsible for agricultural development and use of land and water resources through application of engineering principles (as they understood them); to discuss facets of their administrative structure and political economy, and show that technical innovation altered the historical development of societies through increased economic advantages.

One path in the development of history of technology originates from discovery processes that utilize archival historical and archaeological resources. From these sources, early scientific and engineering principles that form the technology foundation of modern societies are uncovered, analysed, and categorized and then shown to be early steps to later useful, modern inventions. An alternative, but less deterministic, path originates from the viewpoint that while some engineering developments may serve a society dealing with survival and economic development issues, they represent an empirical trial-and-error process with no real understanding of underlying scientific principles and thus hold only academic interest with minor relevance to the history of science. For cases of the latter category, there may be scientific and engineering principles contained within an archaeological context but in formats and forms unfamiliar to the methodologies of modern scientific description. Buried within the prescientific terminology of observed scientific phenomena in ancient scripts may be the seeds of conceptualization of basic principles, albeit in difficult to recognize formats and descriptive terms. Depending on the depth of the scientific background of the investigator of archaeological works or the translator of archival texts, perceived insights may only be partial revelations of the original thoughts and concepts of ancient engineers. If early origins of technology are buried in an archaeological context, then different modes of interpretation may give a forced meaning of artefacts and cultural remains to fit a current theory.

Thus, without a clear understanding of the scientific and engineering accomplishments and capabilities of ancient societies, the default position of social explanations for change becomes but a fragmentary picture of societal development. Furthermore, concepts derived from social, political, and economic explanations of societal development, political structure, and organization may de-emphasize the role of technical advances that were catalysing agents of progress and societal evolution. Since societies of the ancient and modern world share water resource concerns, examination of solved problems in the hydraulic sciences in ancient pre-Columbian, Middle Eastern, and South-East Asian societies provide not only comparisons of the knowledge base of these societies, but also information on which parts of the world led the discovery and application of universal hydraulic principles that catalysed their development. Provided a logical basis can be constructed to understand the rationale behind their accomplishments, then insight into thought processes related to their understanding of the natural world and how knowledge was applied to practical applications can reveal aspects of the cognitive processes operational within their societies.

On this basis, the technical advances of selected ancient societies are examined by study of the archaeological remains of water conveyance structures and systems by modern computer analysis methods to gain insight into their hydraulic science knowledge base. The viewpoint advanced is that ancient societies, experiencing demographic and climate stress conditions unique to their ecological and geographic environment, all shared a concern for evolution to new societal structures that efficiently integrated technical advances to provide economic and survival advantages for their populations. Changes in governmental structure may then be thought of as evolving from necessity to better promote these advantages for the benefit of their populations so as to justify the authority and judgement of elites and their continuance in power. While political convolutions and natural disasters often cancel progress (as history demonstrates), more ordered societies with an enlightened administration in control of their political, economic, and territorial domains, and abetted with a productive natural environment, logically promote a path towards economic health and welfare for their citizenry. A better understanding of technical accomplishments and their relevance to societal development is therefore a first step in understanding the inner workings of elite administrative structures and, consequently, a main theme of the research results in the chapters that follow.

As examples of different viewpoints in interpreting field data through archaeological interpretive philosophies (Renfrew 1982; Renfrew and Bahn 2000; Markus and Stanish 2006), themes of logical positivism, processualism, postprocessualism, cognitive processualism, functional processualism, cultural relativism, environmental determinism, oriental despotism/hydraulic society coupling, bottom-up/top-down theory, and Marxist/Engelian socialism are current, as well as many other theories related to social processes behind societal evolution. It is understandable that within different interpretive contexts artefacts and cultural remains can have different interpretations as to their meaning and role in a society's development. Carr's (1961) view of this interpretive process as '... a hard core of interpretation surrounded by a pulp of disputable facts...' may be relevant as social scientists may be tempted to fit artefacts and cultural remains to current theories and perhaps limit the role of engineering accomplishments as drivers in societal development (rather than the opposite viewpoint). Basic questions may arise from discovery of artefacts with perceived technical content as to whether they illustrate bureaucratic efforts to encourage innovative enterprise or are the result of independent, individual focus on problem resolution followed by a bureaucracy to manage the discovery for the benefit of society. Certainly Roman technological innovations appear to be an indispensable part of their rise to world prominence made possible by a professional class of architects and engineers capable of impressive public works. It can be concluded that the Roman governmental system recognized, encouraged, and rewarded creative civil engineering activities and gave prominence to visionary talent that created and projected state civilizing influences, demonstrated state power, and authorized its leadership to dominate and reconstruct conquered societies in their image. From this example, the success of institutionalizing technical progress with a bureaucracy designed to promote progressively more ambitious construction and water projects has served as a model for later Western societies' political structures that valued science and engineering as fundamental to bring economic benefits to their populations. As for societies outside the classical Roman and Greek world, notably those of ancient South America, South-East Asia, and remote provinces of the ancient Middle East, the relation of technical innovation to societal development and administrative structure remains in a formative research state as the full range of knowledge about these societies is absent.

Since only a small fraction of early scientific literary works survive, the state of early knowledge has been largely ceded to interpretation of archaeological remains and the skills of interpreters to extract the design intent behind public works. Given prescientific notions about modern engineering definitions of force, pressure, work, energy, velocity, temperature, heat, mass, and power, yet further interpretive barriers exist when technical literature is available to interpret ancient technology. Even when attempts to interpret cultural remains in terms of sociological, psychological, and cognitive science models of political economy and societal structure occur, commentary that '...some sciences, especially the social and human sciences, are still trapped by prescientific uses of words and their associated concepts...' (Watson 2005) highlights this interpretive problem. Thus, the descriptive language favoured by anthropological theories that attempt to analyse creative human endeavour may fall conceptually and linguistically short of capturing the essence of human creativity processes as shown through their technical innovations and accomplishments. Other interpretative constraints exist, particularly in South American pre-Columbian studies, where no native written languages existed to guide interpretation. Here cultural, technical interpretations, and information derived from the archaeological record or books written by Spanish conquistadors and priests, expressed worldviews and interpretations typical of science levels and understanding in medieval Europe.

Considering the unfamiliar bureaucratic institutions of past societies compared to known Western models, there are further considerations as to how inventions and innovations develop within structurally different systems to create economic progress. The bias that comes through archaeological investigations of cultural remains decoupled from the thoughts of those that created the objects is recognized as a problem in the interpretation of ancient societies. Although recent archaeological models of postprocessualism attempt to add the human element back to account for the range of accomplishments, the social and state-of-mind underpinnings that permit and encourage human creativity are hardly understood in modern societies and perhaps less so for past civilizations for which vastly different social and political environments existed. Even considering these observations, scholars have put together a reasonable factual prehistory of technology based on archaeological and archival resources (Sarton 1960; Kirby 1990; McNeil 1990; Crouch 1993; Forbes 1993; Hamey and Hamey 1994; James and Thorpe 1994; Levi 1995; Cohen and Drabkin 1996; Humphrey 1998; Landels 2000; Grewe 2005). The basic question still remains: What has been missed in the understanding of ancient technical developments by all the filters of interpretation and understanding as applied to only a partial record of the archaeological remains and the few surviving texts from the past?

Since the same physics governs natural phenomena then as now, computer reconstruction and 'reverse engineering' studies of ancient hydraulic structures offer the possibility of rediscovering the design intent behind archaeological remains. The task of showing the practicality of ancient inventions by this means and the types of problems solved in antiquity is one goal of this book. A further purpose is to add observations about the societies that created technical innovations and the governmental and societal structures that managed these advances, particularly when resonance to the role of engineering in modern societies is observed. In this context, when selected engineering accomplishments of the ancient world are examined and shown to conform to a logical basis based on optimal use of skills and resources, then an ancient version of modern macroeconomic theory may emerge to demonstrate that application of basic, universal economic principles underlie their technical and administrative accomplishments.

Examination of the many accomplishments of the ancient New World and Asian societies is made to counter the vision of science as having roots mainly in Old World classic civilizations. In addition, new results related to Old World civilization's engineering accomplishments are added to what is already known of their hydraulic engineering technical base. As far as theories go to explain how ancient civilizations functioned and their creation of new technologies, some ideas are presented that show that observed behaviour in irrigation agricultural development (primarily using multiple examples from New World agricultural societies) follows a basic, common sense paradigm: maximization of food production with optimum use of land, water, labour, and management resources guided by state-organized agricultural management techniques. Much of the interpretation of different societies' accomplishments is based on the author's experience as a hydraulic engineer viewing other hydraulic engineers' accomplishments from different worlds and times; the passion involved in creation and recognition of hydraulic solutions can be shared across the centuries as perhaps only members of the brotherhood of engineers can understand.

New insights and interpretations are based on use of modern computer analysis techniques; this involves ancient water conveyance structures being recast into computer models and computations performed to calculate water flow characteristics—the net result being revelation of the design intent and methodologies of the ancient engineers to control water flows and an assessment of their discovery of hydraulic engineering principles. Additional analysis involving operations with key (non-dimensional) parameter groups vital to a hydraulic society's function are presented—the thought is that these groups, which are vital to optimize agricultural production, underlie universal macroeconomic principles used in some manner (albeit in very different notation, units, and format) to make the agricultural productivity decisions whose results are observed in the archaeological record. This implies that there are basic macroeconomic principles that underlie human behaviour to improve their conditions and that these principles apply to civilizations ancient and modern. For assessment of the degree to which modern societies exercise these principles, statistical data are available; for ancient societies, the path is more difficult as available hydraulic technologies must first be discovered, then interpreted to determine their relevance to economic principles that govern production optimization. Further steps involve the cognitive processes that gave rise to the inventiveness ethic directed towards success in improving living standards—all to be done across centuries of imperfect preservation, lost or imperfectly interpreted records, and influences from little-investigated and unknown civilizations. The chapters ahead involve examination of engineering advances with intent to show that the societies administering these advances acted in creative and rational ways to solve practical problems that challenged their existence. This view portrays ancient societies in a rational manner through emphasis on technical achievements relevant to their common human concern for survival and economic and social progress forged from a balance between secular and religious concerns. The main theme to be followed is to present the technical underpinnings that underwrote societal progress, the social and administrative programmes that inspired, organized, and managed labour, and the cultural, economic, and political parameters that permitted implementation of new agricultural and water management strategies for different ancient societies. It should be noted that elite power structures are in the best position to implement ideas as they have the oversight to conceptualize a global system beyond dispersed unit operations, organize a strategy for implementation of new technologies, and then provide the logistics, labour, and command function to make the system work for the economic betterment of the population. Since many archaeological hydraulic structures were made with a high degree of planning and engineering skill, it is logical to think that they arose from a central intelligence source capable of integrating information and controlling operations involving vast labour and technical resources to accomplish their objectives.

Of the hydraulic engineering works of ancient societies many have been noted but few analysed for their technical content and place in the history of science. This is understandable as insight into technical accomplishments requires intimate involvement with site details coupled with analytical capability, experience, and imagination to see what is apparent (and not apparent) in the archaeological remains to discover lost pieces of history. Communication between ancient engineers and their modern counterparts is best done by understanding the problem to be solved and the goals to be accomplished using the analytical/empirical tools of the time. When this is done, revelations regarding the technology base and the reasoning process behind the accomplishments of ancient engineers are revealed and give perspectives on their ability to solve hydraulics problems. This process contains elements of reverse engineering as only fragmentary remains constitute the base from which their solutions can be extracted; imagination mixed in with analytics then infills the missing space to define their scientific knowledge base. As the physics of water flow is decided by nature, technical solutions from different eras and different parts of the ancient world yield insights into visions of nature and its control, therefore analysis of archaeological hydraulic works contains insights into how societies and their administrative functions operated and their level of understanding of nature's rules. Occasionally this process reveals ancient discoveries showing remarkable advances in the hydraulic sciences; then, as now, empirical observation coupled with some analytic framework forms a large part of the hydraulic sciences. Although Western science has codified fluid motion through equations, correlations, and test observations, some alternative view of fluid motion in different parts of the ancient world must have been operational to achieve workable solutions. All of these thoughts and musings are the subject of this book along with the wish that future researchers will have a somewhat revised view of the engineering accomplishments of past civilizations, resulting in reinterpretation of their contributions to hydraulic technology.

The science of hydraulics is seen as having early stirrings in the Greek and Roman worlds (White 1984). While some of their successes are basic to scientific progress and germinated applications useful to the modern world, most ancient theoretical concepts of the mechanical world have faded into obscurity based on their prescientific notions of nature's laws. It is traditional to think of Roman hydraulic engineers as practitioners, but not theorists, although this view largely rests on lack of an understanding of how they achieved success with their monumental engineering works. Few Roman engineering-related texts survive and, of those, little is demonstrated of theoretical concepts that underlie fluid behaviour. Despite this conceptualization difficulty, many complex water systems existed and indicated that a substantial knowledge base was operational but lost through the ages. With European discoveries of analytical methods in the 16th to 20th centuries, the hydraulic sciences developed through an analysis and test framework with many discoveries arising from successful mating of analytical solutions to observed phenomena. Key developments by Bernoulli, Euler, d'Alembert, Chezy, Navier, Saint Venant, Poiseuille, Froude, Manning, Stokes, Helmholtz, Kelvin, Reynolds, Rayleigh, and later by Bakhmeteff, Prandtl, and von Kàrmàn, laid the foundation for the modern science of hydraulics (Rouse and Ince 1957). While theoretical technical developments in hydraulics are usually attributed to European traditions, the technical knowledge base and contributions of many early civilizations in Old and New Worlds are not fully known, primarily due to lack of detailed analytical studies. This book attempts to re-examine and restore the contributions of these ancient civilizations and to expand the history of hydraulics to include new contributors.

Cities of the ancient and modern worlds share common requirements: adequate potable water supplies to maintain hygienic standards and domestic requirements for their citizenry and creation of a water distribution system to support their agricultural base. As technologies to improve the efficiency and scale of these requirements have evolved over millennia through engineering advances, the story of the technical accomplishments of ancient societies needs to be reassessed as modern scientific computational advances now permit greater penetration and understanding of the purpose and function of ancient water conveyance and distribution structures. In addition, recent advances in geomorphologic and paleolimnology science related to ice cap and lake sediment core analysis permit reconstruction of ancient climate patterns. New understanding of environmental, climate, tectonic, and seismic forces, and their influence on changes in landform and agricultural field configurations, provides further ways to interpret the archaeological record (Moseley 1977; Keefer and Moseley 2004). Knowledge from these fields superimposed over temporal and spatial changes in settlement and agricultural landscape patterns observed from the archaeological record, together with knowledge of technical innovations and social and political organizational change, permit new interpretations for climate-based changes in the agricultural and socioeconomic landscapes of societies. Since climate variation effects on water supplies are important to ancient societies, insight into their use of historical observations, data recording, analysis, forecasting, and management techniques lie buried within the archaeological remains of their hydraulic structures. Archaeological hydraulic structures thus represent all of the planning and projection ideas put into final form using the available technology base and reveal defensive insights into how ancient societies coped with temporal climate and weather effects to maintain the function of these structures. Of the many technical innovations in water systems design and function, many hydraulic engineering discoveries attributed to Western science in later centuries can be seen to have much earlier origins and serve to revise the current history of science knowledge base. Analysis of water supply and distribution systems, and the governmental and the societal organizations that efficiently managed these resources, thus provides a new avenue of information about these societies and their technological underpinnings not easily obtained from traditional archaeological methodologies and interpretative means.

The first chapter of this book details discoveries in the hydraulic sciences in the ancient New World as well as the technical underpinnings in computation, surveying, and data recording present in these societies. Here the many varied ecological niches and climate/weather variations under which ancient New World societies flourished have led to a wide variety of agricultural solutions tailored for optimization of agricultural productivity—a virtual 'library of innovation' demonstrated the creativity of these civilizations. Further chapters delve into Old World hydraulics technology relevant to sites not previously analysed for their technical innovations regarding urban water distribution systems—here computer analysis techniques examine Roman, Greek, Israelite, and Nabatean archaeological remains to discover the depth of innovation of these civilizations. Finally, later chapters visit the Far East to examine ancient Khmer and Balinese water engineering to complete the world tour of ancient hydraulic science.

In summary, analysis of ancient hydraulic structures reveals not only insight into the technology base of these societies, but also the asset management structure and the degree of applied intelligence of state institutions to conceptualize, design, control, and organize the management of these systems. Since the archaeological record contains the evidence of successes and failures of technical and managerial achievements, as well as design efforts to respond to climate, weather-related, and geological variations in the design and function of systems, new avenues of information about ancient societies' political, technical, and managerial thinking can be extracted. Since ancient world conceptualizations and interpretations of the physical world influenced thoughts on control and manipulation of natural forces, insight into the creativity and knowledge levels of different societies presents yet further discovery. The chapters ahead involve elements of this research to tell a new and revised story of the achievements of ancient societies.

The viewpoint taken in this book is one of a modern-day engineer reviewing the works and accomplishments of his ancient colleagues. Perhaps this is best stated as a work dedicated to appreciation of the problems encountered, the technological means available, and the solutions made to resolve vital issues related to agricultural production and urban water supply systems. Underlying these accomplishments were the development of governmental structures with central planning and organizational skills that revealed the priorities that societies faced with environmental challenges related to agricultural and city development. The engineers' role in these societies is therefore emphasized as the provider of technologies to carry out the plans of the ruling elite; therein resides the subject of the book.

1

Ancient pre-Columbian Peru, Bolivia, and Mesoamerica

1.1 CANAL SYSTEMS OF PRE-COLUMBIAN PERU: THE CHICAMA–MOCHE INTERVALLEY CANAL AND THE MOCHE INTRAVALLEY IRRIGATION SYSTEM, 800–1450 CE

Introduction

Irrigation agriculture is a transformational technology used to secure high food yields from undeveloped lands. Specific to ancient South America, the Chimú Empire occupied the north coast of Peru from the Chillon to the Lambeyeque Valleys (Figure 1.1.1) from 800 to 1450 CE (Late Intermediate Period (LIP)) and carried canal reclamation far beyond modern limits by applying hydraulics concepts unknown to Western science until the beginning of the 20th century. The narrative that follows examines hydraulic engineering and water management developments and strategies during the many centuries of agricultural development in the Chimú heartland of the Moche River Basin. The story examines how Chimú engineers and planners managed to greatly expand the agricultural output of valleys under their control by employing advanced canal irrigation technologies and the economic and political circumstances under which large-scale reclamation projects took place.

The following time period conventions are used in the discussion that follow:
Preceramic and Formative Period (3000–1800 BCE)
Initial Period (IP) 1800–900 BCE
Early Horizon (EH) 900–200 BCE
Early Intermediate Period (EIP) 200 BCE–600 CE
Middle Horizon (MH) 600–1000 CE
Late Intermediate Period (LIP) 1000–1476 CE
Late Horizon (LH) 1476–1534 CE.

Chimú political power and state development was concentrated in Peruvian north coast valleys. Each valley contained an intermittent river supplied by seasonal rainfall runoff/glacial melt water from the adjacent eastern highlands. Over millennia, silts carried by the rivers from highland sources formed

Figure 1.1.1. Map of Peru showing major coastal valleys and highland sites.

gently sloping alluvial valleys with fertile desert soils suitable for agriculture. An arid environment tied the Chimú economy to intravalley irrigation networks supplied from these rivers; these systems were supplemented by massive intervalley canals of great length that transported water between river valleys, thus opening vast stretches of intervalley lands to farming. The Chimú accomplishments and achievements in desert environment agricultural technologies brought canal-based water management and irrigation technology to its zenith among ancient South American civilizations, with practically all coastal cultivatable intervalley and intravalley lands reachable by canals brought under cultivation.

The following sections provide a record of the achievements of the Chimú over many centuries in utilizing advanced technical means to design, operate, amplify, and modify their agricultural resource base subject to climate and environmental changes affecting land areas and water supplies. A major technical obstacle facing Chimú administrators was the need for continuous improvement of irrigation technology and expansion of agrarian land areas to meet demographic growth needs; improvement in the reliability of irrigation systems under climate duress was a further obstacle that challenged the social welfare status of the governed population and required much in the way of planning and innovation to counter. The maintenance of surplus food resources available to the ruling class to provide merit and reward distribution to elite administrative classes was a further consideration as this largesse guaranteed continuity of the ruling power base by consent of the elite classes and thereby permitted the dynastic successions characteristic of north coast governance systems. The intelligence behind agricultural development and the ability of administrators and technocrats to maximize food resources, given limited water, land, and technical resources, is therefore the archaeological gold that can be mined to demonstrate the practicality and rationality that underwrote the success of Chimú society through their administrative structures, which conceptualized and executed major irrigation projects. Frequently, an overlay of ritual and ceremonial practices accompany an administrative structure capable of maintaining a well-organized agricultural base; this activity certifies that deities are in cooperative agreement with the elite ruling classes that control ritual practices. This pairing is well known in ancient societies where practicality and religion cooperate to enhance the legitimacy of the ruling classes. History from many eras in many parts of the world has seen aspects of this shared division of power between state and religious arms and it can be confirmed that ancient South American societies were not immune to such arrangements to control servile populations.

In the sections that follow, the coastal valleys under Chimú control containing vast areas of canal-sourced agricultural and water supply systems are examined from a hydraulic engineering point of view to show the practical intelligence and pragmatic side of the managerial system behind their operation. Subsequent sections demonstrate that defensive hydraulic measures were in place to protect water transport structures against flooding events. Analysis of these measures provides insight into the hydraulics knowledge and the managerial systems in place to organize and exploit these technological advances.

The question of the existence of a research/engineering arm as an integral branch of Chimú governmental structure to complement and advance irrigation technology naturally arises. The scale of development projects in terms of design, construction, and operation of large intravalley and intervalley canals is a strong argument for governmental structures to analyse, organize, and carry out these tasks. The operation of irrigation system networks required analytical/statistical oversight to gauge the design strategy of proposed systems and the effectiveness of existing systems. The goal of maximization of food resources leads to an optimization problem that must have been considered by the Chimú given the variables of water, land, labour, and technology resources and how they were to be best utilized. The results of this Chimú macroeconomic model, as observed from archaeological data, are then useful to show what the Chimú strategies and operations were, and the forms and formats in which Chimú technocrats provided answers. Key variables such as time, arable land area, water flow rates, population growth requirements, canal technology base, labour force availability, climate, soil fertility, and food production rates were of concern to ancient hydraulic societies' development and undoubtedly served in optimization models to assess and monitor productivity. It is tempting to think that these key variables (in formats and notations vastly different from Western science), which formed the basis of a Chimú macroeconomic optimization model, are universal determinants describing the function of any hydraulic society and the importance of measuring the magnitudes of these parameters was practised in some manner by these societies. The planners, accountants, record keepers, and engineers of Chimú society that had a role in the production optimization of intricate irrigation systems that required continuous modification and design changes must have had some form of measurement of these key variables to gauge the success of their designs and modifications. The narrative that follows analyses archaeological field data to assess the technology and strategies utilized within the structure of a Chimú macroeconomic model to gauge the rationality and creativeness of government decision makers—all to better understand how these societies managed centuries of successful agricultural development.

The physical setting of the Andean world

The Andes are composed of the extended, parallel eastern Cordillera Negra and western Cordillera Blanca mountain ranges. The higher elevation eastern and lower western ranges bracket lower intermountain uplands that drain rainfall mostly into the Amazon except in the land-locked, far-south altiplano region and the central Peruvian Huallaga Valley/Santa Valley drainage outlet to the Pacific. Biotic diversity is pronounced and with 84 representatives of the world's 104 life zones, Peru has the largest number of ecological life zones per unit area on earth (ONERN 1976; Earls 1996). However, diversity is asymmetrically distributed by altitude, latitude, and longitude. As in all mountain ranges, ecological zones are stratified by altitude and far fewer species of plants live at high elevations than at low ones. Andean mountain ranges divide the continental climate. Normally, all rainfall in the eastern Cordillera Blanca comes from the Atlantic with a longitudinal gradient in precipitation. Fronting the Amazon Basin, the high eastern Andean escarpment receives abundant precipitation, creating a rain shadow to the west. Consequently, biodiversity is greatest along the lower Atlantic flanks of the eastern Cordillera. The eastern escarpment flanks are steep and therefore difficult to farm. Because the eastern watershed reaches deep into the intermountain sierra, it receives and discharges approximately 90% of all rainfall in the range. Sierra basins have relatively modest slopes amenable to rainfall and runoff farming. Cultivation, in conjunction with high-altitude grasslands for agropastoralism, was the basis for large sierra populations in pre-Columbian times.

Biodiversity is limited in the arid Pacific watershed as this area receives and discharges only 10% of central Andean precipitation. Whereas rainfall farming is possible at high elevations, below 2,500 m the sierra is arid and below 1,000 m the coast is hyper-arid from northern Peru into northern Chile. Coastal aridity, low temperature, persistent southeasterly winds, and coastal fog are attributed to unusual circulation patterns of wind and water in the region. Air currents are driven by the counterclockwise anticyclone system of the mid-Pacific, leading to a low-level jet stream parallel to the South American coastline. This system drives upwelling of cold seawater, which produces an adjacent 300 m-thick cold air layer lacking thermal convection cells preventing rainfall. The result is coastal desert with perpetual wind, almost constant cloud cover and fog kept in place by an inversion layer as well as the barrier of the Andes that prevents disturbance by Amazonian weather patterns. Seasonal runoff from high-elevation rainfall supplies 60 short rivers that descend the western escarpment along steep parallel courses

(Figure 1.1.1). Each valley contains a source of seasonally intermittent river-sourced irrigation water whose flow rate and duration depends on its watershed collection zone. The valleys vary in size and most contain a core of alluvial soils that permit farming by utilization of the river within the valley as an irrigation source. Each northern and some southern valleys indicate that irrigation-based agriculture flourished and served as the foundation for many civilizations over the millennia.

Peruvian northern river valleys have more abundant water supplies than southern valleys because of a latitudinal rainfall gradient. To the south, the eastern and western ranges and the sierra uplands become progressively higher, wider, and dryer. This culminates in a high-altitude (*c.* 4,000 m), 800-km long land-locked altiplano basin. Lake Titicaca occupies the northern end of the altiplano where heavy seasonal rains and abundant land support large agropastoral populations. However, the southern reaches of the altiplano extending into Chile form extremely dry desert areas and consequently support small populations. Northern Peruvian valleys generally show lower tectonic uplift rates than southern Peru valleys; the consequence is that while northern valleys show some river downcutting, nevertheless the rivers can be accessed by canal systems, leading water to lower elevation regions. In contrast, southern valley rivers are deeply incised and lands only irrigable by subterranean water channels intersecting the water table close to mountain zones. The geological, weather, and climate history of different regions therefore dictates the different types of water supply and agricultural systems that can be used and the diversity of agricultural systems suited to local ecological and geomorphic conditions throughout Peru is thus of great interest. The agricultural diversity of highland agriculture is generally limited on the basis of use of low-temperature-resistant, high-moisture-tolerant crop types. Coastal agriculture permits more diverse crop types due to fertile valley alluvial soils and smaller diurnal and seasonal temperature variations but is limited by annual/seasonal water supply variations and dispersed, limited field system areas requiring long transport and distribution irrigation canals. Thus, with many varied ecological zones throughout Peru, many agricultural adaptations and variations were possible for the many societies that occupied different sectors of the landscape. The following section details one such adaptation by the Chimú state on the coastal Pacific margins.

The geographical setting of the Chimú Empire

Within the river valleys and desert margins of the north Peruvian coast lie vast networks of irrigation canals that have sustained the agricultural base of pre-Columbian civilizations for millennia. The Moche River is one of 60 active drainages on coastal Peru and lies within the medium-sized Moche Valley, encompassing about 1,560 km^2 of arable land; this valley was the seat of the Chimú Empire and their capital city of Chan Chan. Because the Andes are not well forested, highland rains cause substantial erosion and rivers transport large sediment loads that formed, over millennia, low-slope coastal valley alluvial plains that supported areas suitable for irrigation agriculture. For most of its 110 km course, the Moche River is entrenched in a narrow canyon that rapidly descends the western Andean slopes. At about 400 m elevation, the flood plain broadens to about 1.25 km and below 200 m the river enters coastal flat lands where the valley widens into a broad alluvial triangle some 25 km wide at the shoreline. Most of the arable land lies north of the river and much of this land is divided into three plains designated the Pampa Esperanza, Pampa Rio Seco, and Pampa Huanchaco surrounding Chan Chan; this area is designated as the Three Pampa area. The major north coast rivers that supplied canal networks originated from seasonal rainfall/snowmelt runoff west of the Andean continental divide; these rivers begin their westward journey through deeply entrenched mountain canyons that broaden into fertile river valleys on the Pacific coast margin. Within north and central coast valleys, ancient civilizations mastered the principles of irrigation technology starting from short, low-slope canal systems found in early Formative Period 4700–3300 BCE sites in the Zaña Valley (Dillehay *et al.* 2006), through Preceramic times (e.g., Huaca Prieta in the Chicama Valley have canal-fed, sunken field plots associated with a nearby lake north of the site; Caral in the Supe Valley, at approximately 3000–2000 BCE, have low-slope, canalized spring-system-derived agriculture), and through Early Intermediate Period (EIP) to LIP times culminating in major Moche and Chimú canal systems. Vital to irrigation agriculture is knowledge of open-channel flow hydraulics together with canal surveying and construction techniques. These engineering disciplines, applied within a framework mindful of the successes and failures of previous canal designs and future requirements of replacement systems, led to technical innovations among early coastal civilizations. These innovations evolved from the need to maximize the agricultural land area and canalized river water available for irrigation while minimizing construction time and labour, subject to the constraints of the available technology base. The economic decisions involved in this process therefore reveal aspects and insights of the water management philosophy and political structure of a society insofar as archaeological synthesis allows.

Historical setting

From the capital city of Chan Chan, administrative oversight over a vast network of agricultural fields and canal systems was maintained over the centuries to ensure a sustainable agricultural base for an expanding population. The city itself was composed of nine major trapezoidal walled compounds (Rowe 1948; Lumbreras 1974; Moseley and Mackey 1974; Moseley 1992a; Moseley and Day 1982) acting as seats of successive generations of royalty. A typical walled compound designated the Rivera complex (Figure 1.1.2) exhibits many rooms of various sizes and functions interconnected through labyrinthine passageways and corridors; outside compound walls constructed from adobe bricks can exceed 15 m in height. Typically, compound internal areas range from the smallest (Rivera) at 50,000 m^2 to the largest (Gran Chimú) at 210,000 m^2. Within the walls of these compounds the strategic planning for agricultural development projects took place addressed by technical specialists. While the technology base used to solve hydrological problems will never be known with certainty, it is possible to reverse engineer probable methodologies by analysis of known Chimú

Figure 1.1.2. The Tsudi compound, one of the nine walled compounds within the Moche Valley Chimú capital city of Chan Chan.

measurement and computational devices as well as application of modern hydraulic analysis methods to archaeological remains of canal systems. This procedure applied to Chimú canal systems of the Moche and Chicama Valleys (Figures 1.1.3–1.1.6) provides insight into Chimú administrative structure as it demonstrates the methodical nature of their decision and execution strategies. In contrast to reconstructing history from archaeological methods emphasizing social explanations drawing from art history, mortuary practices, ceramics, iconography, and architecture, the analyses presented in the following pages provides a view of the Chimú as a largely secular society well advanced in technical knowledge.

Figures 1.1.3 and 1.1.4 show the multiplicity of LIP intravalley Moche Valley canals sourced by the Moche River that supplied water to field systems. Figure 1.1.5 shows intricate canal details in the Pampa Huanchaco area surrounding Chan Chan. The 74-km Intervalley Canal (Figure 1.1.6) as shown in Figures 1.1.3 and 1.1.4 was designed to lead water from the Chicama River south to an intersection point (F) with the Moche River sourced Vichansao canal (canal N2, Figure 1.1.3) located northeast of Chan Chan. Some canals in the Three Pampa field system area (Figure 1.1.3) were designed to be supplied from two rivers in adjacent valleys—initially from a Moche River inlet and later, after abandonment of the N3 canal, by the Intervalley Canal. The canals shown were not necessarily contemporary but rather represent all known Chimú systems existing after hundreds of years of use, modification, reconstruction, and abandonment in the time period 800–1450 CE. The canals shown represent a progression of use, modification, and abandonment, and thus represent a sequence of new replacing old designs. The reasons behind the replacement process are important to understand Chimú decision-making processes and are the subject of the sections that follow.

On excavation of many of the Three Pampa canals (e.g. Figure 1.1.7), each major canal branch was shown to exhibit sequential stratigraphic phases of different construction within the earliest canal bed. Figure 1.1.8 shows several typical canal cross-section construction phases for canal branch cuts in the Pampa Huanchaco system (Figures 1.1.3 and 1.1.4). Many of the canals show relocation and placement excursions of certain branches associated with different temporal phases. These phases (denoted 1, 2, 3 in Figure 1.1.8) are characterized by differences in lining material, usage indications (silt layers and oxidation lines) and/or basic changes in cross-sectional geometry and effective water transport canal area and many of these area changes were achieved by infilling to radically alter the cross-sectional canal shape and carrying capacity. The presence of these canal cross-section phases observed from excavation data were the first indication of severe contraction of the

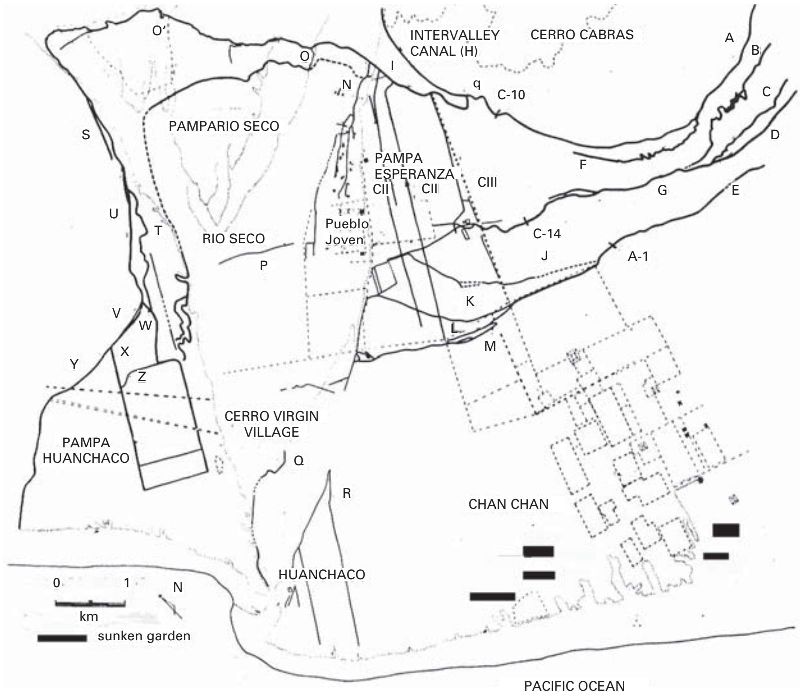

Figure 1.1.3. Overview of Chimú north side Three Pampa (N) and south side (S) Moche Valley canals adjacent to the Moche River.

water conveyance system due to a decline in water supply and led to investigation as to possible climate and geophysical reasons for the canal cross-sectional modifications. Sorting out the temporal sequence of the many canal phases and branches is vital to understand the reasons for sequential abandonment of major canal systems and the reasons behind construction of differently placed new designs incorporating advances in hydraulic technology. Commensurate with spatial and temporal changes in canal placement are changes in the spatial and temporal configuration of Chan Chan's compounds (Kolata 1982), indicating a dynamic relation between city planning and growth, and the surrounding agricultural field systems land use based on the best economic use of land resources.

To understand the reasons for the canal cross-sectional area sequence changes found in all Three Pampa canals as well as the abandonment/reconstruction sequence of canals shown in Figures 1.1.3–1.1.5, it is necessary to first consider the geodynamic forces acting to distort the coastal landscape. As a result of steady subduction of the Nazca Plate under the South American

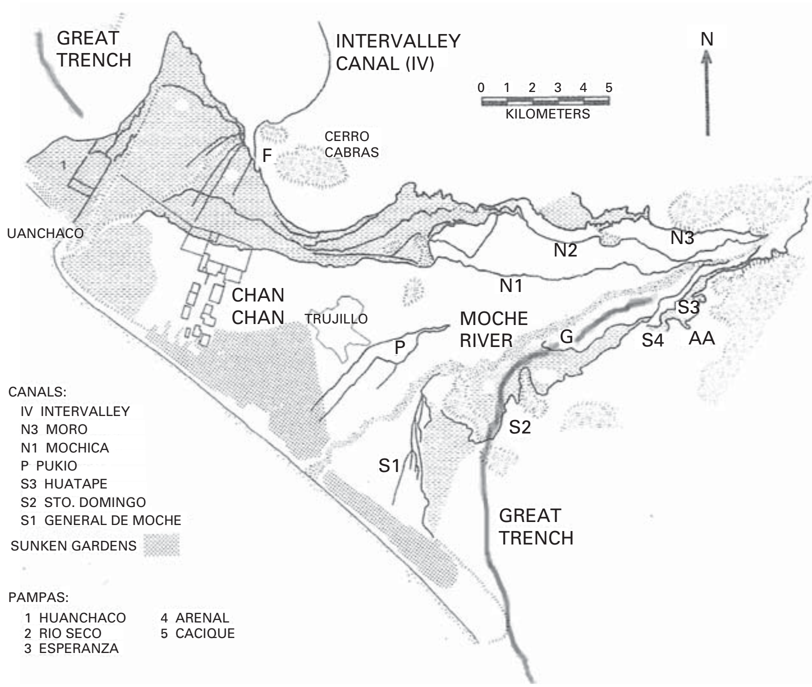

Figure 1.1.4. Pampa Huanchaco, Esperanza, and Rio Seco canals surrounding Chan Chan. The Intervalley Canal (IV) intersects the Vichansao Canal (N2) at point F. Canals: N1, Mochica; N2, Vichansao; N3, Moro; P, Pukio; S1, General de Moche; S2, Sto. Domingo; S3, Huatape. Pampas: 1, Huanchaco; 2, Rio Seco; 3, Esperanza; 4, Arenal; 5, Cacique. Hatched area: sunken gardens.

Plate, the Peruvian coastal environment is continually subject to tectonically driven uplift, subsidence, and seismic disturbances (Sandweiss *et al.* 1981; Richardson 1983; Moseley *et al.* 1992a,b, 1998) as primary effects inducing topographic landscape distortions over time. Coastal Peru is tectonically unstable with a long-term uplift of the coastline at an average rate of 1.8 cm/year (Wyss 1978) indispersed with sporadic seismic events (Sandweiss *et al.* 1981), one of which was recorded between south 8°30′ and 9°0′ resulting in notable landscape distortion. Secondary landscape changes result over long time periods as natural weathering processes establish new equilibrium topographies (Moseley *et al.* 1997, 1998). Tectonically induced displacements acting on coastal zones alter canal slopes, causing their flow characteristics to change. Typically, Chimú canal slopes are less than 0.5°and minor tectonically induced ground slope distortions over time can render systems dysfunctional

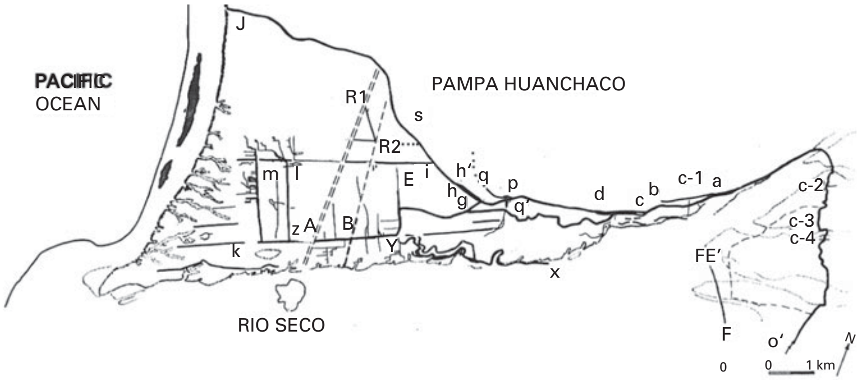

Figure 1.1.5. The westernmost Pampa Huanchaco canal branch past point o (Figure 1.1.4), indicating o J, g z, g i m, and o X Y branches, trial extensions (a b, q p, f), and crossroads R1 and R2.

and require new replacement systems to be constructed (many silt-lined canals that once functioned presently run uphill, verifying coastal distortion effects). Seismic events combined with pre- and postseismic dilatational distortions (Grolier *et al.* 1974; Wyss 1978; Haney and Grolier 1991) and ground settling can lead to patterns of local subsidence or elevation imposed on the gradually uplifting coastal margin containing the entire network of Chimú canal systems. While sea level changes in post ice age times were levelling off and uplift was a continuing process, shoreline changes were manifest as evidenced by observations that the shoreline was 3 km inland from its present position at the start of the common era (Pozorski *et al.* 1983) as observed near the Casma Valley. As an example of coastal uplift in Chimú occupied coastal areas, there is a 3- to 4-m wave-cut marine terrace along the north and south sides of the Moche Valley originating in quaternary times after the sea level stabilized; these terraces exist in other areas of northern Peru (Richards and Broecker 1963). All Preceramic maritime sites extending to early Moche occupations are atop or inland of the wave-cut bluff. Below the bluff are sunken gardens with Chimú, Colonial and modern settlements but no evidence of earlier occupation. This observation coupled with evidence of the river downcut banks of the Moche River indicates that geomorphic forces and landscape distortions were an active consideration in deciding Chimú canal building and modification strategies.

Numerous examples exist of silt-lined canals that functioned before and/or during LIP times but now point uphill or have sinusoidal beds, attesting to cumulative distortions (excepting Colonial canals with deliberate positive and negative meandering slopes used to establish land claims in this period).

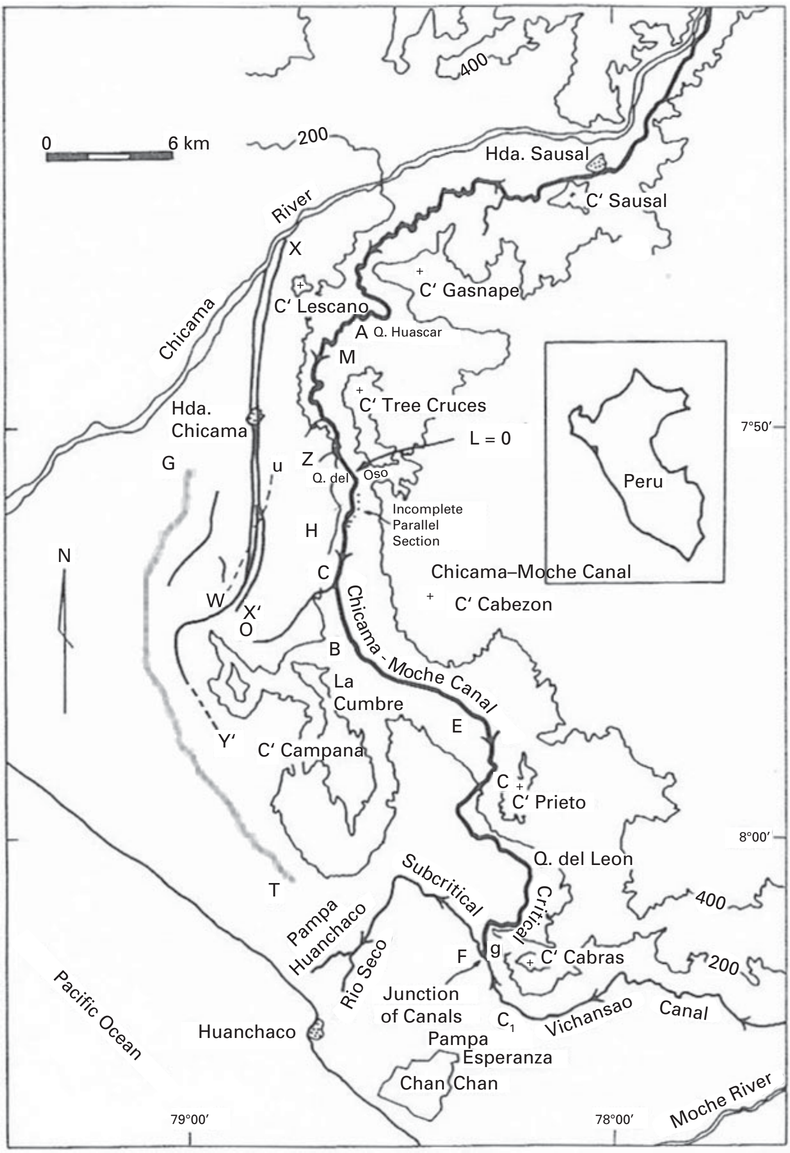

Figure 1.1.6. The Chicama Moche Intervalley Canal. Canals X X′, X Y′, C O, H, M, A, and Z lead to adjacent Lescano and Quebrada del Oso field systems. G T denotes a great trench.

Figure 1.1.7. Pampa Huanchaco canal excavation revealing the cross section geom etry and stone lining.

Tectonic forces driving coastal and valley landscape changes cause rejuvenation effects on steep gradient river valleys, resulting in river downcutting. The presence of raised and angled beach areas subject to strong offshore winds (Haney and Grolier 1991) leads to travelling sand dune formation in some areas, while winds can deflate other areas, producing sequences of site burial and exposure. Further geomorphologic effects are introduced by the infrequent El Niño rains and flash floods acting to erode and resettle debris on a landscape. Historic records indicate that El Niños occur at a frequency of 2–10 years with durations that last from 2 to 6 years (Dillehay and Kolata 2004; Dillehay *et al.* 2004). Over a 297-year period from 1690 to 1987 some 87 El Niño events have been recorded; based on events in recent history, the 1925 and 1982 El Niño events proved catastrophic to transportation systems, isolating communities in Peru for many months while also destroying the agricultural infrastructure. Also occurring are pan-Andean droughts, causing yet further stress on agricultural systems—notable are droughts in the 562–594 CE, 636–645 CE, and 1100–1320 CE time periods, which severely affected civilizations throughout areas within present-day Peruvian and Bolivian geographical boundaries (Thompson *et al.* 1985, 1986 1995b). The El Niño events result in coastal flooding and severe disruption of agricultural systems as well as the social fabric dependent on their production.

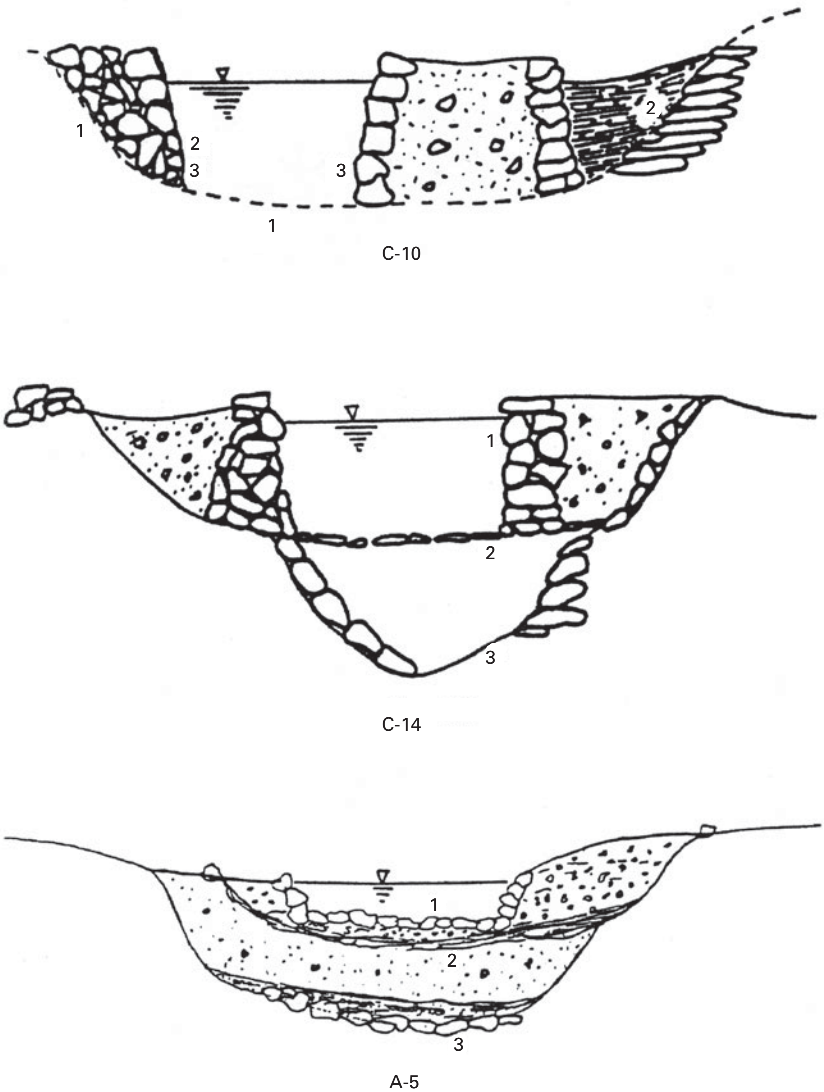

Figure 1.1.8. Cross section profiles C 10, C 14, and A 5 on the A and C branches (Figure 1.1.4) of Pampa Huanchaco canals. C 10 shows a contraction sequence from an early parabolic cross section 1 to parabolic cross section 2 then finally to cross section 3 blocked by adobes. C 14 shows an early parabolic cross section 3 infilled to smaller parabolic cross section 2 contracted to smaller cross section 1. A 5 shows contraction from early cross section 3 to 2 and then to 1 indicative of drought induced canal modifications from lessening water supplies.

Runoff leads to large-scale mass wasting by erosional carving of a new equilibrium landscape. Redeposition of flood-transported sediments, as well as eroded river beds and side slopes within valleys, leads to further landscape non-equilibrium configurations to be acted on by prevailing winds while sediments carried by flood-swollen rivers carrying erosion debris mix with northward oceanic currents to cause coastal beach ridges that mark the passage of major El Niño events. For cases where coastal uplift is active, separate beach ridges composed of washout debris characterize separate El Niño events (Richardson 1983; Sandweiss 1986; Moseley *et al.* 1992b; Rogers *et al.* 2004). Where uplift is minimal, beach ridges formed from El Niño flood deposition events (Moseley *et al.* 1992 a,b) can block soil transfer processes to coastal areas by wind and later flood events leading to an infilled shoreline margin behind the ridge. By continual cycles of this process over time, a sequence of spatially separate ridges can appear and alter the geomorphic conditions under which an agricultural landscape is to be developed. Coastal valley topography has therefore been dynamically changing throughout time from a combination of natural sources and accordingly had presented challenges to coastal civilizations to develop defensive strategies of canal design and water management policies to maintain and expand the irrigation agriculture base.

Historical canal development in the Moche Valley

While versions of Chimú canals are evident from the archaeological record, and indications of climate and geophysical changes affecting canal use are suggested from excavation data, a broader picture of canal development history is available from earlier canal remains. By including greater time depth, the effects of recurring cycles related to climate and geomorphic effects prove invaluable for interpretation of reasons for changes in canal placement patterns.

Early in the history of the Moche Valley, great trench canals (Ortloff 1988) many metres in width and depth led from the upstream reaches of the Moche River across Moche Valley southside desert regions (Figure 1.1.4); a further great trench remnant led southward from the Chicama Valley into the Moche Valley (Figures 1.1.6 and 1.1.4). The intravalley great trench that lies wholly within the southside of the Moche Valley represents Moche River diversion to the south of the site of Moche or possibly a canal to direct water into the intervalley Moche–Virú Valley region for irrigation. Aerial photographs (Figure 1.1.9) and ground observation (Figure 1.1.10) indicate the large size of these canals. Although it is reasonable to associate these trenches with the EIP Moche society due to the proximity of the site of Moche, the trenches may have Initial, Preceramic, and/or Early Horizon (EH) origins or be associated with early Salinar or Gallinazo (pre-Moche) structures in the Moche Valley. Here landscape changes resulting from fluvial and alluvial silt deposits, and flood-related valley erosional deposits as well as El Niño mass wasting events largely obliterated the relationship of these canals to datable early structures. Since many large EH monumental structures occur in this time period in north and central coastal valleys, great trenches may match the monumentality and scope of these constructions and represent early ideas of intra- and intervalley water transport to solve water supply and drainage problems. The fact that the southside great trench canal segment currently extends to and disappears under waves of the Pacific shoreline (Figure 1.1.4) indicates that its construction and function, if used for irrigation, was based on a different valley topography, which was transformed in later times by tectonic distortion effects. This is evidenced by canal segments that presently run uphill and have a silt base verifying the presence of active coastal distortions that rendered the previously active canal system inoperable. A further possibility for the southside great trench may be to bypass El Niño floodwater south of the site of Moche, although this function would require an inlet control that activated above a given river water height. This possibility cannot be ruled out as great trench outlets to field system surfaces have yet to be discovered. Thus, indications of a tectonically active coast were present in changes in the slope of the southernmost canal that rendered it inoperative. While the dating and function of these canals remain enigmatic, their presence nevertheless signals the early start of water manipulation and control practice in the valley. As environmental changes with time altered the Moche and Chicama Valley landscapes on which great trench systems were constructed, new irrigation strategies were required by later inhabitants and subtle design changes were introduced to eliminate the limited applicability of great trench designs for agricultural development purposes. Where trenches crossed erosional gullies (quebradas), erosion from El Niño flood events caused washouts, requiring aqueducted trench reconstruction at near the original slope, but now through the eroded, flood-deepened quebradas. Development of state-controlled corporate agriculture in the EIP to LIP mandated abandonment of vulnerable great trench designs with their limited reach to valley bottom agricultural lands and their replacement by high-level contour canals starting from the upvalley river neck and radiating laterally out onto steep parts of the upper valley (Figure 1.1.11) and onto the hillside margins bounding the valley. Such canals originating from high-level river inlets include large downslope areas for irrigation agriculture. The earliest and highest of the contour canal designs shown in Figure 1.1.4 (northside N3

Moro, southside S3 Huatape canals) were thus introduced with the dual benefits of being able to reach more downslope land area due to their high elevation and invulnerability to devastation from valley floor El Niño flood damage.

As tectonic coastal uplift and concomitant river downcutting proceeded, upvalley canal inlets became stranded by deepening riverbeds, necessitating changes in the branching canals and inlet systems until canal inlets could once again accept river waters. As river downcutting proceeded as a result of coastal uplift, inlets to field system feeder canals were cut deeper to accept river flow and an enlargement of the downstream canal was required. As an example of river downcutting, Figure 1.1.12 shows exposed downcut banks of the Moche River adjacent to the southside site of Moche. Since the steep bank contains layers of occupational debris, it may be concluded that occupation surfaces were eroded through by downcutting river action that continued during and after site occupation. Each riverbed deepening episode, accelerated by occasional El Niño events, led to configuration changes in irrigation canals led off from the river. As riverbed deepening ultimately stranded an irrigation canal inlet, a defensive strategy was to run a newly constructed canal along the side wall of the entrenched riverbed at a higher angle than the riverbed and to start inlets far upstream in the valley neck. The problem with this strategy was that

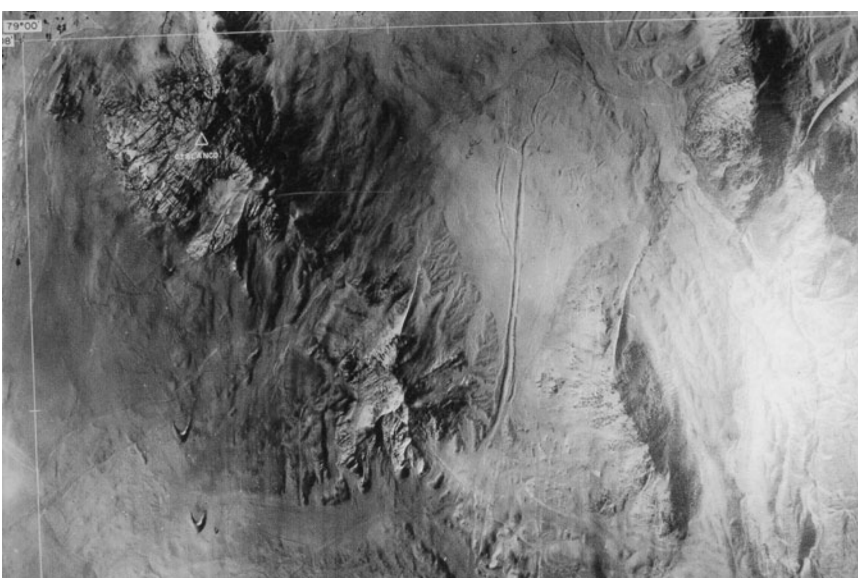

Figure 1.1.9. The southernmost Great Trench in the Moche Valley.

Figure 1.1.10. Ground view of the Great Trench in the upper reaches of the Moche Valley south of the Moche River. The scale is given by the figure standing at the bottom of the trench.

Figure 1.1.11. Highest elevation canal (Huatape S3, Figure 1.1.4) on the southern face of Cerro Orejas in the Moche Valley designed to provide water to upvalley farming areas.

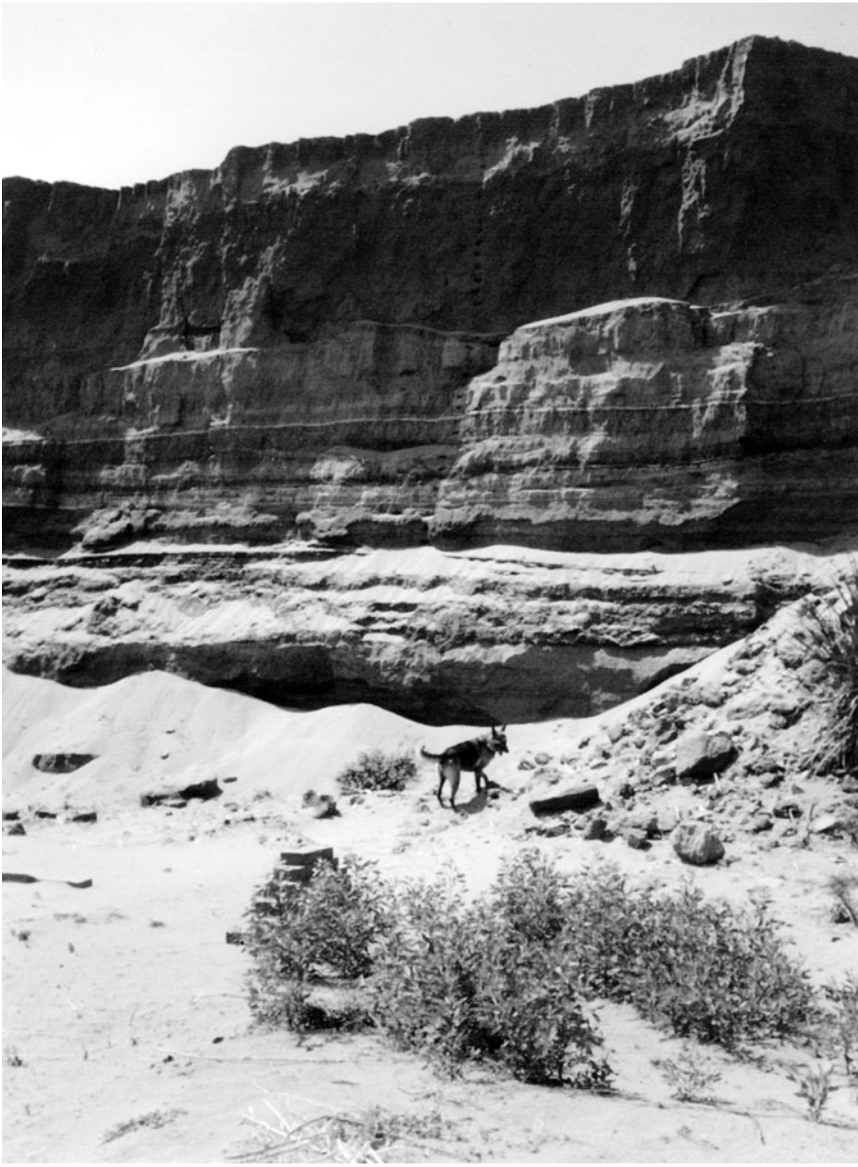

Figure 1.1.12. Southern bank of the Moche River at the site of Moche. The bank shows layers of cultural remains indicating downcutting episodes in late Moche and Chimú times.

as the riverbed deepened, the side wall canal's slope tended towards higher angles (and approach horizontal) to irrigate the same amount of land that was reachable from earlier riverbed depths. The low canal angle therefore limited the water flow rate available to field systems. As the riverbed deepened further, the next construction phase involved moving the canal inlet further downstream; this permitted the irrigation canal to elevate water from the entrenched river and maintain a slope that allowed for the required flow rate to supply field systems. This new configuration resulted in the loss of downhill field area as the canal inlet was now located further downstream. As progressive riverbed deepening continued under coastal uplift, new downstream inlet locations gradually removed land from cultivation as the side wall canal systems elevating water from the riverbed must maintain sufficient slope to permit the required flow rate to field systems. Canal slopes approaching low, near-horizontal values are therefore non-tenable to maintain field system agriculture.

The gradual river downcutting process and its effect on agricultural land area is best illustrated by Figure 1.1.13. Figure 1.1.13A shows the predowncut configuration of irrigation canals where the canal inlet is easily cut from the river (rightmost line extending from the upvalley neck to the ocean). As the riverbed downcuts (Figure 1.1.13B), canal O–P can no longer be reached by the lower river level. A new canal (X) of higher slope climbing along the riverbank is required from the same upstream inlet to reach the reduced agricultural area (Y), which is now less than the original area from the prior configuration. To supply canal O–P in Figure 1.1.13A from the original inlet for the further downcut riverbed shown in Figure 1.1.13B would require a canal slope higher than horizontal and thus be non-functional. Extension of this strategy is limited by how far upvalley the inlet can be placed given the narrow, steep-sided mountains that bound the river at far-upstream locations. The new canal of Figure 1.1.13B must have a slope higher than that of the river at the inlet yet maintain a slope adequate to permit the required flow rate for irrigation of the field system. The result shown in Figure 1.1.13B implies that less agricultural land was available. As downcutting proceeded further (Figure 1.1.13C), the canal inlet migrated further downstream and less downslope land was available for irrigation. Thus canals O–P and M–Q were successively stranded and only small land areas remain for agriculture as a result of river downcutting rejuvenation effects.

Provided expertise existed in very low-angle surveying, expansion of agricultural field systems could occur from any canal inlet as lower canal slopes translate into more included downslope land area. However, if river downcutting progresses and does not stabilize, then the reduction of land area under cultivation is the inevitable consequence. This model thus explains the

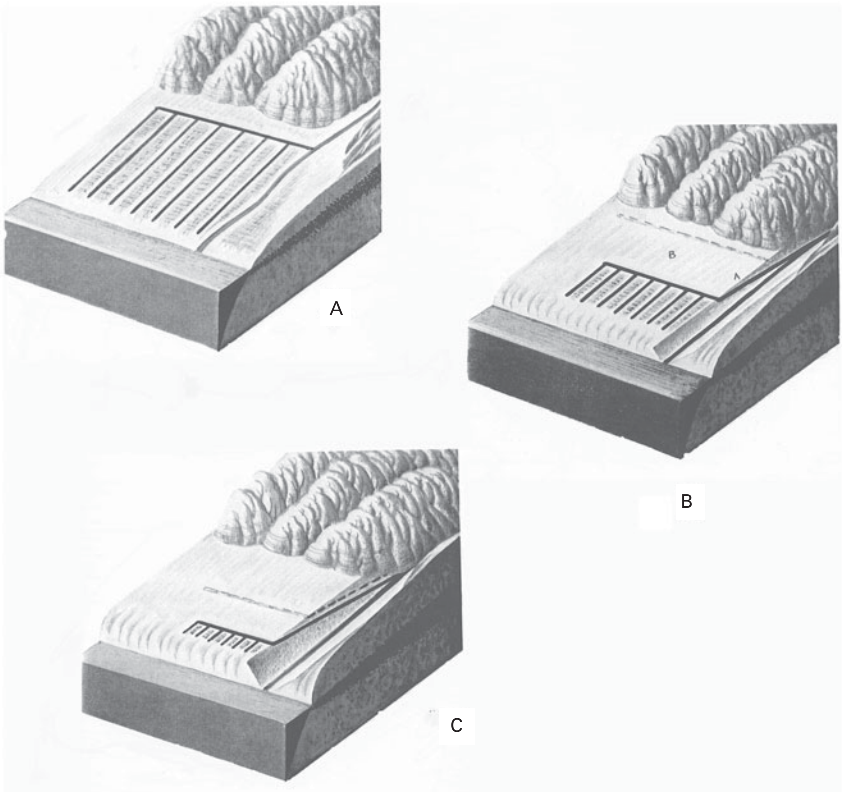

Figure 1.1.13. A, The early, pre downcut phase of the north side Moche Valley irrigation system; high elevation distributive canals are sourced by a main canal originating near the valley neck. B, From downcutting, a new supply canal climbs from the entrenched river at a higher slope than the river leading to lower placed distributive canals and farming area shrinkage. C, Final downcutting stage where the supply canal climbs out of the deeply entrenched river and intersects the land surface in a far downstream location leading to further farm area loss. This process underlies the north side N3 to N2 to N1 and south side S3 to S2 to S1 canal construction/ abandonment sequence.

descending elevation canal sequence observed in the intravalley canal system shown in Figures 1.1.3 and 1.1.4. Early canals are high-elevation systems with inlets close to the valley neck; subsequent downcutting progressively lowers the riverbed and strands the earlier inlets, forcing new canals to be cut further downstream and resulting in progressive land loss. The canal temporal sequence shown therefore represents successive abandonment of the highest canals progressing to the lowermost canals and provides an explanation for the chronological sorting of the canals. In this case, the General de Moche Canal (S1, Figure 1.1.4) represents the final collapse configuration of the southside canals. On the northside, the last and lowest elevation canal (N1, Figure 1.1.4, and, in further detail, canals E–M, E–J, and E–K in Figure 1.1.3) pierce the Grand Chimú compound walls within Chan Chan to irrigate areas within the compound. This indicates that the only alternative left to produce food crops from working canals was to trade urban area for farm area. A spring-sourced canal system (pukio P, Figure 1.1.4) provided some further irrigation potential but in the last phases of canal operation this was a minor contribution to the agricultural base.

In summary, canals progress in time from valley bottom great trenches to high-elevation contour canals; from these canals, a progressive valley northside abandonment/construction sequence of N3 to N2 to N1 occurs; on the southside, a S3 to S2 to S1 sequence occurs based on uplift-induced river downcutting rejuvenation effects. While geophysical effects help to explain the canal sequence, climate effects on canal design and placement in the LIP are also a significant part of the canal story as major drought is known to occur in the time period dating from *c.* 1000 CE forward several centuries. This drought plays a role in understanding the evolution of Moche Valley canals and its effect is introduced in the sections that follow.

Summary of canal design strategies

To maintain the maximum size of an irrigated area, inlet placement of supply canals to field systems ideally must be upstream of the river downcut knick point (the point past which the downcutting proceeds in the river bed) as the river becomes deeply entrenched downstream of this point due to ongoing tectonic activity. A new river profile is established by means of erosive bed slope cutting until an equilibrium profile is established. From field observations, it appears that tectonically induced coastal distortion occurred in early Chimú or late Moche period times, changing surface topography and initiating rejuvenation episodes manifested in river downcutting episodes. Sand inundation from uplifted and/or aggraded sand beaches and constant strong onshore winds covered late Moche V near-coast settlements and canals, and signalled the end of Moche occupation at about 600 CE at the end of the EIP in the Moche Valley. Observations are well documented of Moche canals distorted into uphill slope positions but containing silt depositions from previous (downhill) use. It appears that continuous tectonic processes were active in Chimú times and led to abandonment of early high-elevation canals and construction of new systems consistent with topographic changes induced by tectonic forces. In this environment, great trench canals were replaced by high-elevation contour canals with far-upstream inlets positioned to include maximum downslope agricultural area. The latter half of the LIP appears to be deflationary, with sand shifting from zones previously banked against mountain ridges. Easy traverse of the previously gentle slope, sand-filled environment by large, low-slope trenches on valley bottoms was no longer viable and the emphasis shifted to contour canals that could include large downslope farming areas. The S2 southside canal (Figure 1.1.4) exemplified a canal where the highest possible river inlet elevation was chosen to recapture lands with the Pampa Cacique region and to gain extension to the site of Moche; collapse of this system from downcutting effects led to the far-downstream S3 General de Moche system. On the north side, the highest N3 (Moro) canal ultimately was replaced by the longer N3 Vinchansao Canal, which opened the Pampa Rio Seco and Huanchaco areas for agriculture (Figure 1.1.3). The far-downriver, late N1 system was built when the Vichansao system failed—ostensibly from lack of drought-induced water supplies (as will be subsequently detailed). The 74-km long Intervalley Canal between the Chicama and Moche Valleys (Figure 1.1.6) was an example of a contour canal built on the deflated environment with a high Chicama Valley upvalley intake. This canal was intended as drought remediation system to reactivate desiccating Moche Valley canals with water from the higher flow rate Chicama Valley and its special technology is the subject of subsequent discussion.

As downcutting proceeded, most probably accelerated by El Niño events amplifying riverbed erosion, changes occurred forcing a downstream migration of canal inlets with loss of downslope arable lands, leading to loss of agricultural area in the Moche Valley. Whether contraction of the agricultural base of lands adjacent to the Moche Valley led to expansion and conquest of the northern valleys with their greater water and land areas by the Chimú in the post-1100 CE period is an open question; nevertheless, the conquest and later control of northern valleys is well established in the archaeological record.

The gradual decline of irrigated agricultural land manifested throughout the centuries of coastal occupation, as observed in the archaeological record, is explained in part by the dynamic rejuvenation model which canal dating verifies. El Niño rains appear many times in each century and there is evidence for frequent flooding events in architectural and field system remains in the LIP archaeological record. These events frequently leave beach ridges sequences created by sedimentary outwash deposits from coastal rivers interacting with northward-flowing ocean currents. The presence of uplifting coastal margins sometimes promotes ridge separation, but in the absence of significant uplift, aggradational infilling from aeolian and flood sediment transport serves to produce apparent ridge separation between flood events. The occurrence of seismic events that loosen and displace ground surface rock, gravel, and sand can provide an amplified material load transported by El Niño rainfall surface runoff to source beach ridge formation and can result in greatly amplified ridge material deposits stretching for many kilometres past river mouth outlets. Ground slope changes due to seismic and/or tectonic activity further unsettle the equilibrium of surface materials to promote their mobility under surface water runoff. The debris load begins sorting and deposition on entering the offshore current with coarse gravels depositing first and fine grain materials carried further and depositing later to compose ridges. The result is formation of spatial beach ridge sequences corresponding to sequential major El Niño events formed either when coastal uplift elevates, strands, and separates the ridges, or when aggradational sediment transport isolates an individual ridge and subsequent flood events create a new ridge located closer to the shoreline. With wave and ocean current action on these sediments, finer materials are gradually brought onto beach areas to be transported inland by strong coastal onshore winds in the form of translating dune and barchan fields. The dynamically changing coastal topography coupled with climate and weather events therefore contributes in part to the canal and agricultural field reconfiguration process in the Chimú heartland. Against this backdrop of a dynamically changing environment and its consequences to agriculture, Chimú engineers originated design strategies to deal with current and anticipated water supply problems. The strategies and technical innovations in the sections that follow show the logic and thoughts of the Chimú administration used to counter obstacles posed by natural forces.

While part of the canal sequence history can be ascribed to dynamic landscape changes brought about by tectonic forces, additional considerations derive from LIP climate changes that affected water supply (detailed in a subsequent section). The combination of coastal distortions and climate change effects punctuated by devastating El Niño rains (Nials *et al.* 1979), which severely eroded valley topography and necessitated major canal placement revisions, presents further reasons behind the multiplicity of canal systems that underwent multiple modification and abandonment cycles over the course of Chimú ascendancy on the north coast. The story of the continuous struggle against nature to maintain the canal systems and the innovation and rational decision-making skills that accompanied this effort marks the Chimú as great contributors (and survivalists) in the annals of history.

Intravalley canal technology

Mapping and excavation details of the intravalley Moche Valley irrigation network in early Chimú times have been recorded (Moseley 1977; Ortloff *et al.* 1985). To fully understand Chimú technical accomplishments, the emphasis in this section focuses on later Chimú developments in the Three Pampa area as this later development phase incorporates high technology levels and, consequently, a means to discover achievements in hydraulic science.

The Moro Canal (N3, Figure 1.1.4) is the highest elevation and earliest preserved canal on the northside and although it could potentially water the greatest downslope area, it carried the smallest percentage of Moche River flow rate because of its low slope. During Moche III–IV times (*c.* 400–600 CE), an early version of the Moro Canal most probably supplied canal B–G on the Pampa Esperanza (Figure 1.1.4) through N3 (Figure 1.1.4). The Moro Canal slope averages 0.003 radians (0.172°), and excavated profiles reveal two usage phases. The earlier phase was in use during Moche IV and early Chimú times (600–950 CE) while the second phase is a Chimú construction built after El Niño-derived flooding about 1000–1100 CE. The early-phase canal mainly served upvalley areas and was abandoned in later Chimú times. The 30-km replacement Vichansao N2 canal consisted of a number of unlined segments connected to N3 (Figure 1.1.4), which were dug through stabilized sand drifts banked against Cerro Cabras. The Intervalley Canal (Figure 1.1.6) intersected N2 to provide water to canals on the Three Pampa area (Pampas Huanchaco, Rio Seco, and Esperanza) in an attempt to reactivate the drought-reduced intravalley system. Since the intake of the Vichansao was at lower elevation than the Moro, a low slope was needed to intersect the later reused distal end of the Moro. As the Vichansao slope averages 0.0003 radians (0.017°), a large channel cross-sectional area was required to obtain the calculated 65% flow rate increase over the last-phase Moro flow rate. The Vichanasao–Huanchaco–Esperanza system represents both peak land usage and peak percentage of Moche River water flow utilized for irrigation.

The Vichansao Canal exhibits four major usage phases with progressively smaller nested canal cross-sections reflecting a declining flow rate over time and was abandoned during the last phase owing to Moche River entrenching effects and drought conditions. A canal cross-section contraction sequence of five phases in the Huanchaco system (Figures 1.1.3, 1.1.4, 1.1.5, and 1.1.14) reflects the flow rate decline in the Vichansao Canal based on the contracting cross-sectional areas of the canal phases. Owing to low canal slopes, the Manning equation (Morris and Wiggert 1972) for normal flow is assumed for flow rate calculations. While early Vichansao and Huanchaco canal phases had large flow rates due to the large cross-sectional area of the earliest phase of the canal, later Huanchaco phases show deliberate filling-in of older canals (Figures 1.1.3 and 1.1.8) within the same bed and construction of later phases supporting lower flow rates. These sequential reductions in cross-section and flow rate are dual responses to drought and downcutting processes that lowered the flow rate into the main supply canal to the Huanchaco system. The canal usage configurations shown in Figure 1.1.14 using the notation from Figures 1.1.3 and 1.1.5 are determined by computer search through hundreds of Vichansao–Huanchaco–Esperanza canal phase cross-section

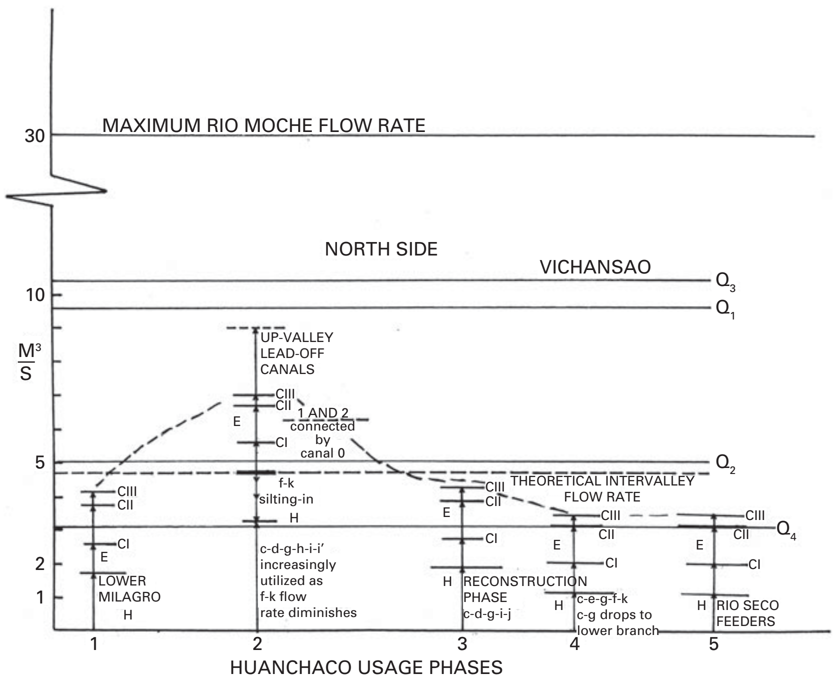

Figure 1.1.14. Flow rate diagram of major north side canals on Pampa Huanchaco from excavated profile cuts on the Pampa Rio Seco (denoted C 1, C 2, and C 3 in Figure 1.1.4 and CI, CII, CIII in this figure). Excavation data of the Vichansao and five excavated profile phases of the C canals show a drought induced decline in water flow rate (dashed line) in phases 2 to 5 after expansion from early phase 1 times. The early Vichansao canal with flow rate Q_1 was adequate for expansion of the Three Pampa area but later declined to Q_2. Q_3 was redesigned to intercept the high flow rate from the Intervalley Canal; Q_4 is final acknowledgement of a low flow rate from the Moche River under drought conditions and lack of Intervalley Canal waters reaching the Vichansao destination.

Table 1.1.1. Maximum Moche Valley north and southside canal system phase flow rates (Figures 1.1.3 1.1.6 and 1.1.14)

Canal system	Phase	Flow rate (m^3/s)
Northside Canal and Pukio Springs		
Serrano (N3 upper branch)	1	0.75
Moro (N3)	C1 (last)	2.5
	C2 (earliest)	6.1
Vichansao (N2)	Q_1 (earliest)	9.4
	Q_2	5.0
	Q_3 (reconstruction)	10.9
	Q_4 (last)	2.9
Pukio Alto (P)	1	0.6
Pukio Bajo (P)	1	0.5
Mochica (N1)	1	9.8
Maximum Moche River		30.0
Southside canals		
Cerro Orejas (S4)	C1 (earliest)	0.5
	C2 (last)	0.2
G Canal (Figure 1.1.4)	1	1.2
Santo Domingo (S2)	1	1.6
Huatape (S3)	1	0.7
AA Canal (Pampa Cacique)	1	2.2
(Later modification to S3)	2	4.0
General de Moche (S1)	1	1.9

geometries for flow paths supporting a common flow rate. Measured wall roughness factors and slopes permit flow rate estimates matched to Vichansao flow rates associated with its various phases. Canal flow rate calculations for the north- and southside canal systems (Table 1.1.1) provide the basis for the results given in Figure 1.1.14 and form the basis for determination of the temporal abandonment sequence. The Vichansao canal in its last phase was severely contracted and served only upvalley feeder canals close to its inlet with the loss of large tracts of land once reached by canals in the Pampa Huanchaco and Esperanza field systems. With sequential abandonment of the Moro and Vichansao Canals, the N1 canal was constructed, resulting in loss of irrigable land between these canals. The N1 flow rate matched that of Vichansao phase 1; its inlet placement downstream of the Vichansao inlet signals the final abandonment of most of the Three Pampa field systems. While drought is a key element in gradual reduction of canal irrigation potential, a severe El Niño event at *c.* 1000–1150 CE (Moseley and Deeds 1982) resulted in destruction of lower Pampa Esperanza canals. New canal reconstruction, now constrained by erosional changes in landscape, severely reduced the agricultural areas available for reactivation and altered Chan

Chan growth patterns as formerly available agricultural land was now used for northward city expansion purposes and construction of new royal compounds (Kolata 1982).

Several conclusions can be drawn from Figures 1.1.3–1.1.5 and 1.1.14. From Figures 1.1.3 and 1.1.4, canal A–q of N2 Vichansao phase Q_1 supplies the Esperanza CI, CII, and CIII canals, downstream Huanchaco canals, the Pueblo Joven area and upvalley canals. After peak flow rates indicating adequate water supplies, the dashed line in Figure 1.1.14 reveals a steady decrease in Vichansao Q_2 flow rate through CI, CII, and CIII canal branches and downstream canals indicative of the smaller nested cross-sections carrying less water.

Reconstruction Q_3 canal cross-section geometry indicates the intention to carry a large flow rate but this was not realizable due to progressing drought. The Q_2 phase of the Vichansao Canal closely matches the design flow rate of the Intervalley Canal at about 5 m^3/s—this indicates that the Intervalley Canal was intended to resupply desiccating Moche Valley canals through connection at point F (Figures 1.1.3 and 1.1.4) through reactivation of the phase 2 Vichansao Canal to supply the Huanchaco and Esperanza area canals with Chicama Valley water. As the Intervalley Canal also experienced water shortages as the drought deepened and never functioned to its full design potential, Vichansao Q_3 was widened again in anticipation of supplying mostly upvalley canals. The final phase Vichansao Q_4 flow rate signals the collapse of the Huanchaco Canal system and water supplies to all but the lowest northside N1 canals. With the advent of a major El Niño event at 1100 CE, Vichansao phase 3 reconstruction canals emphasized upvalley branches as parts of the Huanchaco system were abandoned (g–J, Figure 1.1.5; branch Y, Figure 1.1.5). Vichansao phase 4 indicates that the lower g–y–z branch, Figure 1.1.5, may still have been in use to serve field plots of region. Final Huanchaco phase 5 served limited Rio Seco field plots (q–N–O) but signalled the near abandonment of the Huanchaco system.

On the southside of the Moche Valley, the S3, S2, and S1 systems (Figure 1.1.4) represent successive canal replacements as water shortages intensified in the post-1100 CE drought period. Extensions of intakes further upstream were limited by valley-neck bedrock obstacles and new canals could only be built leading off from the stabilized riverbed downstream of the active downcutting zone. The final and lowermost S1 southside canal represented the final contraction event with substantial land lost to cultivation. This is paralleled by the lowermost northside canals that breeched compound walls of Chan Chan, indicating the premium placed on capturing cultivatable lands with any water supplies that could reach this area. Interestingly, a large defensive trench about 5 m deep encircles the northern parts of Chan Chan cutting these late canals; this trench is probably a defence tactic against invading Inka forces at 1380 CE.

During the many years of operation of the Vichansao and Three Pampa canals, it was apparent to Chimú engineers that a gradual decrease in water supply was occurring and that changes in canal cross-section must be made to accommodate decreasing water supplies. Intravalley canal beds needed to be raised to bring water to field system surfaces and new water supplies brought in. The proposed solution to this problem was the Intervalley Canal (Figure 1.1.6) designed to shuttle water from the Chicama to the Moche Valley through the dividing mountainous intervalley area. Sections of this canal are built on terraces up to 30 m in height (Figures 1.1.15 and 1.1.16) north of Quebrada del Oso and through desert pavement south of this location. Upper reaches of the canal were cut on hill slopes and through sand dunes until the junction with the Chicama River was reached at a far-upvalley location. The terraced portions of the 74-km long canal are mainly masonry lined (Figure 1.1.17) with a major aqueduct spanning the Quebrada del Oso (Figure 1.1.15). By an Intervalley Canal junction with a point sufficiently far upstream along the Vichansao Canal (F, Figures 1.1.3, 1.1.4, and 1.1.6), the Three Pampa region was to be restored to agricultural production. The design Intervalley Canal flow rate (Ortloff *et al.* 1982) reveals parity with the Vichansao Q-2 flow rate (Figure 1.1.14), confirming the intent to reactivate the Three Pampa area. While computer methods were used to calculate this result, the methodology used by Chimú engineers is unknown; given the rugged topography over which the canal was constructed, the matching of the flow rates between different canals is a remarkable accomplishment. The presence of side weirs located along the Intervalley Canal played a role in regulating the canal flow rate and these were most certainly activated to release water from the canal during severe El Niño events. Intervalley Canal flow was designed to be added to limited Vichansao flow to further expand the Moche Valley land area under cultivation by means of reactivating the q–I–S–U–W–X upper branch of the Huanchaco system (Figure 1.1.3). The sum of proposed Intervalley Canal and Vichansao Q-2 flow rates was nearly equal to the intended Vichansao Q-3 flow rate; this could represent a strategy of widening the Vichansao canal cross-section to accommodate increased water flow or, if Vichansao Q-2 flow continued to decrease (which is evident by its final Q-4 phase), replacing Vichansao flow entirely with Intervalley flow.

The Intervalley Canal contains many small aqueducts crossing the numerous small quebradas while contour canals enter, circle around, and exit larger quebradas at a fixed slope. In several cases this strategy was revised in later modifications and shunt aqueducts were constructed across the quebrada mouths, thus eliminating the long contour canal path around the interior

Figure 1.1.15. The Intervalley Canal at Quebrada del Oso.

Figure 1.1.16. The Intervalley Canal at point M (Figure 1.1.6) north of Quebrada del Oso. The canal is built on 20 m high fill terraces on mountain slopes for much of its length.

walls of the quebrada. This improvement shortened canal length and reduced seepage and evaporation losses. The Intervalley Canal's route passed by many lower elevation field areas suitable for cultivation by feeder canals leading from the main canal; fields at Lescano and Quebrada del Oso (Figure 1.1.6) are typical examples. South of Oso, partially completed leadoff canals exist but no preserved field systems are evident. These intermediate fields indicated that all available land area was used for farming in addition to what was possible from reactivation of Three Pampa fields. During Intervalley Canal construction, it may be surmised that these intermediate fields could produce crops pending final connection with the Three Pampa system. It may be surmised that complex water scheduling accompanied use of the Intravalley Canal as many different field areas and destination canals were served on a rotating basis.

The Intervalley Canal was conceived from necessity; its scope and design required a leap forward in technical innovation. The urgency of constructing an alternate supply canal to the failing Three Pampa system necessitated the Intervalley Canal be quickly constructed to match the Vichansao Q-2 flow rate. The problem of finding the shortest canal path requiring the minimum construction labour and time, while providing safeguards against flood damage, led to many technical innovations. However, the many construction

Figure 1.1.17. Stone lined canal section exhibiting dual step construction north of Quebrada del Oso. The upper path is both a canal inspec tion walkway and a hydraulic control feature activated by high water heights.

phases of the Intervalley Canal attest that the same distortion effects contributing to disable the Three Pampa system were at work over the Intervalley Canal's great length. As final canal phases on the Three Pampa area do not show modification to larger cross-sectional canal profiles indicative of new water supplies from the Intervalley Canal, it is questionable if the Intervalley Canal provided flow south of Quebrada del Oso. The final N3 and S3 canals attest to the final effects of extended drought and landscape distortions on collapse of the Three Pampa area.

Technical innovations and water management strategies

The earliest usage phases of the Pampa Huanchaco and Esperanza canal system (Figure 1.1.8) exhibit cross-sectional profiles characteristic of water erosion of sandy soils. Later profiles, which reflect increasingly smaller cross-sections and lower flow rates, are stone lined and built within beds of earlier canal phases. This construction technique takes advantage of thick silt deposits within earlier beds, which significantly reduce canal water seepage. Huanchaco phase 3 postflood construction canals present the opportunity for major design innovations. In Huanchaco system constructions (Figure 1.1.5, branch g–J) and the reconstruction branch (g–A–m–l), Chimú engineers increased canal flow rate by means of increasing the hydraulic radius and decreasing the wall roughness factor that was observed in the post-phase 2 use of low-wetted perimeter, masonry-lined channels as opposed to earlier, wide-base channels with large wetted perimeter and unlined earth banks (Ortloff 1988). There is a trend towards canals of higher hydraulic efficiency by use of new cross-section geometry in the post-phase 2 stone-lined canals. For these canals, the channel geometry is close to the optimal half-hexagon trapezoidal profile required to maximize flow rate by minimizing flow wall shear resistance and wetted perimeter for fixed slope and cross-sectional area using straight-sided walls (Morris and Wiggert 1972). Evolution of trapezoidal canal cross-sections was seen as hydraulically efficient and predates their use in western hydraulic channel designs by several centuries. Calculation of critical and normal depths, slopes, and roughness factors for excavated intravalley channel profiles indicates subcritical flow for all phases. Thus, constrictions or obstacles placed downstream in the canal raised water height upstream to provide a method for elevating water into feeder canals. All field system inlets excavated are raised above the canal floor, requiring a water level rise to activate; the changes in cross-sectional area and canal bed elevation seen in sequential profiles maintained high water level to permit activation of field system inlets. Another change designed to increase canal efficiency was the reduction in channel sinuosity. This change permitted a greater flow rate through the channel for the same hydraulic head. Thus, it appears that the postflood reconstruction Huanchaco phase 3 canals was an attempt to make the reduced flow from the Vichansao supply the maximum flow rate possible by reduction of downstream flow resistance. Vichansao phase Q-4, which is associated with Huanchaco phase 4 and 5 canals, indicated that the water supply decrease was felt back to the Vichansao intake, implying water supply difficulties over the entire valley.

Intervalley Canal technical innovations

Because of technical problems inherent in designing a canal through mountain and sand dune terrain requiring frequent terrace constructions, the

Intervalley Canal contains the most information about Chimú ideas on optimal canal design and water management techniques. Analysis of the hydraulic characteristics of the canal therefore reveals insight into the knowledge base inherent in its design and function. One feature of the Intervalley Canal is the appearance of many canal lengths exhibiting frequent wide variations in streamwise cross-sectional geometry and wall roughness. While social explanations may entail separate, non-communicating work parties with their own versions of how a canal should be designed resulting in these variations, more technical analysis reveals the true intent of the canal designers.

Table 1.1.2 shows geometric data of a 1.6-km section of the Intervalley Canal measured at metre stations (first column of Table 1.1.2) starting at the northern edge of the Quebrada del Oso as the 0-metre reference location. Bed slopes have been adjusted for tectonic angle changes (Ortloff *et al.* 1982) by methods to be subsequently described. In Table 1.1.2, i_b is the canal bed slope, Z is the section modulus, n the Manning roughness factor, B the canal bed width, D_n the normal depth, and D_c the critical depth. The section modulus Z is defined for different canal cross-sectional geometries (typically idealized trapezoids (t), parabolic (p), triangular (tr), rectangular with corner fillets (r), nested, symmetric double parabolic shapes (np), and asymmetric parabolic (ap) in Ven Te Chow 1959, Table 2.1. The notation (t) denotes an idealized trapezoidal shape that has different side wall angles and bottom widths depending on the station location. The appearance of these streamwise geometrical changes is the first hint that some technology related to manipulation of canal cross-sectional geometry is in place to control water flow characteristics.

Two such sections where dramatic canal cross-sectional geometry change was in place are found north of Quebrada del Oso and at point C, Figure 1.1.6. Each of these canal segments exhibit local streamwise variations in opposing side wall slopes, masonry wall roughness, bed slope, and width. As both sections lie upstream of large aqueducts, their function appears to be related to control of the water flow entering the aqueducts.

To test the hypothesis of canal designs that control water flow in a prescribed manner, a scale 1:6 model (Figure 1.1.18) of the channel section at C exhibiting changes in cross-section was made, instrumented with velocity measuring devices, and tested in a hydraulic flume over a Froude number (Fr) range characteristic of typical design and off-design conditions. Here $Fr = V/(gD)^{1/2}$, where V is the average flow velocity, g is the gravitational constant, and D is the hydraulic flow depth. Observed streamline patterns and velocity profile surveys at the water surface were used to interpret the qualitative function of the geometry changes. A small elevated weir placed

Table 1.1.2. Geometric data of the Intervalley Canal: distances measured starting from a reference point (Station 0) 1.6 km from the Quebrada del Oso aqueduct

Station	i_b	Z	n	B (m)	D_n (m)	D_c (m)
0 20	0.026	2	0.027	3.603	1.253	1.861
33	0.009	2	0.028	2.201		
40	0.009	2	0.027	3.658		
120	0.017	1.82	0.036	2.896		
147	0.017 r	1.82	0.027	3.962		
170	0.015	0	0.022	3.962		
220	0.015 p	0	0.023	4.267		
226	0.015	0	0.025	1.524		
258	0.012 r	2.014	0.032	2.643	0.610	0.689
276	0.009	2.014	0.027	3.048	0.541	0.630
306	0.009	2.014	0.025	3.048	0.412	0.389
356	0.009 t	0.580	0.026	5.791	0.413	0.389
406	0.015 np	0.580	0.025	5.791		
456	0.015 p	0.580	0.025	5.791	0.344	0.389
506	0.015 ap	0.290	0.022	7.925		
556	0.015	0.290	0.025	7.925		
606	0.015	0	0.025	7.925		
656	0.015 p	0	0.025	7.925		
706	0.015	0	0.025	7.925	0.288	0.316
756	0.015	0	0.026	7.925	0.459	0.466
792	0.015	0.500	0.031	4.572	0.930	0.755
806	0.015 tr	2	0.032	0.506		
856	0.015	2	0.032	0.506	0.896	1.303
906	0.015	2	0.032	0.506		
956	0.017 t	1	0.032	1.219	0.875	0.893
1006	0.009	1	0.032	0.914		
1106	0.009	1	0.032	0.457	1.143	0.981
1156	0.017	1	0.025	1.372	0.856	0.981
1206	0.017	1	0.031	0.914	0.954	0.981
1256	0.017 t	1	0.022	2.438		
1306	0.017	0	0.028	2.134		
1356	0.017 t	1	0.028	2.438	0.498	0.774
1406	0.017	0	0.024	2.438	0.707	0.702
1456	0.017 t	0	0.026	4.267	0.707	0.702
1606	0.012 t	1	0.029	2.438	0.629	0.656

t, trapezoids; p, parabolic; tr, triangular; r, rectangular with corner fillets; np, nested, symmetric double parabolic shapes; ap, asymmetric parabolic

high in the channel wall is also present in the field channel but not included in the hydraulic model (but indicated in subsequent figures). At low inlet Froude numbers (Figure 1.1.19A), the subcritical flow experiences a net velocity decrease from expansion effects related to the larger exit than inlet area. Flow streamlines follow canal contours smoothly without separation effects similar to potential flow patterns. At higher subcritical inlet Froude numbers,

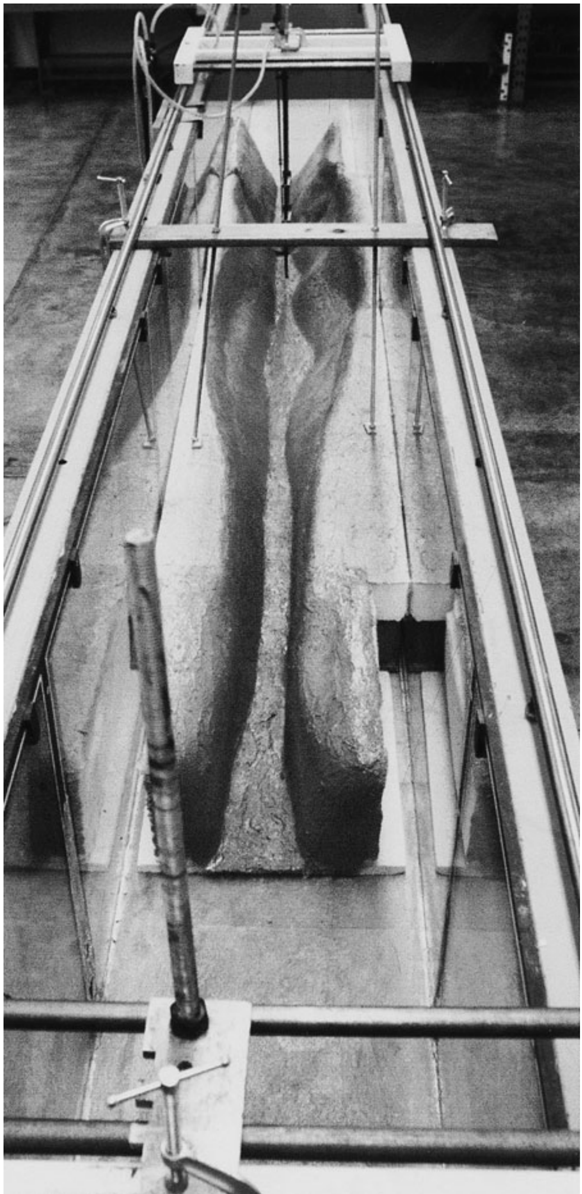

Figure 1.1.18. A 10 m hydraulic flume model used to observe flow patterns induced at Intervalley Canal section M (Figure 1.1.6) ahead of an aqueduct.

a standing vortex appears in the concave hollow (Figure 1.1.19B); this closed-streamline pattern reduces the channel width in this area, creating an 'effective wall' bounded by the outer vortex streamline. Downstream subcritical expansion further lowers water velocity. For supercritical inlet flow, the 'effective wall' created by the standing vortex acts as a supercritical choke and creates a hydraulic jump at the throat section (Figure 1.1.19C). Typically a hydraulic jump results from a supercritical ($Fr > 1$) flow encountering an obstacle or a contraction of the stream by an 'effective wall' beyond a critical separation distance. The presence of the turbulent water zone downstream of the jump is effective in transferring energy to the recirculation zone and its width and circulation strength increase as a result. As the postjump flow is subcritical, downstream expansion results in a velocity decrease. At high supercritical inlet Froude numbers (as may be expected from El Niño inflows into the canal), a complex interaction of the strong oblique hydraulic jump (Figure 1.1.19D) with the recirculation zone results in a subcritical downstream zone that experiences velocity reduction due to expansion. It may be envisioned that at even higher Froude numbers, the jump may migrate upstream of the overflow weir and the increased downstream water height cause outflow from the side weir; the overflow weir has a spill height from the bottom that may be adjusted by inserting stones and may have served to drain off water under heavy rainfall conditions. All of these conditions may occur depending on canal flow rate but at least for design conditions equivalent to $0.6 < Fr < 1.5$, the flow patterns exhibited by Figures 1.1.19A–D are expected to apply.

A plot of the ratio of outlet (FR-OUT) to inlet (FR-IN) Froude number reveals (Figure 1.1.20) that the higher the inlet Froude number, the lower the outlet Froude number. Thus, this unusually shaped section is effective in reducing the outlet Froude number by employing a sophisticated mix of sub- and supercritical hydraulic phenomena operational in different Froude number ranges. In practical terms, the canal shaping is effective in lowering and stabilizing the outlet flow velocity no matter the velocity of the inlet flow, although water height changes occur throughout the transitions. Since erosion of the aqueduct side wall lining increases for high-flow velocities, the velocity decrease is effective in preserving the unconsolidated aqueduct lining over a range of high inlet Froude numbers, $Fr >> 1.5$, resulting from El Niño rain runoff into the channel.

For the channel bed width distribution upstream of the aqueduct at Quebrada del Oso (Figure 1.1.21, first panel), bed slope undergoes change every 5 m and the asymmetric side wall angles and wall roughness change radically along this length (Table 1.1.2). The situation is further complicated by the fact that cumulative distortions acting during the approximately

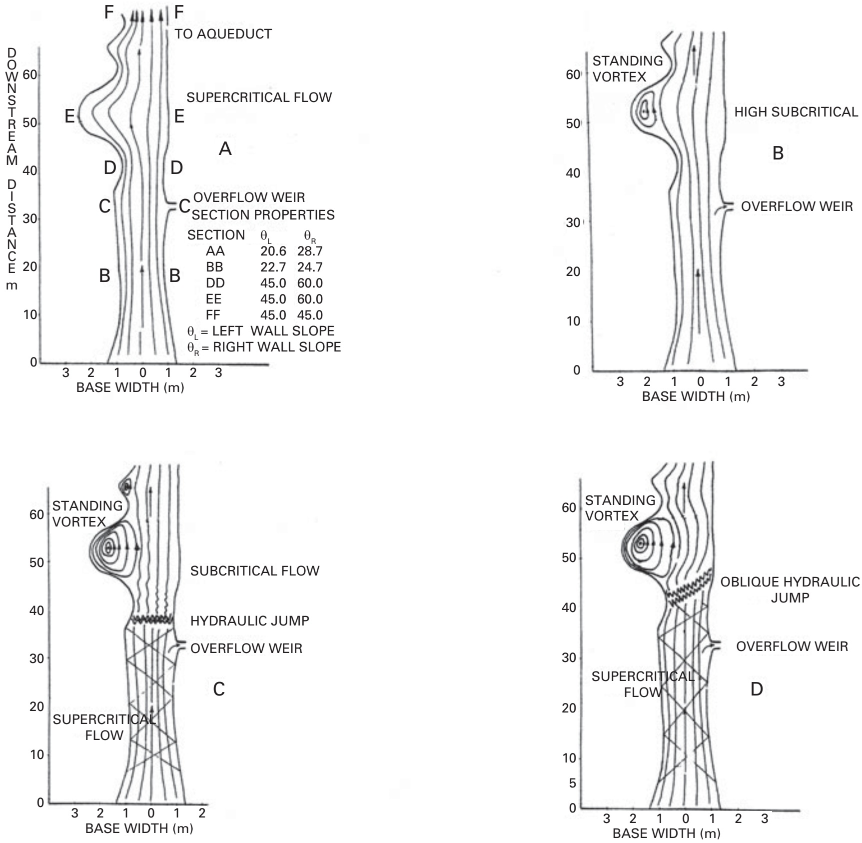

Figure 1.1.19. A, Low Froude number flow streamlines observed at the water surface; streamlines follow wall contours without separation. The elevated side weir releases water at high water heights. B, High subcritical flow streamlines, $Fr < 1$. C, Super critical streamline pattern for $Fr = 1.25$; a vortex narrows the effective channel width, causing back resistance and a hydraulic jump with downstream subcritical flow. D, High Froude number ($Fr >> 1$) streamline pattern; a standing vortex further chokes the flow passage area and causes an upstream oblique hydraulic jump.

1,000 years since construction have altered the bed slope (by settling, rainfall washout of the canal bed, and tectonic, seismic distortions), so that the original slope must be estimated. A computer solution of the local streamwise Froude number distribution can be made (Ortloff *et al.* 1982) under the assumption that the original slope will yield flow heights safely contained within the channel walls at the flow rate equal to that of the destination Vichansao Q-2 canal. Since wall heights frequently vary from 0.3 to 3.0 m,

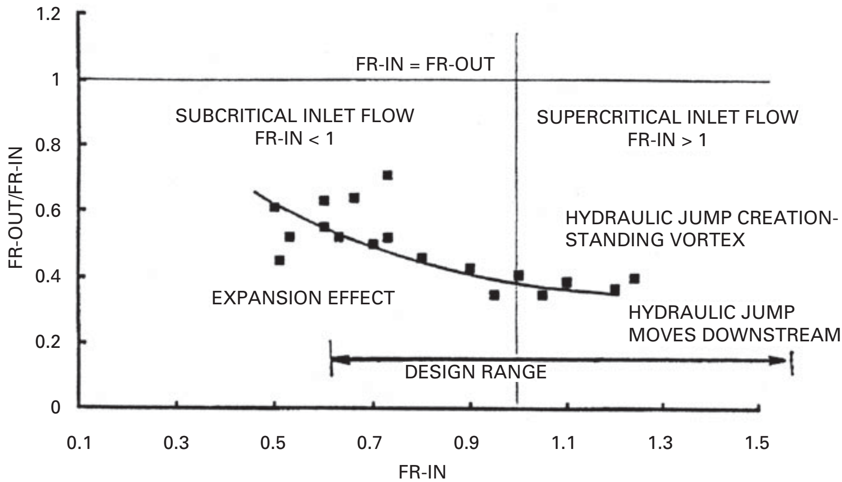

Figure 1.1.20. Ratio of outlet to inlet Froude number from test measurements taken from the model shown in Figure 1.1.18. Test results over a wide range of Froude numbers indicate velocity reduction to a downstream aqueduct to reduce side wall erosion.

some 500 checkpoints in the computer calculation test the validity of the assumed slope. Using the adjusted slope (which equals the original design slope when the system was constructed) results for the calculated local Froude number distribution indicate that values between 0.6 and 1.5 are maintained and large deviations from critical flow ($Fr = 1$) are corrected by deliberate channel cross-sectional shaping and wall roughness changes in both sub- and supercritical flow regimes. These changes along the length of the canal segment indicate knowledge of hydraulic controls that operate differently under sub- and supercritical conditions. Some canal sections contain hydraulic jumps created by supercritical choke sections to change supercritical to subcritical flow; use of contraction sections to induce hydraulic jumps is frequent along this section. The $0.6 < Fr < 1.5$ operational range of the canal (Figure 1.1.21, second panel) is close to modern standards and has two advantages: large amplitude, surface wave instabilities associated with unit Froude number flows are avoided, eliminating overflow and amplified erosion conditions, and the maximum flow rate can be achieved in a canal for a given inlet head. The third panel in Figure 1.1.21 indicates that the critical slope is continuously adjusted not only by slope changes, but also by Manning roughness and canal cross-sectional changes. Although modern practice would dictate a constant channel cross-section and bed slope, the ancient canal was not permitted this option due to bedrock sections that limited the

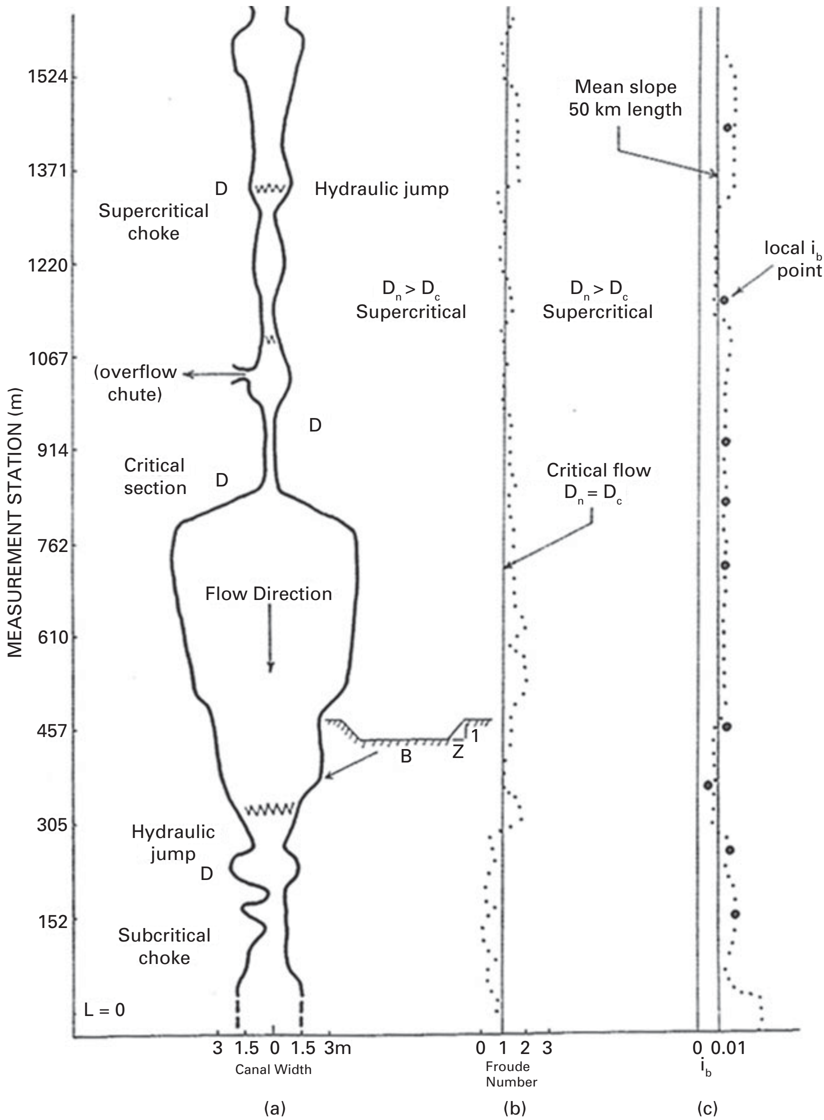

Figure 1.1.21. Flow and geometric properties (a) of a 1,525 m Intervalley Canal section north of Quebrada del Oso (L = 0, Figure 1.1.6). Canal cross section, slope and wall roughness variations maintain Froude number (b) in the range $0.6 < Fr < 1.4$. Local slopes (c) are close to local critical slope values.

slope that could be attained. In this case the remaining options to vary cross-section and wall roughness were utilized, indicating a working knowledge of the interaction of the three important parameters that govern open-channel flow: bed slope, cross-sectional shape, and wall roughness. While open-channel flow technologies were developed in Europe in the 18th and 19th centuries, it is clear that a similar knowledge base was employed in ancient South America canal designs several centuries before and therefore South America has an earlier claim to this technology.

Examination of flow patterns shows a supercritical to subcritical transition before entry onto the large aqueduct structure at Quebrada del Oso, leading to a low-velocity flow that limited channel side wall erosion. This segment of the channel indicated many phases of construction in response to distortions over the long period of canal construction. Apparently, a high subcritical Froude number design was intended for the canal, with local use of channel shaping to produce a low subcritical flow over aqueducts to limit erosion. In the case of the aqueduct at Quebrada del Oso, the channel contraction induced a hydraulic jump that converted the incoming supercritical to subcritical over the low-slope aqueduct. Overall, the Intervalley Canal's design is close to the $Fr = 1$ optimum (Morris and Wiggert 1972) for maximum flow rate water transport for the inlet to outlet height difference.

From the numerous placement and design options for the Intervalley Canal in the region between the Chicama and the Moche Valleys, if a very low slope, subcritical design were selected, a large cross-section area canal with an inlet far downstream in the Chicama River would be needed to produce an adequate flow subtraction from the Chicama River to support field systems en route. This design would exclude valuable upslope arable land and would not be able to join the Vichansao Canal to reopen the Three Pampa area. Because of the large cross-sectional area, the canal would need to be excavated to great depth through sand to bedrock (or with a wide base), thus limiting slope options. If a supercritical Intervalley Canal design were selected, a long canal path would need to start from an entrenched, upvalley Chicama River intake and traverse the rugged interior mountain range; this would require many long terrace and multiple aqueduct structures subject to major canal side wall erosion problems and would require a large construction labour force in remote areas. The canal path ultimately chosen is consistent with the urgency to rapidly complete the canal and is the best design possible from a labour minimization and hydraulic efficiency point of view while permitting the maximum adjacent arable land en route, as well as being positioned for the vital hookup with the Vichansao Canal. Clearly, analysis preceded the design of the canal as its technical content, placement, and labour minimization satisfy some optimization criteria exercised by Chimú administrative functionaries.

In exploration of the Intervalley Canal, some surprising findings were encountered. Specifically, exploration of the mountainous area above the Quebrada del Oso canyon indicated an occupation zone 30 m above the course of the Intervalley Canal. This region contained sinuous channel field systems typical of Chimú fields. The only conclusion is that there may be an as yet undiscovered higher branch of the Intervalley Canal which branches off the Chicama River and leads to this site or high-level springs. Explorations of the inlet from the Chicama River indicate a higher elevation canal branch but the length and further connections to intermountain sites and field systems remain unexplored. This project should be on the list for future explorers as finding the 'lost canal' (if it exists) would certainly give further perspective to the engineering skills of the Chimú to construct a canal system in a most difficult mountainous terrain.

The economic advantage of the Intervalley Canal can be seen by examining Figure 1.1.22, which shows the seasonal river hydrographs (river flow rate during a yearly cycle) of the Chicama and Moche Rivers. The design intent of the Intervalley Canal was to subtract water from the Chicama River and add it to Moche River water to source canals. To demonstrate the concepts involved, the adjusted hydrographs of the Chicama River minus the Moche River flow and Moche plus Chicama River flow are shown in Figure 1.1.22. Since Intervalley Canal supply was to be input into the Vichansao Canal, the maximum Intervalley Canal input flow onto phase 1 systems would supply water from 1 to 1½ months beyond that from the Moche River alone; these water transfer supplements are shown as darkened areas on Figure 1.1.22. On the basis of the diminished Vichansao Q-2 flow rate, an extra 6 months' watering is possible to increase agricultural production in the Moche Valley. Part of the economic strategy was to maintain agricultural output in the face of declining Vichansao flow rate and to use the lower flow rate Huanchaco post-2 phases, with their smaller adjacent areas, for longer periods of time with the help of the Intervalley to Vichansao linkup. The fact that the Intervalley Canal was designed to produce a flow rate to match that of the far-distant Vichansao system indicates use of a technology base worthy of modern practice.

Reflections on Chimu irrigation strategies

The Intervalley Canal contribution to the Three Pampa area was meant to augment the Vichansao flow rate and return the Moche Valley Three Pampa area to productivity. Phase 3 of the Vichansao shows a canal widening effort to increase flow rate; this attempt may have been successful in supplying

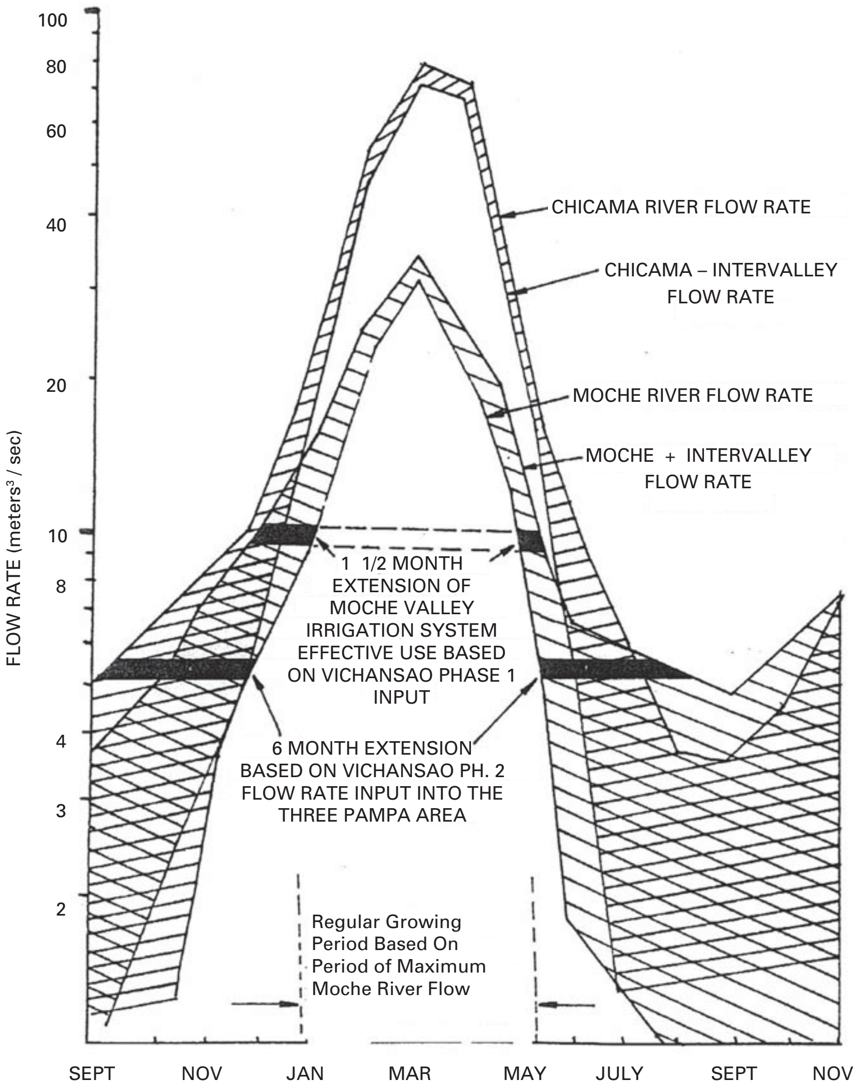

Figure 1.1.22. Hydrographs of the Chicama and Moche Rivers. A fraction of Chicama River water was to be diverted into the Intervalley Canal to Moche Valley irrigation systems by reactivating the Vichansao Canal phase Q_3, extending the Moche Valley growing season.

upvalley systems, but Huanchaco phases 4 and 5 clearly indicate the decline of water supply to this region and the final necessity for installation of the N1 and S1 canals with large losses in agricultural land area.

The decision to divert excess Chicama River flow to supply the Moche Valley lands may have been influenced by the presence of Chimú nobility in Chan Chan and the special status of the adjacent field systems. The desire not to have lands surrounding the capital city barren may have provided the political rationale for extraordinary state-directed efforts to marshal labour forces to reopen the Three Pampa area by use of the Intervalley Canal. Since Chan Chan had a large population of artisans producing high-status trade and luxury goods (ceramics, metalwork, and textiles) for the ruling elite classes of the city, the local fields served to produce crops (largely cotton) for those purposes as well as for the sustenance of the residents of the large agricultural zone adjacent to the royal compounds of the city. The Pueblo Joven and Cerro Virgen villages (Figure 1.1.3) were primarily for agricultural workers outside of the capital city and reflect the low status accorded agricultural workers as manifested in low-quality burial goods and the rudimentary architecture of the compounds. The decision-making governance of Chan Chan therefore may have attached importance to nearby field systems for their industrial as well as agricultural output benefits; perhaps defensive considerations of not relying on distant valleys for food supply played a role in their deliberations. Other considerations may be that Chicama River water exceeded agricultural land requirements and that a fraction of this supply was best used to supplement that of the lesser flow rate Moche River, utilizing the already well-developed canal network in the Moche Valley. Other reasons relate to impending drought obviously observed from declining river flow rates: the diversion of Chicama waters would be a way to keep the Moche Valley seat of empire productive at the expense of less politically important zones. A further reason for bringing water to the Three Pampa area was that Chan Chan derived its water supply largely from deep wells within the city. Water draining into the aquifer from the canal-fed field systems recharged the city wells. In the presence of tectonic uplift, however, the land slowly rises above the water table. The recharge effect was therefore important to raise well water levels to limit the amount of well depth lowering over time. Since there were upwards of 80 large and deep walk-in wells (Figure 1.1.23) throughout the city, it was perhaps more economical in the long run to resupply the field systems and wells at the same time.

Although the calculated original slope of the Intervalley Canal is higher than that of the Vichansao Canal, the difficult intervalley terrain required precision surveying to produce a workable canal. The multiple canal phases within the earliest canal bed and canals adjacent to the last Intervalley Canal

Figure 1.1.23. Descending spiral ramp well to groundwater level within the Rivero Compound.

phase represent efforts (over more than 100 years, according to C^{14} dates taken from organic debris recovered from the Intervalley Canal in the form of burnt aquatic reeds on canal side walls from cleaning efforts) to obtain a workable canal in the presence of continuous tectonic distortions. The fact that corrections to the slope in one part of the system required reconstruction extending over many kilometres up- and downstream complicates the modification process as canal geometric and slope changes affect the hydraulics far upstream in subcritical systems. For supercritical systems, upstream influence does not occur, but as can be seen from Figure 1.1.21 (second panel), the Intervalley Canal flow is mixed sub- and supercritical flow, complicating design changes as bed slope and wall roughness changes were made. The presence of numerous supercritical flow regions along the canal length served an additional purpose: these regions do not transmit upstream influence effects from canal geometry changes in downstream subcritical regions. The use of canal cross-sectional shaping, wall roughness, and local bed slope changes to modulate flow to remain between Froude number limits were the major innovation of the Intervalley Canal. The bed slope may have been limited by hard-to-excavate bedrock patches, but wall roughness and cross-section geometry were skillfully varied to control Froude number. While the canal functioned optimally at a Froude number of unity, practical necessity dictated only piecewise satisfaction of this criterion by near-critical flow zones.

Along the Intervalley Canal, canal segments contouring inside deep quebradas were replaced by later aqueducts across quebrada mouths, thus saving several kilometres of canal path and reducing seepage losses. In other locations, multiple trial canal paths were laid out and partially dug to explore bedrock depth and construction options to reduce labour input. Large boulders were used for the construction of culverts that underlay the base of aqueducts spanning the mouths of quebradas. When El Niño rains collected to form torrents flowing down quebradas blocked by aqueducts, the boulders forming the aqueduct base allowed flow to pass through and prevented water entrapment behind the fill structure, which led to washout of aqueducts. With the probable abandonment of the segment of the Intervalley Canal from the Quebrada del Oso to the Vichansao linkup, the N1 canal, as a last resort, was extended towards Chan Chan. Compound walls within the city were breached, and irrigation agriculture occurred within city walls in the final stages. This collapse of the Moche Valley agricultural base was near completion in the 15th century, despite heroic efforts to extend its lifetime.

Regardless of reasons to initiate the Intervalley Canal (and to reconfigure the intravalley canals), the labour, planning, and infrastructure necessary to proceed with construction projects to minimize labour input, achieve maximization of its flow rate, match reactivation of the Three Pampa region, and ensure optimum placement of the canal indicated that planning and technical knowledge accumulation was a central activity of the administrative levels of Chimú royalty. While specialists existed for craft production, it may be surmised that similar branches of government were charged with the technical aspects of canal design, construction, and modification activities that showed cognizance of the many destabilizing factors that affected their function. This implies that the record keeping and monitoring activities of field productivity function were vital to the operation of government beyond ceremonial activities and that practicality based on technical knowledge played a significant role in the state apparatus.

Climate considerations

With advances in the reconstruction of the Andean paleoclimate through ice core analysis (Thompson *et al.* 1985, 1994, 1995a,b, 1996; Shimada *et al.* 1991), it is now possible to estimate periods of drought and excessive rainfall over many centuries (Figure 1.1.24). In particular, the 800–1450 CE period is characterized by many significant climate changes that affected agriculture.

The Quelccaya icecap (Q, Figure 1.1.1) is located in southern Peru (13°,56′S; 70°,50′W) and is the source of climate data obtained from analysis of ice layer thickness related to yearly cycles of precipitation intensity; additional data are available from the Huarascan icecap in northern Peru. Yearly deposits of organic material from westward Amazonian winds leave C^{14} datable organic layers that delineate the various thickness ice layers and add chronology to the climate proxy record. Analysis performed by Thompson and co-workers has shown that climate trends obtained from this source apply throughout Peru in the time period of interest to this study.

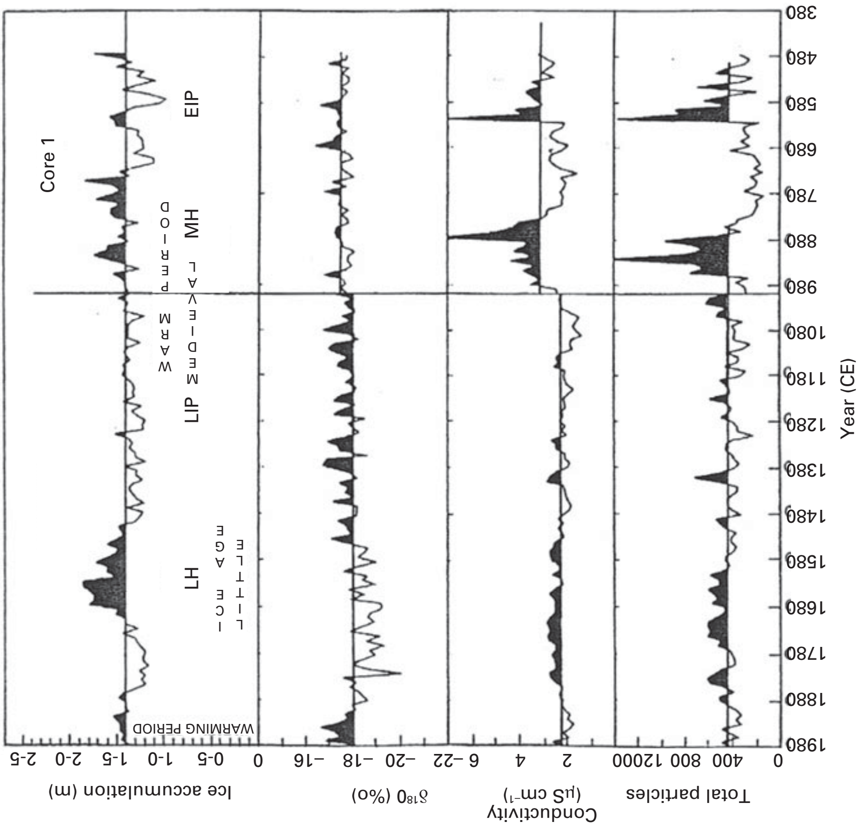

Figure 1.1.24. Climate data obtained from the Quelccaya ice cap (Thompson 1982) showing particle density, conductivity, $\delta^{18}0$, and ice accumulation thickness in the Early Intermediate Period (EIP), Middle Horizon (MH), Late Intermediate Period (LIP) and Late Horizon (LH).

Icecap data (Core 1) in the form of the 9-year moving average of ice layer thickness from Quelccaya over the period 800–1400 CE have been supplied by L. Thompson (1990, personal communication) and are summarized in Ortloff and Kolata (1993). Periods characterized by sequences of large ice layer thickness are wet periods with sequential years of above-average precipitation; sequences of small ice layer thicknesses indicate extended drought periods. Accumulations shown are given as metres of ice equivalent. As seen from Figure 1.1.24, a decrease in the mean precipitation level from pre- to post-1100 CE is statistically significant and lasts throughout the LIP, indicating climate change. In addition to the overall precipitation decrease in the post-1100 CE environment, a second period of more severe drought occurs from 1250 to 1320 CE, within the already reduced precipitation period extending from 1100 to 1400 CE. The cumulative effect of a relatively small (*c.* 5–10%) yearly decrease in the mean pre-1100 CE precipitation levels in the post-1100 CE environment ultimately affects agriculture. Up to 1100 CE precipitation accumulation increases, indicating large cumulative water resources (in lakes, groundwater, rivers, snowcaps, and icecaps) available to all forms of agriculture; past 1100 CE, the situation changes and due to lower amounts of precipitation, a gradual decline in available water resources occurs, ultimately affecting agricultural productivity. A further view of changes in the 800–1400 CE time period based on 3- and 9-year moving averages of the ice layer thickness reveals that if pre- and post-1100 CE data are viewed as separate normal distributions (Figure 1.1.25), then it can be demonstrated that these distributions are statistically independent to a high degree of confidence by means of the *t*-test in combination with the Kolmogorov–Smirnov test for a normal distribution representation of the data. Note that the *t*-test, which assumes normal distributions for populations, may have the normal distribution hypothesis relaxed for cases where large data sample sizes are available, as in the present case. In terms of the statistical measure, details are shown in Table 1.1.3 in terms of standard definitions associated with the *t*-test.

A climate change to drought conditions appears to occur past *c.* 1100 CE. Here drought means that average yearly precipitation amounts decrease by 5–10% from previous, pre-1100 CE norms and the cumulative effect is felt by gradual decreases in water table and runoff amounts to river valleys rather than any sudden change in water supply. According to data supplied by L. Thompson, observed wet periods in post-1025 CE time include short time episodes from 1165 to 1195 CE, 1200 to 1230 CE, and 1305 to 1335 CE within the overall 200+ year drought period.

Given these changes and the trends described in the previous sections, it is possible to piece together the environmental change and societal response of

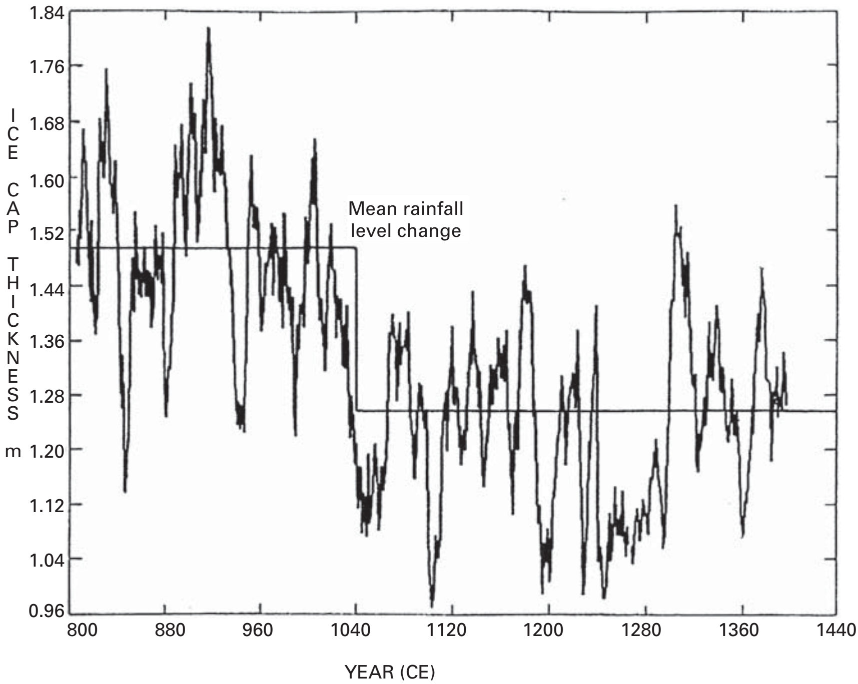

Figure 1.1.25. 800 1440 CE Quelccaya ice cap thickness. The t test indicates pre and post 1000 CE climate data are independent normal populations signalling climate change from wet to an extended drought period.

the Chimú as climate-related to some degree. Specifically, the Huanchaco and Vichansao Canal profile changes shown in Figure 1.1.8 can be interpreted as LIP drought-response measures indispersed with episodic influences from river downcutting accelerated by major El Niño episodes. As water resources decreased due to drought, connected Vichansao and Huanchaco Canal cross-sections were made continuously smaller and elevated to bring lesser amounts of water to surface field systems of decreasing area. The use of hydraulically efficient, low-flow resistance canal cross-sections in the form of stone-lined,

Table 1.1.3. Pre and post 1025 CE annual ice accumulation averages

Group	*n* (sample points)	x_m (mean)	*s* (standard deviation)
Pre 1100	200 years: 325	1.487	0.382
Post 1100	200 years: 376	1.232	0.316

$T = 8.457$; degrees of freedom $= 403.7$; $p = 0.0005$

half-hexagon shapes permitted higher flow rates of reduced amounts of water to fields to sustain irrigation needs. The Intervalley Canal can now be seen as a labour-intensive, emergency project to tap Chicama Valley water to supplement declining Moche Valley water supplies reduced by progressive drought to reactivate the Three Pampa area. Intervalley Canal water added to declining Moche River supplies was used to extend the growing season to provide additional food resources in anticipation of lean years to follow and many structures within Chan Chan appear to have a storage function. Despite occasional respites in drought, the long-term trend of persistent drought necessitated Intervalley Canal construction as a permanent solution for increased water supplies. C^{14} dates from the Intervalley Canal, as well as estimates of construction time required, indicate a multidecadal construction time indicative of the awareness of administrative officials to note yearly changes in water supply trends. Chimú administrators next devised a plan to overcome the water supply problem using available hydraulics and surveying technologies to map an optimum intervalley canal path, plan logistics to implement construction, and then marshal necessary labour resources for construction. The result was an integrated network of inter- and intravalley canals with options to transfer agriculture within, along, or to different valleys depending on available water and land resources. This operational strategy functioned for many centuries to provide a stable economic base for the Chimú and acknowledged climate effects in their planning stages.

Water management strategies of the Chimú

Given the narrative thus far presented, the water management strategy of the Chimú can be graphically represented in Figure 1.1.26. This figure represents the history of various key parameters governing irrigation agriculture in the Moche Valley during the Chimú occupation. The curves shown represent land area under cultivation (A), total flow rate of all supply canals (Q), construction labour input (Ψ), and engineering sophistication index (Φ) all within the time interval of Chimú occupation of the north Peruvian coastal area. The index Φ is primarily based on the ability to survey low-slope angles on the order of those observed from field survey of the Three Pampa area. These curves and the calculations to derive specific values originate from data analysis performed previously (Ortloff *et al.* 1982, 1985; Ortloff 1988).

From Figure 1.1.26, a steady increase in land area, water supply, input labour, and technical sophistication index characterize pre-1100 CE LIP times and indicate a period of expansion towards full exploitation of all of the Moche Valley's agricultural lands. Surveying skills play a role as increases in

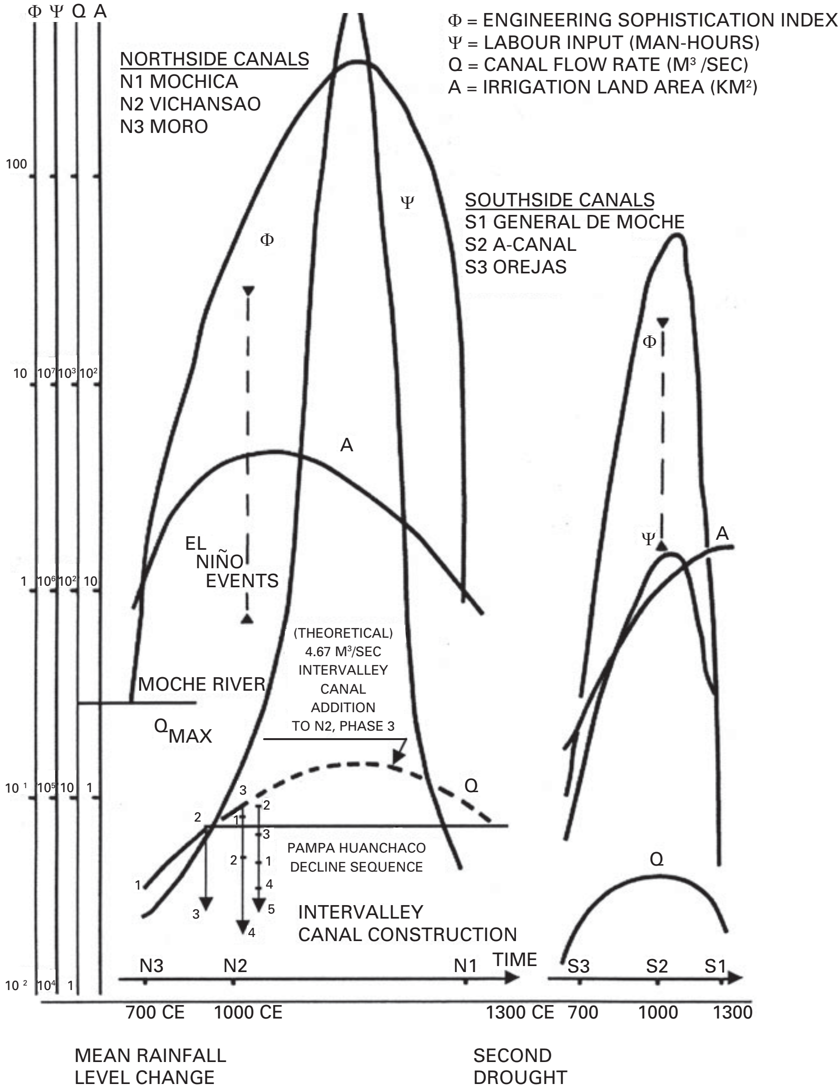

Figure 1.1.26. History diagram of north and south side cultivated land area, labour input, canal flow rate, and engineering sophistication index during Chimú occupation of the Moche Valley. North side canals: N1, Mochica; N2, Vichansao; N3, Moro. South side canals: S1, General de Moche; S2, A canal; S3, Orejas. ϕ, engineering sophistication index; ψ, labour input (labour hours); Q, canal flow rate (m^3/s); A, irrigation land area (km^2).

low-angle measurement technology enable more high-elevation canals to include more downslope agricultural areas as represented by the N3 high-elevation canal that provided water for the Three Pampa area at its maximum extent and AA, S2 canals for agricultural areas on the southside of the Moche Valley. With the advent of post-1100 CE declines in precipitation level, lower canal flow rates (Q) occurred as both canal profiles and climate data attest. High-level Moche Valley north- and southside canals dropped out of use in sequence from tectonic and drought-induced effects gradually eliminating the Pampa Huanchaco, Esperanza, and southside canals from use and decreasing available land area (A) for cultivation. Although the gradual decline in canal flow rate was addressed by redesign of the cross-sections in the Pampa Huanchaco and Esperanza areas to improve their hydraulic efficiency, the trend towards decreased water supply was irreversible in the post-1100 CE environment. Phase 3 profiles (Figure 1.1.14) indicate that about a third of the phase 2 flow rate was available for Three Pampa fields as the drought continued. After many years of decline, new water sources were sought to revitalize the area by means of the Intervalley Canal linkage to the N3 canal. This massive construction project required labour resources from throughout the empire as well as new technologies (Φ increase). With a design flow rate of 4.67 m^3/s (Ortloff *et al.* 1982), the Three Pampa systems could theoretically be revitalized through the N3 system since the Intervalley Canal matched that canal's flow rate. As the Intervalley Canal was probably functional at least as far south as the Quebrada del Oso, and may have functioned to some degree up to the Vichansao connection, the full capability of the Intervalley Canal was never realized due to lack of a sustainable Chicama River flow rate and the restoration of the Three Pampa area not completely realized. As the drought period extended over many decades, the water supply to canals (Q) gradually declined and land area under cultivation (A) declined precipitously. The city of Chan Chan, despite decreasing water supplies from rivers and canal seepage, could maintain its vitality to some degree by deepening the depth of its wells to the water table surface and employ sunken gardens (mahamaes) excavated to the phreatic zone of the water table to maintain limited agriculture. This shift in use of labour resources (Ψ) represented a survival tactic as canal irrigation use declined. Although city life could continue to some degree, the irrigation agricultural base was compromised and undoubtedly the farm labour population base could not be sustained indefinitely without adequate food supplies. The city of Chan Chan was not without political recourse, however, as valleys to the north containing large flow rate rivers and developed agricultural systems were next subject to conquest and consolidation within the expanding empire (Topic 1990)—possibly as a response to maintain the agricultural base of the society.

The story of Chimú canal operational strategy is therefore one of modification of canal spatial locations in a logical manner given the constraints imposed by natural forces on the viability of these systems. Apparently the strategy was to maximize food production by redistributing all available water resources to available lands—as some portion of arable lands became non-reachable by Moche Valley canals due to downcutting, other lands were opened via the Intervalley Canal distributory system in lands between Chicama and Moche Valleys to compensate for intravalley land losses. As in modern societies, the Chimú demonstrated flexible resource allocation strategies combined with technical innovations that addressed problems derived from observed changes in their natural environment over time. In this sense, Wittfogel's (1957) arguments resurface about whether bureaucracies are created to solve problems or problems create bureaucracies to provide solutions. Observing the Chimú, it appears that their bureaucracy was very efficient in guiding sustainable agricultural production through many centuries while addressing nature's provocations in creative and innovative ways.

Surveying technology

Surveying technology was vital to Chimú canal projects and its application yields insight into administrative structures that were responsible for projects derived from the technology and innovation base available to Chimú engineers. Since surveying was key to laying out contour canal paths, and surveying of very low canal slopes key to including large downslope land areas suitable for agriculture, a hint of how the surveying may have been performed (Ortloff 1988) comes from a LIP ceramic vessel in the Archaeological Museum in Huaraz described by Rostworowski (1960). It consists of a vertical hollow cylinder about 18 cm in height with an outer diameter of *c.* 5 cm capped by a shallow bowl. The cylinder has opposing cruciform cutouts on both sides. The bowl rim is parallel to the sight line from the centre points of the opposing cruciform openings so that when the bowl is brimmed with water, the cylinder is held vertically. A hollow sighting tube inserted at an angle through the vertical parts of the opposing cruciform openings allows a known angle to be sighted with respect to an artificial horizon created by the water surface. A schematic drawing of this device is shown in Figure 1.1.27A. Using the principle behind this device as a guide, a modified bowl (Figure 1.1.27B) was constructed and used in field tests to gauge its effectiveness in surveying small angles. The hollow sighting tube passes through an opposing cruciform opening with calibration marks to denote fixed angle positions in the vertical direction. When water is placed in the bowl and levelled with the three levelling marks in the bowl interior, the sighting tube placed at the cruciform intersection point is exactly level and parallel to the water surface. Relative to this position, an angle may be set by moving the sighting tube to a vertical marker position along the outer cruciform groove. Its use is based on simple low-angle geometric principles, as shown in Figure 1.1.27C. A constant slope can be surveyed by first marking a height h on a surveying rod equal to the height of the sighting tube; next an 'artificial horizon' horizontal line is surveyed and marked on the rod placed a distance L from the centre of the bowl. The division of h by L may then be performed by counting the number of times (n) the rod height h 'fits' into the distance L (or, more accurately, by the method of the next section). As $L = nh$, then $\Theta = 1/n$ to a good approximation for large n and small angles. Once an angle is surveyed, hydraulic calculations proceed in parallel to confirm the engineering basis for the selected canal system design. Use of the instrument in field survey revealed that angles less than 0.25° are easily surveyed. Although no surveying bowl has been found intact to exactly match

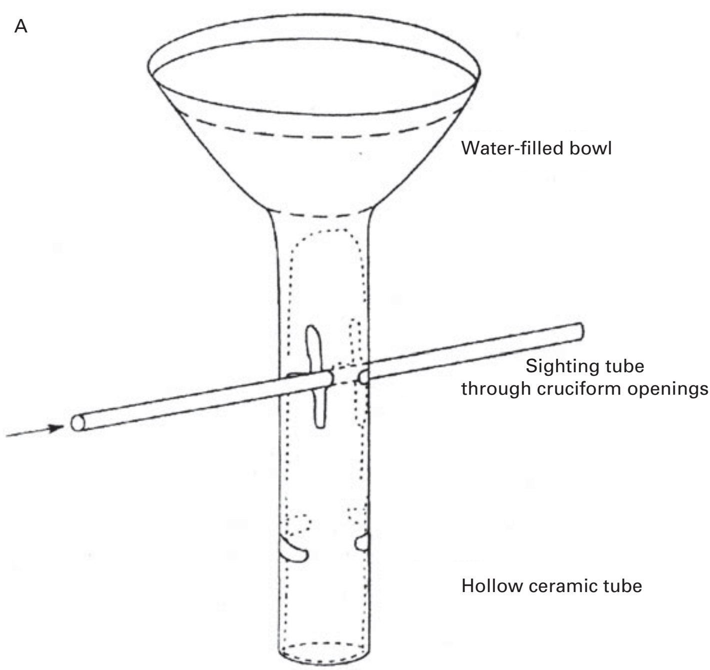

Figure 1.1.27. A, Schematic of a Chimú surveying instrument based on a ceramic located in the Huaraz Museum, Peru. B, Extension of the Figure 1.1.27A concept in the form of a surveying instrument with an artificial horizon derived from the water level contained within the bowl. C, Use of the surveying instrument for practical angle measurement of canal slopes.

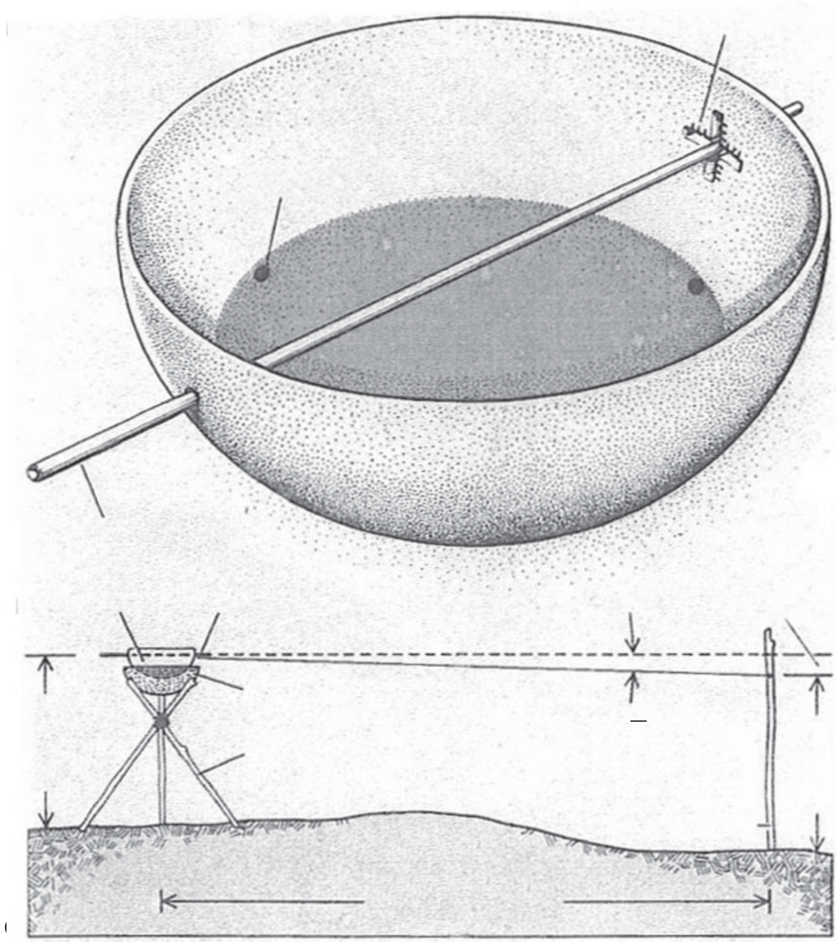

Figure 1.1.27. (Continued)

the one proposed, nevertheless the presence of accurately surveyed canals implies that some equivalent technology was used to perform these tasks, perhaps using an instrument identical to that described.

The mathematical basis of Chimú surveying and measurement techniques

Since design of canal systems on the scale of the Intervalley Canal required surveying and calculation to originate a design, a review of the computational and recording ability of Chimú engineers is next described. While surveying skills are manifest by intravalley and Intervalley Canal designs, little is known about the mathematical basis for the Chimú capability to produce near-critical hydraulic flow designs. Although the default position is one of empirical observation to govern hydraulic designs, this may preclude recognition of some form of hydraulic calculation that falls outside of traditional Western engineering formalisms. It is clear that some recognition of the interrelationship between canal wall roughness, bed slope, and cross-section was known and utilized for both sub- and supercritical flow regimes. While these concepts are well known in modern hydraulic theory, there are simple tests to determine the flow regime that require only observation. This distinction is important as the flow regime (sub- or supercritical) produces opposite hydraulic effects when the flow encounters channel constrictions, obstacles, and cross-sectional changes. For example, to simply determine the flow regime, if a rod is thrust into a moving stream, wave patterns will be formed around the rod. If the waves form a downstream 'V' pattern, then the flow is supercritical and the flow reacts differently to channel constrictions and openings than for subcritical flow, for which a deformed water wave ring structure exits centred around the rod. If the flow is close to critical, then relatively flat standing waves exist ahead of the rod. In modern terms, for supercritical flow, the 'V' pattern half angle $\mu = \sin^{-1}(1/Fr)$, where Fr is the local Froude number. Such a simple test may have been part of Chimú practice based on empirical observation of different flow regimes and how they respond to different geometric canal details.

If bed slope, wall roughness, and cross-section are selected over a canal section containing flow, then a selection from these parameters may be changed to obtain the flow regime necessary for a specific application that is based on establishing near-critical flow conditions. Although empirical methods exist to test the flow regime, it is tempting to think that some calculation base existed to predict how the canal should be built based on hydraulic principles known to the Chimú. If this is the case, some computational methodology should be present in the archaeological record to carry out numerical calculations. Of course, social explanations of the technology inherent to the Intervalley Canal would ascribe much to empiricism and guesswork; a more balanced view is that a project of this scope required much in the way of planning, technical skills, logistics, and execution to accomplish. With regard to surveying skills, the need for low-slope canals to include large downslope arable land areas dominates design considerations. The low-slope canals are most always subcritical and simple empirical relationships govern the relationship between normal flow rate, canal cross-sectional area, and slope according to Western 19th century discoveries (Rouse and Ince 1957). If such an empirical relationship were discovered in some format (probably very different to Western notation), then a basis would exist for canal design flow rate prediction. In essence, any pretence towards assigning some mathematical structure to Chimú methods in hydraulic design and surveying practices must first demonstrate methods whereby arithmetic calculations can be done. Without this basis, little can be accomplished as uncertainty and guesswork predominates over any rational basis for decisions and designs.

It is known that 13th and 14th century Inka counting systems were based on a 10-base system, i.e. measurements of groups of 1, 10, 100, 1,000, etc. Although known to be used for taxation, tribute, storage accounting, and census purposes, there were antecedent counting systems before the Inka. Recent discovery of a knotted, multistring quipu at Caral (3000 BCE) as well as quipus found in early coastal and highland societies implies that calculation capability existed that could be transcribed as data to the knotted string accounting systems. Calculation devices (Radicati di Primegio 1972) found in archaeological contexts have shown that mathematical operations of addition, subtraction, multiplication, and division are possible with the yupana, a multicompartment calculation device found in Chimú contexts on the Peruvian north coast (Figure 1.1.28). The yupana apparently works by representing base ten numbers by bead distributions within columnar compartments; operations between columns allow all standard arithmetical operations to be performed as would be required by surveying practice; results from the yupana can then be stored on quipus (Radicati di Primegio 1972; Ascher

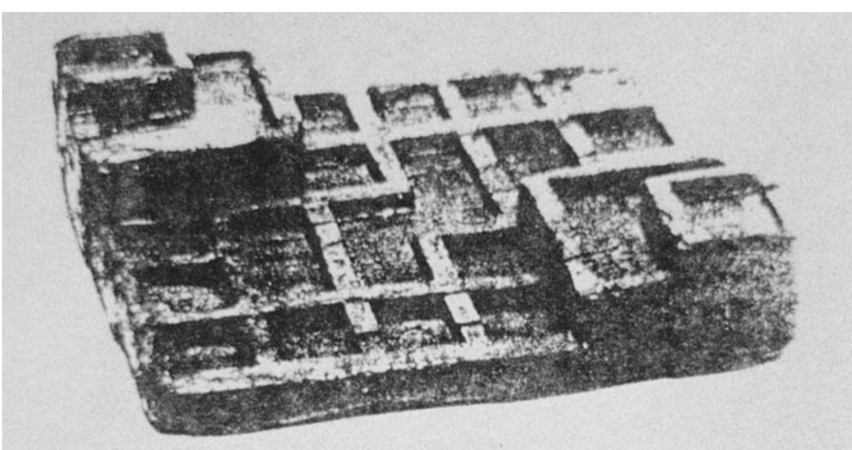

Figure 1.1.28. Wood yupana containing compartments that facilitate arithmetic calculations. Many yupanas have been found in urban contexts at Peruvian sites.

and Ascher 1981). Combinations of yupana and quipu are shown in Spanish Colonial texts (Guaman Poma de Alaya 1613) in a manner which indicates their combined use as calculation and data storage devices (Figure 1.1.29). The continued use of these devices from the earliest quipu found at Caral (3000 BCE) into late Inka times (16th Century CE) demonstrates that the quipu was a fundamental language and data storage tool invented at the dawn of Peruvian history; however, its translation code remains enigmatic to the present day. While use of calculation and data storage devices presume something to calculate, it remains unknown how the Chimú might have utilized such devices to perform hydraulic calculations. For surveying, however, some applications of those calculation devices found in archaeological contexts may be presumed, utilizing the surveying methods thus far described.

Figure 1.1.29. Colonial Period text (Guaman Poma 1543) showing dual use of a quipu knotted string recording device and a yupana calculating board.

With the ability to measure shallow angles and perform arithmetic operations, a preliminary canal path can be surveyed. For example, a mean canal bed slope (θ_b) can be estimated as $\theta_b \approx \Delta h/L'$ for shallow angles. As topographic constraints can alter the trial canal path (such as subsurface bedrock, impassable obstacles, ravines, sand dune accumulations, and complex topography), variations will invariably modify the L' length and local bed slope angles. Canal design in a complex topographic environment therefore involves multiple design iterations and resurveying exercises before all hydraulic design, slope, and path placement objectives are met.

To illustrate a surveying application, the steps utilized in the design of the Intervalley Canal provide an example. From previous discussion, an optimum contour canal path was selected to run on foothill slopes, elevated terraces, and across relatively flat sand areas on its way to the Vichansao Canal linkup (Figure 1.1.6). Some difficulty in maintaining a constant slope may appear due to obstacles and excavation difficulty encountering hard bedrock but variations in canal cross-section shape, area, and wall roughness may be employed to maintain a Froude number within acceptable limits (as Table 1.1.3 data appear to indicate). A required canal flow rate can next be estimated from a combination of the average bed slope θ_b required, an average canal cross-section area, shape, and average wall roughness, assuming a subcritical, normal flow, and some empirical way to relate these parameters for a preliminary flow rate prediction. Presumably centuries of canal operation had established an empirical base to permit this calculation. The next step involves estimates of the location of the Chicama River inlet position given the canal outlet destination position and the required average bed slope. The trial canal path from inlet to exit then requires 'spot point' surveying capable of locating numerous points on foothill slopes of a trial canal path. Some of these points may require terrace structures to support the canal. The spot surveying is best done from a vantage point on a relatively flat reference plane in view of the trial canal path. The spot points are then mountainside-marked points along the trial canal path. The use of independent spot points to determine a preliminary canal path on foothills and mountainsides is vital to a successful preliminary design as a canal surveyed downstream from an inlet point (or uphill from an outlet point) by Figure 1.1.27C methods is subject to accumulated angle errors along long lengths that negate the hydraulic design intent of the canal.

If the Intervalley Canal path survey is conducted over 50-m intervals by methods shown in Figure 1.1.27C starting from the destination point, then about 1,500 separate measurements need to be taken, increasing the probability for cumulative errors to occur. The use of independent spot points taken from a vantage point on a plain in view of the mountainsides supporting the canal path therefore helps to determine on-route spot points whose interpoint paths can be refined by local pathwise surveying at later construction phases. The spot points should be located at incremental distances along the entire canal path at some average trial slope, to ascertain what obstacles require special local surveying and hydraulic considerations. The spot point preliminary survey followed up by in-path surveying by Figure 1.1.27C methods then provides an iterative method to refine the local canal path; this in turn provides the data necessary for the project management bureaucracy to work on logistic details. In investigation of the construction site a thousand years later, in situ stacks of crude plates made for distribution to workers for meals while working on the project were located—obviously this part of the logistics chain was the mundane task of some bureaucrat involved in the planning stage of the project and showed the completeness of Chimú logistical skills applied to engineering projects.

Some hint of the methods employed for spot surveying is given by linear desert markings still visible on the plains between the Chicama and Moche Valleys some distance from the foothills where the Intervalley Canal runs. The desert markings consist of two or more faint parallel lines several kilometres long traced on flat desert pavement about 0.5 km from the visible mountainside to be spot surveyed. These lines, shown in Figure 1.1.30 as E–E and E′–P, suggest a possible method to locate spot surveying points on the mountainside. These points, when connected, trace a path at average angle θ_b. If two angle fixes α_1, β_1 are made to a given point, then from Figure 1.1.30, height h_1 is determined by:

$$h_1 = L \sin\ \alpha_1\ \sin\ \beta_1/\sin(\alpha_1 - \beta_1) \sim L_1\alpha_1\beta_1/(\alpha_1 - \beta_1)$$

provided E–E is located on level terrain. Point A_1 is therefore located and its height h_1 calculated from the above equation. Note that for distant locations where (radian) angles are small, $\sin x \approx x$, and that an angle can be expressed as a length ratio. This presumes, however, that the means to perform division lies within the calculation capability of the yupana and its decimal representation of numbers for heights and angles. A further survey point A_2 at a distance L_2 downstream of A_1 can next be spotted by moving the survey device a distance L_2 along the parallel line set and measuring $\alpha_1 = \alpha_2$ and $\beta_1 = \beta_2$. If a further angle γ is measured, then:

$$\gamma L \sin\ \beta_2/\sin(\beta_2 - \alpha_2) \approx \gamma L\beta_2/(\beta_2 - \alpha_2) \approx \Delta h \approx L_2\theta_m$$

for small angles. Spot point B can be approximately located a distance L_2 from A_1 at an angle θ_m from the horizontal. For purposes of obtaining some accuracy in the spot calculation, L_2 should be sufficiently small so that small

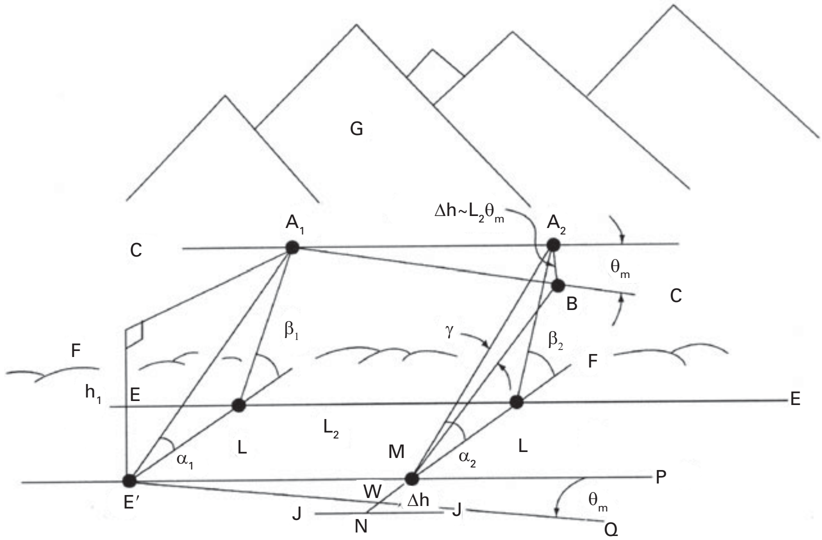

Figure 1.1.30. Angle and position parameters used for spot surveying to lay out a canal trial path on mountain slopes; the canal path and slope is later refined by the locally applied surveying methods of Figure 1.1.27C.

errors arising from A_2 being in front of (or behind) A_1, as seen from above, are minimized. Again, some of the operations on angular relationships are facilitated if the prescribed angles formed by integer length ratios are utilized in the preliminary setting-up of the surveying instrument.

The relationships shown hold for a land plane slope that coincides with an artificial horizon, i.e. the land surface is parallel to the water surface in a surveying bowl. Several other cases are of interest for possible spot surveying techniques. If, for example, the surveying instrument is moved a distance Δh from a point M to N (Figure 1.1.30) and set up to maintain the α_2 angle as before, then a distance equal to $\Delta h' = \Delta h \tan \alpha_2$ marks the spot point below the sight point location on the mountainside. A more interesting possibility arises if the desert pavement lines are surveyed and laid at an angle equal to θ_m, the mean canal slope angle. Since the desert pavement area before the Intervalley Canal is downslope and reasonably flat, this option could have been utilized in the instance under discussion. This technique would be to survey parallel ground lines set at an angle equal to θ_m; this corresponds to line E′–Q and angle PE′Q measured from horizontal line E′–P in Figure 1.1.30. For this case, if the distance M–W was set equal to $\Delta h/\sin \alpha_2$ by locating the surveying device along line E′–Q, then a spot point will be located a distance

Δh down the sight point on the mountainside. Since θ_m is usually a small angle in the order of a fraction of a degree, all the methods mentioned above would be capable of producing an estimate of a spot point location and height from the reference plane to help define the preliminary canal path in the mountainous zone north of Quebrada del Oso on the visible face (from the plains below) of the hills and mountains along which the canal was to run.

Of course, the idea could be advanced that to survey the canal one simply starts at the destination point and uses streamwise surveying methods to traverse the 74-km path using the desired θ_m angle. One observation countering this approach is that contour canal slopes traversing the sides of steep ravines are usually less than the mean slope. For spot points on either side of a ravine, a contour canal connecting these points (by running along the interior walls of the ravine) will have an effective slope of:

$$\theta_e = \Delta h'/S$$

where $\Delta h'$ is the height difference between spot points and S is the contour canal length between spot points. Since $\theta_e < \theta_m$, some adjustment in wall roughness and canal cross-section must be made to maintain flow within the desired Froude number range. This implies that spot points are set at the entrance and exit to the ravine at a crossing angle of θ_m but the effective canal slope within the deep ravine is less owing to the longer canal length. By manipulating the wall roughness, the canal cross-section shape and area, and the local bed slope, the Froude number can still be made to fall within design limits. If the spot procedure was not followed and the slope at all locations was θ_m, then the canal would have a greater length and would need a somewhat higher intake location. The problem with higher elevation inlets is that the Chicama River valley neck becomes a deep, steep-sided canyon in the upstream direction, making it difficult, if not impossible, to construct an inlet. Constraints on the inlet location (as well as the outlet position) therefore dictate the mean minimum canal cross-section area needed to obtain the desired flow rate in the most hydraulically efficient manner. In the present case of the Intervalley Canal, all requirements needed to construct a functioning system were apparently met. There was easy access to spot surveying stations with a view of the mountainous terrain on which the canal path was located and this path permitted construction of a canal with a Froude number varying around unity.

This surveying method guarantees that spot points were made first and local slope corrections performed later by streamwise surveying methods based on hydraulic considerations to keep the Froude number within a prescribed range. The spot surveying method limits drift of the preliminary path as spot points are surveyed to lie along the predetermined canal mean slope. Where bedrock obstacles prevent local adherence to this slope, variations in wall roughness and canal cross-section shape can maintain the Froude number within prescribed bounds and the mean slope can resume after this local section. Since terraces supporting the canal (Figure 1.1.16) could only be put into place after a survey of spot points was made (prior to terrace construction), a further argument for the spot point system can be advanced. With the approximate heights of terraces supporting canals determined, work teams could begin the task of terrace construction. The terrace platform would be subject to streamwise surveying and filling/cutting to correct local angle errors. With the preliminary survey path decided and estimates made of fill material volumes required for terraces and aqueducts, excavated material to be removed and transported, and canal lining material requirements, a basis could be provided for the labour support and transport logistics required to finish the project in a given time. These details then form the basis for the work plan envisioned by the project administration.

From ground survey of the southern reaches of the Intervalley Canal it appears that the system was carefully surveyed with occasional exploratory pits dug to test the bedrock depth compared to the desired canal depth. These pits are still visible and indicate local design alternatives related to terrain problems.

It appears that the plan was to finalize construction of the canal starting from the northern end and then construct canal off-takes to provide irrigation water to field systems adjacent to the canal. These field systems were concentrated (Figure 1.1.6) at Cerro Lescano and in field areas F, M, and H, and at Pampa del Oso (CO). The system may have worked on a rotating basis, distributing canal water sequentially to field systems along the western side of the canal with the majority of the water scheduled for the Moche Valley. A large stone-lined reservoir, now destroyed, was situated at the canal terminus in the Moche Valley to allow for storage of water and as a surge damper before distribution to the Moche Valley canal network. As the design flow rate of the Intervalley Canal closely matches that of the Huanchaco phase 3 to reactivate canal systems in the Three Pampa area, this alone reveals the depth of planning that went into the design of the Intervalley Canal system.

Although trigonometric notation (sine, cosine, and tangent) is used in the above formulae for shallow angles, the operations represented are only shorthand notation for calculations based on knowledge of length ratios between sides of triangles and the angles they subtend. The arithmetic operations indicated are capable of being carried out by yupana operations. Such operations imply the existence of standardized length scales in the Andean cultural sphere as described by the work of Rostworowski de Diaz Consejo (1960).

The conclusion is that the relative heights of spot points at a shallow canal declination angle of θ_m can be measured from a vantage point location and then corrected by more accurate, localized streamwise surveying methods to produce a contour canal path that meets hydraulic requirements. Judging from canal angles from field survey, Chimú engineers apparently could measure canal angles to tenths of a degree or less (Ortloff *et al.* 1985) using an instrument based on the principles shown in Figure 1.1.27C. Apparently, surveying techniques and traditions from past times were remembered and improved. Earlier examples of surveying accuracy in ancient South America *c.* 300 CE are the Nazca lines with (lateral) accuracies of less than 0.1°/km, Caral canals with accuracies of 0.05°, Tiwanaku (Bolivia) canals *c.* 800 CE with accuracies better than 0.001°, and Chimú canals with accuracies of 0.1° in the time period 800–1400 CE. Since canal building is vital to all hydraulic societies, it is not unexpected that surveying techniques should appear in refined form, with an associated mathematical base to perform necessary computations, to ensure the survival and growth of irrigation-based societies.

The ability to vary canal bed slope along the canal path and adjust wall roughness and canal cross-section and area to achieve the desired near-critical hydraulic flow was a vital element of the Chimú design technique. Field survey of a typical canal lengths indicate many streamwise slope changes accompanied by compensating adjustments in wall roughness and canal cross-section (Table 1.1.3). Despite popular notions of vast manual labour resources available for construction projects, the truth is that reducing labour input minimized the logistics necessary to support large projects over years of scarce food resources resulting from drought. Thus Chimú canal designs reflect optimization over many different technical and economic objectives.

The concept of scaling distances from a model to full-scale field application, as exemplified by the Nazca lines, may be a well-known example of the Andean geometry knowledge base. Although no written records exist to verify Chimú knowledge in this area, complex architectural constructions and city planning require knowledge of length–ratio angle relations. On a smaller scale, some Chimú and Moche ceremonial jewellery pieces show angular symmetrical divisions that require 360° to be divided into a number of equal angular segments; while this may be accomplished by trial-and-error methods, still the implication is that the capability for division and angle measurement was present to facilitate the layout, albeit on a smaller scale than field surveying. While geometric knowledge is expected, the depth of knowledge is not known from the archaeological record except for possible insights extracted from canals with sophisticated designs. From a reverse engineering point of view, plausible methods based on the use of the surveying instruments described earlier can be constructed. In the section that follows, some details of the calculation methodology used to facilitate such operations are described.

Yupana arithmetical operations

A typical yupana found in a Chimú context is shown in Figure 1.1.28 and has multiple grid compartments to facilitate base ten operations. The principle of operation is based on representing numbers in column form. Each vertical box in a column represents a decade increment and numbers are represented by beads distributed in the boxes. As an example, Figure 1.1.31 represents a hypothetical yupana trigonometric table in which the relationship between the side lengths of a right-angled triangle is shown. The angles may be represented in equivalent Western notation as degrees, radians, or slope (ratio of angle opposite side h to adjacent side L). While the slope representation shown produces a table of 'universal values', the angular notation and units used by the Chimú remains unknown.

Simple arithmetic operations such as those suggested by the surveying formulae can be performed by manipulation of markers between yupana columns. The markers may be beads and colour-coding may have been introduced for clarity. Figure 1.1.32 shows adding operations involving numbers in column form. Addition of the first four columns (10,568 + 8,389 + 4,265 + 4,434) gives the sum (27,656) shown in the rightmost column. Calculations are performed by adding markers in horizontal rows (starting from the lowest row) and carrying over the excess to the next decade box in sequence. This process is carried out from the bottom to the top row to produce the sums of the columns shown in the rightmost column. More complex multiplication operations are shown in Figure 1.1.33. Here multiplication of 254×137 in yupana format is shown in the upper panel. Lower panels represent decomposition of 254 into decadal parts for multiplication by 137. The original multipliers are successively decomposed into simpler multiplication operations (distributive law) with carry-over operations to successively higher decimal rows. The results of the separate three-stage operations are then added to give the number as shown in the topmost yupana panel. Extra rows below the computational grid in the last two panels are necessary for 'adding zeroes' resulting from multiplication by numbers having factors of 10 and 100 in later stages. These operations may explain the function of some of the elevated compartments in the yupana (Figure 1.1.28) and may relate to the shift register concept commonplace in multiplication/division operations performed in base n systems. Division may be handled using the operations described. For example, if the division $b = c/a$ is sought

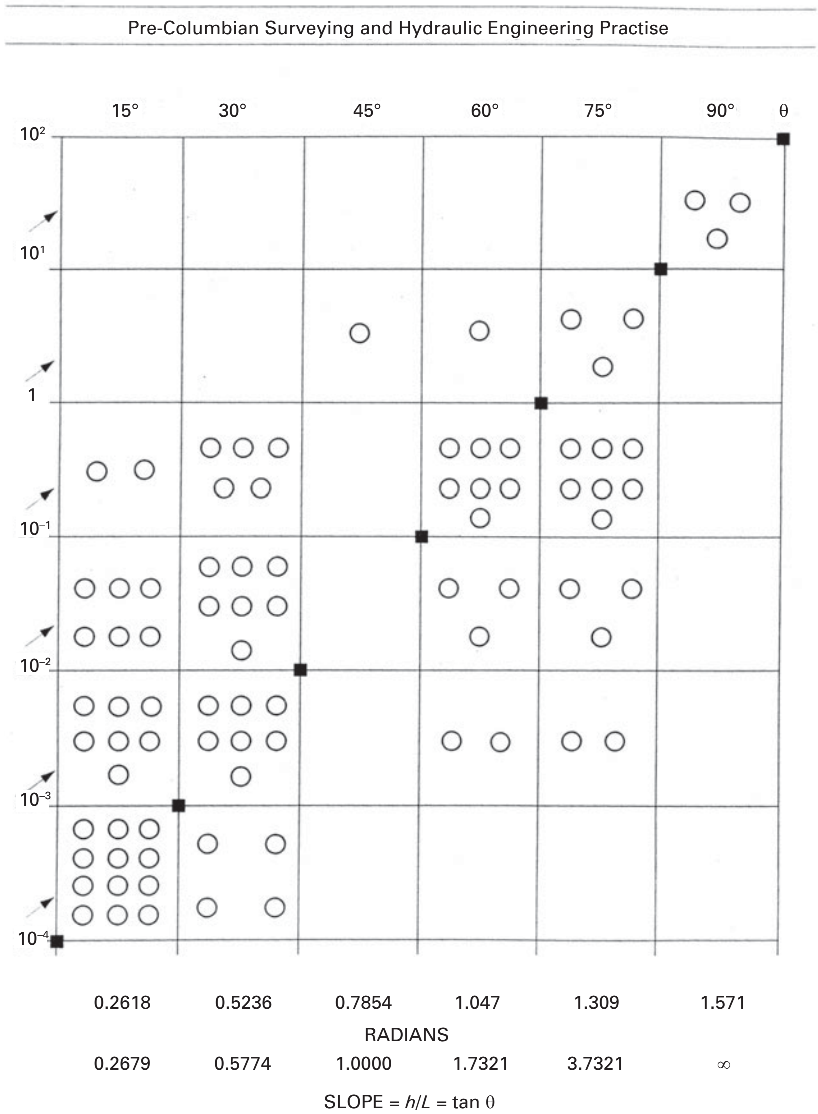

Figure 1.1.31. Yupana trigonometric table for angles from 15 to 90° in radians and *h/L* ratios. Angle measurements in a base 10 system facilitate the calculations necessary for spot surveying calculations.

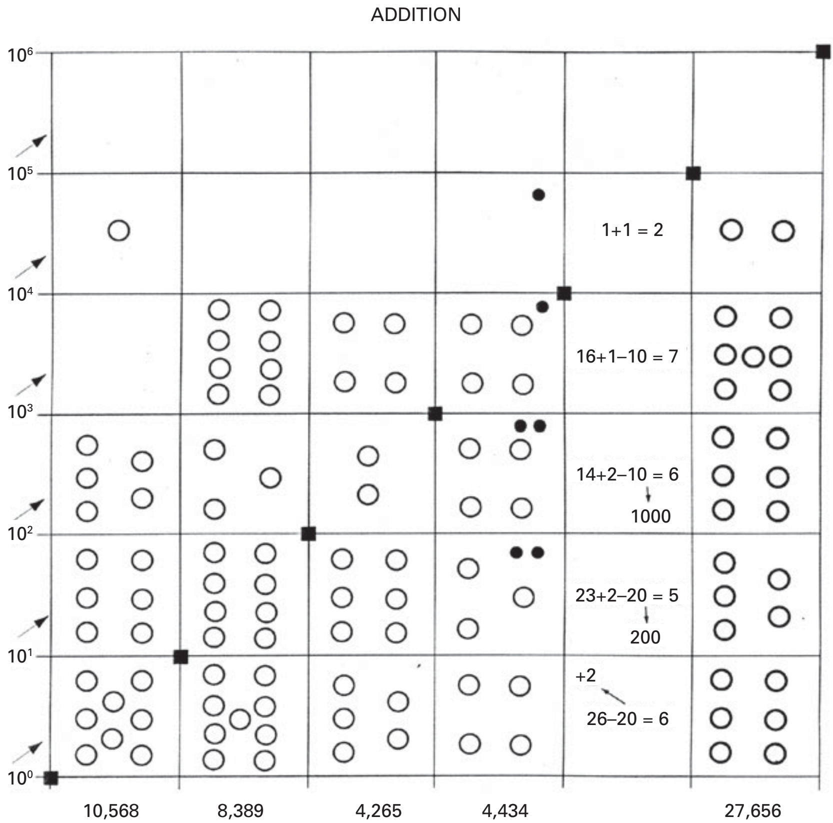

Figure 1.1.32. Yupana representation of the addition of four numbers represented in column form (10,568 + 8,389 + 4,256 + 4,434) to sum to 27,656.

where *c* and *a* are given, then $ab = c$. Therefore a trial *b* multiplied by a given *a* can be computed and compared to the given *c*. This iteration procedure ultimately can produce the division operation although there are other ways to perform the operation on the yupana. Similarly, the square root of a number *N* may be found by iteratively finding a number *d* such that $dd = N$ and *d* is $(N)^{1/2}$. The powers of numbers are easily obtained by multiple multiplications of a number. Using yupana operations, the calculations in the surveying formulae could be used to place spot points along the desired canal path. Engineering data could then have been conveniently stored in quipu form, where numbers (in columns) are represented in knot groups on individual strings (Ascher and Ascher 1981). If the sequential knot groups on a string represent a column of numbers according to the yupana scheme, then the possibility arises that some arithmetic operations could be carried out by manipulating strings relative to each other and transcribing the results on subsequent strings in the sequence. This avenue of research is just beginning as deciphering of quipu notation has so far only progressed to the simplest levels.

Application to low-angle surveying practice

When low angles are to be measured, simplifications can be made in surveying techniques. As $\tan\theta \approx \theta$ (in radians, for small θ), an angle can be defined as the ratio of height h to length L. A sample table of h/L measurements is shown and related to corresponding angular values (shown in radians) in Figure 1.1.34. As an example of how this chart could be used to perform a field survey, suppose a field measurement of $L = 100$ (units) and $h = 2$ (units) had been made by Figure 1.1.27C methods. A search of the chart then reveals that the declination angle is just 0.02 radians (column 2–3, Figure 1.1.34).

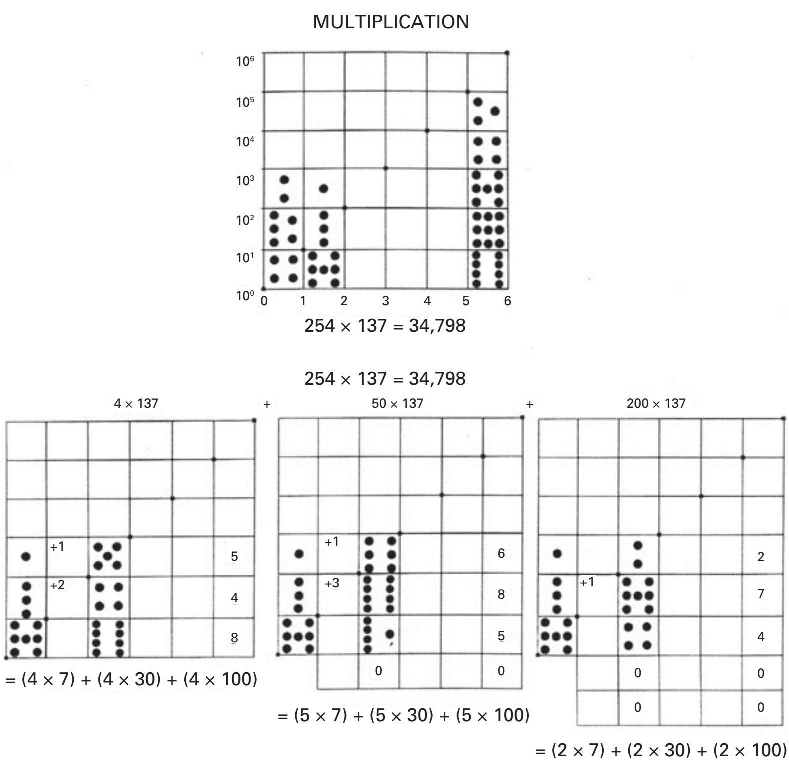

Figure 1.1.33. Example cases of multiplication in yupana format.

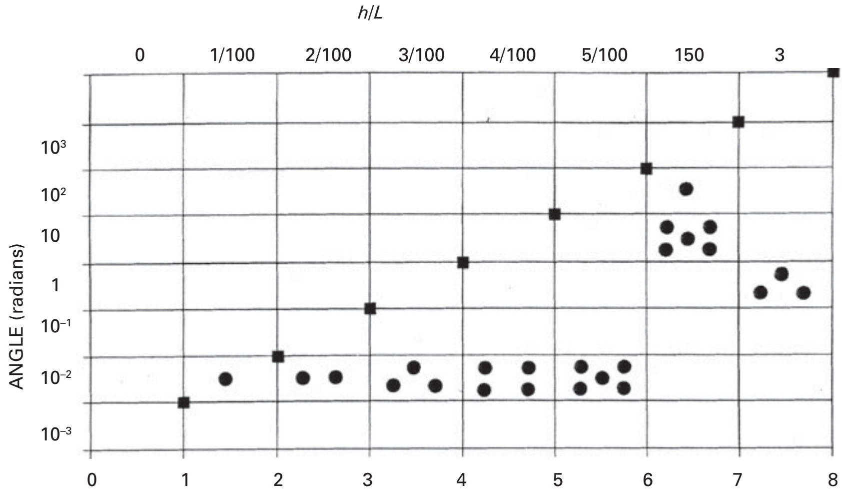

Figure 1.1.34. Yupana calculation performed for the low angle surveying problem described in the text.

Alternatively, if an angle of 2/100 radians is measured (perhaps by suitable calibration marks on the surveying instrument) and if $L = 15$ (units) has been measured, then the declination angle height (or drop-off distance from the surveying instrument to the surveying rod position) is $L\theta = (150) \times (2/100) = 3$ (units) to a good approximation. This operation is carried out by multiplication of column 2–3 by column 6–7 to produce the result shown in column 7–8 of Figure 1.1.34. Low-angle path surveying practice is therefore easily accomplished by yupana operations.

In final analysis, on one hand there is the Intervalley Canal with its sophisticated surveying, construction techniques, systems optimization, and hydraulic features. Additionally, many hundreds of kilometres of intravalley canals lying within valleys under Chimú control further testify to mastery of canal irrigation technology over many centuries. On the other hand, there is the sole existing example of a possible Chimú surveying instrument together with known calculation devices (yupanas) able to perform arithmetic calculations. The quipu is the data-recording device for calculation results. The actual technology base used for the design of these canal systems is lost from the archaeological record and may never be known. The steps presented in this reconstruction of the technology base are within the surveying and calculation instrument's capability and are consistent with the ground markings extant below a large segment of the Intervalley Canal near Quebrada del Oso. On this circumstantial basis, the preceding study provides at least plausible connecting links from process to product within the limits of the technology known to Chimú engineers.

Finally, the narrative presented gives a view of the Chimú as methodical in pursuing major engineering projects by planning and utilizing the technical resources that led to centuries of successful agricultural development. While the exotic ritual life and iconography of ancient South American civilizations continually provides fascination and tends to define societies due to the pre-eminence of archaeological work focused in these areas, a balanced view is advanced here in terms of the practicality of the ruling and administrative classes necessary to design, construct, and operate major hydraulic works vital to the agricultural base that supports a society. The north coast river valleys individually controlled by the Chimú, Moche, Lambeyeque (Sipán), and Lima cultures in EIP to LIP times were lined with extensive systems of irrigation canals and, in certain cases, with intervalley connections. Notable examples of intervalley systems (Kosok 1965) are the Lambeyeque Supe–Motupe–Reque system connected in part through the Taymi and Racarumi Canals, the Rimac Valley canals, the upper Jequetepeque canals (Ravines 1982) and the Intervalley Canal. While only the Intervalley Canal is analysed in the above sections, undoubtedly many technical innovations await discovery from analysis of the other intervalley canal systems. It may be surmised that a common irrigation technology base developed continually from early foundations and provided the economic underpinning of all the societies involved in construction of canal systems.

Chimú social organization

From the outline of the development and decline of the Moche Valley canal systems, several water management aspects are examined to provide insight into the governmental structure of Chimú society. From calculations of the technical sophistication index (Φ) and the labour index (ψ) for certain key canals (Figure 1.1.26), estimates of construction labour time can be obtained. For most of the intravalley canals, it appears that a crew of specialists directing a labour force of perhaps 300 men for several months would have sufficed to build major canals, based on labourhour construction estimates. Major projects such as the Intervalley and S2 Canal would have required recruitment outside of Chan Chan's locally available labour pool. Since time was of the essence for incorporation of Intervalley Canal waters into the Moche Valley, large numbers of workers were necessary for completion of the system to replace the declining intravalley systems. C^{14} dates for the Intervalley Canal show about 50–100 years of construction time but this includes later modifications so that the first phase construction time was probably much lower. For labour estimates, 1,000 men working 10 hours/day for 150 days/year for 50 years could have completed the Intervalley Canal down to Quebrada del Oso based on the volume of construction material moved. Additional workers to convey supplies to construction workers plus infrastructure, logistics, and administrative support workers would have increased the total numbers required to undertake major projects. Since agriculture was in decline in the Moche Valley at the time of construction, importation of food resources from other parts of the empire and harvest time synchronization must have played a part in the overall labour supply totals.

The total infrastructure necessary for the project therefore consisted of several thousand workers of different categories under the direction of central administration in the capital city. Since the city was mostly populated by royalty, retainers, and artisans (Moseley and Day 1988), and since agricultural workers were largely located in outlying communities adjacent to the cultivated areas distant from the capital city, clearly the labour pool of thousands of workers must have been drawn from non-elite classes from different parts of the empire by mandate of the rulers. To support the hypothesis that outside workers were required for major building projects, it has been observed (Moseley and Day 1982) that discrete sections of adobe bricks used in royal Chan Chan compounds contain different 'makers marks' implying different worker crews from different areas were utilized, most likely drafted by state bureaucrats to pay a 'labour tax' to the state. The establishment of an optimal system design in terms of maximum canal flow rate and minimum construction labour expenditure required that the labour expenditure remain controllably small while completing the project as rapidly as possible. Since the technical sophistication of the Intervalley Canal was high, it can be assumed that a team of water management specialists were directing the project and continually exercising their hydraulics and civil engineering skills. Thus, to the city craft specialists involved in metalworking, ceramics, textile production, and support of royal compounds, there must be added a specialty group involved in the design and direction of large hydraulic and irrigation projects under the command of Chimú royalty. In the absence of major emergency projects, this group easily could have directed the maintenance and elaboration of relatively low sophistication canals; for major systems, years of route surveying, labour estimation, supply logistical planning, and hydraulic calculations by specialists must precede work initiation. Since the population of Chan Chan has been estimated to be 20,000–40,000 (Moseley and Day 1982), the construction labour force must have been recruited by a 'labour tax' on worker communities dedicated to agricultural, city compound building, and non-specialized (i.e. non-craft) labour. Such communities were organized to support bureaucratic staffs and craft specialists of the city. Rural administrative centres at Quebrada del Oso, Cerro de la Virgin, and Pueblo Joven (Figure 1.1.3) served as main villages to house and administer workers connected with nearby agricultural field systems but additional labour was certainly available from other valleys under Chimú control. Thus, a proportioned society composed of elite and labour classes divided into specialty trades was a part of the Chimú design of an ideal society necessary to sustain coastal life for many centuries. Clearly, status within the system regulated the degree of reward; the impression is that all were provided for adequately, although agricultural workers were clearly at the bottom of the economic scale, as evidenced by the quality of grave goods from rural centres.

Within the capital city, vast compounds of living quarters, workshops, kitchens, livestock pens, and storage rooms adjoined royal compounds. The royal compounds frequently had only one small narrow entranceway through the outer compound wall and the internal complex of rooms and storage complexes had limited access entranceways requiring further administrative permission to penetrate. The outlying warren of adjoining rooms was for the retainers, artisans, and support labourers necessary for the daily operation of the city. The success of the agricultural system over centuries lay behind the increasing growth and prosperity of the city. Conquest added further prosperity as the metalworking resources of the northern polities were absorbed into the empire, together with their agricultural resource base and population available for labour. Since labour tax was the apparent practice, vast city building and hydraulic works were well within the capability of the state, due to the large population of the empire. In drought times, the contraction of Moche Valley irrigation systems was countered by expansion into large flow rate river valleys to the north to increase productivity (Eling 1986; Keatinge 1998). Thus, state control expanded as the complexity of directing resources forced an empire-wide perspective onto the ruling class of Chan Chan through complex water management and agricultural policy directives. Centres of provincial administration in the northern valleys (such as Farfán and Pacatnamú in the Jequetepeque Valley, Manchan in the Casma Valley, and Chiquitoy Viejo in the Chicama Valley) that mirror some features of Chan Chan architecture are likely manifestations of a centrally controlled agricultural strategy (Keatinge 1988). Older regional cities in conquered valleys appear not to be used in this fashion, as new administrative centres were built in central locations to effectively manage hydraulic works installed (or taken over) by Chimú hydraulic engineers.

Following Wittfogel's (1957) characterization of hydraulic societies as '... large-scale and government managed works of irrigation and flood control ...' it is apparent that the Chimú fit this category. For Chimú society, there were several features in place to drive water management policy, the foremost of which was the ability to devise technical solutions to water supply problems at early stages of their evolution. This assumes the ability to observe problems in their early stages, project the consequences, and then derive a solution to counter the worst-case scenario. Therefore, an observational science oriented to geophysical and climate-related problems was in place to anticipate future problems and provide solutions. In this sense, the Chimú response to problem solving utilized engineering strategies and management techniques that resemble modern ideas about how to conduct business and produce benefits for the population from elite-class directives.

1.2 TIWANAKU RAISED FIELD AGRICULTURE ON THE PAMPA KOANI, BOLIVIA, 600–1100 CE

As opposed to canal-sourced irrigation on the Peruvian coast, different agricultural practices were associated with highland societies due to high precipitation amounts. The following narrative describes one such unique system that maintained the Tiwanaku society for many centuries and brought forward the innovative nature of this society to invent an agricultural system perfectly tailored to their ecological base.

The ancient city of Tiwanaku in modern-day Bolivia is located on the high altiplano adjacent to Lake Titicaca (Figure 1.1.1). Details of its political history, climate history, geomorphology, iconography, cultural development, settlement pattern history, and agricultural base have been described by recent research (Kolata 1986, 1996, 2002; Kolata and Ortloff 1989a,b; Dillehay and Kolata 2004; Janusek 2004). The Tiwanaku Empire flourished between 600 and 1200 CE with Chiripa antecedents extending back several centuries. Because city excavations are not extensive, the earliest roots of the city of Tiwanaku are not precisely known but at least by 600 CE, a final form of the agricultural system and city architecture was in place.

The raised field agricultural system (Figure 1.2.1) devised by the Tiwanaku in the Pampa Koani area adjacent to the main city centre sustained growth of their civilization on the high-altitude (4,000 m) altiplano region. This system, subject to occasional nocturnal freezing temperatures, cold winter climate, extensive flooding and field salt deposits, excessive rainfall and drought periods, saturated soil conditions, high groundwater, and poor soils characteristic of the lacustrine boundaries of the nearby saline Lake Titicaca nevertheless provided the agricultural base for many centuries of the Tiwanaku civilization. The raised fields consisted of mounded earth berms derived from

Figure 1.2.1. Pampa Koani raised fields on the Taraco Peninsula on the Bolivian altiplano north of Tiwanaku. Raised fields are earth mounds surrounded by water filled swales.

excavated trenches that penetrated the high water table in the flat areas on the southern margins of Lake Titicaca (Figure 1.1.1). Typically, raised fields ranged from 30 to 100 m in length and were separated by water-filled troughs 2 to 4 m in width. Groups of raised fields formed random orientations and typically Pampa Koani raised fields covered about 100 km^2 in areas north of Tiwanaku.

From early origins at about 300 CE, the development of raised fields apparently progressed through observation of more successful designs that resulted in improved agricultural output. By 600 CE, full development of the raised field systems with supporting spring water supply and canal/river drainage systems to regulate groundwater height were in place and functioned successfully until fragmentation of the Tiwanaku Empire in the 1100–1200 CE time period due to societal and economic structural changes influenced to some degree by protracted drought conditions (Ortloff and Kolata 1993; Janusek 2004) affecting the agricultural base of the society. Because of the different agricultural system of the Tiwanaku based on raised field, groundwater-based farming as compared to the runoff-based, canal irrigation systems of coastal areas, response to drought is totally different in the highlands. Excavations of field systems near the site of Lukurmata north of Tiwanaku revealed deeper, earlier phases of raised fields with much shorter wavelengths (distance between midpoints of troughs) than later phases (typically 1 to 2 m compared to 10–20 m). Successive strata reveal a progression towards the last phase of raised field designs, obviously resulting from observations of increased productivity designs and/or changed lake height and water table conditions. In light of the harsh seasonal weather and long-term climate conditions prevailing in the altiplano region, the selection of the raised field systems as the optimum agricultural system successful over many centuries deserves further analysis to understand both the technical benefits and the vulnerabilities of this type of groundwater-based system.

Heat storage aspects of raised field systems

One parameter limiting the successful operation of raised fields systems is heat storage capability. Due to freezing temperatures encountered during altiplano nights, root crops, mainly tubers, frequently freeze, resulting in crop degradation. Using the traditional, present-day approach of planting in moist level field areas, this destructive occurrence is frequent in severe cold spells. Raised fields, as subsequent discussion will show, have interesting heat storage capabilities to mitigate these effects and provide a safety margin for crop survival and illustrate aspects of the Tiwanaku technology base.

In order to analyse the effects of heat retention on crop survival under cold season, diurnal temperature variations, a computer model was developed to investigate the phenomena involved. Insight can be gained by considering a one-dimensional, unsteady heat conduction problem governed by the heat conduction equation. This equation describes the spatial and temporal penetration of heat into a medium from a heat source or temperature imposed on a boundary of the region given an initial medium temperature. For a preliminary analysis, properties of wet soil are used and a constant temperature imposed on a boundary; the solution of the heat equation for temperature within the medium, $T(x, t)$, can be written in terms of the error function (erf) of argument $x/2(\kappa t)^{1/2}$, where t is time, κ is the soil thermal diffusivity (equal to the thermal conductivity divided by the product of the density times the specific heat), and x is the depth into the medium from the surface plane at x = 0.0. For integration limits from 0 to α, in terms of the error function

$$\mathrm{erf}(\alpha) = (2/\pi^{1/2})\int_o^{\alpha} \exp(-\xi^2)\ \mathrm{d}\xi$$

then

$$T(x,\ t) = T_0 \mathrm{erf}[x/2(\kappa t)^{1/2}]$$

gives the temperature distribution $T(x, t)$ within the medium initially at temperature T_0 at $t = 0$ for $0 < x < \infty$ and, for $t > 0$, the $x = 0$ boundary maintained at $T = 0$.

From tables of the error function, $T = T_0/2$ at $x/2(\kappa t)^{1/2} = 0.477$; the initial temperature in the soil has dropped to half its initial temperature at a depth $x = x_1$ from the $x = 0$ top plane at a time equal to $[x_1/(0.477)]/\kappa$. The mechanism for the temperature drop is the continuous heat flow from the interior of the medium to the constant low-temperature ($T = 0$) boundary at $x = 0$. From this solution, the time for a temperature reduction to $T_0/2$ at $x = x_1$ depends on the thermal diffusivity, κ. From the table of κ values for different media, if the medium of heat conduction is air, then cooling at a depth of x_1 to $T_0/2$ takes place rapidly as the thermal diffusivity for air is a large number so that the time to cool to $T_0/2$ is a small value. If the medium for heat conduction is wet, sandy soil, the time to cool (at x_1) is considerably larger. If the medium is water, then time to cool to $T_0/2$ is about 133 times greater than if the medium is air. The thermal diffusivity thus regulates the heat storage and transfer capability of a given medium. The lower the thermal diffusivity value, the more heat storage effect occurs in a given medium.

Based on these observations, given a moist soil medium (such as that found in raised field systems), if heat is absorbed internally by means of daily solar flux input, then the possibility for heat retention during cold nights is high. In other words, the time required for moist, heated soil to cool is long because its thermal diffusivity is small. The heat retention capability of soils then acts as a protective enhancement to preserve root crops against cold (subfreezing) altiplano night temperatures that would ordinarily destroy crops. The presence of water in the swales of the raised field systems further enhances the heat storage capability of the system. Because the thermal diffusivity of water is low, it will retain heat for long periods and thus serve as a heat source for the adjacent field ridges during cold nights. Dark, decomposed organic matter lining swale bottoms serves as a solar radiation trap to keep water temperature high during cold nights. By means of these heat transfer mechanisms, at least a very simplified heat transfer analysis shows that night-time heat release can be slow, thus retaining heat within the ground over long times to promoting crop survival.

To study this heat retention effect in greater detail, the heat transfer model is increased in sophistication to more closely model actual Pampa Koani and Lukurmata raised field system environments. To this end, a finite element model of an excavated raised field profile was constructed duplicating actual geometric values taken from field measurements and was used to solve more complex, non-linear, transient temperature distribution problems in a multi-property medium. Water is assumed to exist in the swales to a prescribed height.

Effects of conduction, convection, and radiation that influence the transient medium-temperature distribution are included in the model. In this model, many different media types occur. For example, the raised field depth profile, considered in two-dimensional form, is divided into saturated soils (below the height of the water in the swales) and soils above the swale water level in phreatic and vadose zones having lower water content than saturated soils. The phreatic and vadose region soils obtain their moisture through capillary action from subsurface groundwater and retain moisture within the soil pore structure. The air above the raised field system, as well as the bottom stone lining of the soil mound, is included in the model. Heat input is through solar radiative flux into the soil and water surfaces. Heat loss from the soil and water surfaces occurs from reradiation and free convection to the atmosphere. Heat conduction occurs through the various soil types, the ambient air, and water contained in the swales, depending on temperature and specific heat differences.

The ANSYS finite element code (Swanson and DeSalvo 1985) was employed to analyse resulting heat flows to obtain transient soil temperatures over a 24-hour cycle. Time averaged solar flux values as a function of month in the Bolivian altiplano are obtained from Duffie and Beckman (1974) and surface heat transfer coefficients for free convection as well as reradiation emisivities and related constants are estimated from literature sources (Duffie and Beckman 1974; Kreith 1973). Because solar flux varies on an hourly basis over a 24-hour cycle, an ANSYS cosine distribution was made to represent the diurnal solar flux variation; similarly, as air temperature changes continuously on a 24-hour cycle, typical input temperature values over time were used as input to the heat transfer problem. These temperature values are estimated from observations taken on a 24-hour basis in a typical altiplano harvest season month. Thermophysical properties of all model materials are specified from literature values.

The results of the analysis are shown in Figure 1.2.2A–C over day and night-times. Within the noon-to-early afternoon period, when solar flux and air temperature peak, the soil temperature exhibits a maximum on the soil surface and heat transfer warms the interior of the mound (Figure 1.2.2A). As solar flux and air temperature decrease towards late afternoon and early evening, surface soil temperature decreases while internal soil temperatures remain high, owing to the low thermal diffusivity of the moist soil and water compared to air. Towards evening and night (Figures 1.2.2B and C), the temperature maximum is clearly internal in the interior of the soil mounds while the outer soil layers experience temperature minimums. The presence of groundwater at a near uniform temperature above that of the ambient air effectively serves to direct heat flows upward at night, decreasing slightly the heat storage effect of the high thermal diffusivity soil. During the day, the low groundwater temperature ensures a thermal gradient, improving the input heat transfer. The presence of swale water is effective in maintaining higher than ambient air temperatures in the interiors of the field platforms as swale water temperature during a typical cold altiplano day is higher than ambient air temperature by the radiation capture effect. The heat transferred by conduction into the interior of the mounds is therefore an additional contributor to the heat storage effect. The zone of interest for root crops is the moist vadose zone between the mound surface and water height in the swales; observation of the mound temperatures at night indicates that heat storage maintains internal soil temperatures warmer than air temperature with the consequence of preventing root damage during subfreezing altiplano nights. Although only a few degrees Celsius separate internal from external temperatures during the night, the night-time heat loss is not sufficient to induce a phase change from water to ice, i.e. the heat stored per unit interior-mound volume exceeds the latent heat of fusion necessary for the phase transition. Since this phase transition occurs at near-constant temperature, the amount of heat stored is critical to delay root crop destruction by freezing. Since near-freezing temperatures are encountered in the interiors of raised fields, a certain amount of time is required to extract the latent heat of solidification from the soils and root crops before freezing occurs. Usually this time is in the order of several hours so that daily warming removes the possibility of further freezing taking place.

While these effects provided raised field agriculture with a high survival rate during cold altiplano nights, an additional effect occurs. The native aquatic macrophytes such as *Myriophyllum elodea*, *Potamogeton*, *Ruppia*,

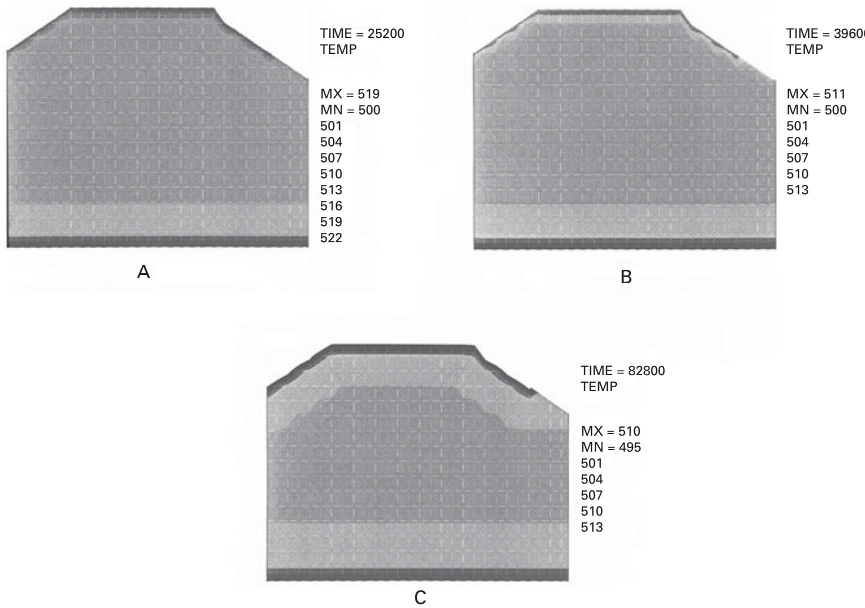

Figure 1.2.2. A, Internal temperature profile ~10am: the internal mound temperature has increased by heat conduction from the warm ambient air temperature and high solar flux. B, Internal temperature profile ~3pm: afternoon solar flux and air tem perature decrease but mound internal temperature remains high from the high specific heat of the moist mound interior and low conduction heat losses from high afternoon air temperatures. C, Internal temperature profile ~1am: surface layers are cool but the mound interior is at a higher temperature and retains heat to delay the freezing that would cause crop root damage.

and *Schoenoplectus tortora* dredged from the swales between field platforms and used as green manure to replenish macronutrients (nitrogen, phosphorus, potassium) in the soil undergo decomposition and, mixed in with topsoil, generate additional heat during their oxidation, augmenting the heat storage effect. While details of the problem may differ (wind effects, time-of-the-year effects, solar flux values, air temperature changes, different soil moisture levels, etc.), the results obtained are expected to apply in a qualitative sense.

Field measurements were made for air, swale water, and ground temperature at various times during the diurnal cycle to check the qualitative predictions of the model. Generally, the heat storage effect was confirmed, leading to the conclusion that maintenance of swale water height, by surface and/or groundwater transfer, represented a benefit for the productivity of the agricultural system under severe weather conditions. Although the hypothesis of frost mitigation in high-altitude raised field systems has been suggested previously (Denevan 1970), the finite element model describes in detail different heat transfer pathways that govern the success of the raised field systems. Striking experimental confirmation of the heat conservation effects was obtained during the 1987–88 growing season in the Lakaya sector of the Pampa Koani. A 1.5-hectare plot of land with well-preserved raised fields was reconstructed by local Aymara communities between August and September 1987, and planted with a variety of indigenous crops (principally potatoes) and introduced crops. No commercial fertilizers were applied to the experimentally rehabilitated fields, and cultivation and weeding proceeded in a traditional manner. On the nights of February 28 and 29, 1988, the Bolivian altiplano in the Pampa Koani region suffered a killing frost, with temperatures in the Lakaya sector dropping to −5°C in some areas. Substantial zones of potato and quinoa cultivation on unmodified plains and hill slopes along the southern rim of Lake Titicaca were severely damaged by this heavy frost. Many traditional potato fields within a few hundred metres of the experimental, reconstructed raised field plots experienced crop losses as high as 70 to 90%. In contrast, losses in the experimental raised fields of Lakaya were limited to superficial frost lesions on the leaves of potato plants. Barley, broad beans, quinoa, kañiwa, onions, and lettuce were equally unaffected. Only ten experimentally placed maize plants were lost in this hard freeze in the reconstructed raised fields, out of several hundred planted. This differential in plant survival attributed to field heat storage effects was clearly a discovery made by the ancient Tiwanaku farmers that made survival and prosperity happen in an unlikely area for agriculture. As a further qualitative measure of the heat storage effect, frequently a fog can be seen over the fields at night. In scientific terms, this is warm water vapour evaporating from the fields and swales, and condensing as fog as it encounters cold air. This path can be traced on a psychometric chart to show the thermodynamics of the process and confirm that an elevated temperature heat source is available to drive the evaporation process.

As a result of these observations, several 1,000 m^2 test plots of potatoes in Lakaya reconstructed raised fields were harvested, with average yields ranging from 18 to 33 metric tons per hectare. This yield contrasts with an average potato harvest of 3 to 8 metric tons per hectare obtained from the traditional, shallow-furrow dry farming techniques practiced in the area (MACA 1985; Kolata *et al.* 1996a). Although this yield differential between traditional and experimental raised field systems reconstructed from Tiwanaku precedents may be partially attributed to the fact that experimental fields were constructed in areas not cultivated in 1,400 years, where higher yields may be expected from fallowed fields, the radically different impact of the same subfreezing temperatures experienced in the two cultivation methods was significant. Empirical evidence supporting the heat conservation hypothesis continues to emerge in the study area. Frosts have significantly affected crop production in this area in every recorded agricultural cycle since 1987. Major frosts in 1990 and 1991 resulted in a similar experience of differential crop survival on raised fields versus control plots on hill slopes cultivated by shallow-furrow dry farming. Experiments explicitly directed towards testing the thermal properties of raised fields in middle latitude, temperate geographical zones in the USA (Illinois) (Riley and Freimuth 1979; Riley *et al.* 1980) tend to confirm this hypothesis, even though the suggested pathways of frost mitigation in their experiments differ from those proposed above.

In summary, the inventions and observations of the ancient Tiwanaku in advanced farming techniques efficient at high altitudes can be shown, in light of modern-day experiments and observations, to have played a role in their many centuries of expansion with a secure agronomic base. In combination with colonies at different locations in different ecological zones trading resources to and from the capital city, a secure network of food supply of vast variety was maintained as the underlying base of success of their empire.

Tiwanaku hydraulics

Because of the large rainfall amounts delivered to Pampa Koani in the rainy season, drainage canals are integral to regulating the amount of infiltrated rainfall into groundwater. The drainage canals capture surface runoff from adjacent hill and mountain watershed terrain and shunt inflowing floodwater directly into Lake Titicaca. The drainage canals also serve as seepage canals to drain excess groundwater from saturated field systems or, if interconnected to swale networks, help regulate swale water height directly by surface outflows. It is therefore expected that some measure of Tiwanaku hydraulics knowledge will be demonstrated in the design and function of the drainage canals. Specifically, designs made to rapidly transport water should show knowledge of critical and supercritical flow dynamics, maximization of flow rate controls, erosion control, limitation of hydraulic jump formation, and flow height regulation (by side drainage weirs that activate at different flow heights, for example) under different flow rate conditions. These technologies can be extracted by subjecting Tiwanaku designs to modern hydraulics analysis methods to determine the level of engineering expertise inherent in their designs.

Analysis of a main aqueduct structure in the Lukurmata area (Kolata 1996) that served primarily to shunt rainfall runoff directly into Lake Titicaca to limit erosion and mass sediment transport to occupation areas is discussed next. The site of Lukurmata is a satellite settlement area 10 km north of Tiwanaku. Because of Lukurmata's location adjacent to the large raised field system complex on the Pampa Koani, it served to house administrative managers and workers for the raised fields as well as providing a civic centre for the performance of religious and civic functions. Excavations revealed a large number of individual multiroom housing units with water supplied through channels into houses from adjacent springs. While this settlement contained a substantial population, numerous inhabited mounded settlements within the field systems imply yet more local control of field areas. The Lukurmata urban settlements were located on the southern shore of Lake Titicaca between 16°45′ S and 68°30′ W in the Catari sub-basin.

As a result of torrential rainfall runoff events in the December to March rainy season, large alluvial fans exist at the ends of the numerous steep quebradas that characterize the mountain ranges on the north and south sides of the Catari drainage bounding the Pampa Koani field system. The aqueduct to be investigated lies at the end of a typical quebrada that had been artificially modified to guide large volumes of runoff water into an elevated, artificial fill aqueduct structure carrying runoff across a field system directly into a moat surrounding the base of a civic-ceremonial district temple with direct drainage access to Lake Titicaca. Dating is assigned to Tiwanaku IV–V phase (*c.* 400–1100 CE). The aqueduct served to limit saturation of adjacent field systems and allow for additional farming areas close by Lukurmata settlement areas. The sides of the aqueduct were reinforced with closely packed riverbed cobbles (Figure 1.2.3) to stabilize the outer walls of the earth-fill structure. Some tie-in to residential drainage channels from housing areas may also have been in place but current estimation of the aqueduct's purpose centres on transport of rainfall runoff away from the farming and housing areas adjacent to the aqueduct. Since seasonal rainfall runoff amounts vary considerably over years of operation, it is of interest to examine the unlined, interior shape of the channel to determine its transport effectiveness under different flow rate conditions.

Since the flow rate of water through the aqueduct/canalized quebrada system depends on the intensity and duration of rainfall runoff, an internally lined channel of a given shape and cross-section was not utilized by Tiwanaku hydraulic engineers. Instead, rainfall runoff was directed onto the surface of internal fill material and permitted to cut a natural, erosion-shaped channel that would have an optimum, low-resistance cross-section provided by nature. Presumably when the channel was carved out during a near-maximum flow rate event, this section would be sufficient to contain all lesser flow rates. Although this philosophy of channel construction is unusual, it nevertheless

Figure 1.2.3. Stone lined side wall of the Lukurmata aqueduct. The aqueduct directs rainfall runoff from adjacent hill slopes into the centre section of the aqueduct between stone outer walls.

represents a viable method for accommodating input flows that varied considerably in magnitude and duration; in theory, the eroded shape will be a stable, minimum resistance profile for a given flow rate to maximize the water transport flow rate.

Hydraulic analysis

To determine the function and operation of the aqueduct, modern hydraulic theory is utilized. Several parameters govern fluid flow through a canal bed: bed slope (θ_b), right and left channel side wall slopes (θ_R, θ_L), base width (B), and the channel Manning roughness coefficient (n). In addition, the flow classification (subcritical, critical, supercritical) describes whether a change in cross-sectional area of the canal has an upstream influence (subcritical flow), no upstream influence (supercritical flow) or creates a localized disturbance zone in the form of a transition between supercritical and subcritical flow characterized by a downstream height increase and a velocity decrease (hydraulic jump). To determine if sub- or supercritical flow exists in a channel, an initial computation of the theoretical normal depth D_n and the critical depth D_c based on channel cross-section (assumed constant over the canal reach) and bed slope is made. The theoretical normal depth is defined as the hydraulic depth at which uniform flow exists in the channel and is obtained by solution of the Manning equation for water depth given an assumed known flow rate and bed slope. If $D_n > D_c$, then subcritical flow exists on hydraulically mild slopes; if $D_n < D_c$ then supercritical flow exists on hydraulically steep slopes. In the case of subcritical flow, the Froude number, defined as $Fr = V/(gD)^{1/2}$, where V represents the mean water velocity, g is the gravitational constant, and D is the hydraulic depth, is such that $Fr > 1$ for supercritical flow, $Fr < 1$ for subcritical flow and finally, for the special case where $D_n = D_c$, critical flow at $Fr = 1$. Maintaining the Froude number close to unity, or theoretical normal depth close to critical depth, results in a maximum flow rate for a given intake-to-outlet height difference for a fixed channel cross-sectional area. In a channel subject to erosion by design, it is of interest to see the relation between the observed (nature cut) canal cross-section profile, the engineered structural design, and the flow dynamics that resulted to determine how the aqueduct functioned in practice. Here, only the final reach of the aqueduct is erodible—the long upstream reach of this part of the channel is a large, natural quebrada. Presumably, after an erosion event was completed, the lower channel was backfilled ready for the next rainfall runoff event.

For purposes of analysis, the Lukurmata quebrada/aqueduct may be idealized into a series of trapezoidal cross-sections spaced at discrete distances along the streamwise length of the channel starting from its far-upstream reach (i.e. the aqueduct undergoes cross-sectional shape changes along its length). It is assumed that smooth, quadratic shape transitions occur between the representational trapezoidal cross-sections to create a smooth representation of the interior surface of the channel. Each localized section is characterized by an idealized trapezoid, bottom width B, side wall slopes θ_R and θ_L, and bed slope θ_b, measured along the streamwise direction (Table 1.2.1) from excavated data from the last erosion episode when the aqueduct was last used (currently the aqueduct is silted over after 1,200 year abandonment). The first measurement station, Q', was taken at a point in the upper reach of the channel in the quebrada; subsequent stations are measured in the downstream direction. Here h is the water height at the end of the section.

The principal and a secondary eroded channels excavated cross-section in the aqueduct are shown in the upper right-hand corner of Figure 1.2.4. These profiles are slightly non-symmetrical due to fluid rotation induced by channel sinuosity upstream of the entrance region of the aqueduct. Stratigraphically,

Table 1.2.1. Geometric details of the Lukurmata Channel and calculated depth results

Station	B	θ_R	θ_L	θ_b	ΔS (m)	D_n (m)	D_c (m)	Fr	Profile type	h (m)	n
Q′	5.0	15°11′	30°15′	4°48	9.40	0.19	0.35	1.0	S 2	0.19	0.025
P	4.7	17°32′	18°10′	4°12′	23.0	0.18	0.37	2.5	S 2	0.18	0.025
O	4.7	17°32′	18°10′	4°10′	29.8	0.18	0.37	2.5	S 2	0.18	0.025
M	4.7	17°32′	18°10′	4°46′	29.7	0.17	0.37	2.7	S 2	0.17	0.025
N	7.6	11°30′	9°49′	4°46′	29.7	0.13	0.27	2.8	S 2	0.13	0.025
M′	4.0	18°50′	8°54′	3°03′	14.0	0.18	0.44	2.7	S 3	0.18	0.025
L	4.3	10°35′	9°13′	5°20′	30.0	0.17	0.43	2.8	S 2	0.17	0.025
K	8.3	17°07′	31°36′	4°02′	21.0	0.13	0.24	2.4	S 2	0.13	0.025
J	8.3	17°07′	31°36′	5°37′	3.80	0.12	0.24	2.4	S 2	0.13	0.025
I	7.2	15°47′	19°52′	5°37′	30.0	0.13	0.27	3.0	S 3	0.12	0.025
H	16.0	13°16′	9°18′	5°03′	16.0	0.08	0.16	3.7	S 2	0.12	0.025
G	5.5	9°56′	5°24′	3°36′	30.0	0.16	0.37	2.6	S 3	0.15	0.025
F	13.7	17°03′	7°54′	5°40′	30.0	0.09	0.50	2.6	S 2	0.09	0.025
E	1.8	9°56′	4°20′	5°37′	30.0	0.22	0.95	6.0	S 3	0.12	0.025
D	1.8	9°56′	4°20′	5°37′	5.00	0.22	0.22	2.9	S 3	0.22	0.025
D′				4°17′	40.8					1.10	0.030
A	4.06	10°	80°	2°24′	6.0	1.05	2.16		S 2	0.87	0.030

the profile segment designated A–B in Figure 1.2.4 is reasonably distinct, while the segment from B to D represents the remnants of an earlier channel that has been infilled. A small pocket of gravel (E) probably represents an erosional subcut induced by a later, low flow rate erosion episode passing through the D–E–C channel. The cross-section A–B–C therefore probably most closely represents the last profile as far as archaeological excavation data permit interpretation.

The aqueduct fill material is composed of gravels, clays, and mixtures of cobbles of various dimensions. The Manning roughness coefficient is estimated to be 0.030 for aqueduct internal channel walls, and 0.025 for quebrada walls of the upper channel. Assuming non-cohesive, unconsolidated fill material and erosive behaviour over the entire wetted perimeter of the lower channel, hydraulic theory can be employed to predict the shape of the erodible section to compare this prediction to the observed excavated geometries. Note that the erodible channel section, for a given angle of repose of fill material and a given discharge and slope, yields a channel shape of minimum wetted area, minimum top width, maximum mean water velocity, and minimum excavation. This behaviour is consistent with nature acting to produce a maximum efficiency erosive channel configuration with minimum energy involved in its production. To compute typical eroded channel shapes $y(x; \theta)$ as a function of the angle of repose of the fill material θ, the differential equation:

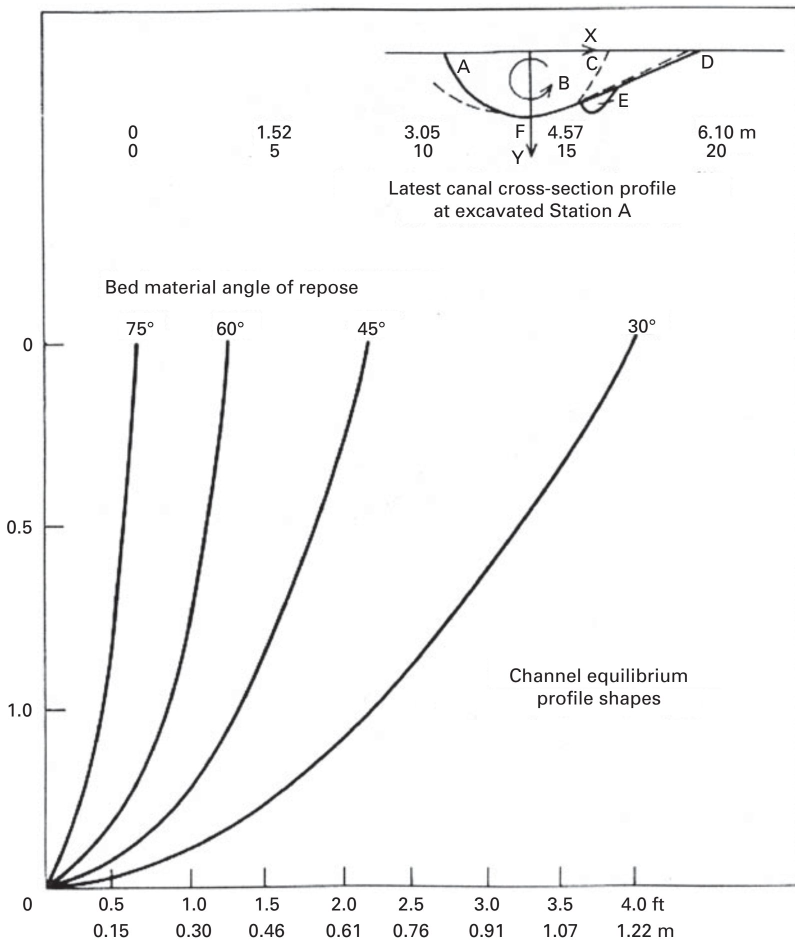

Figure 1.2.4. Channel cross sectional shapes caused by flow erosion for soil types with different angles of repose. The inset figure represents field data for the sequence of eroded cross section shapes.

$$(dy/dx)^2 + (y/y_o)^2 \tan^2 \theta = \tan^2 \theta$$

(Chow 1959) governs the cross-sectional shape where $y = y_o$ at $x = 0$ (the channel centre, Figure 1.2.4), where θ is the angle of repose of the fill material and the $y = f(x)$ solution represents the stable channel shape. A solution to the above equation is:

$$y = y_o \cos[(\tan\theta / y_o(x))]$$

and is shown in Figure 1.2.4 for various fill material repose angles. Observing a repose angle of about 30 to 40° for excavated dry fill, the computed erodible profile is comparable in channel cross-sectional shape to the Lukurmata aqueduct segment A–F in Figure 1.2.4 and its extension to segment F–C. Of course, larger flow rates would carve out larger channels and several remnant earlier channels of greater size may be observed below this latest one. This sequence of eroded channel profiles of varying geometries suggests the possibility of a sequence of heavy precipitation episodes in the past. For cases of large flow rate events, given a hypothetical scenario of stone-packed lower bedding, side wall erosion naturally leads to wide, flat-bottomed profiles similar to those observed below the A–F–D channel in Figure 1.2.4. Up to this point, consistency has been demonstrated between actual observed and computed cross-section channel profiles, reinforcing the conclusion that no lining has been used for channel bed material.

In order to gain insight into the design purpose and expertise base behind the aqueduct, hydraulic calculations were made to assess the function of the system. Starting from point Q′ at the uppermost reach of the drainage channel (Table 1.2.1), a critical flow point is assumed together with an estimated flow rate of 3.07 m^3/s; this value is arrived at from estimates of flow at the base of the drainage channel observed during the height of an average rainy season. Independent of the critical flow assumption at Q′, the flow will soon accelerate to supercritical flow due to the steep slopes (generally greater then 4°, Table 1.2.1) of the drainage channel. Normal and critical flow heights calculated and shown in Table 1.2.1, as well as Froude numbers, indicate the presence of supercritical flow over most of the steep channel length. As the source of the computed results in Table 1.2.1, using the trapezoid shape approximation mentioned earlier, the channel area (A), wetted perimeter (P), hydraulic radius (R_h), hydraulic depth (D), and section factor (Z'), are given by the relationships in the following equation set:

$$A = By + (y^2/2)(Z_R + Z_L)$$
$$P = B + y[(1 + Z_R^2)^{1/2} + (1 + Z_L^2)^{1/2}]$$
$$R_h = A/P$$
$$D = [By + (y^2/2)(Z_R + Z_L)]/[B + y(Z_R + Z_L)]$$
$$Z' = [By + (y^2/2)(Z_R + Z_L)]^{3/2}/[B + y(Z_R + Z_L)]^{1/2}$$

where $Z_R = \text{ctn}\ \theta_R$, $Z_L = \text{ctn}\ \theta_L$ and y is the water height from the base of the trapezoid. Critical depth is determined from a solution for $D_c \equiv y_c$ from:

$$Q = (gZ')^{1/2}$$

while normal depth $y_n \equiv D_n$ is determined from the numerical solution of the Manning equation (English units):

$$Q = (1.49/n)(R_h^{2/3})AS^{1/2}$$

for a given flow rate (Q), local bed slope ($S \equiv \theta_b \equiv i_b$) and Manning roughness coefficient (Chow 1959; Henderson 1966; Morris and Wiggert 1972). Here $Q = VA$, where V is the average velocity in a cross-section. The distance ΔS between water heights h_i (lower integration limit) and h_j (upper integration limit) is obtained by numerical integration of

$$\Delta S = \int_{h_i}^{h_j} \{(1 - Q^2B/gA_m^3)/[i_b - (nQ/1.49R_h^2/^3A_m)^2]\}(dD/dy)dy$$

where integration over y proceeds from substitution of Q, A, R_h, and D (and its derivative with respect to y) from the above equation set and use of local Table 1.2.1 geometric data in the streamwise direction. The results of this procedure are shown in Table 1.2.1, where h represents the calculated flow height at different stations along the channel starting from station Q′. Table 1.2.1 indicates that the flow height approaches the normal depth at each station location; this is the expected behaviour of a supercritical flow as it approaches its asymptotic depth D_n. As indicated in Table 1.2.1, the local Froude number ranges between 2.5 and 3.7 in the upper channel, while the Froude number at station D, the entrance to the aqueduct, is 2.9. Flow depth at D is equal to the normal depth (0.73 ft, 2.23 m) at the aqueduct entrance region. Thus, the channel flow upstream of the aqueduct is smoothly transitioning in depth between stations, close to the local normal depth, and locally uniform throughout its length. The upper drainage channel then efficiently transports water such that the water surface is nearly parallel to the channel bottom. The purpose of these computations is to determine typical flow conditions at the entrance region to the lower aqueduct. The design of this hydraulic structure offers the deepest insights into the expertise of Tiwanaku engineers and the nature of the problems they perceived in attempting to contain seasonal flows within the drainage channels within the Lukurmata urban environment.

Since the lower aqueduct channel is erodible, the first calculations are designed to determine if the flow in the lower aqueduct is still uniform and supercritical for the parabolic channel sections shown in Figure 1.1.4. The principal problem with respect to the hydraulic characteristics of the lower aqueduct is to determine whether the geometry and structural features of this channel generate a hydraulic jump or support a smooth transitional supercritical flow. If a hydraulic jump developed at the juncture of the upper and lower channels, then severe erosion and turbulence would destroy and wash out the unconsolidated interior fill material in a non-controlled manner. The hydraulic jump would also cause severe overflow problems due to the large water height increase characteristic of high Froude number supercritical flows. To answer these questions, Figures 1.2.5 and 1.2.6 are constructed.

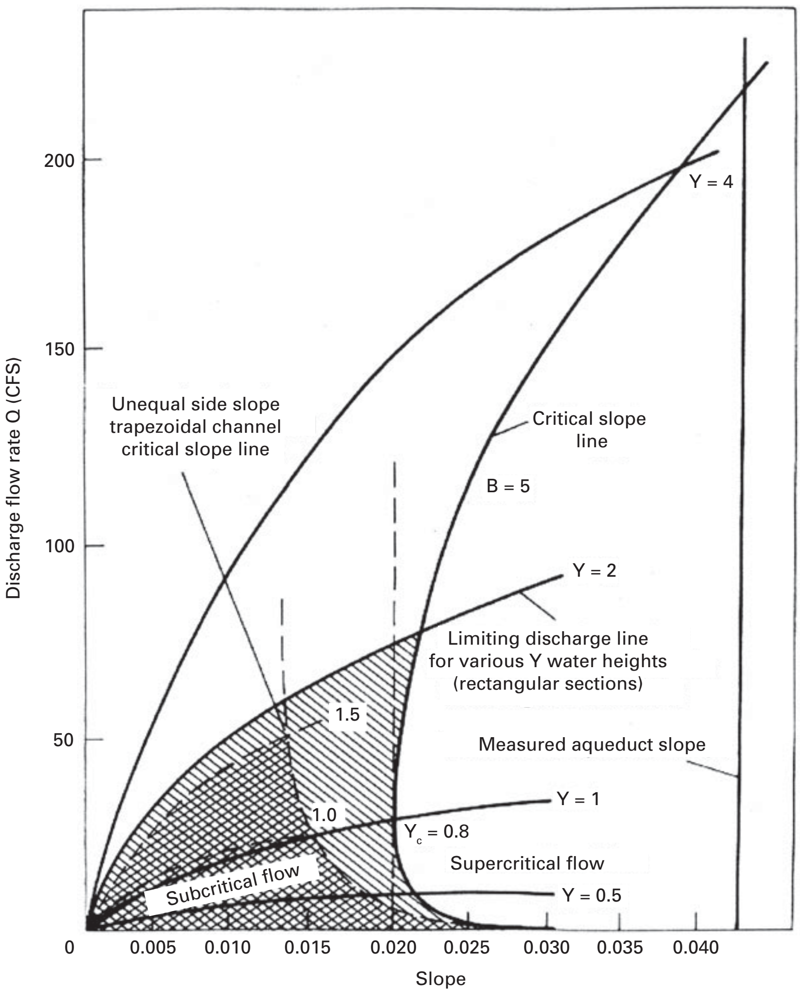

Figure 1.2.5. Discharge flow rate for different channel slopes illustrating flow regimes for different water heights (Y) in the idealized rectangular channel for unequal side slope angles.

On plots of flow rate versus lower aqueduct slope, the critical slope line demarcates the presence of critical flow. According to Figure 1.2.6 (note that English units (i.e. feet) are employed consistent with the traditional form of the Manning equation: for conversion purposes, 1 ft = 0.3048 m, 1 $ft^3/s = 2.83 \times 10^{\ 2}$ m^3/s), assuming a rectangular canal cross-section, a

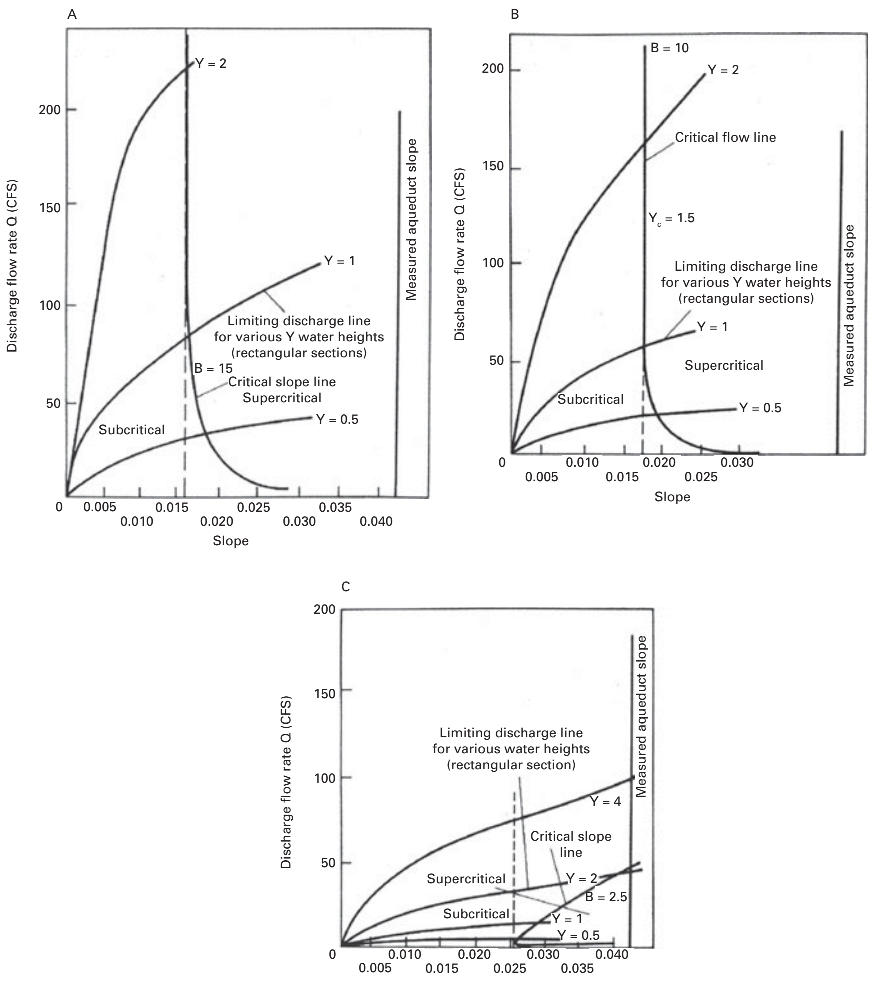

Figure 1.2.6. Discharge flow rate cases for different base width (*B*) rectangular cross section channel geometries illustrating the flow regimes for different water heights (*Y*) in the channel.

channel with a slope of 0.015 supporting a flow rate of 26 ft^3/s with a flow depth of $y = 1.0$ ft would be subcritical for a bottom channel width of $B = 5$ ft. A slope greater than 0.020 would support a supercritical flow. For a subcritical flow on the lower aqueduct, a hydraulic jump must occur to change the upper channel supercritical flow to subcritical flow. Since the measured aqueduct slope is 0.043, it can be concluded that the lower aqueduct supports a supercritical flow for the class of $B = 5$ ft channel widths. Continuation of the search for possible subcritical flows among the class of wider eroded profiles characterized by a bottom width of $B = 2.5$ ft (Figure 1.2.6C), $B = 10$ ft (Figure 1.2.6B), and $B = 15$ ft (Figure 1.2.6A) for a range of possible y flow depths that the aqueduct could support reveals that subcritical flow does not exist on the lower aqueduct at the measured slope of 0.043 for a wide variation of bottom widths that include the excavated profile widths (Figure 1.2.6A) and widths up to the width of the aqueduct.

A calculation made for a non-rectangular channel cross-section reveals that the rectangular cross-section calculations are conservative with respect to slopes at which the critical flow line exists and provide a lower bound for curved profile cases. Over a variety of eroded channel bottom widths, flow depths, and flow rates therefore, the lower aqueduct always supports a supercritical flow. Accordingly, for a wide class of eroded profile shapes there exists a smooth supercritical transition from the exit normal depth on the upper channel to a higher normal depth on the lower aqueduct. The value of this depth can be obtained by solution of the Manning equation for given Q, n and B for any eroded profile shown in Figure 1.2.6.

Past end station A, the aqueduct curves smoothly to the northeast while maintaining its full structural width. The coordinates (x, y) of the curved section are given in Table 1.2.2. By characteristics methods, the supercritical turning of the flow and height change can be determined (Chow 1959; Henderson 1966; Morris and Wiggert 1972). However, the key problem here is the effect of backwater height on aqueduct flow. This height is basically the Titicaca lake level, which is known to have varied considerably in historical times; the lake level fluctuated as much as 5 m within a 2-year period (Carmouze and Aquize-Jaen 1981). For the case in which this level is high and intersects the supercritical aqueduct flow, serious erosion problems potentially destructive to the structural integrity of the aqueduct could be generated by development of highly turbulent hydraulic jump. Referring to Table 1.2.1 and Figure 1.2.7, the supercritical flow on the aqueduct approaches the normal depth line $Y_N = D_n$ on an S-2 profile (see Chow (1959) for a discussion of these profile characterizations). If the backwater height is below Y_N, then no upstream effect is induced in the supercritical flow. If the backwater

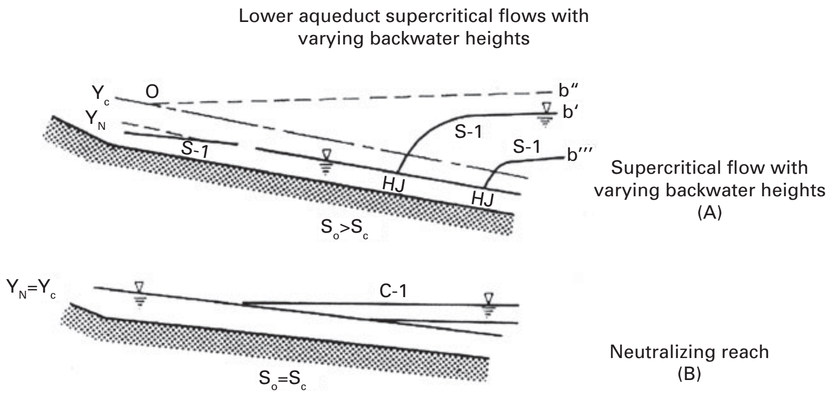

Figure 1.2.7. Flow surface geometry influenced by different backwater heights (*b*′, *b*′′, and *b*′′′) and channel slopes when slope exceeds the critical slope (A) but is equal to the critical slope (B), the neutralizing reach case.

level is high (b‴), however, then a hydraulic jump (HJ) will occur on the aqueduct, leading to massive erosion of the unconsolidated, unlined bed canal fill in the vicinity of the jump's water height increase. For instance, for the hydraulic characteristics of the lower portions of the aqueduct for which $Fr = 2$ and the bed slope of the channel is 0.043, the hydraulic jump height can approach three times that of the pre-jump water height. As the backwater height increases, the jump moves up the aqueduct, causing additional damage to the hydraulic structure through amplified erosion effects. Moreover, for high backwater levels, it is anticipated that fill material soils would be further compromised by the wetting action of the intersecting lake level and be more easily eroded by the high-speed water passing over the saturated soils.

As the backwater height further increases (Figure 1.2.7A), the theoretical limit 0–b″ on an S-1 curve is reached and the aqueduct is submerged. The geometry of the curved, distal portion of the Lukurmata aqueduct slightly raises the height of the flow over the normal depth through Froude wave interaction, while slightly decreasing the supercritical velocity (Table 1.2.1). Here the effect of the backwater height change is to produce an immediate step-up in water height before the hydraulic height adjustment to the backwater height described above. This effect limits the erosional potential of the hydraulic jump on the lower reaches of the aqueduct, and suggests that the Tiwanaku engineers may have explicitly incorporated the curved section of the aqueduct into their design to mitigate structural deterioration. Another elegant solution to eliminate, or mitigate, the impact of potentially destructive hydraulic jump on the lower reaches of an aqueduct is to construct a neutralizing

Table 1.2.2. Coordinates of the aqueduct curved east wall

ΔS (m)	x (m)
0.00	0.00
0.50	0.00
1.00	0.30
1.50	0.56
2.00	0.92
2.50	1.38
3.00	1.92
3.50	2.24
4.00	3.33

reach (Chow 1959). This entails establishing the aqueduct bed slope equal to the critical slope, thereby causing backwater levels to approximate horizontal lines (C-1 profiles) which intersect the surface of the flow without causing turbulence (Figure 1.2.7). This is equivalent to a hydraulic jump of zero height. The curve for the trapezoid section critical slope S_c is found from selection of Y values in $Q = (gZ')^{1/2}$ to produce Q (or discharge rate of flow) values. The Q and Y values are then substituted into the Manning equation to determine S_c values. This method is used to determine the S_c curves in Figure 1.2.6.

For the A–F–D channel (Figure 1.2.4), the intersection of the critical slope line with a $Y = 2$ ft height flow occurs at a critical slope of approximately 0.02. This critical slope is well below the measured aqueduct bed slope of 0.043, therefore no neutralizing reach was possible for the A–F–D parabolic channel as a preventative measure against canal erosion during conditions of high rainfall and high lake levels intersecting the lower reaches of the aqueduct. Incomplete remains of earlier erosion channels appear in the A–F–D channel as illustrated by the cross-section shown in Figure 1.2.4. Many of these channel remnants are partially destroyed by later erosional and refilling events. Consequently, no secure time sequence of channel configurations can be readily discerned. However, it is clear that a sequence of wide-base, parabolic channels characterized by high rates of flow are intercalated with low flow rate incised channels and represent the time histories of multiple large rainfall events over long time periods.

Calculations based on rectangular canal sections made for the variety of base widths ($B = 2.4$, 5, 10, and 15 ft) in Figure 1.2.6 show the critical slope line for different possible water depths in the channel. For all cases where $B > 5$ ft, a neutralizing reach is impossible for the assumed flow rate. The limiting discharge line is calculated from the Manning equation using S_c and a given depth. The flow is still supercritical for these cases and hydraulic jump phenomena can still be expected to occur in the lower reaches of the aqueduct channel under conditions of elevated backwater height intersecting the lower reaches of the aqueduct. Interestingly, for hypothesized massive channel flow rates generated by torrential rainfall events, there are some possibilities of a neutralizing reach condition for $B < 5$ ft channels, if this base width can be maintained during an erosion event. For $B = 2.5$ ft and $Y = 2$ ft (Figure 1.2.6A), for example, the intersection point A lies close to the measured aqueduct bed slope of 0.043. This indicates that the channel can function as a neutralizing reach for this set of flow rate, base width, and water depth conditions, thereby eliminating an on-aqueduct hydraulic jump for any backwater depth.

The basic problem encountered in the aqueduct design is that the input flow rate, which depends fundamentally on rainfall intensity and duration, varies radically from event to event. A standard design channel therefore cannot be built to perform transport tasks efficiently for a wide range of input flow rates. In this context, the erodible channel technique evident in the Lukurmata aqueduct serves design purposes well since it carves out the 'necessary' channel to support a given flow rate, maintains a nearly uniform flow throughout, and, in inundation conditions where the lake level is high, can function as a neutralizing reach to eliminate on-aqueduct hydraulic jumps near the exit region of the aqueduct. The presence of several deep, flat-bottomed channel profiles with base widths in the range 5–10 ft in the Lukurmata aqueduct suggests massive rainfall events in the early history of the hydraulic structure. The lower flow rate events are more likely to produce 'permissible' velocities (Henderson 1966) and achieve the equilibrium parabolic profiles illustrated in Figure 1.1.5. Since the high water velocities in the hydraulically steep aqueduct purposefully cause erosion of bed and wall material, the aqueduct design can be considered as 'adjustable' to any runoff flow rate condition. After an event, the aqueduct can be resupplied with fill material to reconstitute its core and be ready to function at the next event. This type of adjustable channel design, although non-conventional, served its intended purpose well as its large bed width could accommodate any size of runoff flow rate by creating a least-resistance, erodible bed shape that could rapidly drain runoff without hydraulic jump formation. Although the hydraulic considerations mentioned above are somewhat complex, practical results can be achieved by empirical observation and trial-and-error methods (perhaps represented by some of the erodible profiles). Regardless of the methodology used by the Tiwanaku, the goal of achieving a smooth supercritical flow, without an intermediate hydraulic jump occurring on the lower aqueduct, is a complex task and points to the existence of a considerable base of hydraulics knowledge.

The Pajchiri transport canal

To gain further insight into the design of Tiwanaku hydraulic structures, the aqueduct system at Pajchiri is next considered. The site lies north of Luquermata (Figure 1.2.8) and is accessible by a causeway when Lake Titicaca levels permit; otherwise, land passage around the lake edge is required to reach the site. Similar in structure to the Lukurmata aqueduct, but not in design purpose, the Pajchiri system consisted of four aqueducts, of which three had an upper channel consisting of an artificially canalized quebrada and a lower connecting channel that conducted water over an open plain on an elevated structure constructed of parallel stone retaining walls infilled with earth, stone, and gravel (Figure 1.2.9). As at Lukurmata, the modified quebrada channels of the aqueduct reached into high montane catchment basins where they were charged by rainfall runoff, permanent springs, and subterranean seeps. The fourth Pajchiri aqueduct was not associated with an artificially modified quebrada but rather consisted of an elevated, stand-alone hydraulic structure linked by a surface canal to an artificial spring-charged reservoir adjacent to the principal civic-ceremonial precinct of Pajchiri. Unlike the Lukurmata aqueduct, the hydraulic structures at Pajchiri were much larger,

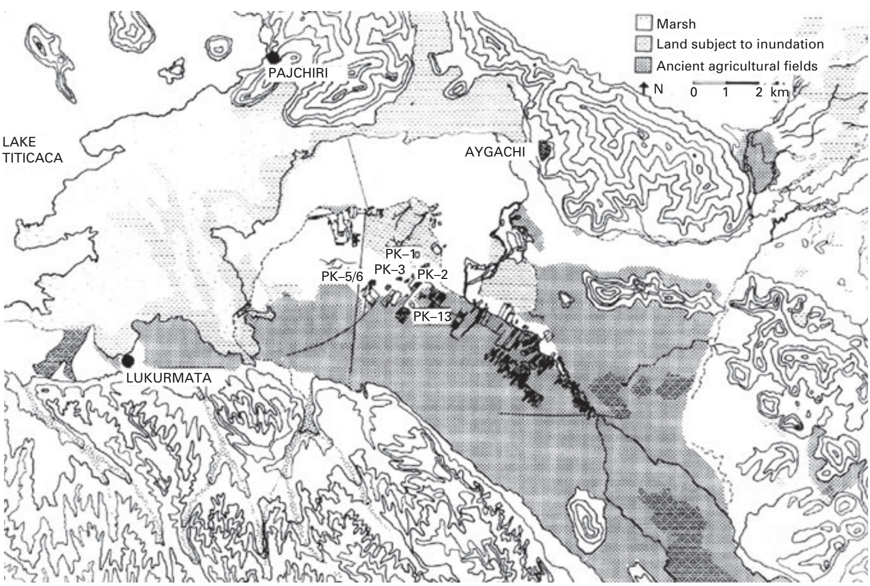

Figure 1.2.8. The Taraco Peninsula showing Pajchiri and Lukurmata on the eastern margin of Lake Titicaca. Tiwanaku lies 10 km south of Lukurmata. Dotted areas are raised field zones.

Figure 1.2.9. The Pajchiri aqueduct.

running over a kilometre in length and achieving maximum structural heights between 4 and 7 m. The structures were carefully built with cut stone retaining walls rather than the river cobbles that characterized the structure at Lukurmata.

Unlike the Lukurmata aqueduct, whose function was to transport rainfall runoff rapidly into the lake, the Pajchiri aqueduct had well-constructed stone drop structures linked to small feeder canals that were intended to distribute water to local raised field systems arrayed between the aqueducts.

Field work on the Pajchiri aqueduct entailed surface measurements of channel widths, cross-section shapes, and canal bed slopes on a 90-m mid-structure aqueduct segment. Measurements were taken at 3-m intervals over this segment, commencing at a point approximately 300 m from the spring/reservoir water intakes; the results are shown in Table 1.2.3. As observed from the base width (*B*) column, the canal shape profile of this aqueduct exhibits

Table 1.2.3. Structural details of the Pajchiri expansion contraction aqueduct section

Station	B(m)	S_b	Z_L ctn θ_L	Z_R ctn θ_R	D_c (m)	D_N (m)	D_c (m)	D_N (m)
0	1.05	0.37	1	1	0.41	0.28	0.26	0.19
3	3.00		1	1	0.22	0.15	0.14	0.19
6	3.25		1	1	0.21	0.15	0.13	0.10
9	3.00		1	1	0.22	0.15	0.14	0.10
12	3.30		1	1	0.21	0.14	0.13	0.09
15	3.00		1	1	0.22	0.15	0.14	0.10
18	3.00		0	0	0.20	0.16	0.14	0.10
21	3.10		0	0	0.21	0.16	0.14	0.10
24	3.20		0	0	0.20	0.15	0.13	0.10
27	2.70		1	0.58	0.23	0.16	0.15	0.10
30	2.30		1	0.58	0.20	0.18	0.17	0.12
33	3.10		1	0.58	0.22	0.15	0.14	0.10
36	3.20		0	1	0.21	0.15	0.13	0.10
39	2.80		0	1	0.23	0.16	0.15	0.11
42	2.65		0	1	0.23	0.17	0.15	0.11
45	2.65		1	1	0.24	0.16	0.15	0.11
48	2.65		1	1	0.24	0.16	0.15	0.11
51	2.65		1	1	0.24	0.16	0.15	0.11
54	2.26		0	0.58	0.25	0.19	0.16	0.12
57	2.26		0	0.58	0.25	0.19	0.16	0.12
60	1.90		0	0.58	0.28	0.21	0.18	0.14
63	1.90		0.58	1.19	0.29	0.20	0.19	0.13
66	2.02	0.033	0.58	1.19	0.28	0.20	0.18	0.13
69	2.38		0.58	1.19	0.25	0.18	0.16	0.12
72	1.72		0	0	0.28	0.24	0.19	0.16
75	1.61		0	0	0.28	0.26	0.19	0.16
78	1.42		0	0	0.31	0.28	0.20	0.18
81	1.40		0	0	0.31	0.29	0.21	0.18
84	2.26		0	0	0.25	0.20	0.21	0.13
87	2.30		0.041					

an expansion–contraction design. Upstream and downstream of the analysed section the channel width is relatively uniform. This leads to the question: Does the design feature of a shaped canal that expands and contracts in channel width perform a hydraulic function or was the canal shape simply a product of non-standard construction techniques?

Table 1.2.3 lists the normal ($Y_N = D_n$) and critical ($Y_C = D_c$) depths for assumed typical flow rates in the range of 1.0 and 0.5 m^3/s from spring/reservoir water sources. For both flow rates, $Y_C > Y_N$, indicating the presence of supercritical flow. In most cases, the difference between Y_N and Y_C is in the order of 20–30%. The flow depth is therefore close to the local value of the normal depth. Because the critical depth is not excessively divergent from the normal depth, and the slope is not excessively greater than the critical slope, the flow rate will be close to the maximum possible for the given slope, channel area, and initial specific energy. To avoid flow at the critical state and its inherent instability, the flow is maintained in the low supercritical region with a Froude number ranging from 1.5 to 2.5.

The lower normal water depths in the vicinity of the expanded channel 'bulge' compared to upstream and downstream water depth, enhanced the function of the drop structures and smaller feeder canals with low intake heights constructed perpendicular to the main channel in this region. The flow velocity was small into the drop structures when the water height was only slightly above the intake height. This may aid in irrigation strategies that required slow water input over long time periods rather than rapid flow over short time intervals with large volume flow rates. The lower intake heights of the drop structures, made possible by the locally lower water height in the expansion region (i.e. supercritical flow in a channel expansion region undergoes a velocity increase and a height decrease), permitted easy manipulation of the secondary water distribution system: simple sluice gate structures of small stones could be used to block the intakes to regulate water supplies to the feeder canals.

Despite the presence of well-elaborated drop structures and secondary feeder canals, it appears that the principal function of the Pajchiri aqueducts was to transport excess water from surrounding spring and quebrada systems to the lake basin during large rainfall events. There are a total of four aqueducts running through the field systems at Pajchiri. Each appears to channel water from specific local drainage basins and spring systems. The presence of near-critical slope canals reinforces the transport rather than distribution aspect of these canals and in this respect, it is important to note that several segments of raised fields at Pajchiri were cut on laboriously constructed terraces between the aqueducts. This is a clear indication of design response to high groundwater conditions and saturation of soils destructive to agriculture.

The aqueducts at Pajchiri can best be interpreted as hydraulic structures that supported continually functioning drainage canals designed to remove excess water from areas of field reclamation, thereby maintaining a stabilized water table at a level below that of crop root systems. The drop structures and feeder canals along the aqueducts were incorporated into the structures to add water into field systems to regulate water table height, i.e. the use of drainage and water supply functions of the aqueduct could be used to modulate water table height in different adjacent field plots for different crop types. If the water table was allowed to rise too high, accumulated salts could interfere with crop development and drown root systems. Therefore, regulating the water table height was critical and the systems thus far discussed appear to have been designed to this end. A further function related to using reservoir-stored water to flush accumulated salts from field systems is also vital to the agricultural environment. The use of a canal width expansion–contraction zone (summarized by field measurements in Table 1.2.3, where the subscripts L and R denote left and right in the streamwise direction) in the aqueduct likewise creates a local lowering of water height that activates low-lying drop structure inlets. Here, as $D_N < D_c$ for typical Q flow rates, flow is supercritical so that a canal width expansion alters water height, thus activating the side weir. This feature may be important to prevent excess water from entering the field systems during heavy runoff flows as the higher flow rates just increase the flow Froude number, resulting in faster flows of lower height that are below the drop structure inlet heights. Thus, higher flow rate, higher Froude number flows automatically are transited down the aqueduct to empty into the lake to prevent additional water from saturating the agricultural fields.

Summary and conclusions

Two aqueduct systems at Tiwanaku urban settlements have been analysed to interpret their design features and provide insight into Tiwanaku hydraulics knowledge. Both appear to employ supercritical open-channel flow and serve as drainage systems intended to prevent excess water from entering groundwater, raising the water table, and making agriculture untenable. For the Lukurmata aqueduct, an erodible, lower channel system was constructed to collect runoff from mountain sources and divert it to Lake Titicaca directly. This aqueduct had features related to the use of a neutralizing reach to eliminate on-aqueduct hydraulic jumps in the presence of elevated lake levels. The aqueduct supported a flow with water depth near normal depth values, implying near-constant supercritical velocities that provide rapid drainage of the runoff to the lake. The wide-bed, erodible bed concept is unusual, but were a fixed geometry channel used, it would require knowledge of worst-case flood runoff rates, which may not have been available in other than anecdotal form. The use of a channel that carves its own minimum resistance cross-section tailor-made to any flow rate then solves a difficult problem in an elegant manner. After flood events, the eroded channel was infilled and prepared for the next event without memory of prior flood erosional events. This design prevented the continual erosional-deepening of the channel in the presence of sequential flood events that ultimately would wash out the aqueduct structure were it built with a given channel configuration.

The Pajchiri aqueduct's function was diversion of excess runoff water to the lake to avoid the problem of saturated soils needing long evaporation and drainage time to be suitable for agriculture. Since the aqueduct slopes were constructed near the critical slope, maximum flow rates from spring and drainage basins to the lake outlet of the aqueducts were achieved. Again, drainage was vital for preparation of agricultural fields, with the option to provide water from reservoirs to field plots when necessary to increase the height of the water table for different crop types. This consideration arises from the intensity and duration of altiplano rainfall amounts that severely limited agricultural development without an active drainage strategy in place. By aqueducting heavy seasonal runoff flow and diverting it to the lake, Tiwanaku hydraulic engineers were, in effect, conserving the habitability of the urban and agricultural environment.

1.3 FLOOD DEFENSIVE SYSTEMS OF THE HOYA HONDADA AQUEDUCT IN THE JEQUETEPEQUE VALLEY

The picture developed thus far of coastal Chimú and altiplano Tiwanaku water systems is one of innovative exploitation of the natural water resource base in particular ecological zones. Since the memory and realization of destructive climate and weather variations, as well as catastrophic El Niño runoff events, threatened the agricultural base through field system destruction, it may be expected that defensive measures to protect against these events will be found in canal system design. This section outlines one such discovery in the north coast Jequetepeque Valley of Peru.

While only a few of the valley irrigation systems under Chimú control have been extensively explored, mapped, and analysed, some canal hydraulic control features have been discovered that warrant analysis as they provide a window into the level of hydraulic science existing within the Chimú Empire. Early preliminary surveys of canal systems and irrigation agriculture field systems on the north coast of Peru were conducted by Kosok (1965). Later, more detailed survey and mapping of the Jequetepeque Valley systems (Eling 1985), the intravalley Moche Valley systems (Ortloff *et al.* 1982, 1988; Ortloff 1993, 1995) and the Moche–Chicama intervalley systems (Ortloff *et al.* 1985) as well as major canals in the Lambeyeque Valley (Shimada 2003) were reported. While these studies largely constitute the extent of north coast, LIP canal system survey, mapping, and analysis, an extension of the discovery process involves analysis of the hydraulic functioning of known systems to discover the degree of technical innovation present. While many of the historical, architectural, cultural, and artistic achievements of the north coast Chimú of ancient Peru have been described in the literature (Moseley 1992a, 1998; Keatinge 1988), field studies have noted evidence of defensive hydraulic structures to control water flows. Since all major valleys under Chimú control show evidence of massive state-sponsored, hydraulic canal infrastructures to support irrigation agriculture, it follows that hydraulic science was co-developed to provide tailored flow rate canals to systematically supply field systems. As considerations of soil and crop types, crop water demands, field system watering strategies, valley topography, geophysical landscape change, and defence from drought and large rainfall runoff events influenced canal design and placement, an accompanying hydraulic science with the flexibility to design, modify, and defend canals according to these considerations is expected from the archaeological record. Most probably cumulative observations of water flow phenomena over time served to provide a database for the empirical design principles used for canal layout and design. While no Chimú writing systems are known at present, calculation and data storage systems existed, although their application to hydraulic design methodology, water resource allocation, and historical climate records remains as yet only partially explored.

As canal delivery flow rate relies on inlet geometry, bed slope angle, canal cross-section, wall roughness, and flow characterization (subcritical, critical, supercritical), allied technical disciplines related to route layout, surveying, water delivery sequencing, and routing through multiple canal branches are important in understanding Chimú hydraulics practice. To provide insight into water control practice, the present chapter details an investigation of a canal hydraulic feature of the Chimú Talambo–Farfán Canal, which is located in the Jequetepeque Valley (Figures 1.1.1 and 1.3.1). While the remains of the canal system are of Chimú origin due to association with the site of Farfán, some upstream canal segments may be associated with earlier valley occupation by Gallinazo and late period Moche occupants. For the present analysis, however, only the last Chimú phase of canal construction is analysed.

The Talambo–Farfán Canal originates far upstream in the valley neck of the Jequetepeque River and passes hillside Chimú occupation zones in the Talambo region through a series of aqueducts and deep canal cuts through upvalley hills before emerging onto the agricultural plains southeast of Farfán. The canal was extended to provide water to the extensive agricultural field zones directly south of the Chimú mountain redoubt of Farfán Sur on the southern face of Cerro Faclo (Figure 1.3.2). A later extension of the canal crosses a sequence of deep quebradas in the foothill region of Cerro Faclo by

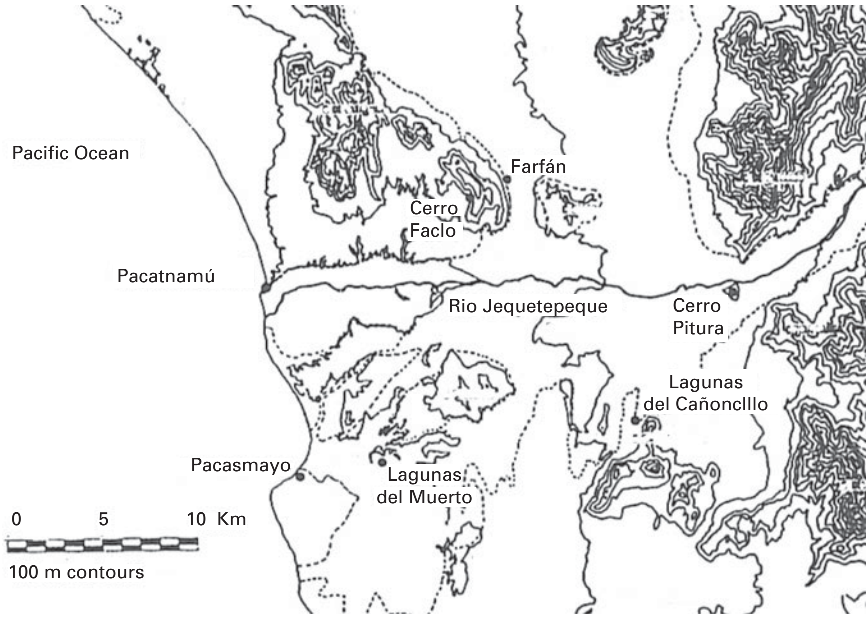

Figure 1.3.1. Map of the lower Jequetepeque Valley showing key sites in the vicinity of Pacatnamú and Farfán.

means of three large earthfill aqueduct structures level to the land surface height before encountering the last in the aqueduct sequence, the Hoya Hondada aqueduct (Figure 1.3.3). The entire canal approaches 35 km in length, measured from the inlet location. For the deep and wide Hoya Hondada quebrada, new aqueduct design considerations were applied in contrast to upstream aqueduct constructions. The upstream aqueducts were fill constructions at the height of land surfaces on either side of the narrow gorges they traversed; the Hoya Hondada aqueduct was composed of a long, low-height aqueduct deep within the quebrada with a steep approach chute from the upstream bluff (Figure 1.3.3). After canal passage over the low aqueduct, the canal continued up the downstream side wall of the quebrada (while still retaining its downward slope) to field systems located on the southern boundary of the Pampa de Faclo, approximately 8 km east of Pacatnamú (Figure 1.1.1). The intent of the canal extension west of Farfán Sur was apparently to provide water to settlements and field systems in the south edge of the pampa east of Pacatnamú. While canal extension to the city limits of Pacatnamú may have been the intent of the canal builders, traces of a continuous connection path to the city are yet to be discovered. While many canal remnants are found on the plains around Pacatnamú, they may be remnants of Moche canal bases remaining after a deflationary episode.

The canal and aqueduct design within the Hoya Hondada quebrada contained many novel hydraulic features indicative of the state of Chimú hydraulics knowledge. For example, a high-velocity, supercritical water flow down the steep 40° downward chute lead-in canal to the Hoya Hondada aqueduct would create a massive hydraulic jump at the angle-change junction with

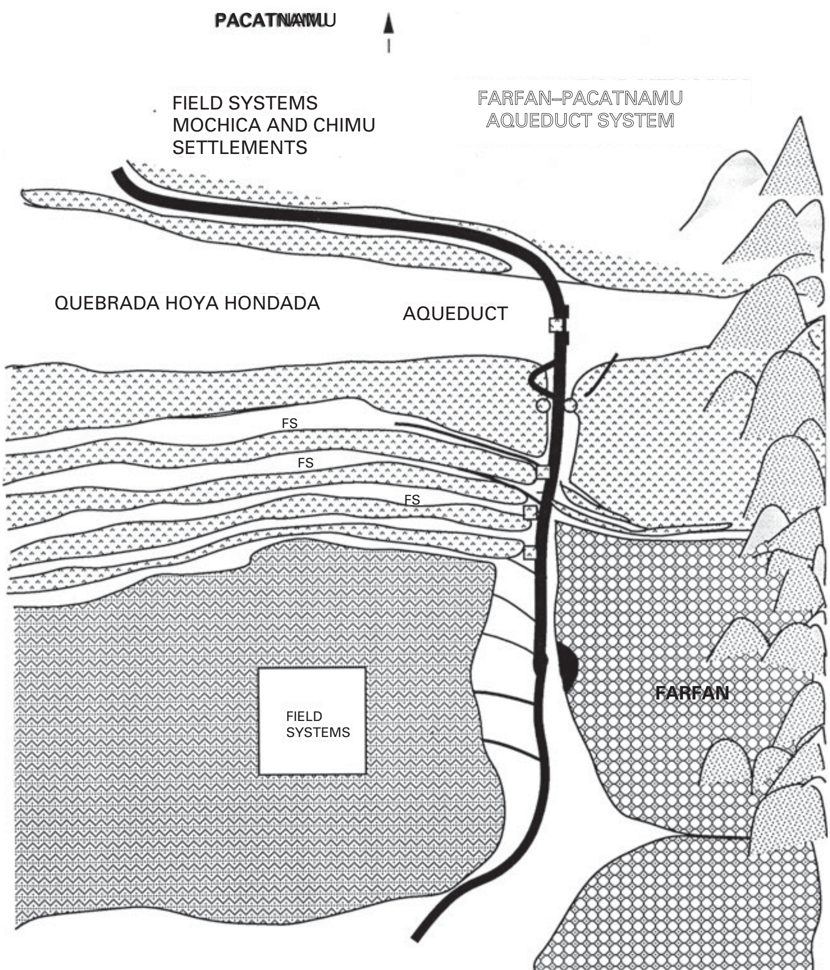

Figure 1.3.2. The canal passing between Farfán and adjacent field systems (FS) crossing over numerous quebradas by aqueducts en route to the Hoya Hondada aqueduct.

Figure 1.3.3. The Hoya Hondada aqueduct showing the channel path to the plateau containing Moche and Chimú sites with the site of Pacatnamú 8 km to the west.

the low-slope aqueduct. The hydraulic jump would have led to severe canal bed erosion from turbulence effects as well as side wall overflow from the aqueduct unless upstream hydraulic controls were in place to limit both the velocity and flow rate of water entering the steep-angle chute, particularly during an El Niño event. An upstream canal control to limit severe erosive and overflow effects is therefore integral to the preservation of the lower aqueduct.

Engineering analysis

Past extensive field systems (Eling 1985) bordering the Farfán Sur area, which provided part of the agricultural base of the Chimú administrative centre of Farfán, the canal enters a foothill region west of the Cerro Faclo coastal mountain range cut by many deep quebradas transverse to the canal direction. The deep quebradas, formed over time from successive El Niño rainfall runoff events sculpting erosional channels in the soft soil deposits, formed natural obstacles to canal extension. In order to bridge the multiple quebradas, a series of large earth-fill aqueduct structures and many small aqueducts were constructed to extend the Talambo–Farfán canal to the vast Pampa de Faclo. While aqueducts upstream of the Hoya Hondada quebrada were built at the height of the opposing cliff faces to maintain the small bed slope of the canal, as the canal approached the largest and westernmost Hoya Hondada quebrada, a different aqueduct design strategy was used. Due to the extreme width (100 m) and depth (20 m) of this quebrada, a high height aqueduct design typical of upstream aqueducts would act as a massive dam, impounding El Niño runoff water to great depth and subjecting the aqueduct to breakthrough, undermining, and sliding failure. While some Chimú aqueducts have large boulder bases or stone-lined culverts to permit flow passage, such preservation strategies fail when the impound water height becomes high and the water volume accumulation rate upstream of the dam far exceeds the flow rate capacity of culvert structures. For the Hoya Hondada aqueduct, a different design strategy was used: the aqueduct was set low in the quebrada about 5 m from the natural quebrada bottom surface with a 25-m long steep chute joining the high-elevation part of the canal to the low aqueduct. Although the Hoya Hondada aqueduct is deep within the quebrada, a low-slope canal extension running up the opposing quebrada side wall is in place to provide water for settlements on the Pampa de Faclo (Figure 1.3.3).

The hydraulics problem associated with the steep chute relates to the rapid gravitational acceleration of water down the chute and the formation of a large hydraulic jump at the steep-angle chute, near-level aqueduct slope change junction. The severity and height of a large Froude number hydraulic jump is sufficient to destroy the aqueduct by turbulent erosion processes acting on the unconsolidated fill structure (the aqueduct channel is unlined) unless hydraulic controls are in place in the channel upstream of the chute to dissipate stream energy, lower stream velocity, and/or remove excess water from the canal (which is another mode of stream energy loss). Reducing the channel water velocity to lower magnitude reduces the height of the downstream hydraulic jump significantly and reduces turbulence intensity to a level that does not imperil the integrity of the fill aqueduct structure. Provided flow control and energy dissipation can be accomplished by an upstream hydraulic control structure, the aqueduct structure can resist damage from channel bed erosion even during large El Niño events.

Investigation of the channel upstream of the Hoya Hondada aqueduct shows that an energy-dissipation hydraulic structure was installed to influence flow behaviour. The hydraulic structure consisted of two pairs of opposing boulders with a 70 cm separation distance between each boulder (Figure 1.3.4) and a 13.2 m downstream separation distance between boulder pairs. The channel containing this structure has variations in width and side

Figure 1.3.4. Dual opposing boulder chokes in the canal upstream of the Hoya Hondada aqueduct.

wall angle between the boulder pair region; this region is shown in an idealized CFD model conforming to field measurements (Figure 1.3.5) and includes a side weir just upstream of the downstream boulder pair. The overflow weir led to a channel on the downstream side of the Hoya Hondada aqueduct that shunted water higher than the weir height into the quebrada downstream of the aqueduct. The hydraulic function of the control structure was subjected to analysis (FLOW-3D 2007) to determine its function.

CFD analysis results were developed for sample input flow velocity values from 1.5 to 5 m/s, corresponding to the maximum flow height that can be contained within the canal at the initial entrance ($x = 0.0$ m) station of the model. A range of flow velocities were employed to investigate conditions under which the dual boulder pair system influenced flow patterns to reveal the design intent of the constructors. Results indicated that as velocity and channel flow rate increased past a critical flow rate, water height increased ahead of the downstream constriction and the side weir released water from the channel, thereby decreasing the net flow rate transported downstream to the aqueduct. The height of the water in excess of the side weir height then regulated the amount of water shunted into the drainage channel directed into the quebrada. The release of excess water in the canal during an El Niño event therefore would limit erosion and overflow events in the lower aqueduct

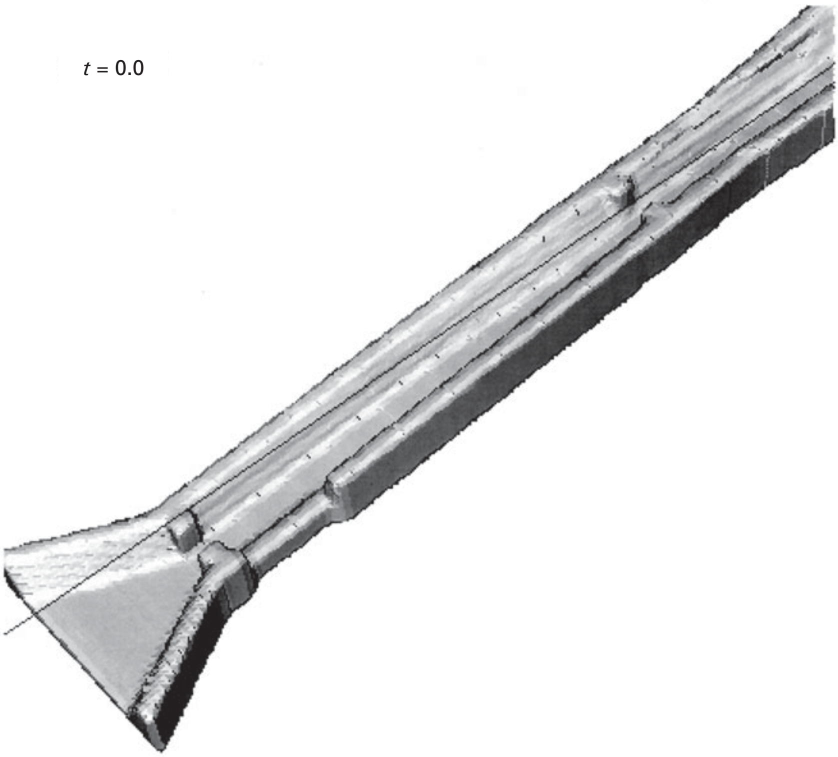

Figure 1.3.5. Canal computer model (FLOW 3D) from field measurements illustrat ing the dual choke system internal to the canal. The side weir between chokes activates to shunt water from the canal during excessive runoff events.

structure. The hydraulic mechanism producing this effect involves an explanation in terms of hydraulic open-channel flow concepts. For high water velocity (equivalent to a large volumetric flow rate) entering the channel constriction formed by the furthest downstream boulder set, water velocity in the constriction (throat) between boulders continually increases as the backed-up water level upstream of the boulder pair increases. At a critical height of upstream water level where the throat Froude number approaches unity, the throat is considered choked, i.e. the flow rate through the choke is the maximum possible independent of upstream water height (Chow 1988; Morris and Wiggert 1976). The furthest upstream choke apparently activates (i.e. produces a choked throat) at incoming stream velocities past about 7 m/s while the downstream choke activates at approach velocities about 3 to 5 m/s.

This is because the Froude number increases in the zone downstream of the first choke due to water gravitational acceleration and channel cross-sectional geometry changes on a hydraulically steep slope, i.e. water velocity increases while depth decreases in the zone before the downstream choke. Thus, although each boulder set has the same geometry and lateral separation distance, the flow upstream of each boulder set has a different Froude number history resulting from the interaction of the flow with the complex cross-sectional geometry changes between boulder pairs, which accounts for the different behaviour of each choke system for different input flow rates. Since flow into the downstream choke is supercritical over the range of input flow rates at the $x = 0.0$ m station, the second downstream choke acts to form a hydraulic jump ahead of the choke with an exit flow rate limited by critical conditions. As the choked flow rate of the downstream choke is less than that of the upstream choke, the difference must be equal to the flow rate shunted over the side weir to maintain a constant water level between chokes; here the induced hydraulic jump serves to elevate the water level ahead of the downstream choke, causing spillage into the side weir. With the double choke structure in place, the maximum transmissible flow rate appears to be in the order of 4 m^3/s, which was considered by Chimú engineers to be the

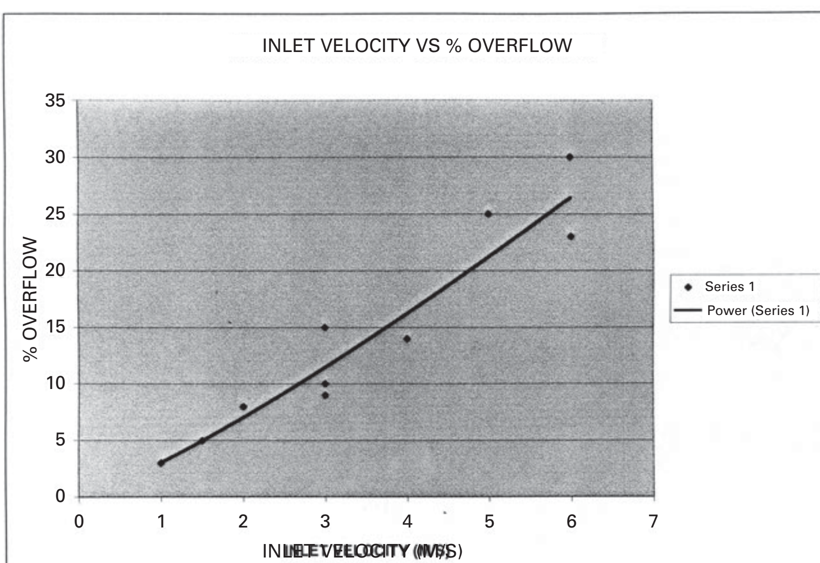

Figure 1.3.6. Computer results illustrating that past ~4 m/s velocity about 20% of the flow exits the side weir. At higher velocities, the overflow percentage increases.

maximum flow rate to limit the downstream aqueduct from hydraulic jump damage. Note that for flow rates less than ~3 m^3/s the chokes are essentially inactive and permit water passage without restriction or side weir overflow. Figure 1.3.6 indicates that for an inlet velocity past 4 m/s, a higher percentage of the inlet flow is shunted over the side weir to maintain the transmissible flow rate at ~4 m^3/s. A sample discharge over the side weir is shown in Figure 1.3.7 corresponding to a 6 m/s inlet flow.

The double choke system described is augmented with a further downstream energy-dissipation system on the steep-slope channel. Figure 1.3.8 shows the contour path of a channel bifurcation that occurs about 30 m downstream of the double choke system. The smaller, left-directed channel is at a lower slope and circles a small hill before rejoining the main channel at the junction point. The lower subcritical velocity stream from the lower slope channel acting on the main postchoke supercritical stream has the effect of creating an energy-dissipating hydraulic jump in the channel that converts

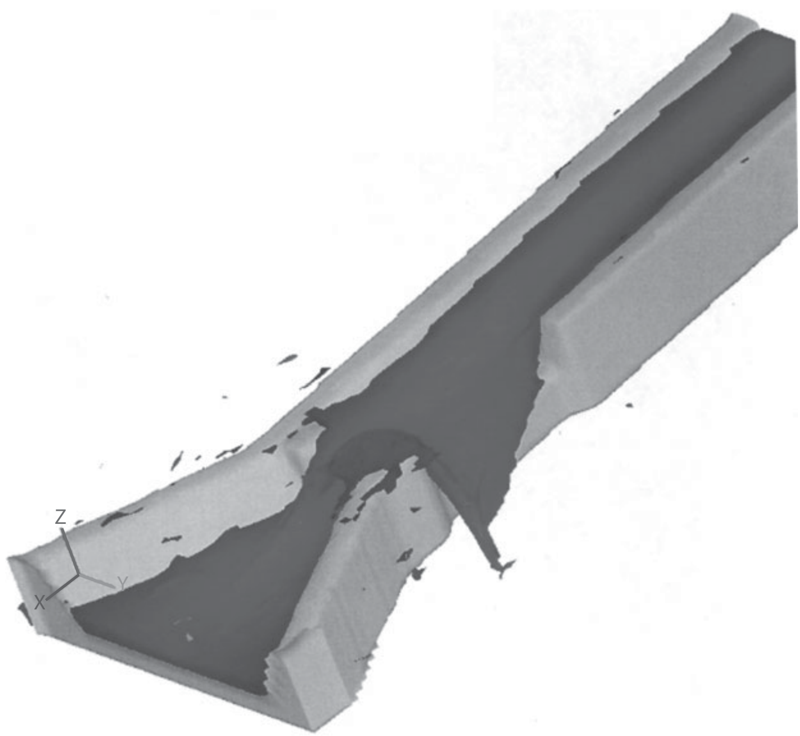

Figure 1.3.7. Computer simulation of water flow in the canal, indicating overflow activation of the side weir due to the downstream choke limiting the passage flow rate.

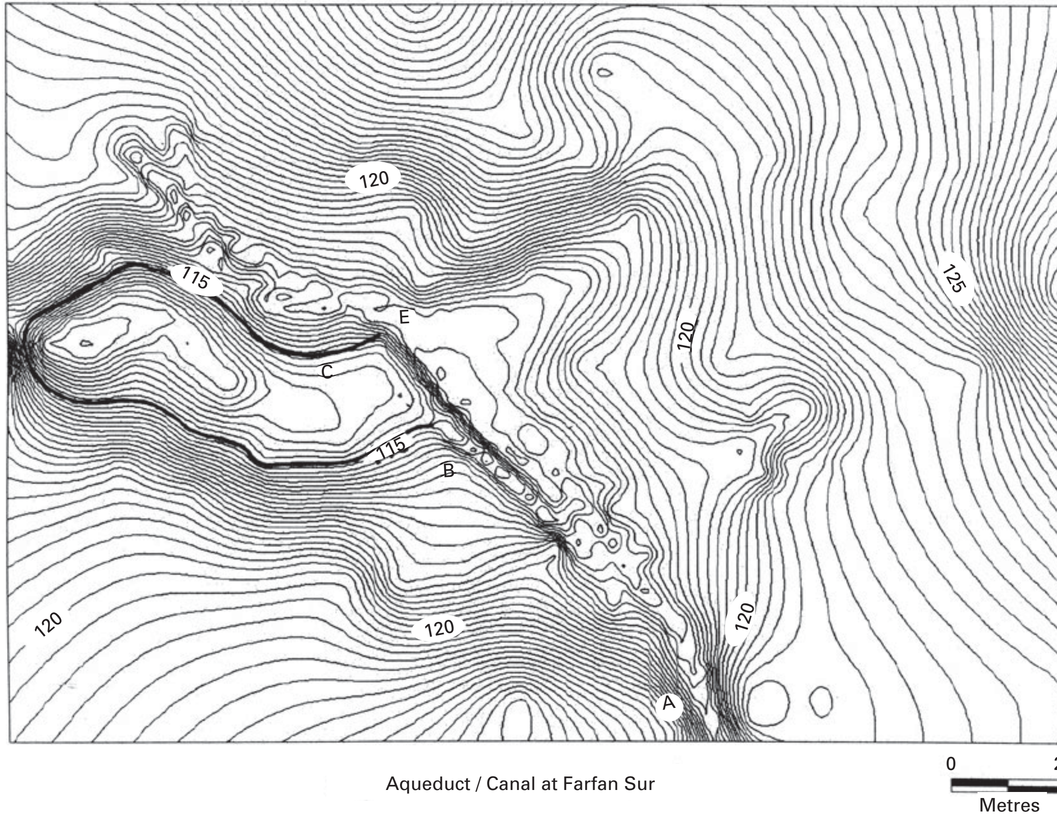

Figure 1.3.8. Contour map of canal A B showing branch contour canal C subtracting flow from the main channel. Diverted subcritical flow rejoins supercritical flow at E, creating a hydraulic jump and furthering flow energy dissipation ahead of the steep downstream chute.

stream energy into random turbulent and potential (height change) energy. This has the effect of subtracting further energy from the stream approaching the chute-aqueduct junction zone. The net effect of the two energy reduction controls (the first from limiting the flow rate by means of the overflow weir and the second from an intersecting stream-hydraulic jump energy-dissipation mechanism) is to reduce entry velocity and flow rate onto the Hoya Hondada aqueduct and thus limit the hydraulic jump erosive and overspill damage. Here the hydraulic jump height is reduced at the chute-aqueduct junction by lowering the volumetric flow rate and employment of energy-dissipation mechanisms. Although a large part of the steep-slope channel is no longer extant, there is evidence that stones placed in the chute bed may have provided a further energy-dissipation mechanism to reduce stream velocity. Such protective controls then served to limit erosion damage to the Hoya Hondada aqueduct arising from massive El Niño rainfall runoff from the nearby Cerro Faclo mountain range. Large canal flow rates arising from water washing into the canal could easily produce conditions of excessive canal flow rate beyond the design flow rate and destroy the Hoya Hondada aqueduct by a massive hydraulic jump at the channel-aqueduct junction without the side weir overflow and other protective features. By diverting water over the weir together with use of other energy-dissipation controls, excess water and energy were removed from the canal to provide a protective hydraulic feature for the aqueduct.

As settlements on the outlying southern section of Pampa Faclo were somewhat remote from the Farfán centre, it may be surmised that water resources reserved for this sector were proportional to its importance. The fact that water could be directed to this secondary location perhaps indicated that further expansion of the area's agricultural potential was anticipated but still in the construction phase. Yet the major effort to construct multiple elaborate aqueduct structures to bring water to this zone through difficult topography perhaps indicated that a valuable agricultural resource in the Pampa Faclo land area overrode labour-to-build considerations, perhaps because of unrelenting population increase pressures.

Technology overview

Previous studies (Ortloff *et al.* 1982, 1983, 1985; Ortloff 1993, 1995) have noted evidence of elements of hydraulic controls to regulate water flows in inter- and intravalley canal systems controlled by the Chimú. The transition to LIP Chimú from EIP Moche eras saw a vast expansion of cities, administrative centres, and agricultural zones as well as a development of hydraulic technology that permitted intra- and intervalley canal network development to exploit all available land zones with agricultural potential. Field survey of the Jequetepeque Valley revealed mainly Chimú sites with Moche antecedents. The site of Cañoncillo to the south of the valley (Figure 1.3.1) is typical of an earlier Moche site overlaid with later Chimú occupation zones; regardless of the occupier, the area is intensely overlaid with agricultural remains from both societies, attesting to its importance as flat land assessable by southward directed canals from the Jequetepeque River. The valley's geographic position, however, makes it a natural crossroad of coastal and highland influences over late EIP, Middle Horizon (MH) and LIP (some evidence of which is indicated by the ceramic diversity discovered at San Jose de Moro, e.g. Wari, Cajamarka, Gallinazo, Lambeyeque-styled, northern highland, and classic early and late Moche ceramic types). Consistent with this diversity, importation of hydraulic technologies showing highland influence probably occurred, particularly technology related to control of water flows involving steep gradients. While low-slope coastal canal systems rarely indicate this technology and are based on subcritical flow controls, highland systems usually reflect the need for energy-dissipating, supercritical flow controls due to the higher canal slopes present and the more varied and broken topography. Thus technical transfer related to supercritical hydraulic technologies may be imported (along with ceramic types) from highland sources to explain some of the unique features present in the Hoya Hondada aqueduct. If population pressures existed with demand for land and water resources, then the technical means to build new types of aqueducts to open up agricultural areas would be a key import that could lead to expansion of urban settlements. Additionally, climate changes that altered water availability would be a further factor that would drive technology importation to maintain agricultural productivity and provide the basis for changes in agricultural development patterns.

This section provides an example of an application of hydraulic technology that either accompanied expansion of agricultural lands or made the expansion possible. In the present case, the supercritical technology manifests itself as a control device used to limit water flow rates in canal sections, presumably as a defensive measure against aqueduct washout during El Niño events. Observations of numerous flooding events in the Jequetepeque Valley over the time period of Chimú occupation have been well documented (Dillehay and Kolata 2004). Other examples of steep-slope channel constrictions formed by opposing stones set with a narrow opening are numerous within the Farfán field system area. Basically, channel constrictions of this type create a hydraulic jump ahead of the constriction, with high height, low-velocity water entering the throat. As the critical velocity is reached in the choke, low-velocity water enters field system distributive channels, permitting gradual soaking into root systems. The supply channel, to maintain a stable hydraulic jump without overflow, must therefore be constructed to allow just sufficient flow rate for this purpose and a choke width suitable for the supply flow rate. This requires manipulation of canal slope, wall roughness, and cross-sectional area (or canal size) to achieve this balance. This design capability appears to be well understood by Chimú engineers as demonstrated by this and many prior canal design examples (Ortloff *et al.* 1982, 1983, 1985).

It appears that the Chimú use of hydraulics knowledge was the underlying basis to support large populations well dispersed within multivalley agricultural systems. In contrast to the Chimú, the preceding Moche society possessed fewer technical options to expand and regulate agriculture, particularly in the face of climatic disruptions. The Moche strategy was apparently to extend their canals and field systems to more easily managed land areas with secure water supplies (few Moche large-scale aqueducts and contour canals are found), requiring a lesser degree of technology to construct and maintain.

In the presence of severe drought and other coupled phenomena (sand dune incursion, for one), it appears that migration to more hospitable areas of the north coast with more favourable water resources and more accessible arable land areas was an option (Shimada 1990, 1994). This change in vision between successive societies can be thought of as a direct result of confidence through increased technical innovation and learning that permitted further options to be considered for stabilization of a society. In this sense, an ancient to modern parallel can be seen that ensures the survival of a society.

Examples of hydraulic controls in the form of flow rate limiting and velocity-reducing hydraulic structures point to a little-explored creative aspect of Chimú irrigation agricultural practice and hydraulic science knowledge base. While examples illustrating applications of Chimú hydraulics engineering are somewhat lacking because of limited exploration and analysis to date, undoubtedly more remains to be discovered as focus is given to the exploration and analysis of hydraulic features. By computer analysis of such systems, aspects of Chimú hydraulic science are revealed and point to a new evaluation of the contribution of indigenous South American cultures to the hydraulic sciences.

1.4 THE CANAL AND TERRACE AGRICULTURAL SYSTEM OF THE TIWANAKU–WARI COLONIES IN THE MOQUEGUA VALLEY, PERU, 300–1000 CE

The physical setting

The Moquegua Valley of far-southern Peru (Figure 1.1.1) incorporates a wide variety of ecological environments exploited by different ancient civilizations from early centuries BCE through the first millennium CE with later use of water resources in the Colonial era. Major presences of Tiwanaku and Wari colonial outposts occurred in the upper and mid-range parts of the Moquegua Valley in the 300–1100 CE period (Goldstein 2005; Williams 2006) utilizing the valley's water and land resources for agriculture. Some degree of cooperation between societies is apparent from the fact that different ecological zones were exploited by Tiwanaku and Wari farmers at different times in the Moquegua Valley, and that the Wari ceremonial centre of Cerro Baúl lay prominently within Tiwanaku-controlled territory, but with some evidence of shared occupation. The upper valley is bounded on the east by the foothills of the Cordillera Negra and contains the Torata, Tumilaca, Huaracane, and numerous other runoff channels that originate the Moquegua River from highland runoff and snowmelt zones in the 2500–4000 m altitude range. The mid-valley region (1000–1500 m) consists of flat, sandy, and gravel areas suitable for irrigation agriculture primarily from waters taken from the descending Moquegua River. Descending from this altitude towards the coast, the valley is constricted by high, sandy banks on each side of the river and the low flow rate Moquegua River typically disappears into groundwater without measurable surface outflow to the Pacific Ocean. Typical rainfall amounts on the coastal desert areas of the valley are in the order of a few millimetres per year with rainfall amounts increasing with altitude to 20–200 mm levels. Because of variable, altitude-dependent water arrival amounts from snowcap to high-altitude rainfall zones and differences in water absorbance into various soil types at different altitudes and depending on the duration of individual rainfall events (the rainy season is from November to March) and ground saturation levels, the runoff available for irrigation agriculture at upper, mid-, and lower valley zones is highly variable. Occasional massive El Niño rains and intermittent drought periods add to the unreliability of water supplies in the valley and large diurnal temperature changes in the order of 15°C in upper valley regions challenge ordinary agricultural practices. Despite all the challenges from the natural environment, many creative agricultural systems evolved in these regions from the colonies of major civilizations (Tiwanaku and Wari). Of interest is the fact that both Wari and Tiwanaku colonial outposts occupied and competed (with some degree of cooperation) for the land and water resources of this valley even though the centres of each civilization were distant. The Tiwanaku occupants appear initially to have occupied the mid-valley (1000–1500 m) region about 600 CE and exploited flat areas using traditional canal-supplied irrigation agriculture. The Wari colonists occupied the high sierra zone (2000–3000 m) somewhat later at 700 CE and are focused on areas around Cerro Baúl and Cerro Mejía.

The settlement located on top of Cerro Baúl is mainly of Wari origin and served as the main administrative and ceremonial centre of the area (Moseley *et al.* 2005; Williams 2006); recent research has indicated some evidence of shared Tiwanaku presence at this site. A view of the different adaptive agricultural techniques of these two civilizations in contact is therefore of interest given the different altitude-related ecological base each chose to exploit. Of further interest is the fact that the water resources abstracted at the higher altitude by the Wari occupiers had an effect on resources available at lower altitudes by the Tiwanaku colonists, thereby coupling their fates and raising questions about the cooperative or competitive nature of the interaction.

Wari terrace agriculture technical innovations in the Moquegua Valley

Because of the steep slopes encountered by Wari agriculturalists in the upper valley regions, the use of stepped terraces (Figures 1.4.1 and 1.4.2) typical of mountainous valley systems close to their capital city near present-day Ayacucho was a natural way to employ their technology. Wari influence in far-south regions of the Moquegua Valley starting about 600 CE also showed use of imported terrace agriculture typical of the corporate style prevalent in northern reaches of their empire. Typically, terraces were constructed in the upper valley zone between the Tumilaca and Torata tributary rivers with stone-faced outer walls that contained soils suitable for agriculture and interior bottom cobbles to facilitate drainage. Centred in this agricultural zone was the highly defensible, mesa-top city of Cerro Baúl, primarily used as an administrative centre for the Wari hamlets in this area. Beyond the agricultural potential of the area, copper sources are nearby (attested to by continued mining in the present era) and some production of rolled copper plates has been associated with burnt debris layers and slag at the lower reaches of Cerro Baúl.

Terraces generally operate in two modes: above 3,500 m natural rainfall is sufficient to provide water and from 2,000 to 3,500 m some form of irrigation is usually required. For the latter case, use of long, low-slope canals with circuitous paths from high-altitude snowmelt and rainfall collection zones was a further method of water delivery to isolated mountain slopes and flat areas suitable for agriculture. Of interest for the technological level of planning involved was use of a single canal to distribute water to both sides of a mountain with each side containing terrace systems. This was accomplished

Figure 1.4.1. Terraced multi step field systems (andenes) typical of the highland mountainous agricultural systems used by the Wari, Tiwanaku, and Inka societies. Systems shown are in the Moquegua Valley area.

by use of sinuous, S-shaped canal routes along mountain ridges alternately switching from one to the opposite side of the ridge. If viewed from above, the canal would provide water to alternate sides of the ridge through drop-off canals running down the mountain faces. At some point on the drop-off canal an inlet structure would exist to provide canal water to the lower horizontal terraces. Figure 1.4.3 illustrates the application of this technical innovation. The drop structures from the ridgetop channels led water down steep slopes to terrace structures; as the terraces are immediately below one another, collection channels successively drain water from higher to lower terraces, resulting in nearly complete absorption of water supplies. For cases for which the terraces were located far downhill from the ridgetop canal, a steep drop chute (30 to 60°) was utilized; the chute was filled with cobbles of various

Figure 1.4.2. Canal with drop off outlets on alternate sides of a mountain ridge to supply terraces on each mountain face typical of Wari terrace canal construction techniques in mountainous terrain.

sizes to act as energy-dissipating structures to slow water acceleration. Where erosion-cut drainage channels form riverbeds descending from high altitudes, Wari engineers constructed fill structures along river embankments to contain a water channel collecting runoff and snowmelt water from high altitude. These channels are usually constructed at shallower angles than the riverbed to elevate water over the bank at a prescribed point to provide water to distribution canals feeding terrace systems. Typically, the fill embankments supported canal widths in the order of a metre or less, indicating that the amount of water conducted was tailored for a dedicated terrace section that matched the canal water requirement. As flows are supercritical due to the hydraulically steep angles associated with mountain descent, shallow asymptotic normal depths of high-speed water ($Fr >> 1$) result; the channel depths are therefore relatively shallow, reflecting this hydraulic regime. Here no cobble or other types of resistance obstacles were found in canal beds as they cause transition to subcritical flow by forming a hydraulic jump with increases in water height. Flows therefore are maintained supercritical at low normal depth with lower slope lead-off canals to terraces that were designed to create a hydraulic jump in an inlet structure to lower flow velocity. In many

Figure 1.4.3. Canal supplied terrace system showing a drainage channel on the right to collect non absorbed agricultural water for use in lower sets of terraces.

cases, only one canal was sufficient to provide water to an uppermost terrace, with lower terraces charged with drainage water. Because the Wari were based in the highlands and water distribution must necessarily deal with steep-slope canals, there is a mastery of high-speed water flows in steep canal structures non-typical of coastal water supply systems.

Of the canals established by the Wari, the 14 km El Paso Canal provided water from the Torata River to fields on the slopes of Cerros Baúl and Mejía, and the Tumilaca Basin; branches of the canal led to other areas suitable for terrace agriculture with villages and towns en route. As a result of adequate rainfall past 600 CE, the Wari system became well established without competition from the nearby Tiwanaku state until *c.* 700–900 CE, when Tiwanaku colonists entered the area and established centres at Chen Chen in mid-valley regions supplied by canals from the Tumilaca River. Apparently, because different ecological zones were exploited by Wari and Tiwanaku colonists, both coexisted without conflict for centuries before abandonment around 1000–1100 CE from the onset of drought and associated economic/political changes manifested from this effect. Later establishment of smaller, dispersed communities in the Otora, Chujulay, and Tumilaca tributaries followed, with sites collected towards available water resources with even later (1250–1459 CE) high-elevation, small localized Estuquiña settlements characterized by defensive walls and dry moats protective of local water resources. Later, as drought subsided past 1475 CE, Inka presence is noted and, because of more available water resources, some shift to more productive valley bottom agriculture replaced some of the highland terrace systems.

With regard to Wari systems, observations promote the idea that Wari engineers had superior observational skills applied to hydraulic designs; certainly the long, low-slope contour canal and aqueduct structure leading water to the Wari site of Pikilacta (just outside of Cuzco) affirms the hydraulic skill level of this society. For cases where the land area was remote, a long lead-in canal, sometimes as long as 20 km, was used. While higher rainfall at altitude was a source of water supply to terraces, the main water supply to ridgetop canals originated from the fringes of the icecap melt zone at higher altitudes. This area sees a near-permanent water supply due to seasonal snow and ice accumulation and has aspects of a drought remediation system as increased air temperature that usually accompanies drought conditions caused increased snowmelt and runoff into the ridgetop canals. At least 300 hectares of sierra terrain were modified by the Wari in the upper Moquegua Valley according to their homeland mountain traditions, creating a relatively drought-proof system exploiting high-altitude water resources; this area became the agricultural base of the Wari occupation of the Moquegua Valley starting from the 6th century CE.

Using this system, it may be surmised that water resources were pre-empted at lower altitudes as lower altitude systems depended on runoff from higher altitude sources. Runoff, beyond that extracted from higher altitude agricultural systems, increasingly was subject to absorption in lower valley porous soils, thus diminishing further a scarce resource available to lower valley agriculturalists. Prolonged drought lowers the water table and promotes further absorption and less water available for surface irrigation. By definition, runoff only occurs past higher elevation soil saturation so that only heavy, long duration rainfall can produce surface runoff-intercepted water transferred to groundwater, which may be of limited use to mid- and lower valley agriculturalists basing their systems on canal irrigation.

Drought conditions, such as experienced in the 650–730 CE and 1050–1150 CE time periods, further stressed lower valley agricultural systems, which were primarily composed of Tiwanaku colonies. The picture of higher altitude Wari Moquegua Valley occupation with specialized agricultural technologies competing with lower valley Tiwanaku surface irrigation systems sourced by runoff water in the overlapping time periods invites arguments related to either competitive or cooperative interaction for water resources, particularly in the presence of ecological stress (Williams 1997). Presumably, as both groups coexisted in different ecological zones for a long time and water was abundant during this period, some accommodation between groups was in place as no evidence of fortified settlements existed although the main Wari presence at Cerro Baúl certainly implies that defensive capabilities were a consideration in the selection of this limited-access, high mesa site.

Superimposed on this picture is the minimal understanding of the cultural and political dynamics of the coexisting Tiwanaku and Wari Empires, much less the interaction dynamics of their overlapping colonies vying for agricultural resources in the same valley. While the water distribution problems described above certainly played a role in the relative success of either colony, the increased rainfall in the 9th to 11th centuries CE apparently saw the demise of the Wari occupation, perhaps indicating the prominence of political considerations in deciding the value of maintaining colonies in this area given other options with better chances of utilizing labour resources for increased productivity.

With the Wari absence, the zone between 2,000 and 3,000 m lay abandoned until the later Estuquiña society reoccupied the upper valley in the 13th and 14th centuries CE and reinstated the terrace/canal method of agriculture. Previously undeveloped lands in the upland Torata Valley were terraced and associated with defensive walls and moats around small settlements, presumably guarding the water resource system vital to the settlement's survival. Since climate records indicate drought to some degree in this time period, the defensive nature of settlements may reflect the protection of life-sustaining water resources by these groups. Steep land areas became terraced as settlements close to high-altitude water sources were increasingly constructed; the presence of defensive compounds perhaps implies some competition for water sources among family or extended family groups to provide agricultural self-sufficiency. The clustering of upper valley settlements close to arable terrace lands characteristic of Estuqueña occupation is in contrast to earlier Wari settlement patterns in that Wari canals and agricultural lands were frequently remote from their settlements. Long canals to relatively low-slope patches of arable land and/or terraces on steep slopes appear to be controlled by small settlements strategically placed to control large and somewhat distant land areas. This arrangement implies dominance of the land areas and the uncontested presence and control of the water resources.

Tiwanaku and post-Tiwanaku agricultural technology in the Moquegua Valley

Tiwanaku colonies in the Moquegua mid-valley regions appear to rely on traditional canal irrigation agriculture to relatively flat areas (Goldstein 2005). Compared to the raised field agriculture practised in the areas adjacent to the Tiwanaku capital on the margins of Lake Titicaca, little precedent exists for technical transfer of this technology to river-based irrigation agriculture. However, in keeping with innovation of an agricultural system suitable to the environment, low-slope canals appear that lead to complex field systems. These fields were arranged in bermed sections with internal furrows to conduct water between elevated mounds that constituted the planting surfaces. In this manner, water was circulated into and remained in furrows to slowly diffuse into the mounded soil ridges to reach root systems, in much the same manner as the raised field systems but on a much smaller scale. As this innovation in agricultural technique appeared without precedent, it most probably signals a selection from a large repertoire of agricultural solutions applicable to different ecological zones and conditions.

Of interest are later post-Tiwanaku (1150–1400 CE) Chirabaya coastal society uses of ground seeps as a basis of their agriculture; other areas from Yaral (*c.* 10 km southwest of Moquegua City) to Moquegua City in the sierra foothills also are part of their agricultural domain (Satterlee *et al.* 2000). The Moquegua River disappears into groundwater as the coastal, lower valley regions are approached. On the shoreline cliff faces, groundwater seepage occurs some 5–10 m below the ground surface. By means of channels, the low flow rate seepage was collected and channelled to sunken field systems to supplement the water supply to crop areas. The sunken fields were dug to take advantage of the groundwater phreatic zone close to the surface and were further irrigated by supplemental water collected from channelled groundwater seepages adjacent to the field systems. As only small populations could be maintained by the small water resource base, individual coastal valleys (Pocoma, Miraflores, Carrizal, and Chuza) each had individual hydraulic infrastructures that supported small population centres (Clement and Moseley 1991; Satterlee *et al.* 2000). As rainfall levels increased in the 12th and 14th centuries CE (Thompson *et al.* 1985), augmented groundwater levels made the post-1100 CE coastal agricultural system viable, albeit of minimal extent and capability until final abandonment in 1400 CE (Ortloff and Kolata 1993). This system represents yet another adaptation to exploit water resources in non-conventional form given the ecological restraints of the lower Moquegua Valley region.

During the Inka occupation of the valley (1450–1532 CE), similar terrace/canal agricultural methods to those previously utilized by the Estuqueña (Satterlee *et al.* 2000; Stanish 1985) were employed, with the addition of typical Inka infrastructure elements such as tambos, roads, storage facilities, and administrative facilities to optimize the production and distribution of food resources from this area. The administrative site of Camata near Cerro Huayco (Mathews 1989) reflects the different mindset of the Inka Empire as new agricultural fields and terraces overlaid older Estuqueña systems. Later use of coastal seeps in Colonial times (and continuing to the present) for industrial crops (olives, wine grapes, cotton, etc.) provided some sustenance and market income for the community and individual family settlements of the area. Only a very small fraction of lands previously farmed were utilized and even these only relied on easily maintained, low technology water transfer systems close to settlement areas. The passing of great civilizations that once developed and managed these lands for food production under extreme variability in ecological and climate conditions is now part of the historical record, leaving only traces of their inventiveness and creativity for future historians to appreciate.

1.5 THE AGRICULTURAL SYSTEM OF CARAL—THE OLDEST CITY OF PERU, 3000 BCE

The Supe, Pativilca, and Forteleza Valleys of the Peruvian central coast, located less than 185 km north of Lima (Figure 1.1.1), contain a concentration of Preceramic sites that date back to 3000 BCE (and perhaps earlier, as future research may reveal). The presence of sites in the Supe Valley, long overlooked by archaeologists, are certain to rewrite the early history of pre-Columbian Peru as New World cities and monuments contemporary with Early Kingdom Egyptian Pyramids indicate that statehood had been achieved in Peru far earlier than thought and that previous ideas about highland origins for Peruvian civilization must now be rethought as having origins centred in the North-Central Coast and Supe Valley areas. For the Supe Valley alone, sites (from west to east along the Supe River) such as Aspero (15 ha), El Molino (7 ha), Piedra Parada (33.5 ha), Limán (0.5 ha), Era de Pando (80 ha), Pando (2 ha), Lurihuasi (38 ha), Pueblo Nuevo (55 ha), Miraya (36 ha), Chupacigarro (9 ha), Cerro Colorado (1.0 ha), Caral (66 ha), Allpacoto (23 ha), Peñico (22.5 ha), Huacache (7.6 ha), Cerro Blanco (0.8 ha), Capilla (0.2 ha), and Jaiva (4.2 ha) attest to the dense occupation of Supe Valley areas. Associated Preceramic and Formative sites in neighbouring valleys and highlands (El Paraiso, Rio Seco, Bandurria, Aspero, Los Galivanes, Culebras, Las Haldas, La Galgada, Huaricoto, Pirura, and Kotosh, among others (Moseley 1975)) imply development in this period of urban complexes and religious centres with highland/coastal communication and trade links, although many of these sites are separated by time, artistic styles, religious motifs, and political economic bases.

Figure 1.5.1A shows an aerial view of Caral located 20 km inland from the mouth of the Supe River; the site is composed of numerous platform mounds, sunken-court circular ceremonial centres, plazas, walled compound areas, and urban housing zones. The largest major pyramid (basal footprint 153×28 m) is fronted by a circular court of diameter 23 ± 0.5 m; the summit is composed of courts and rooms ornamented by geometric friezes and painted/plastered walls. This major platform mound overlooks a large rectangular plaza framed by more than a dozen monumental structures (Figure 1.5.1B); many of which contain elaborated fire pits with underground draft passages used for ceremonial functions. As an early example of elite architecture and urbanism indicating a hierarchical administrative structure, the site demonstrates the necessary combination of traits and organization that signal the formation of statehood and the cradle of civilization in ancient Peru. Figure 1.5.2 shows the easternmost pyramids typical of the site architecture canons. While the architectural details of the site are well documented (Shady 2004, 2007), aspects of the political, economic, artistic, religious, and urban life of Caral have been advanced by the site's principal excavator (Shady 1997, 1998, 1999, 2000, 2004, 2007; Shady and Leyva 2003) to detail the cognitive and cultural foundations on the path to statehood. Site field data has proved that maritime resources provided at least 50% of the food supply of valley inhabitants while the remainder was derived from field systems based on canal irrigation derived from canalized spring systems (pukios) and seasonal rainfall runoff water originating from the Supe River. Apparently an economic system developed based on trade of marine resources from coastal sites with agricultural/industrial products originating from farmed inland sites. The earliest agriculture was based on industrial products such as the cotton, gourds, and reeds necessary for clothing, fishing line, nets, and basketry as well as for housing construction and watercraft to supply coastal fishing community needs. Later, expansion into cultigens was required to supply the increasing population's carbohydrate requirements through organized agricultural development of canal and pukio-supplied field systems.

The Supe Valley is unique, compared to all other north and central coastal valleys, in that the water table remains high throughout the year, permitting multiple crop cycles. Numerous springs occur within the valleys margins (Figures 1.5.3 and 1.5.4 are typical pukio systems) from coast to highland locations and are channelled to supply water to field systems and flat agricultural areas associated with valley sites. This situation differs from other coastal valleys where the main source of water is from intermittent seasonal rivers supplying extensive canal systems to reach field systems. The abundance of water may be ascribed to a fault system running the length of the valley through the agricultural zone (Figure 1.5.5) which channels sierra water directly into the relatively shallow alluvium soil layer from sierra seasonal rainfall and river flow and thus produces multiple spring systems in depressed areas intersecting the water table (which is usually only 1–2 m below the soil surface). Clays within the fault zone bring water close to the surface and deposited silt layers over the bedrock base trap the aquifer, causing springs to appear in areas where top layer thickness is small or non-existent. Local farmers anecdotally attribute the high water table to 'amuñas' which they describe as water descending from highland lagoons through underground channels (likely faults in the bedrock base rather than synthetic channels) to sustain the groundwater level. Some precedent for this type of high-altitude lagoon water supply system exists (Avila 1986) in upland areas of neighbouring northern valleys, but research and exploration remains to be done to support the basis for the valley water source. The fact remains that the water table only varies by less than 1 m from the wet to the dry season, indicating that some unique geological circumstances are present to keep year-round water table height relatively constant.

Since an abundance of water exists at present, it is not unreasonable to infer that similar conditions existed in previous eras and that this favourable situation for agriculture provided one reason for the establishment of early societies within the Supe Valley together with the marine resource base available from coastal sites. Sites within the valley are located on elevated plateaus along the mountainous valley sides and are thus protected from river flooding while preserving valuable bottomland for agriculture. Thus the early Preceramic sites within the Supe Valley were ideal locations given the readily exploitable economic base the valley provided.

This section focuses on the technology involved in the canal and water system design of Supe sites. Early 5000 BCE contour canals in the upper Zaña Valley demonstrate the origins of contour canal technology; later Moche and Chimú systems demonstrate accomplishments in the 300–1480 CE time period. The importance of Caral is therefore to provide information for the canal technology 'learning curve' in the time period from 3000 BCE to the Formative and later periods to track the development through time of the technology base of irrigation agriculture.

As a measure of the ability of Caral engineers to survey slopes, measurements were taken at the inlet of a canal remnant that originally ran along a terrace structure on the north margin of the site of Caral (Figure 1.5.6; canal A, Figure 1.5.7) and supplied seasonal river water to field areas west of Caral towards the site of Chupacigarro through canals C and D (Figure 1.5.7). A branch of this early canal provided water to agricultural field areas on the lower plateau above the river bed, as shown in Figure 1.5.7, as well as for upper plateau canal (Figure 1.5.8). As Caral was abandoned in late Preceramic times (*c.* 1800 BCE), no immediate use of this canal branch occurred after site abandonment. Due to the shifting of the riverbed and stream braiding, fixed inlets like those at A (Figure 1.5.6) were inefficient and easily stranded and were later replaced by more flexible designs that relied on pukio sources and easily modified fill-terrace structures supporting canals. This canal construction type permitted water to enter upper plateau field areas (C, D, E) on a year-round basis while outlets could drop water to lower plateau areas next to the river. Later occupation at the site is noted (Figure 1.5.7), indicating the use

A

Figure 1.5.1. A, Digital Globe (Google Earth) aerial photograph of the site of Caral in the Supe Valley showing major temple complexes and urban areas. B, Site structures from ground survey and ongoing excavations (derived from Shady 1997).

B

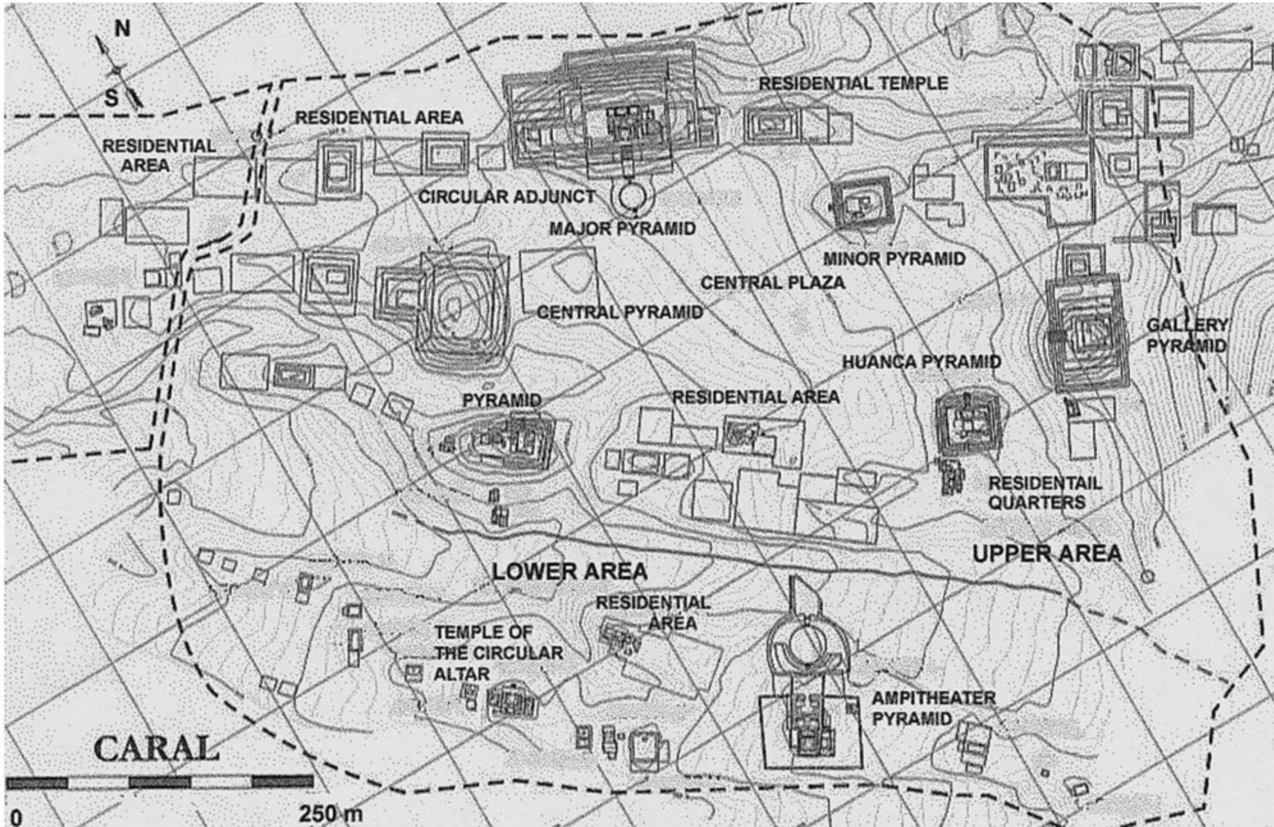

Figure 1.5.1. (Continued)

Figure 1.5.2. Ground view of the Huanca and Gallery pyramids.

Figure 1.5.3. Large modern pukio in the mid Supe Valley used to direct water to adjacent field systems.

Figure 1.5.4. Canalized pukio providing water to an adjacent field system. The spring sources derive from high altitude snowmelt and runoff zones conducted through Supe Valley fault zones.

of the same agricultural base by later societies (EH Chavin, MH, Chancay, and Colonial period ceramics are found on site) as agriculture was later re-established after a decline caused by some geophysical or political circumstance in post-Caral times. Canal A originated at the valley neck (or choke point) of the Supe River (Figure 1.5.7) and was designed to capture a given fraction of seasonal river water by means of a terraced canal at a slightly higher slope than that of the river at the inlet juncture choke point. (The choke point of a river is defined as the location of the narrow river channel as it emerges from rocky highlands onto alluvial valley plains; this upvalley point is the origin of the highest elevation, longest reach canals possible for coastal alluvial valleys.) The canal slope relative to the horizontal (but higher than the riverbed declination slope) was found to be 0.32 and 0.59° by separate measurements along the first 100 m of the abandoned canal segment. The

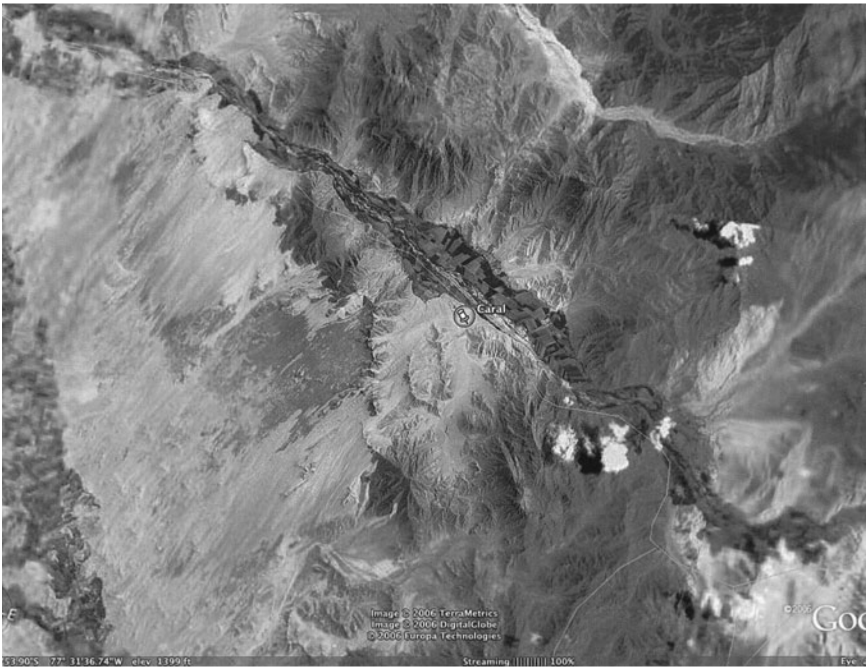

Figure 1.5.5. Google Earth photograph of the environment around Caral illustrating sand seas in southern valley areas that source sand inundation into the mid and coastal Supe Valley areas.

Figure 1.5.6. Canal inlet (A) originating from the Supe River choke point running along the north bank of the elevated plateau on which Caral is situated. The canal was originally directed toward Chupacigarro.

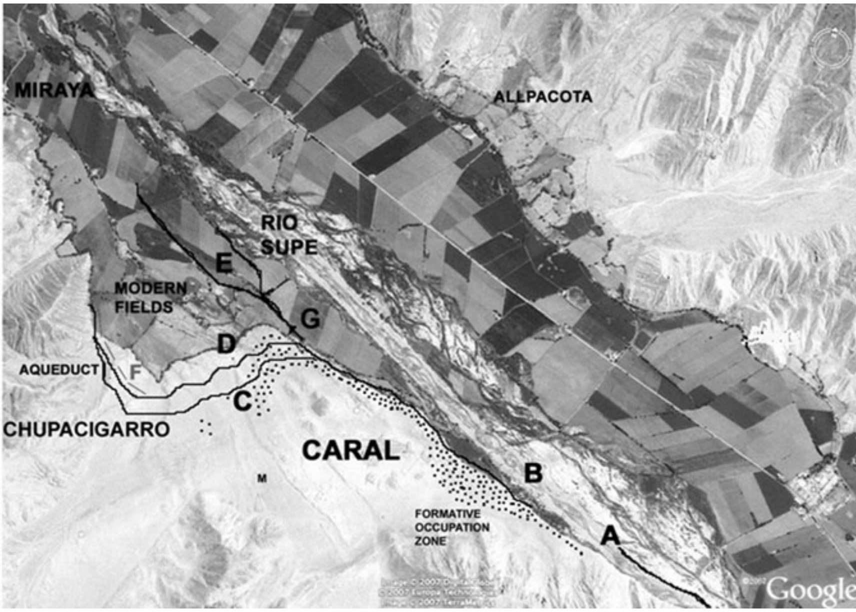

Figure 1.5.7. Canal network (A, B, C, D, E) for irrigation agriculture contemporary with Caral's field systems north of E. Downstream agricultural areas were supported by pukio and low level, river sourced canals.

slopes measured are consistent with high levels of surveying accuracy noted in past and future eras in Peru and form a 'Preceramic point' on the technology learning curve that indicates continuous development of surveying technology over a 6,500 year period.

For instances where the Supe River partially flooded the lower plateau field systems during the rainy season and reduced agricultural areas, parts of four elevation-staged terraces above the flood zone on the lower plateau below Caral (areas east of G, Figure 1.5.7) were utilized to continue agricultural production to supplement upper plateau areas west of G that could be supplied by pukios reattached to the B–C terrace embankment canal system (Figure 1.5.7). The presence of low-slope, pukio-supplied and/or intermittent river-supplied canals built on an artificial terrace embankment having drop structures to lower terrace field systems indicated that low-slope surveying technology was vital for this agricultural system and was the basis for development of the flexible agricultural landscape throughout the ages. This technology, demonstrated at Zaña sites at 5000 BCE through Chimú times four millennia later, was in continuous development and recognized as key to the exploitation of land and water resources from earliest times. Since the

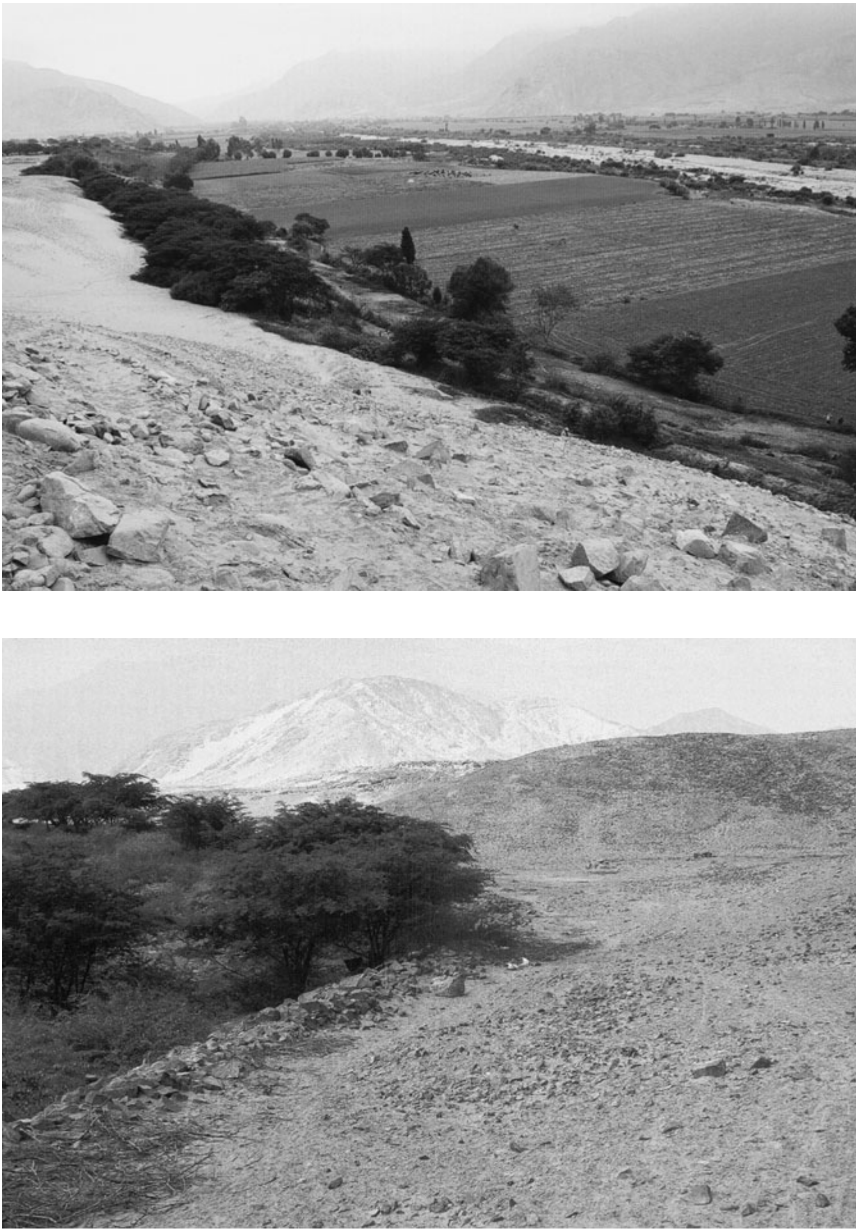

Figure 1.5.8. Aqueduct canal fronting Chupicagarro (lower frame). This canal is among the oldest canal systems in the New World. Ramped canal C from a valley bottom pukio to the upper plateau fields adjacent to Caral (upper frame).

terrace embankment of the later canals climbed up to the plateau on which Caral's monumental architecture was located and could distribute water to both upper and lower plateau fields, evidence from a cross-sectional cut of the lower terrace embankment revealed a layered structure, indicating purposeful accumulation of silt from cleaning episodes and permitting development of the terraced embankment agricultural area with fertile soils. Upper plateau canals (C and D in Figure 1.5.7) provided water to field systems close to the inland site of Chupacigarro. Figure 1.5.8 shows the upper plateau surface canal C leading to the nearby aqueduct; Figure 1.5.9 shows canal cross-sectional profile phases at G infilled with silt, denoting ultimate non-functionality commensurate with site abandonment. At present, modern fields overlay portions of ancient fields northwest of canal D in Figure 1.5.7, using a new pukio-sourced supply canal (D) led up through embankment canal B. On the assumption that ancient and modern use of pukio water was basic to valley agriculture, that climate variables were as favourable then as now, and that the same farming areas used today are similar to those of past eras, then the present-day robust agricultural productivity mirrors that of the past. From Figure 1.5.7, it is noted that the modern agricultural areas are based on similar canal usage designs and locations as in the past and rely on pukio supply for the most part; these designs, past and present, reflect the most logical, flexible approach to agriculture in the Caral area and show that the use of 5,000-year-old technology is still relevant. Elsewhere in the valley, ancient sites were located close to pukios for their water and an intricate network of canals, some modern and some ancient, sourced from these springs still provide water for the valley's agriculture.

Since the site flourished for many centuries given the favourable climate and water supply that sustained the economic system, it is of interest to speculate why this site and others in the valley were abandoned late in the second millennium BCE. Evidence indicates that Caral's monuments were carefully buried on site closure and that site abandonment proceeded in a deliberate rather than a hurried manner. While suggestions have been made about abandonment resulting from social, cultural, and economic advantage changes leading to creation of other population centres towards north and south coast regions, explanations based on compromise of the economic base of Caral may also explain the abandonment (Sandweiss *et al.* 2009). Evidence from the site indicates that several large earthquakes occurred during the site's lifetime, as demonstrated by reconstruction of several pyramids in the form of overlays over earlier structures, accompanied by reorientation of stairways and sunken circular courts from previous configurations. Similar evidence of large earthquakes at the Preceramic site of Aspero (south of Huacho on the Peruvian coast) triggering two architectural reconstruction events, followed

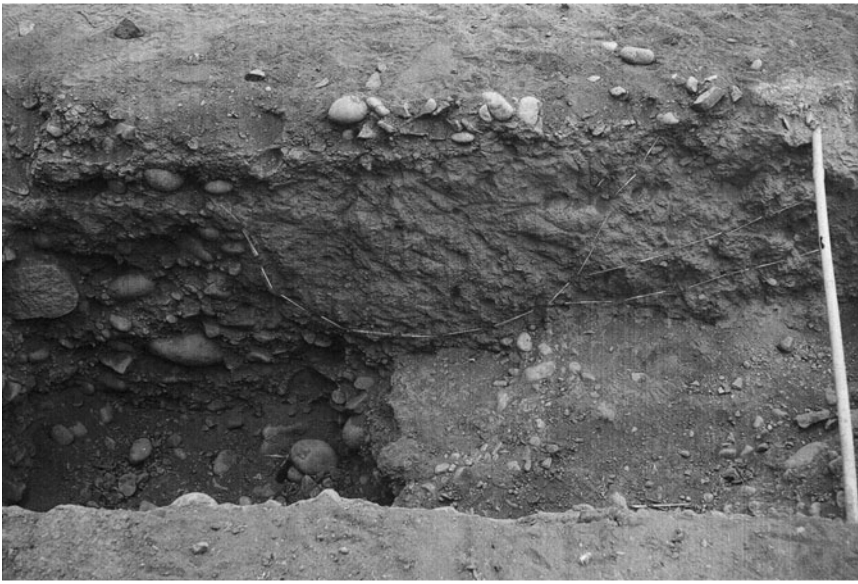

Figure 1.5.9. Excavated canal profiles (white dashed lines) at G (Figure 1.5.7) show ing multiple use episodes and ultimate abandonment from silt infilling.

by final site abandonment and a later debris layer covering construction remains, signalled marginalization of the site from its previous importance as a fishing and ceremonial centre. One source of environmental landscape change that influences the Preceramic period agricultural environment arises from the onset of El Niño events at about 3800 BCE after eustatic sea level stabilization in the 5000 to 4000 BCE time period. El Niño flood events over land surfaces are the source of soil and sediment outwash to coastal areas and provide the mechanism for beach ridge sediment deposits. Examination of beaches north of river mouths from the Salinas de Huacho to the Forteleza River indicates the presence of a vast cobble and sorted-gravel debris ridge (example shown in Figure 1.5.10) extending many kilometres in length lying between the current ocean shoreline and the inland wave-cut bench originating from ocean level stabilization between 5000–4000 BCE. The immense size and length of this (presently undated) ridge (denoted the Medio Mundo Ridge) was apparently formed by a mega-Niño event (or events) (Rogers *et al.* 2004; Sandweiss *et al.* 1996) that eroded valley bottoms and side wall margins with flows heavy with entrained sediments that then exited river mouths, engaging the northward Peru Current and deposited as an extensive beach ridge. Figure 1.5.11 indicates two debris and silt layers resulting from El Niño-derived

Figure 1.5.10. Beach ridge northward from the mouth of the Huara River (part of the Medio Mundo Ridge) originating from a major El Niño event (or events) in Pre ceramic times.

Figure 1.5.11. Excavation at the Preceramic site of Aspero (contemporary with Caral) showing multiple thick silt layers deposited from two separate large El Niño events in Preceramic times.

surface wash at the coastal site of Aspero which, in association with datable cultural remains, tend to fix two such mega-Niño events well into the end of the Preceramic period and bracket the dates of formation of the Medio Mundo Ridge.

Current thinking about the demise of Caral's agricultural base (Sandweiss *et al.* 2009) indicates that the 100-km long Medio Mundo beach ridge, formed by outwash flood sediments interacting with offshore coastal current, trapped flood sediments from later El Niño events, leading to vast sand and soil fines seas inland from the beach ridge that together with aggraded soil and clay deposits, augmented the surface extent of coastal areas. These sand seas and areas of soil fines, acted on by strong onshore winds, then provided massive sand and fines incursion on to near-coast agricultural lands, limiting agriculture in mid-valley and coastal areas. The limited inland, narrow valley bottom farming area bounded between steep-sided mountains were then vulnerable to flood destruction that reduced the agricultural productivity to subsistence levels, thus limiting sustainable Supe Valley population levels. Examination of sand accumulation patterns in the valley (Figure 1.5.12) indicate that relic dunes and sand accumulation exist on both north and south sides of the valley with dune ripple patterns indicating a sand source originating from the southwest of the Supe Valley. It may be assumed that sand accumulation at one time largely covered agricultural fields and made agriculture untenable with sand and sediment deposits originating from derived effects of the Medio Mundo beach ridge originating from El Niño events. A further consideration marginalizing agricultural production in a post-El Niño environment arises from consideration of valley bottom land soil saturation and the time required to restore the water table for agricultural use; heavy rains compromise soil moisture and groundwater restoration time, particularly when the water table is high year-round owing to the special water environment of the valley. El Niño deposits of transported debris and erosion of fertile topsoils further compromise the agricultural base of the valley. El Niño effects are well-known to upset the marine resource base, alter normal fishing patterns, and limit the productivity of shellfish and fish gathering coastal communities. The presence of vast on-land sand seas is noticed along the coast as a result of sediment aggradation caused by the Medio Mundo Ridge; these areas source the sand inundation present in the Supe Valley and appear to have a major role in reducing the agricultural base of valley society. For these reasons, the coastal Preceramic site of Aspero (3055 BCE and earlier) may decline in importance. A further consideration resulting from Medio Mundo formation and sediment shifting due to ocean currents is the blocking of normal river drainage patterns; this causes the formation of entrapped bays that gradually infill with river sediments and alter the ecological balance. This

Figure 1.5.12. The lower Supe Valley with major sand deposits on both sides of the valley indicating that at one time sand may have infilled the valley, limiting agriculture.

geophysical circumstance is noted in entrapped bays and lagoons (Bandurria, Medio Mundo, and Paradiso) that alter the shellfish types and amounts available as a food resource (from rocky shoreline shellfish types to freshwater bay-based shellfish), alter the fertility of farm areas and food crop types (by brackish water saturation more conducive to reed growth), and limit drainage of agricultural fields. Lower Supe Valley soil profiles cut by drainage canals show an accumulated river-transported soil overlay altering early shoreline environments and radically changing the mixture of possible crop types. While many of these events develop on different time scales, their cumulative effect is to ultimately alter the previously established ecological base and alter the agricultural landscape in a manner to challenge the continued existence of a society dependent on pre-existing land and water resources.

As a summary of possible environmental alteration mechanisms affecting the economic base of Supe society, earthquakes in combination with mega-Niños closely spaced in time can provide vast amounts of cobbles, gravel, fines and sand washed from river mouths and down-sloped landscape areas to form beach ridges on interaction with the northward-flowing ocean current. Laterally separated beach ridges or a consolidated single ridge can result from El Niño events (Ortlieb *et al.* 1995; Rogers *et al.* 2004) and provide sand sources for inland transport. Here the offshore steep benthic seabed angle in the mid-north central coastal area is conducive to a cumulative beach ridge formation that would collect sediments from multiple flood events into a single ridge of massive proportion (the Medio Mundo Ridge). Aeolian sand is observed (Figure 1.5.12) on the north and south sides of the Supe Valley, indicating the presence of sand transfer from areas south of the Supe Valley that may at one time have covered most valley bottom agricultural zones. Provided all (or some) of these events initiated within a time period contemporary with Caral's final tenure, then a possible gradual collapse mechanism related to agricultural contraction can be posited for the termination of the Preceramic sites in the Supe Valley as a result of effects generated by massive El Niño events. The proposed collapse/transition model provides a research direction for future investigators to explain the collapse of coastal Preceramic societies and the abandonment of their settlements. While questions remain about the social and political organization of the society, the mobility and distribution of the population between farming and fishing centres, administrative control mechanisms, farming technology, climate variables, and labour mobilization focused on centralized building and economic infrastructure projects, it is clear that a hierarchical structure was in place to organize Caral society and achieve centuries of successful existence. Again, further research will tend to clarify these many questions to provide an accurate picture of early Preceramic cultural and societal development.

In conclusion, slope data taken from canal remnants and upper plateaus indicates that low-angle surveying was well understood at 3000 BCE and formed the basis of agriculture in lands surrounding Caral and other valley sites. Given the continuity of irrigation agriculture from Zaña origins at 5000 BCE, through Supe Valley examples at 3000 BCE and later examples in north coast valleys up to 1532 CE, there were 6,500 years of successful and innovative irrigation technology development in coastal Peru. It may be claimed that the long duration and success of Peruvian irrigation technology throughout millennia has claim to a prominent place in the history of hydraulic technology. While early Mesopotamian societies may lay claim to irrigation trechnology origins, many of their systems faltered through lack of understanding of field drainage and fresh water flushing which ultimately led to field salt accumulations that limited agricultural productivity. The South American contributions to irrigation science appear to have a deeper understanding of the technology and means to sustain irrigation agriculture as evidenced by the many millennia of successful operation that underwrote the sustainability of many different societies living under many different ecological conditions.

To close the discussion and illustrate the generic principles of beach ridge formation that are vital to support the hypotheses thus far presented, a three-dimensional computer model of the Peruvian coast from Santa to Virú Valleys (Figure 1.1.1) was made showing the sloping offshore benthic seabed and upland areas within the Santa and Virú Valleys (Figure 1.5.13). El Niño floodwater containing a heavy sediment load from upvalley watershed collection zones is conducted through the Santa River valley to interact with offshore ocean currents. A two-fluid model is utilized: fluid 1 is ocean water characterized by kinematic viscosity ν_1 and density ρ_1, and fluid 2 is El Niño sediment-laden river flood water characterized by a large value of kinematic viscosity ν_2 and density ρ_2 compared to ocean water. Depending on the floodwater sediment load, ν_2/ν_1 can range from 1 (no sediments) to 10 (heavy sediment loading and high absolute viscosity). River current velocity is selected to represent a minimum value to induce river bed and sidewall erosion, and sediment (sand, gravel, and an assortment of rock sizes) transport mobility and the northward offshore current velocity is set low to represent near cessation during El Niño events. A sea level value is set commensurate with the stabilized 5000 BCE level. By using actual length and velocity scales in the model, Reynolds and Froude numbers are similar between the computer model and actual values; time scales between actual and computer time can be shown to scale as $(\nu_2/\nu_1)^3$ by dimensional analysis methods. This provides a measure to determine the El Niño duration time required to deposit ridges of known size and volume. Note that the area represented by the model is on the order of 1,035 km^2.

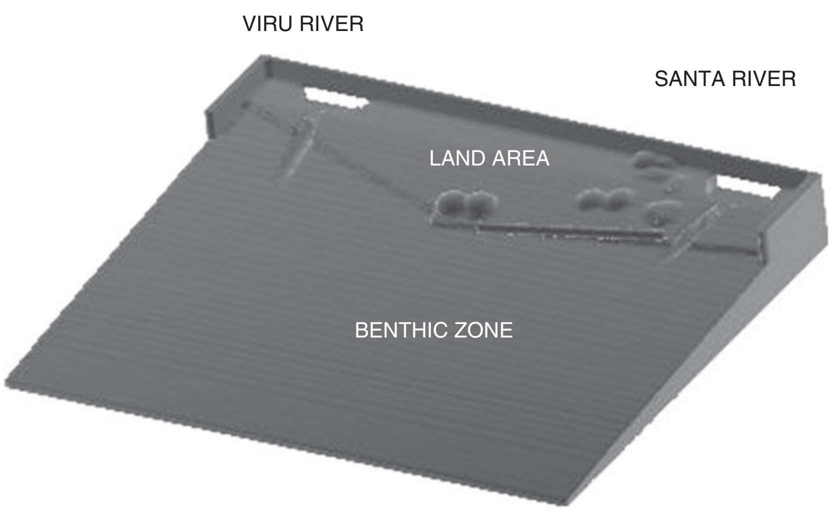

Figure 1.5.13. CFD model of the offshore seabed and elevated land surface between the Santa and Virú Valleys on north coastal Peru. Inland basins duplicate the catch ment areas off the individual valleys.

FLOW-3D calculations were run to determine the mixing of the sediment-laden flood water with ocean water for a 30-day flood event. Results (Figure 1.5.14) for a sediment load 5.4 times that of ocean water indicate that a long subsea ridge with density gradations is formed parallel to the shoreline, along with deposits at the river mouth. This deposit configuration occurs for several reasons: (1) the out-rushing sediment particles entering ocean water above the steeply sloped seabed encounter high hydrostatic pressure together with viscous drag effects and the particles settle at locations according to their momentum and inertia, (2) the sediment particle deposition near-parallel to the shoreline occurs as the increasing hydrostatic pressure presents a barrier to further forward motion and particles follow the path of least resistance to lower hydrostatic pressure at near-shoreline locations, (3) northward ocean currents and wave action continually agitate and transport deposits in the current direction, adding to the length of the ridge and resorting its composition, and (4) the out-rushing fluid velocity from the river mouth interacts with the ocean and creates

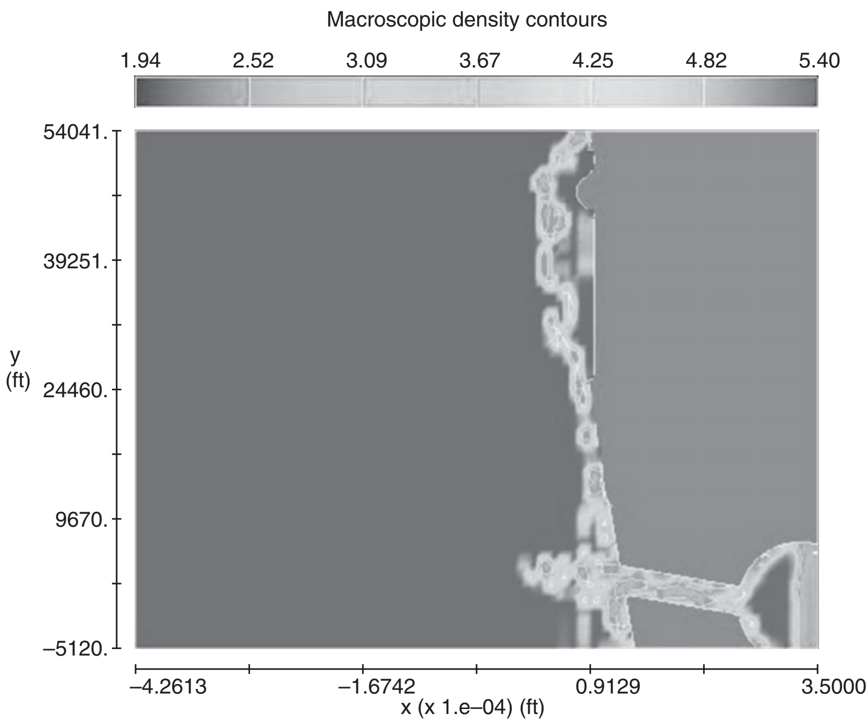

Figure 1.5.14. Density distribution of El Niño flood sediments ejected from the Santa Valley interacting with the offshore northward ocean current, leading to formation of an offshore sediment ridge.

vortex and circulatory velocity patterns that drive sediments back to shoreline locations to add material to the ridge barrier. While only riverborne sediment transfer is considered in the present example, many additional opportunistic drainage channels develop during flood events, leading to multiple drainage paths to lower coastal areas. Flood sediments reaching the coastline then accumulate behind ridges to infill coastal zones. Of course, only a qualitative picture is represented by model calculations as details vary with flood intensity and duration, coastal geomorphology, soil properties, transportable sediments loads, and other variables. Multiple ridges forming parallel to the coastline as a result of sequential El Niño flood episodes and coastal progradation, as observed in Santa Valley field studies (Sandweiss 1986), can then be explained by the processes demonstrated by the present set of calculations.

1.6 A MATHEMATICAL MODEL OF HYDRAULIC SOCIETIES IN ANCIENT PERU

Introduction

Aspects of the technology base and achievements of pre-Columbian coastal and highland societies have been described in previous sections. With this in mind, investigation of the structure of the decision-making processes behind these achievements and the utilization of available technologies by the technocrats of these ancient societies to construct agricultural systems best suited to maximize agricultural potential is next considered. Some questions arise: Is there some fundamental theoretical underpinning that governs the behaviour of hydraulic societies? Do the technocrats that guide agricultural strategies and hydraulic constructions use strategies that follow rules that can be elucidated by macroeconomic models based on principles related to maximization of food resources? Are the conclusions from the models confirmed by archaeological observables and are the predictions of the mathematical model those utilized by the technocrats of these ancient societies albeit in formats unique to their cultures and understanding of technology? The investigation proposed focuses on discovering if there are universal principles expressed through a mathematical model that govern the behaviour of irrigation-based societies based on their intelligence to design agricultural systems to their best advantage. With this task in mind, a mathematical development is presented to find answers to these questions.

The progress of civilizations of pre-Columbian Peru and Bolivia obtaining agricultural resources from rainfall, river, or spring-fed irrigation systems are controlled by a number of important parameters related to the water supply flow rate, land area under cultivation, climate, labour force, population size, irrigation strategy, technology base, soil productivity, and topological landscape constraints. While other variables related to the social, political, and economic structure of a society are important, these variables may to some degree be dependent, rather than independent, variables in that a well-managed and functioning agricultural base may provide the rationale for many of a government's administrative functions and thus help to decide aspects of the form of administration. In this sense, the collection and analysis of agricultural production data as well as the mandate to alter and control agricultural strategies to improve production is inherent to higher administrative levels and thus the 'rules' by which they operate are of interest. An investigation as to what these rules may be can proceed from an approach of first determining basic parameters that are important to characterize agricultural phenomena and then devising 'rules' that govern the behaviour of hydraulic societies by combinations of these parameters to form a governing equation to yield 'laws' relevant to hydraulic society operation. The success of this approach is determined by the comparison of predictions of a model equation to examples from the archaeological record to determine if observed agricultural strategies fit model predictions and 'universal laws' apply.

A mathematical model governing the interrelation of key variables of importance to hydraulic societies can be constructed by means of Buckingham's Pi Theorem (Buckingham 1914a,b). The goal of the model is to discover if optimization of food resources and production is a key concept behind the actions, decisions, and designs observed in the archaeological record of the agricultural development of Andean societies. Since any equation governing the interrelationship between key variables will depend on a function of non-dimensional groups formed from these variables, the potential to extract an underlying mathematical structure governing the behaviour of hydraulic societies is possible and can be used to interpret the logic behind events in the archaeological record. The derived model is applied to the history of five pre-Columbian Peruvian/Bolivian hydraulic societies to determine if observed trends from the archaeological record are largely based on strategies to maximize food resources. The agricultural systems used to demonstrate the applicability of the model include the Chimú Moche Valley canal irrigation system, the south Peruvian coast Chirabaya system dependent on spring-fed irrigation, a highland post-Tiwanaku system dependent on terrace agriculture in the Moquegua Valley, the Chimú aqueduct and canal system located in the Jequetepeque Valley, and the agricultural system and settlement patterns of the Jequetepeque and Moche Valleys in late Moche times.

Civilizations drawing agricultural resources from land areas by means of canal-based irrigation systems, whether river or spring fed, are governed by basic economic considerations that decide agricultural strategies. The strategy selected presumes maximization of agricultural output given an accounting of land, water, labour, and population resources that, given the constraints of the available technology base, leads to a predictable positive result. Usually such strategies include an iterative procedure whereby failed or inefficient strategies are corrected by revised decisions to form a 'learning curve' directed towards best utilization practices using available resources. Since societal economic survival depends on maximizing agricultural output through employment of technical strategies, any model representing a relation between key variable groups must demonstrate that predictions follow observed trends in agricultural development and population change with time. If an agricultural strategy is successful and surpluses are generated, then it is expected that population will rise to the level of food production and some redistribution will take place according to elite-class privileges. On the contrary, if an incorrect strategy is selected, then food resources may be limited, resulting in a lower stable population size to match the available resource base and some restrictions on the distributory largesse and privileges of the ruling classes. Even if surplus agricultural production is distributed by elites to compensate or reward different segments of the population according to their perceived importance to the administration, or as exchange for valuable services, the recipients are ultimately beneficiaries with the potential to increase their numbers even when the population rise of this class of society may occur in groups not directly related to production. A population decline may occur if an agricultural system has no defense from destructive climate and weather effects, and this vulnerability causes either temporary or permanent damage to field system output. By observing trends in the archaeological record that conform to model predictions, an argument may be made that decision processes made by bureaucratic agencies of ancient societies may be related to their observation of some version of the same parameter groups to decide on appropriate agronomic strategies.

Pi Theorem analysis

A method of forming combinations of dimensional variables into a smaller set of non-dimensional groups is available from the Pi Theorem. As only an arbitrary function of the non-dimensional groups can be composed from this procedure, some latitude exists as to how to construct a model equation; again any equation form selected must correlate its predictive capability to archaeological field data.

In order to derive a mathematical model applicable to explain the dynamics of hydraulic societies (i.e. the relation of population change (or food production) to agricultural variables), it is first necessary to list a set of key variables playing an important role in hydraulic society function. These variables, and assumptions governing their interpretation, are given as follows:

- P, total population at time t of a society drawing agricultural resources from a canal-irrigated, fixed land area A under unified political control (P denoted by new variable A_1 for later use).

  Population in the current model is assumed to be related to the consumable agricultural products produced in a closed area agricultural field/terrace system where population is totally dependent on canal-supplied agriculture. In this case, population can be related through $P = kF$, where k is a constant and F represents a measure of the consumable food supply amount. Here it is assumed that the agricultural product (food supply) produced ultimately matches the needs of the general population obtaining resources from a closed agricultural system although internal redistribution managed by elites may occur as part of the political–economic structure of a society. Note that the above interpretation requires population directly dependent on the canal irrigation resource base in a fixed area but that failure of this base does not necessarily imply decline in population if other agricultural strategies involving other land area types, locations, and/or water supplies are available.
- Q, total volumetric flow rate of canal systems that provide water to an agricultural land area A; the canal system may be sourced by either rivers or springs (Q denoted by new variable A_2 for later use).
- A, land area in cultivation (A denoted by new variable A_3 for later use).
- L_c, total of canal lengths L_c used to supply land area A (L_c denoted by A_4 for later use).
- dP/dt, time rate of change of population P (or food mass required to supply the population) with time (dP/dt denoted by A_5 for later use).
- V_A, volume of terrain removed or altered to produce agricultural terraces (canal-supplied andenes) or canals; this parameter relates to the size of the labour force and the soil volume transfer capacity per unit time (V_A denoted by A_6 for later use).
- t, time (denoted A_7 for later use).
- Φ, (non-dimensional) engineering sophistication index: denotes the level of technology involved in canal surveying applied to solve irrigation agriculture water supply problems for coastal and highland terrace supply canals.

It is assumed that a society has limited import of basic agricultural products as the prime source of their food supply and that major sustenance is drawn from local land and water supplies available to the population. It is assumed that maximums exist for certain parameters, for example, canal lengths can only be extended to a maximum value $L_c{}^*$ because of normal topographic constraints and the total volume of terracing additions or volume of soil displaced, modified, or excavated (V_A) in a steep-sided valley neck, or by canal construction, is limited by $V_A{}^*$. Here Q^* represents the water supply required for full productivity of A^* given the optimum technical level Φ^* applied to maximum terrain modifications represented by V^*. For new innovations exceeding previously established technology levels given by Φ^*, Φ may exceed Φ^*. The values of L_c, V_A, and Q defined above are redefined and now understood to be $L_c{}^*-L_c$, $V_A{}^*-V_A$, and $Q^* + Q$, respectively, without loss of generality for model purposes. For cases where overextension exists, i.e. $L_c > L_c{}^*$ and $V_A > V_A{}^*$, the interpretation is that extension into agriculturally marginal lands has been made and that the labour investment far exceeds the agricultural return, and that $Q > Q^*$ must exist to supply water to these marginal lands, perhaps resulting from positive climate change effects. Extension may also occur if an original optimized canal system needs to be modified by increased length to accommodate some geophysical change that negates the original configuration. An alternative interpretation also exists: if land is made marginal by intermittent drought or ruined by floods, crop failures, shifting of water resources by geophysical activity (river downcutting, for example), sand dune inundation, land abandonment, etc., then A^* may decline in one defined agricultural zone but expand in another zone with better water resources, available land, and a more stable environment. This may manifest itself as changes in societal organization derived from the use of a different water resource base than that previously used, with possible changes in centralization of authority and administration from prior circumstances related to a state-controlled and directed administrative base. In this sense, a successful model equation must be able to predict the effect on population as parts of a system at various times undergo transformations and reconfigurations due to localized geophysical, climate, or socioeconomic effects.

To derive a relationship between the key variables A_1 to A_7 and Φ, Buckingham's Pi Theorem is used. This theorem provides a series of $n-p$ non-dimensional groups that govern the interrelationship between key parameters. Here n is the number of dimensional parameters (7) and p is the number of dimensional variables (3) taken in the form of mass (m), length (l), and time (t). Essentially, the $n = 7$ original variables are replaced by four non-dimensional groups given the three basic scales (m, l, and t) that can be used to characterize each parameter. Since all physical laws can be recast in non-dimensional form, the use of a function of non-dimensional groups follows this rule and can provide the basis for construction of a governing equation to relate the groups. Note that Φ is prescribed to be non-dimensional and thus is excluded as a dimensional variable.

The Buckingham Pi Theorem states that if a functional relationship exists:

$$\mathrm{F}(A_1, \ldots, A_7; \Phi) = 0$$

then this can be recast into the form:

$$\mathrm{f}(\Pi_1, \ldots, \Pi_4; \Phi) = 0$$

where Π_{i} are the non-dimensional groups. Since the dimensions of the $A_1, \ldots, A_7$ parameters are ($m =$ mass, $l =$ length, $t =$ time):

$$\begin{aligned} A_1 &\to m \\ A_2 &\to l^3/t \\ A_3 &\to l^2 \\ A_4 &\to l \\ A_5 &\to m/t \\ A_6 &\to l^3 \\ A_7 &\to t \end{aligned}$$

where population P (= kF) is considered as a 'mass' and population change and $\mathrm{d}P/\mathrm{d}t$ is considered a 'mass change with time'. The mass of a population can be related to population numbers and the mass of an average individual; likewise, the food mass can be related to the daily consumable food product as $F = P/k$, where F is defined to be the mass of food required to sustain the population P.

Using the formalism of the Pi Theorem:

$$\begin{aligned} \Pi_1 &= (m/t)_1^x (l^3/t)_1^y (l^2)_1^z (l) \\ \Pi_2 &= (m/t)_2^x (l^3/t)_2^y (l^2)_2^z (m) \\ \Pi_3 &= (m/t)_3^x (l^3/t)_3^y (l^2)_3^z (l^3) \\ \Pi_4 &= (m/t)_4^x (l^3/t)_4^y (l^2)_4^z (t) \end{aligned}$$

from which, for non-dimensional Π_i, is:

$$\begin{gathered} x_1 = 0,\ x_2 = -1,\ x_3 = 0,\ x_4 = 0 \\ y_1 = 0,\ y_2 = 1,\ y_3 = 0,\ y_4 = 1 \\ z_1 = -1/2,\ z_2 = -3/2,\ z_3 = -3/2,\ z_4 = -3/2 \end{gathered}$$

In terms of the original variables, the function relating the dynamics of population change to key, but time dependent, groups must be an arbitrary function of the non-dimensional groups in the form:

$$f(L_c/A^{1/2},\ A^{3/2}(dP/dt)/PQ,\ V_A/A^{3/2},\ Qt/A^{3/2};\ \Phi) = 0$$

or

$$(A^{3/2}/QP)(dP/dt) = g(L_c/A^{1/2},\ V_A/A^{3/2},\ Qt/A^{3/2};\ \Phi)$$

where g is an as yet unspecified function of the non-dimensional groups. In the above equations quantity Φ has been previously defined (Ortloff *et al.* 1982) and relates to surveying angle accuracy and canal hydraulic design considerations. The notation d/dt denotes the time derivative.

Suppose next that the g function is a combination of the non-dimensional parameter groups in the form given below. Then, in terms of the original definitions:

$$(1/P)dP/dt = K\{[(L_c - L_c^*)/(A - A^* + \Delta)^2 + (V_A^* - V_A)/|A - A^* + \Delta|^3] \times [(Q - Q^*)|Q - Q^*|t(\Phi - \Phi^*)/|A - A^* + \Delta|^3]\} \quad (1)$$

and is proposed as a 'governing equation' (denoted equation 1) to interpret the actions of irrigation-based societies. The $|\ldots|$ notation denotes the absolute value of the contained term, where K is defined to be an arbitrary constant.

Well-designed agricultural systems should produce a population (or consumable agricultural product) increase ($dP/dt > 0$) if an appropriate strategy is utilized; in this sense, population increase is the 'reward' for a well-designed system that has the potential to increase food production. Additionally, A^* is the maximum productive agricultural area reachable by L^* canal systems supplied by the Q^* water flow rate with technology level Φ^*, K is an arbitrary constant, and $\Delta > 0$ represents additional land area either non-reachable by canals or non-productive marginal lands for agriculture. Excursions from * quantities, represented by the history of non-asterisk terms, then determine the growth (or decline) of the food resource or population base dP/dt. For * quantities, $dP/dt = 0$, indicating a maximum population sustainable by full exploitation of all land, water, and technology resources.

The term Q^* denotes a necessary water supply to accommodate A^*; additional available water $Q > Q^*$ (past that amount on which a system design is based and perhaps made possible by climate change effects) is a positive benefit in terms of multicropping and possible increase of dP/dt to higher positive values. Here $Q > 0$ may result from climate-induced wet periods that add water past mean Q^* levels; for drought periods induced by climate change, then Q can drop below Q^* levels and dP/dt can be negative. If $Q < Q^*$, indicating drought-induced water supply decline, then population growth can still be positive but this requires that an overshoot of * values exists, i.e. $L_c > L_c^*$ and $V_A > V_A^*$, indicating some labour-intensive usage of marginal land or canal extension/modification to utilize this land to provide a temporary 'fix' to use low water supplies to support farming at subsistence levels. These cases arise when the terms in the brackets are negative, i.e. $L_c > L_c^*$, $V_A > V_A^*$, and $Q < Q^*$. The trend towards decreasing supportable population may be countered by a technological leap forward $\Phi > \Phi^*$ but, in most cases, this situation may not be sufficient to counter negative trends where the labour investment energy exceeds the energy content of the food produced. Cases for which $Q > Q^*$ signal possible growth periods due to high water supply.

The interpretation of equation 1 is straightforward: when * quantities are approached or reached in an irrigation system, $dP/dt = 0$ representing the maximum population that can be sustained by the irrigation system in a closed area. This maximum case represents maximum exploitation in an area denoted by * terms. Subsequent changes in non-asterisk terms in time determine the trend in dP/dt (either positive or negative) about the * state. Equation 1 is then interpreted as a 'semi-empirical data fit' or macroeconomic model that must possess sufficient structure to explain example cases.

In equation 1, two strategies are represented. Strategy 1 involves a situation for which land adjacent to a river possesses gentle gradients suitable for canal building and irrigation agriculture. Assuming that the obvious irrigation strategy of extending easily constructed canals from a river inlet to an adjacent arable land area is an initial attempt, further extension of this strategy entails increasing the canal length, while possibly maintaining or decreasing its slope, in order to enclose a larger downslope irrigable land area A. Here it follows that sufficient water $Q \geq Q^*$ is available and $dP/dt > 0$ results, indicating a society in growth mode. For cases where $L_c > L_c^*$, $A > A^* + \Delta$, $\Phi < \Phi^*$ (canal construction with no sound engineering rationale into marginal lands), and $V_A > V_A^*$ (shortage of available labour resources), requiring $Q > Q^*$ to reach these marginal lands, then $dP/dt < 0$, indicating the potential for decline of the agricultural base and concomitant population decrease. For $L_c > L_c^*$ and $V_A > V_A^*$, but $Q < Q^*$, dP/dt can be positive but of very small magnitude, indicating an unstable condition due to small water supplies. Such cases may happen when population pressures may force expansion into less productive lands without adequate water resources or the technology sufficient to maintain water flows to support water requirements of certain types of crops.

Because of limits to canal extension and canal slope imposed by both topography and technology, strategy 1 approaches a limit as $L_c \rightarrow L_c^*$,

$Q = Q^*$, $V_A \rightarrow V_A{}^*$ (equivalent to available labour to meet construction requirements), and surveying accuracy limits are such that $\Phi = \Phi^*$ applies, so that the maximum amount of land is under cultivation and $A = A^*$ applies. For this case, $dP/dt \rightarrow 0$ and the population level is balanced with food resources.

Early phases of strategy 1 entail short canals ($L_c << L_c{}^*$), adequate labour for construction ($V_A << V_A{}^*$), relatively high-slope canals ($\Phi < \Phi^*$) to small land areas ($A << A^*$) and adequate water supplies $Q < Q^*$ to make $dP/dt > 0$. Such strategies are typical of very early Peruvian north coast irrigation systems, which were mainly upvalley, localized systems that, in later times, showed gradual extension and increased land area under cultivation utilizing more sophisticated designs (i.e. Φ increasing) as surveying accuracies improved, permitting low-slope canals that enclosed more downslope areas. Such situations permit vast expansion of land area under cultivation once surveying accuracies improve and full exploitation of water resources is achieved. Obviously the agricultural output to labour input ratio is high for strategy 1 canals when easily constructed, near-level field areas are present with high Q. The Moche Valley great trench systems, if they represent agricultural canals rather than drainage paths to alleviate El Niño valley flooding, are clearly $V_A >> V_A{}^*$ systems and may be counterproductive for agriculture but productive to protect existing field plots from flooding under sporadic severe storm conditions.

An alternative strategy 2 operational in mountainous terrain characterized by deeply entrenched river valleys is also considered. For such terrain, strategies of the first type are limited due to the small amounts of level land, forcing a shift to agricultural terraces usually supplied by high-elevation canals and rainfall and/or snow melt sources. For this strategy, initially $L_c << L_c{}^*$ and V_A can be large due to the large labour investment in terrace construction so that $V_A \rightarrow V_A{}^*$ and $A \rightarrow A^*$ represent maximum development of terrace systems over a fixed area. The Φ value can be large as supply canals must be routed in such a manner as to provide water to the maximum of terraced land areas by clever design. Usually such systems exploit higher rainfall absorption and canalized runoff levels at high altitudes or, in some cases, canalized water supplies from high-elevation snow melt zones.

For $L_c << L_c{}^*$, clearly population can increase up to a level represented by $L_c \rightarrow L_c{}^*$ for $Q \rightarrow Q^*$ conditions. Obviously the optimum food supply strategy is to run short canals to large land areas so that $(L_c{}^* - L_c)/|A^* - A + \Delta|^2 > 0$ with a small a labour investment such that $(V_A{}^* - V_A)/|A^* - A + \Delta|^3 > 0$ with $\Phi < \Phi^*$ and $Q < Q^*$ to produce $dP/dt > 0$. This strategy appears early in north coast agricultural field system development. The next best strategy to increase agricultural production involves competition between long canals to large downslope land areas and short canals to steep-slope terrace systems of comparable area, provided the terrain permits this option. The first option is manifest in north coast LIP canal systems while, as a later development, higher elevation canals appear as surveying technology improves ($\Phi \rightarrow \Phi^{*}$), water supplies are plentiful, and labour is plentiful to permit canal construction and expansion of upvalley lands near the valley neck. Here, for both options $L \rightarrow L^{*}$, $A \rightarrow A^{*}$, $V_{A} \rightarrow V_{A}^{*}$, $\Phi \rightarrow \Phi^{*}$, and Q^{*} conditions hold to permit expansion to the full agricultural potential. It is, however, necessary to perform a calculation for the labour input in terms of labourhours to decide (using equation 2 below) if strategy 1 or 2 provides the optimum benefit given the population size and technology available provided low-slope lands and terrace slopes are simultaneously available in a fixed area domain under unified political control. Obviously, if the labour requirements for a project exceed the labour force available or the projected food supply return is not worth the labour investment, this forms a partial basis for a decision as to which option best suits societal requirements. If time constraints apply to decide which option to take, it is possible that a solution can be put into place to increase productivity, albeit in a non-optimum mode.

Since agricultural production is to be maximized for the labour input available from a given population size, it may be desirable to switch strategies from long canals to flat arable areas to valley-neck or nearby mountainous-terrain terrace agriculture if higher agricultural production results (and provided the topography permits of the strategy-sharing option). The decision process involves some evaluation of a set of variables that alter an agricultural strategy to maximize production. Since finite labour resources exist, these resources may be divided between terrace construction (first term) and canal building (second term) labour expenditure by evaluating individual terms representing these options in equation 2 below:

$$(\Delta T)\ ^{1}\{x(V_{A}/k_{1}\ \mathrm{d}R/\mathrm{d}t) + (1 - x)(A_{c}L_{c}/k_{2}\ \mathrm{d}R/\mathrm{d}t)\} = \text{constant} \qquad (2)$$

Here $\mathrm{d}R/\mathrm{d}t$ is the rate of work that can be performed by an individual per unit time (fill volume that can be moved by a worker per unit time), ΔT is a given time interval, A_{c} represents a mean canal cross-sectional area, k_{1} and k_{2} are constants that relate to necessary logistical and peripheral activities that modify the rate of work for each type of building activity, and x is the fractional share of labour in each activity ($0 < x < 1$). If canal building is easier (smaller V_{A}) than terrace building (larger V_{A}) for the same productivity benefit, then given fixed labour resources, $x = 1$ is the obvious choice; if benefit can be gained from a mixed strategy (limited flat area but large terrace area available), then $x = 0.5$ may be the best strategy for area use of fixed labour resources. If terrace systems are the best option from a labour investment point of view, then $x = 0$ applies. This constraint equation decides if labour expenditure is best used to produce maximum agricultural output among the options available. Use of this equation (in some form by administrative technocrats) helps to decide the most effective use of labour resources to produce a 'new' optimum strategy if an 'old' strategy appears to be reaching its productivity limit.

For cases for which strategy 1 is initiated (i.e. near-level field areas easily sourced by short canals led off from a transecting river with arable land area extension by means of longer, low-slope canals), it is clear from equation 1 that as $A \to A^*$, $L_c \to L_c^*$, $V_A \to V_A^*$, $Q \to Q^*$, and $\Phi \to \Phi^*$ then $dP/dt \to 0$, indicating maximum exploitation of the resource base. In certain cases, there may be exploitable nearby mountainous terrain available that could amplify A^* but is not readily utilized perhaps due to technical limitations. This implies that an element of strategy 2 can be initiated. In essence, if the labour to construct and administer both types of agricultural strategies is available, and if topography and water supply permit, then different A^* components can be added as population increases agricultural demand. If topography and workforce levels do not permit the second strategy option and valley canal systems remain the only option, then technology to better utilize available water supplies by limiting canal seepage (by lining) and improving water routing and crop-dependent water-exposure schedules may provide some improvement in productivity to 'effectively' increase Q.

Note that as water resources decrease in drought conditions from previous conditions established in water-rich environments for which $A \approx A^*$, $L \approx L_c^*$, $V_A \approx V_A^*$, $\Phi \approx \Phi^*$, $Q \approx Q^*$, and $dP/dt \approx 0$, for a Q decrease and the same Φ level, dP/dt can be negative. The question then is how to manage a situation to reduce population decline concomitant with declining agricultural production. If there is a corresponding decrease in L, V_A, and A then the population change rate may be stabilized and restoration under new conditions can begin. This new condition may manifest itself as a reduction or abandonment of arable land, canal length contraction, and a contraction and/or partial abandonment of an existing terrace system. If new, smaller * conditions are established for the new system configuration (usually attributed to drought or field destruction by heavy rainfall), then dP/dt may be negative but the population can be stabilized under these new conditions, albeit at a lower level than before. This may be thought of as:

$$P_{\text{initial population}} - (dP/dt)\Delta t = P_{\text{new lower population}}$$

for an estimate of the new stable population size. If population overshoots beyond a maximum corresponding to * values for either strategy, leading to demands on the agricultural resource base beyond its capability, then clearly an alternative strategy, either gradual or immediate, is required to ensure survival and continued population growth. This may entail migration, conquest, or, should these options not be possible, gradual devolution of cities to a more rural basis with small groups sustained by localized, but limited, water sources.

For cases where population is relatively constant, equation 1 indicates that under the stress of a water supply decline (from drought, El Niño-induced disasters, seismic uplift events altering canal slopes, etc.) a technology increase may partially counter the effects of a decreased water supply. This translates into new canal design solutions to increase the water supply to field systems. This Φ increase may result from internal developments or from importation of technology from other contact societies. In terms of equation 1, if the change in technology level is increased, then the productivity increase can extend agrarian success and permit further population growth. This has a parallel to modern economic theory, where productivity growth can increase output from a fixed workforce size. In practice, a technology increase may entail new canal open-channel flow designs to promote larger flow delivery rates, canal linings to reduce seepage losses, covered channels to reduce evaporation, sinuous mounded field system designs to allow more efficient access of water to root systems, and water transfer from areas with a large water supply but small land area to other field areas with better growing potential closer to the final usage destination.

The Intervalley Canal, as an example of the latter case, manifests many optimum technology aspects (near $Fr = 1$ flows for maximum flow rate, canal cross-sectional shaping to maintain Fr within known bounds, sub- and supercritical hydraulics control structures, side wall erosion-reduction controls, flow rate limits by overflow side weirs activated by large rainfall episodes, a tailored flow rate design to match the acceptance flow rate of a reactivated canal system) that permit continued agriculture of an otherwise failed Moche Valley system experiencing drought contraction. Thus an Φ increase can largely cancel localized $A < A^*$ contraction episodes in the Moche Valley provided Q resources are available, in this case from the adjacent Chicama Valley. Were this resource not available, then the Moche Valley would lose its agricultural base and prestige as the base of the capital city of the Chimú society. If a rapid water supply decline occurs at the maximum carrying capacity of agricultural development, then there is little time to increase or even maintain agrarian production by implementation of strategy and technology changes with efficient use of labour resources so that rapid population adjustments inevitably follow. A shift from strategy 1 to strategy 2 may produce some benefits depending on the relative magnitude of terms contained within equation 1 and the availability of terrain to implement strategy 2 conditions. Implementation of strategy 2 may arise due to direct interception of rainfall at higher altitudes on terraces compared to lesser runoff amounts available for coastal river irrigation systems, thus increasing Q and thereby influencing the decision process to change agricultural strategies. An alternative strategy of population movement to a different area (with a new A^* and larger Q) may also be tried by a society at the limit of their resource base to maintain or increase population levels; such migrations (or conquests) based on these conditions have been noticed previously in the archaeological record by the abandonment of the Moche Valley in Moche V times and subsequent relocation to the Lambeyeque Valley site of Batan Grande (and ultimately transition into early Sicán society) and the dissemblement of the Tiwanaku state from its capital city in Tiwanaku V times due to an extended drought period.

While it may be thought that these considerations apply to a single society fixed in a given area, the change in strategies may also come with successive societies replacing earlier ones in similar areas and bringing new technologies with them. In the Moquegua Valley, for example, early strategy 1 Huaracane short canals to available flat land areas are subsequently replaced by a Tiwanaku-influenced colony system utilizing longer canals to flat agricultural areas, thus taking strategy 1 to its * condition limit. The later Wari intrusion saw that a strategy 1 approach was not viable due to Tiwanaku occupation of mid-valley agricultural areas and initiated a strategy 2 approach with the potential of a large untapped A^* increase that could be exploited by high-altitude terrace agriculture and long supply canals at elevated altitudes. This technology was well known to the Wari from use of similar terrace systems characteristic of their heartland in the Peruvian high sierra. While a V_A labour increase was required for the terrace systems, the potential of using familiar technology combined with an increase to A^* limits promised the possibility of an agricultural output increase drawing from high-altitude water supplies (from snowmelt zone and higher rainfall at altitude) with a potential for worker population increases to supply yet more labour for construction and production tasks. Here a potential population increase may lead to expansion of presence in adjacent colony agricultural zones and facilitation of product export between different regions. Obviously, if both Wari and Tiwanaku presence in the same area competed for water resources, other considerations, such as military and territorial conflict, have the potential to arise. However, it appears that no conflict arose as different ecological zones were exploited by these colonists each with different, but independent, water supply sources and technologies. While the presence of a post-1000 CE drought provided a dP/dt decrease, curtailing occupation of the lower and mid-altitude Moquegua Valley and its use for large-scale agriculture, later

Estuqueña occupation established itself at high-altitude defensive locations around available water sources and later Inka occupation saw reuse of some earlier terrace agriculture and lowland valley sites as the drought ended and normal rainfall patterns emerged in the 13th to 14th centuries CE. Only later, during Colonial times, when organizational knowledge was lost of the earlier strategy 1 to strategy 2 transitions (and the management structure to implement the different strategies), did an elementary version of strategy 1 reoccur with short canals to mid-valley flat lands used primarily for commercial and luxury crops for the Spanish overlords.

Example case 1: the Chimú irrigation systems of the Moche Valley

In order to test the model, field data resulting from investigation of the Moche Valley Chimú canal systems (Ortloff *et al.* 1882, 1983, 1985, 1993, 1995) are utilized in conjunction with results provided in previous sections. Provided equation 1 predicts trends in the data, a rationale for logical activity regarding canal system design, construction, administration, and operation based on maximization of food resources has a basis of believability. Although mathematically derived from first principles, the formalism of equation 1 represents a recipe to implement the maximization procedure; it is tempting to believe that Chimú administrative technocrats perhaps had some decision, implementation, and results-monitoring policy that relied on some measure of similar parameter groups to ascertain their success in achieving their objective to provide food and industrial crops for an increasing population. In any event, if model predictions follow the archaeological record, then there is a basis for some form of these basic principles that underlie hydraulic society behaviour.

Figure 1.1.26 summarizes the available data. Shown in this figure are the variations in land area in cultivation A, total flow rate through all canals Q, technology index level Φ, and labourhours of input labour ($\psi = V_A/k_3\ \mathrm{d}R/\mathrm{d}t$) required to construct all major canal irrigation systems as a function of time during the Chimú occupation of the coastal Moche Valley in the LIP. As seen from this figure, Q, L, Φ, and ψ initially increase with time, indicating a strategy 1 Chimú expansion of the agricultural base; in this period of expansion, $L < L^*$, $A < A^*$, $Q < Q^*$, $\Phi < \Phi^*$, $V_A << V_A^*$, and $\mathrm{d}P/\mathrm{d}t > 0$, indicating early canal-based irrigation strategies commensurate with the small population size and adequate land and water resources. The addition of new canals with larger flow rates permitted expansion of arable land area in an environment of adequate water supplies necessary to promote increased population size. In this sense, all parameters tended to * values as expansion of the agricultural base continued in time. The positive $\mathrm{d}P/\mathrm{d}t$ is consistent with increases in technology level Φ, available labour for construction ψ, and suitable land and water resources to exploit in a positive climate environment.

For labour estimates to determine logistics and workforce requirements for proposed large irrigation projects (typically construction of intra- and inter-valley canal systems), note that $\psi = k_3 P$ where k_3 is constant, i.e. available labour power is a given fraction of the total population and, as population increases, more ambitious canal construction projects become feasible with the potential to increase arable land area. For canal systems constructed in flat terrain, $\psi = A_c L_c / k_3 \, \mathrm{d}R/\mathrm{d}t$ for each canal; this estimate applies to the relatively flat Moche Valley area under cultivation. For ψ labour estimates related to construction of terrace systems, note that for a flat hillside of slope θ and area A, the volume of a terrace element is $V_e = (L/2)h^2 \mathrm{ctn}\,\theta$, where h is the terrace height and L is its length. Since there are N terraces on a hillside slope, $NhL\csc\theta = A$ so that there are $A\sin\theta/hL$ terraces on a hill of height H. The N terraces then have a volume of $(hA/2)\cos\theta$. As the rate of soil transfer per worker is $\mathrm{d}R/\mathrm{d}t$ over a time ΔT, the number of workers required is:

$$(\Delta T)\ ^{1}hA(\cos\theta/2)\mathrm{d}R/\mathrm{d}t = (\Delta T)\ ^{1}hHLk(\mathrm{ctn}\ \theta/2)\mathrm{d}R/\mathrm{d}t = \psi$$

where k is a factor multiplying the number of workers required for subsidiary tasks. Such considerations, albeit in units familiar to Chimú technocrats, may have played a role in their planning exercises to expand irrigation networks to cover almost all arable land in all valleys under their control. Here the yupana and quipu were available for calculation and recording.

Depending on the number and configuration of canals and terrace constructions over a given time period, the number of labour hours could be estimated; if population census estimates were available, the k_3 value could be estimated as the fraction of the total population that could be enlisted in construction labour activities. Field data indicate an expansion of arable land resources close to the maximum value ($A \rightarrow A^*$ for $L_c \rightarrow L_c^*$, V_A small) considering topographic and water supply levels of the Moche Valley. Here all development is canal related as few options were available for significant terracing in the Moche Valley because of the preponderance of gently sloped, fertile lands available for canal-based agriculture. At the stage of development at *c.* 1000–1100 CE, further agricultural expansion was not possible without a large increase in technological capability Φ necessary to bring additional land into production; this step was achieved by refinement in ability to survey very small slopes in order to elevate and extend canals to include more arable downslope valley land. The time sequence of canals in the Moche Valley indicates that long, lower slope canals gradually extended and supplemented earlier short, but higher slope canals in upvalley regions and brought virtually all arable land in the Moche Valley under irrigation. As $L_c \rightarrow L_c{}^*$, $A \rightarrow A^*$, valley population had risen to the maximum value supportable by the resource base, assuming no imports of either population or food resources into the valley and weather variations of a benign nature. With technological advances in low-slope canal surveying originating on the relatively flat coastal plains, relatively small increases in labour were required to extend north- and southside valley canal systems to their full extent in the desert environment, i.e. $V_A < V_A{}^*$; this period of expansion is consistent with increases in compound building within Chan Chan and full utilization of technology and labour resources to utilize all available land area for agricultural purposes.

With a decrease in water supply as evidenced by contracting canal cross-sections and abandonment of major canal branches (Figure 1.1.8), the situation changed from earlier growth phases in the pre-1100 CE time period. The decline in water supply is ascribed to drought, tectonic distortions of supply canals, and uplift-induced river downcutting stranding downstream canal inlets. Regardless of the individual influences of various contributions to the decline, decline effects are manifest in the archaeological record. Equation 1 indicates that population change was influenced by changes in water supply, clearly a drastic $Q < Q^*$ decrease precipitated major pressure for new ways to sustain the existing population. Equation 1 indicates that dP/dt decreases as Q decreases and for $Q << Q^*$, $P^{\ 1}\ dP/dt \sim -Q^{*2}t$. Note that $A \rightarrow A^*$, $L_c \rightarrow L_c{}^*$, and $V_A \rightarrow V_A{}^*$ existed at the time of the water supply decline so that the potential for population change is high.

With the water flow rate decline from drought in intravalley canals leading off from the Moche River, new water supplies were sought from the Chicama Valley by means of the Intervalley Canal as strategy 1 limits had been reached and the decline of water supplies was beginning to limit the food supply to an already large population centred at Chan Chan. Although the Chicama River also experienced a drought-induced flow rate decline, its nominal flow rate far exceeded that of the Moche River (Figure 1.1.22) so that the Chicama source was the basis for a Q increase by a transport canal connecting the two valleys. The rise in technical level and labour input for construction of the Intervalley Canal to bring adjacent lands into cultivation (A increases over previous limits) as well as new Q supplies was part of the new strategy made possible by the large labour force developed in prosperous times. This construction labour asset was used to provide new water to the Moche Valley field systems before labour supply suffered an inevitable decline due to shrinkage of food supplies and population decline. This canal may be thought of as an attempt to increase L_c well beyond previous intravalley limits; this was made possible by a new technology (Φ^*) increase related to the construction of a long canal utilizing sophisticated technology through the foothill terrain between the Chicama and Moche Valleys. Note that if $A > A^*$ and $L_c > L_c^*$ by expansion into marginal lands within the Moche Valley, without the additional Intervalley Canal adjacent farm lands, population would begin to decline as marginal intravalley lands would have insufficient water to make them economically productive.

Additional field systems along the Intervalley Canal, which extend A by using land beyond valley confines, permitted an increase in food supply from Chicama water sources and continued $\mathrm{d}P/\mathrm{d}t > 0$. The use of strategy 2 agricultural terraces was available along the Intervalley Canal (Figures 1.1.16) to supplement level field areas adjacent to the canal. While the functioning of the Intervalley Canal to provide water to its destination interconnection with the intravalley Vichansao Canal is not positively established nor negated at present, nevertheless its design represents a major effort to increase water supplies to the Moche Valley.

The Intervalley Canal's main purpose was to supply water to the maximized cultivated land area A^* within the Moche Valley. This was an efficient use of developed, close-proximity intravalley A^* lands by a Q supplement from an adjacent valley water supply and is clearly a rational decision involving use of vast available labour resources. Probable failure of the Intervalley Canal to supply water to the Moche Valley intravalley canal network due to continuing drought ultimately affected the Chicama source and precipitated a deepening crisis. This led to a reduced intravalley area under cultivation and canal configurations of lower capability, as described in previous sections. Episodes of downcutting and El Niño rains appear to further compromise usage of A^* land areas. As lowering water supplies persisted during the LIP, later N1 and S1 canals (Figure 1.1.4) indicated $L_c < L_c^*$ and $A < A^*$ decreases as near-river canals and short remnant upvalley canals came into existence, as represented by the step-down phases of canal construction, i.e. a reversion to strategy 1 in the presence of limited water resources and river downcutting effects. As drought deepened, $L_c << L_c^*$, $A << A^*$, $Q << Q^*$, $\Phi << \Phi^*$, and $V_A << V_A^*$ for the new last-phase canals and the use of the smaller A in equation 1 trends towards the most efficient strategy 1 use of resources in the face of low water supplies to try to keep $\mathrm{d}P/\mathrm{d}t$ from decline. This indicates the optimum use of resources for a lower population size sustainable under adverse conditions. The new reality, however, probably precipitated a population decline and/or dispersal of agriculture and population into northern valleys to obtain their water and land resources. Since the effort to use nearby Chicama water resources with the available large labour force were not fully realized from the Intervalley Canal, and no significant water resources existed in adjacent valleys to the south, the northward expansion appears inevitable due to the large agricultural potential of these valleys.

A further negative situation existed as a result of tectonically induced river downcutting in the Moche Valley to limit irrigable lands. As inlets were stranded by river downcutting, new inlets initially needed to be cut further upstream (as described in Chapter 1.1) with downstream inlet migration following in time. The lead-off canals were led along the side walls of the downcut river bank permitting their entry onto irrigable surfaces at lower downstream locations, therefore reducing available land area. Here the slope of lead-off canals must be higher than the bed slope of the river to capture flow and lead it to land areas; this dictates longer side wall canal lengths (Figure 1.1.13A–C). In terms of equation 1 these trends indicate that the new lead-off canals increase canal length to smaller land areas so that $L_c > L_c{}^*$ and $A < A^*$, making dP/dt negative (with $Q < Q^*$ and $\Phi < \Phi^*$) as a result of the marginally reduced farming area. Thus, while the later canal configurations are optimum under drought conditions, they result in declining sustainable population size from the reduced farming land area. Since the Chimú controlled valleys to the north and south of the Moche Valley with land and water resources, exportation of food from these colonized areas may have provided stabilization of the population in the Moche Valley; nonetheless, the shrinkage of intravalley agricultural land and local water resources necessitated food resources largely from other areas under their control, particularly after the Intervalley Canal ultimately failed to provide additional water into Moche Valley canal systems. The continued contraction of the Vichansao Canal flow rates past phase II (Figure 1.1.14) indicated that valley water resources continued to decrease, leading to further shrinkage of food and industrial crops.

From equation 1 it appears that the rate of population change can increase with time, assuming that the terms in the braces are positive over a reasonable time interval. This indicates that given the possibility to utilize available water and land resources, a population will increase to match the increased resources (or force increases in utilized land area if population overshoots its agricultural support base). Conversely, given population pressures, land, water, and technology resources must rapidly develop to accommodate these pressures or a population decline (or migration) is inevitable if more production cannot be extracted from existing irrigation systems.

Example case 2: Spring-fed irrigation systems of far south coast Peru

To further illustrate application of equation 1, the spring-fed agricultural systems located north of Ilo on the south coast of Peru are examined; discussion of these systems is given in section 1.4. These systems consist of spring-fed minor valleys along the Pacific margin, each of which had supported agricultural production from EIP to Colonial times (Moseley *et al.* 1998; Clement *et al.* 1990, 1991; Ortloff 1989). These spring systems appear to be an early development by coastal Chiribaya inhabitants with peak populations occurring in the 11th to 14th centuries CE. Since Tiwanaku iconography and artistic styles are only vaguely suggested by Chirabaya ceramics, this society appears to have only tenuous roots to previous societies that once dominated the valley areas.

Starting with long canals from spring sources (estimated to be a few kilometres inland from the coastline), strategy 1 field systems were constructed in available level land areas. Early inhabitants appear to have occupied the beachfront ridges between shoreline and agricultural areas. Alternatively, areas not suitable for agricultural purposes were employed for habitation compounds and cemeteries. In early Chirabaya stages, water channels leading from springs and entrenched river channels were constructed to reach minor level areas suitable for farming. As the far-southern coastal valley had relatively little flat area but large amounts of land area in the form of steep-sided canyon walls, use of strategy 2 as a way of increasing agricultural land area through construction of terraces was possible.

As the water supply appeared to be continuously decreasing with time due to uplift interference with aquifers, and downcutting of river channels and drought conditions in the post-1100 CE time period, the field systems could only be reached by longer canals started at higher elevations along the river channel (where the river still had surface water). Since it was apparent that canals passed through arable land on hill terrain on the way to relatively small field plots, and that seepage and evaporation losses represented a loss of valuable water resources, it was apparent that a gradual shift from strategy 1 to strategy 2 was a better option, i.e. building and utilization of low terraces supporting agriculture would supplant long canals supporting distant, small field areas. The labour to build these systems was then directed to constructing low terraces requiring shorter distributive canals. As the population increased in response to new efficiencies and strategies, the labour devoted to construction increased. While the technical sophistication (Φ) required for building terrace systems is low, the supply canals required good surveying accuracy due to the convoluted terrain between water sources and fields. In terms of equation 1, initially $L_c < L_c^*$, $A < A^*$, $Q < Q^*$, and $V_A < V_A^*$ for early systems but the potential for a food resource and population increase from better usage of the land and water resources by means of a strategy 2 shift was apparent. The Φ value was low consistent with early agricultural solutions, i.e. straightforward, low labour-intensive methods were used initially to connect water resources to nearby fields through short canals and canalization of seepage areas. Labour input for minor canal construction was low consistent with initially low population size. With increasing population, potential food resource increased, utilizing strategy 1 methods required that L_c exceed L_c^* as long, unlined canals in sandy environments subject to seepage and evaporation were vulnerable to water loss, particularly under drought conditions where flow rates were low. As the limits of this approach were reached and as the flow rate of the supply stream decreased in time, the long delivery canals were supplanted by upvalley low terraces, which led to an increase in A by more efficient, shorter delivery canals ($L_c < L_c^*$). This shift to strategy 2 required an increase in Φ and ψ as labour was directed towards terrace and canal building, and an increase in V_A towards V_A^*. With this step, A increased and the maximum population rate change was achieved with strategy 2 methods made possible by the labour resources resulting from successful exploitation of earlier systems. With further water supply decreases and despite $A \rightarrow A^*$ with strategy 2 methods, the maximum Φ value was reached (no further technical advances possible); the increased labour supply drawn from the large population was of no avail to further implement methods to increase agricultural production to supply the population as all lands were optimally exploited. At this point, the society had achieved maximum exploitation of all land and water resources ($A = A^*$, $L_c = L_c^*$, $Q = Q^*$, and $V_A = V_A^*$) so $dP/dt = 0$ and maximum food resources along with maximum population was balanced with the maximum carrying capacity from land and water resources. The decline in water supplies post-1100 CE then resulted in the inevitable population decline. Further decreases in Q forced yet further population decline as channel downcutting proceeded from tectonic forces; more labour investment was needed in reworking lead-off canals to supply the terrace systems, leading to a greater fraction of the population enlisted into maintenance and construction of the terrace systems. Since strategy 2 had reached its limits at this point, there may have been emphasis on exploitation of the marine resource base. In terms of equation 1, canal extension phases indicated L_c increasing past L_c^*, V_A close to V_A^*, Q declining, Φ stationary, and A extended to the maximum A^* by strategy 1 methods. Equation 1 indicates that over time under these conditions with the population at a maximum sustainable level, a slow decline ($dP/dt < 0$) began as additional water and land resources were limited. The strategy 2 change to terrace systems after furthest extension of earlier canal systems shows that $L_c < L_c^*$ (new shorter canals to terraces), $V_A \rightarrow V_A^*$ (increased labour to construct terraces), Φ increasing (more complex canal rerouting), Q exploited to its maximum, and a higher A from new lands opened for agriculture. The net result of strategy 2 was a positive change of sign in equation 1, which indicates the potential for further population growth with strategy 2 methods supplanting strategy 1 methods. Despite this change, lack of water resources ($Q < Q^*$)

ultimately led to marginal operation and abandonment of the system with concomitant population decline (or migration) until the area was reclaimed in Colonial times reusing an elementary strategy 1 system based on minor production of luxury and export industrial crops. In summary, transitions observed in the archaeological record appear to confirm that rational decisions were made in agricultural system reconfiguration to maximize food production in accordance with equation 1 predictions.

Example case 3: The Moquegua Valley agricultural system

The agricultural systems located in the Moquegua Valley (Moseley *et al.* 1998; Stanish 1985, 1987, 2006) were a combination of canal-fed terraces located in the Sajena, Porobaya, and Torata River drainages that combined to form the Rio Moquegua (Figure 1.1.1). Six occupation phases were found (Late Tiwanaku, Otora, Estuqueña, Estuqueña–Inka, Inka, and Colonial) dating from the 13th to 18th centuries CE. Initially, in the Tiwanaku III–V periods, Tiwanaku colonies exploited available low-slope land within Moquegua Valley margins for agriculture. Traditional raised field systems associated with the heartland Tiwanaku Empire were dysfunctional in the post-1100 CE time period due to drought-lowering of the water table and desiccation of the spring systems that supplied some of these fields. Although traditional heartland raised field lands were now marginal, population in the post-Tiwanaku V Pacajes phase was still large but now occupied outlying lands where the drought-shifted water table height still permitted limited raised field and wetland agriculture. Colonies in the Moquegua Valley collapsed in the post-Tiwanaku V period as canal agriculture based on declining river runoff diminished due to extended drought conditions. This later phase led to exploitation of new areas with some form of water supply where food production could support dispersed groups balanced with the food production level. In the post-Tiwanaku V period, a change of population focus occurred primarily as a drought response, from lower and mid-valley Moquegua Valley sites into the mid and upper sierra regions of the Sajena, Porobaya, and Torata tributaries where water supplies were more abundant due to higher rainfall and snowmelt supply. Apparently long canals to low terraces were initially preferred over short canals to high-upland, closely spaced, high-slope terraces in early phases. Later, as water supplies continued to diminish, the population shifted further towards the sierra regions with greater water availability. Thus a shift from mid-valley canals to low-sierra terraces to high-altitude terraces appeared in the archaeological record and has been explained as related to increasing water supply availability. That this sequence of events was a preferable strategy from both a labour and productivity point of view can be seen from equation 1. To maximize dP/dt by strategy shifts (albeit by different societies), one consideration is the relative sizes of terms within the braces, i.e. $(L_c{}^{*}-L_c)/|A-A^{*}+\Delta|^2$ compared to $(V_A{}^{*}-V_A)/|A-A^{*}+\Delta|^{3/2}$ for given Q and Φ values. Here L_c is progressively shortened, increasing dP/dt, $V_A \approx V_A{}^{*}$ (the same labour force shifts to a different locale), and $A \geq \Delta - A^{*}$ (similar valley agricultural areas are utilized for terrace land areas). The net result of this, when combined with $Q > 0$ from the altitude shift, is an increase in dP/dt, which verifies the strategy 1 to 2 relocation trend.

A second consideration relates to the labour involved in strategies 1 and 2. In this case, the construction volumes V_A moved relative to the labour (labourhours) involved given the rate of material transfer per worker (dR/dt). In terms of previously defined variables, the labour input (i.e. number of workers) required to construct M canals of length L_c and cross-sectional area A_c in time ΔT_1 is:

$$(\Delta T_1)^{-1} k_1 M A_c L_c/(\mathrm{d}R/\mathrm{d}t) = \psi_{\mathrm{I}}$$

while for a terrace agricultural system with J hills of face area A, slope θ, length L and height H containing N terraces of height h ($N = A\sin\theta/hL$):

$$(\Delta T_2)^{-1} k_2 h H L J(\mathrm{ctn}\ \theta/2)\mathrm{d}R/\mathrm{d}t = \psi_{\mathrm{II}}$$

where ΔT_1 and ΔT_2 are given time intervals for construction and k_1 and k_2 are multipliers related to logistics and administrative tasks related to construction. First, it is clear that short canals ($L_c < L_c{}^{*}$) to large areas requiring relatively small amounts of labour ($V_A < V_A{}^{*}$) lead to strategy 1 success; this configuration promoted dP/d$t > 0$, leading to a maximum at dP/d$t = 0$. For long canals to flat land with low terraces, labour requirements were small and although the size of the first term in the equation 1 brace is negative as $L_c > L_c{}^{*}$ and $V_A < V_A{}^{*}$, the second brace term can be positive depending on the elaboration and extent of the terrace area matching that of the flat lands it replaced. Past this point when further canal extension occurred to bring in new highland sierra lands irrigable by canals, finally $L_c > L_c{}^{*}$, $V_A > V_A{}^{*}$, $A \approx \Delta - A^{*}$, and $Q > 0$ so dP/dt can be negative. This result, and the continuance of declining water supplies even at higher altitudes due to drought, signalled the final transformation from large-scale terrace agriculture to localized settlements clustered defensively around individual water sources which characterized the transformation to late Estuquiña sites from earlier administrative sites that governed large-scale terrace agriculture. This trend, when no further advances were possible with strategy 1 but land and water were available in mountainous terrain, brought forward strategy 2 systems to supplement and ultimately replace strategy 1 systems. An increase in Φ (surveying accuracy to permit canals to reach difficult terrace areas) and ψ and a possible decrease in L_c occurred to produce gains in dP/dt by exploiting mountainside sierra terrain to provide further agricultural land by terracing. Here additional benefit accrued due to higher rainfall levels at altitude channelled into supply canals at higher elevations compared to valley floor river supplied systems.

Equation 1 predictions corroborate the observation (Stanish 1987, 1989) that '... in terms of labour requirements, it is much more efficient to build long canals to cultivate flat land with low terraces [end point of strategy 1] than it is to build short canals to steep land which requires high and closely spaced terraces...' In terms of equation 1, the first part of his statement reads $L_c > L_c{}^*$, $V_A << V_A{}^*$, $A \approx |\Delta - A^*|$, $Q \approx Q^*$, and $\Phi < \Phi^*$ applies; here the dominance of the positive $V_A{}^* - V_A$ labour term makes dP/d$t > 0$, indicating the benefit of this strategy. For the second part of the statement, $L_c < L_c{}^*$, $V_A >> V_A{}^*$ and $A \approx |\Delta - A^*|$ (same land area used), with the same Q but with a Φ greater than the previous Φ^* for strategy 1 conditions; here the negative dominance of the $V_A{}^* - V_A$ term makes dP/dt somewhat negative, indicating Stanish's conclusion in terms of equation 1 parameters.

Movement in the later Otora period was to greater dependence on sierra terrace agriculture in the face of declining water supplies due to drought and was the logical option due to lower runoff water supply available at lower altitudes. Initially use of short canals from runoff streams, followed in time by longer canals to exploit high-altitude snowcap melt zone water supplies and higher rainfall levels, was the only option left in drought conditions. The increased arable area brought about by use of terraces over vast stretches of sierra terrain that could be supplied by canals made the higher labour investment worthwhile with the promise of increased agricultural output. Thus the creation of surplus products (perhaps intended for export or exchange with other population centres) enabled more ambitious projects to be undertaken to enlarge the agricultural base. It is also noted (Stanish 1985) that a shift in settlement and field system location occurred to shorten canal lengths to field systems. This strategy 1 move is consistent with equation 1 predictions as $L_c < L_c{}^*$ and Φ increases to Φ^* both amplify positive dP/dt to higher positive values. Losses by evaporation and seepage, which are functions of canal wetted surface area, flow static head, soil porosity, and soil saturation level, are also reduced by a canal shortening ($L_c < L_c{}^*$) strategy. Use of ridge top canals in the sierra required a large V_A as sinuous canal paths that alternate position from one side of a mountain to the other allow alternate sides of terraced hill slopes to be irrigated. Use of canals in this manner may be viewed as yet another technology improvement (Φ increase) to increase productivity.

The Estuquiña period (1350–1450 CE) somewhat varies trends of terrace agriculture usage. However, drought in this period most probably led to shorter canals from localized water sources; in this case, some regression from large-scale organization to small-scale, defensive settlements around water sources followed. The subsequent Estuqueña–Inka period (1450–1532 CE) is characterized by economic exchange networks to further growth since the maximum agricultural productivity had been achieved from the available land and water resources. In this period, agriculture was shifted back to valley bottoms and expanded due to increased labour availability brought in from conquered areas according to the economic organization of lands and resources imposed by the Inka. Since rainfall levels began to return to earlier levels in the Late Horizon period, alternative land areas in valley bottoms and existing and/or newly constructed terraces were more easily farmed by relocated populations because of a transfer of interest from labour-intensive terrace systems to more easily maintained, less labour-intensive strategy 1 valley bottom systems of high productivity. Since a choice existed between short canals to valley bottom areas (strategy 1) or short canals to remote terraces (strategy 2), both of which probably have the same surface area, clearly the former strategy is more productive due to both location and accessibility as well as upkeep labour and soil fertility reasons.

Example case 4: The Hoya Hondada aqueduct of the Jequetepeque Valley

The Chimú site of Farfán in the Jequetepeque Valley on the north coast of Peru contains an aqueduct system design (section 1.3) that showed significant labour investment to achieve a marginal land area increase. The canal system consisted of a number of small aqueducts that crossed quebradas at an elevation level equal to the bank height and one major aqueduct with a unique low-level aqueduct design. This aqueduct represented a significant technological advance in that it contained unique hydraulic controls to protect against El Niño flood destruction. Use of a canal constriction (choke) that limited flow rate and raised the water level above a side overflow weir combined to limit the amount of water passing down a steep chute onto the low aqueduct. This, in turn, limited the height of the hydraulic jump at the chute/low-angle aqueduct juncture, preventing erosion damage and spillage effects on the aqueduct.

In terms of equation 1, this example represents a strategy 1 concept with $L_c > L_c^*$ (expansion into marginal agricultural land using a very long lead-in canal originating from the valley neck), $V_A > V_A^*$ (large labour investment), and some increase in A beyond A^*. Here Φ exceeded the previously established Φ^* level based on standard use of previously existing canal design technology (as exemplified by aqueducts upstream from the Hoya Hondada aqueduct). From equation 1, the implied population (or food output) change resulting from this system was negative and marginal as agricultural output from marginal lands was hardly worth the labour investment. The above parameter set led to $dP/dt < 0$, which apparently was an incorrect strategy move to expand agricultural production. The question arises as to the rationale for the extension of the canal to marginal areas requiring lengthening of the supply canal to great distance; here evaporation and seepage along the unlined extension of the canal to its full length would seem to limit the amount of water that could be delivered to these remote lands far from the river water source. One answer may lie in a situation where a population increase, based on either importing another valley's agricultural output (and population) and/or a favourable climate cycle making water resources temporarily plentiful, led to a situation where an increase in arable land area appeared to be a good strategy to accommodate population pressures. It is noted that in this area, side walls of some quebradas along the canal length were terraced and supplied with water from the main canal, indicating further use of marginal lands in that sunlight exposure was limited by the depth and position of the quebrada walls. Clearly evidence exists for utilizing marginal lands requiring large labour input to construct and maintain that appear non-efficient from an energy input/output point of view. Since a large valley population existed based on many large living compound areas, labour resources were available to expand into marginal land despite $L_c > L_c^*$ considerations. The increase in Φ associated with the Hoya Hondada aqueduct design permitted the extension to occur to new field systems on an elevated plateau (Figure 1.3.2), as indicated by several small settlements at the end of the canal extension, perhaps offering a possible solution to counter population excess with increases in agricultural lands and some limited water to supply these lands.

In this case, the parameters characterizing this extension imply $dP/dt < 0$, indicating the possibility of limited food resources resulting from marginal gains offered by canal extension to marginal lands as a result of $L_c > L_c^*$ and $V_A > V_A^*$; the overextension of technology past the confident limit of Φ^* is then associated with high water losses, seepage, and evaporation in the long canal to the plateau area. The thought here is that at least some benefit may be gained by use of this canal although it is probably a 'last-resort' system forced by population needs rather than efficiency considerations. Here increased Φ due to hydraulic control advances could prevent damage to the labour-intensive canal and aqueduct, and thus ensure its preservation under sudden high-rainfall events. This at least would justify the labour investment as it would have low need for rebuilding in the event of high-rainfall events. The conclusion here is that population pressures may have forced canal extension to lands thought unreachable (due to the rough quebrada-eroded terrain and distance from the river inlet) but made possible by new technological achievements. At least the land could be developed and water supplies made available, albeit in limited amounts due to the long canal length, to support some population elements although at only the subsistence levels characteristic of low-status field workers. This may indicate that low-status workers may have had no other options to land and water resources except at the marginal fringes of more productive lands (as Chimú Moche Valley agricultural worker settlements at Pueblo Joven and Cerro Virgin Village imply). The observation that steep quebrada walls in partial shadow were farmed and supplied by minor canals indicated the scarcity of arable land and pointed to the need to develop what was considered as marginal land, in this case, land not exposed to sunlight for a large part of the day with little irrigation water. Apparently water supplies to this remote area could be marshalled by closing off all other branch canals to direct water solely into the main canal, implying that water was shared on a rotating basis between all branches from the main canal. Nevertheless, despite intricate water sequencing operations, most water was directed to the most productive fields closest to canals and urban settlements to avoid the losses and wastage associated with long canals to marginal areas with low expected food productivity. In terms of equation 1, canal extension to marginal lands indicated that population beyond the carrying capacity of productive lands had occurred and that water supplies were barely adequate in late LIP times to justify extension to lands that could only provide limited resources, probably to the least privileged members of society. The technology to amplify Φ led to the creation of a workable aqueduct, even when subject to high-rainfall episodes, despite other characteristic parameters indicating $dP/dt < 0$. Apparently the technology involved was such that $\Phi - \Phi^* > 0$ so that the negative magnitude of dP/dt was small. In this case, some lands of limited potential to produce crops would at least provide some additional product even though use of these lands and water resources was in a non-optimum economic, subsistence mode. This land use may represent the only extension alternative left to a vast near-city region developed to A^* and L_c^* levels, and implies that some population stress was forcing this extension to marginal lands. If a non-agricultural use of water for domestic settlements and small-scale agricultural plot purposes was the intent of this system, then perhaps a better rationale can be offered for its use in supplying water to workers managing the large adjacent field systems living in these border settlements.

Example case 5: The Mochica IV–V sequence in the Jequetepeque and Moche Valleys

Discussions of the Moche sequence and final demise in the Jequetepeque Valley (Dillehay and Kolata 2004; Dillehay *et al.* 2004; Shimada 2002) indicate a trend towards decentralization of a single administrative authority and a return to some vestiges of ruralization as manifested by walled enclaves and minor settlements as the Moche presence entered its final phases in the valley. While elements of state religion and ceramic styles remained, the underlying ties to a central authority centred in an administrative centre appear lacking. Speculation as to causes of these changes may be related to known long-term drought events in the pre-1100 CE period (as well as an earlier drought event in the 600–650 CE period which apparently caused the collapse of Moche society in the Moche Valley and subsequent relocation to the Lambeyeque Valley site of Batan Grande) which caused fragmentation of the agricultural base (Thompson *et al.* 1985; Shimada *et al.* 1991). Investigations of field and habitation structures within the Jequetepeque Valley in this time period indicate episodes of flood-deposited silt layers interspersed with aeolian sand layers, indicating occupation interruption events in late Moche times and lending credence to El Niño flooding and drought events as causes for agricultural disruption. Further evidence pointing to village sites with short occupation times and population shifts to sites temporarily provided with some form of opportunistic water supply is also evident, indicating that populations were necessarily mobile within the valley and possibly guarded local water supplies as their source of survival (Dillehay and Kolata 2004). Lack of substantial Moche IV ceramic scatter indicates some form of interruption of previous occupation patterns in the valley. While scenarios involving political upheaval, internal societal conflict, invasion, and ecological upheaval have currency (Dillehay 2001), it is of interest to explore the situation by use of equation 1 as clearly some population and settlement pattern changes occurred in this period.

If initially Moche sites were well established in Moche II and III times by means of canal-supplied field systems when a balance of population to agricultural resources existed, i.e. $Q = Q^*$, $A < A^*$, and $L_c \rightarrow L_c^*$, and Φ and V_A were at sufficient levels to sustain extensive canal-supplied field systems close to their maximum operating capability. If flooding from a large El Niño event caused a drastic destruction of canals from their optimum extension and field system coverage, then L_c^* is reset to small values in the new environment and $L_c >> L_c^*$ as non-functional canal lengths exceed workable, productive * lengths. Emergency labour to reconstitute canals and field systems results in large $V_A >> V_A^*$ and $A << A^*$ due to flood damage (here large Q transferred to groundwater may have a benefit to create desert blooms and local groundwater seeps, but otherwise is destructive to canal-supplied field systems unless defensive controls are in place, as described in Example case 4). Equation 1 then indicates that dP/dt has the potential to become negative within a strategy 1 format as a result of environmental damage.

For drought scenarios the same is true but the decline is amplified by the negative $Q - Q^*$ term. As dP/dt can be negative in both these situations, a possible strategy to maintain $dP/dt > 0$ would be population mobility to other areas where sufficient Q and A exist, if such lands are open for occupation and development. In the absence of this option, the restoration of pre-existing field systems after flood damage may take considerable time and, if drought also prevails as a background event, the restoration may not prove useful in the absence of water supplies.

An immediate response attained without relocation is to exploit water sources in the form of pools, groundwater penetrations through the ground surface (springs), and trapped moisture zones resulting from elevated groundwater zones, all of which required relocation of population concentrations into smaller transient groups that could exploit local opportunistic water resources wherever they appear. Thus population may remain stable but reconfigured into mobile settlements around these transient water resource areas. Thus to maintain $dP/dt = 0$ (maximum population and food resources), Q needs to be sought in any form possible and population needs to be redistributed accordingly where water can be found. Since low labour (ψ) input is key to rapid exploitation of variable water sources, many opportunistic, temporarily occupied sites are to be expected and indeed found in late Moche times (Dillehay and Kolata 2004) in the Jequetepeque Valley. Under duress, reliance on organized agricultural practices and techniques of the past that required higher administrative oversight and organization may have had to be temporarily suspended as drought or floods rendered prior strategies useless; a decline in the governmental structures behind their construction, operation, and maintenance may also have to be suspended as survival by any means prevailed in drought and/or a post-El Niño environment. From results obtained in Example case 4, it is clear that defensive measures were taken in later Chimú times to ensure operation of key aqueducts under flood conditions, perhaps as a lesson learned from earlier Moche occupants of the valley that learned to cope, as best they could, with too little or too much water for their field systems. In terms of equation 1, the observed trends fit the underlying base that explains the historical record.

In the Moche Valley *c.* 600 CE, the site of Moche indicated occupation to the Moche IV period; a later shift to the minor valley-neck site of Gallindo then occurred in the Moche V period. The reason for this shift has been variously ascribed to drought, tectonic/seismic distortion of canals, sand incursion onto field systems, local El Niño flooding, and a variety of political and social effects (Bawden 2001) operational at the main capital city at Moche. While north coast drought appears to be evident in this transitional time period in multiple valleys under Moche control, the consequences of equation 1 may provide a logical reason for observed changes in occupation patterns during the Moche IV–V transition.

Strategy 1 Moche IV agricultural fields were located off the Moche River by northside short canals onto the Pampa Esperanza and southside Moche River regions near the site of Moche. In terms of equation 1, $L_c << L_c^*$, $A < A^*$, and $Q < Q^*$ with a modest technology level Φ consistent with moderate slope surveying capability. As water supplies diminished further towards Moche V times (note that a drought is indicated in this period (Shimada 2002) and uplift/El Niño effects promoted sand incursion and inland dune migration from offshore winds operating on newly exposed beach areas), then, to keep dP/dt zero or positive, one recourse, staying within strategy 1 limits, is to make $L_c << L_c^*$ by moving the agricultural field system location closer to a far-upvalley river inlet. This strategy avoids water losses through long canals due to seepage and evaporation and keeps $V_A < V_A^*$ with the same Φ level. Here, L_c^* is to be thought of as the sum of canal lengths to provide A^* in the pre-Moche V environment with agricultural fields close to the Moche River and the site of Moche. The relocation to an inland valley-neck location (Gallindo) with nearby agricultural fields utilizing a strategy 1 methodology of short canals to close-by field systems, and away from encroaching dune fields, can therefore be viewed as a consequence of survival planning to maintain population levels, although societal and city plan restructuring (Bawden 2001) resulted from reallocation of scarce resources to a new upvalley location. Although some Moche limited occupation remained at Gallindo in Moche V times, apparently a migration north to the Lambeyeque Valley with vast land and water resources guaranteed survival in an environmentally benign area where the Moche society continued their history to later times (transitioning into the Sicán polity) and reinstituted canal building strategies to ensure $dP/dt > 0$ to the end of the EIP. Thus the move to the upvalley site of Galindo was a logical step to utilize scarce water resources by short canals to adjacent upvalley fields in light of the sand coverage of lower valley sites and field systems brought about by severe geomorphological and climate-related events. Similar destruction of Moche sites in the southern part of the Jequetepeque Valley by dune incursion is also noted, signalling some major catastrophic events that affected the coastal regions in late Moche times. While these events disturbed major near-coastal Moche sites, inland, upvalley, and intervalley migration to new settlements at least provided refuge and survival possibilities in new more favourable environments. It is also noted that the drought of 1100 CE affected Middle Sicán society in the Lambeyeque Valley, leading to abandonment of the previous city centre of Batan Grande and re-establishment of a new city centre at Tucume, thus all north coast societies show effects of the pan-Andean drought in this time period.

Partial derivatives of the basic equation

It is of interest to determine the effects of population (or food supply) changes with a persistent water supply decrease ($Q << Q^*$) using equation 1. For this the partial derivative, after some simplification, is:

$$\partial P/\partial Q \approx 2(Q^* - Q)\ \exp\{-KW(Q^* t)^2/2\} \tag{3}$$

where

$$W = \{[(L_c^* - L_c)/|A - A^* + \Delta|^2 + (V_A^* - V_A)/|A - A^* + \Delta|^3] \\ \times (\Phi - \Phi^*)/2|A - A^* + \Delta|^3]\}$$

and K, k are dimensional constants. By assuming W positive and relatively constant over short time intervals consistent with a canal system developing to the maximum * extent consistent with large population requirements and $\Phi < \Phi^*$ to permit ongoing developmental extensions, equation 3 then predicts the effect of drought-induced ($Q < Q^*$) water supply decline on a developing irrigation system. Equation 3 shows that $\partial P/\partial Q < 0$ in the presence of drought as food supplies (and the related population) decrease exponentially with time t^2, i.e.:

$$\partial P/\partial Q \approx \exp\{-c(Q^* t)^2/2\} \tag{4}$$

As Q decreases, $Q^* - Q$ becomes progressively larger, making $\partial P/\partial Q$ progressively more negative. Under drought conditions therefore, some canal system reconfiguration, strategy changes, or relocations (as evidenced by Example cases 1, 2, and 3) and/or technology upgrades (as evidenced by Example cases 1, 3, and 4) follow logically from equation 1 to modify W. Inevitably, in the presence of extended drought, despite changes to reconfigure and modify canals or field systems, food resources ultimately decline and societies experience great challenges in maintaining survival. Note that if $W < 0$, indicating an over-extension condition to marginal lands, then $\partial P/\partial Q$ declines even more rapidly according to equation 4.

Corporate (top-down) or rural (bottom-up) development of agriculture in state formation

Questions as to whether state agriculture develops and coalesces as the sum of individual collective rural enterprises (bottom-up) or is totally state-directed (top-down) (Janusek and Kolata 2004) may be addressed from equation 1 based on which methodology yields the highest agricultural output. This optimum then would influence decisions to maintain individual farming plots controlled by individual family or kin units or accede to state management for oversight and direction to control total output derived from farming units acting cooperatively for the benefit of all. From equation 1, consider n individual farming plots such that $A = A^*/n$, $\psi = \psi^*/n$, $Q = Q^*/n$, $V_A = V_A{}^*/n$ and Φ is constant, i.e. individual labour units control individual small areas and have a proportionate share of land and water resources, and all have the same technology base. On substitution into equation 1, the food supply contains scale factors between $\exp(k_1 n \quad ^4)$ and $\exp(k_1 n \quad ^3)$; k_1, k_2 are constants. Thus large integrated agricultural areas (n small) are ultimately more productive than many individual (n large) areas. This means that for a large number of agricultural units with equal division of land, labour, and water resources (and similar canal lengths to each plot), labour is intensive to construct and maintain the n farming plots but otherwise this system can be highly productive if sufficient labour resources exist. The picture is one of a multiplicity of individual canals led off from a common river to individual plots with no communication or interaction between farmers and field plots, the very picture of individual self-interest. This situation may apply for early stages of agricultural development by a limited population size consisting of individual family or kin units and represents an initial, productive economic strategy. The difficulty in maintaining this configuration as plots and population multiply and canals require tortuous paths to connect distant plots to a river source means that equal sharing of water and land resources with limited labour resources becomes difficult because canals become quite long as a result. If multiple branching canals from a river source are used to penetrate field areas, then smaller branch canals can water individual distributed field plots, resulting in reduced canal length and consequently less labour required for construction and maintainance. This means that a small number of interconnected large plots are ultimately more efficient than a large number of small plots based on cooperative state rules imposed on the many groups formerly operating in a non-cooperative manner. For finite labour resources, this new strategy is apparent as an economic gain. It would therefore appear that rural development based on many-family or extended kin groups operating on land areas just sufficient to provide for the group itself is an efficient use of resources in early societal development stages, provided these groups are few in number and sufficient arable land exists to facilitate this division with equal water access without contestation. As the population grows, the system of many independent plots must eventually run into conflict as equal water division into many separate, but spatially distributed, closely spaced plots requires too intricate a canal water supply system (i.e. $L_c >> L_c{}^*$, labour expenditure $\psi >> \psi^*$ and Φ increases) and some overarching control becomes necessary to transform individual estates into a cooperative, efficient system to keep dP/dt high. This is accomplished if the benefits of subsuming control to a higher administrative unit yield the benefit of more agricultural production for all compared to the previous condition. As not all land is of equal productivity, despite equal division of land to groups, some groups will experience a food production penalty although, in principle, all groups have equal water and land availability. Based on efficient use of the totality of land and water resources to provide for a larger population and share resources between disparate groups with different productivity levels, building main distributive water arteries with collective labour that permit individual farming groups to function collectivity appears to be a better strategy (higher dP/dt) as all groups can share equally from a more efficient use of land and water resources, and a greater share of the increased production of food resources. A system that lessens individual control based on cooperative, rather than competitive, activities can then self-organize into a collective system, with a main bureaucratic overseer and organization to guide progress and redistribution of agricultural resources.

While collectives initially result, as the scale of requirements increases with larger population requirements and societal complexity, evolution into a top-down system with greater oversight, organization, and control features appears as an inevitable state formation. That this was the case, as observed from the archaeological record, is demonstrated by the individual alluyu-based, scattered lake edge, clustered field system organizational patterns observed in pre-Tiwanaku IV phases (300–600 CE), which later evolved into a pattern '. . . of purposeful state development of an integrated, rural agricultural zone in Tiwanaku IV and V times (600–1100 CE) . . .' (Kolata 2003). After the collapse of the Tiwanaku state, reversion to individual land plots run by alluyu kin communities reappeared and exist to the present day, as lower population levels could easily divide vast land resources suitable to the community needs without conflict with neighbouring communities.

Conclusions

In summary, a closed-system model equation relating variables important to agricultural hydraulic societies' population growth (assumed to be related to agricultural product output) has been constructed by dimensional analysis methods and applied to five example cases where archaeological data is used to test the predictive capability of the model equation. The model presented provides a method to explain population (and food supply) dynamics as influenced by agricultural production parameters only. For a successful agricultural system that expanded using new strategies after exhausting the potential of a prior strategy, the 'reward' was considered as positive population (or consumable agricultural product) growth; contrarily, the opposite was true as unsuccessful or badly strategized systems led to hardship and collapse of a society when off-design conditions intervened. As conformance to model predictions imply, agricultural strategy decisions made at group or state level that follow a logic represented by equation 1 imply that procedures and decisions are based on a continual maximization of food resources to make dP/dt positive.

While efficient small group agricultural practices were initially present in early stages of societies, invariably within the larger context of state formation and group coalescence, new production maximums can exist based on groups acting collectively and deciding on optimum strategies to guarantee production continuity and maximum output for available land, labour, and water resources. The construction of defensive measures (to ensure continuity of productivity) that require the cooperative efforts of a large number of workers is then a further benefit of a state-controlled resource management system. The benefits from numerous individual farming plots with individual uncontested access to water are soon subsumed by collective efforts managed with oversight from administrative officials on a state level cognizant of agricultural technologies and systems that can apply to increase efficiency on a large scale. This approach works because cooperative labour can produce more benefits than individual uncoordinated labour, particularly as irrigation systems increase in complexity and extent as a result of larger population demands. The drive towards maximizing agricultural production may promote cooperation between groups on their way to the larger degree of organization necessary for incipient state formation. Of course, the model variables may be extended to include factors such as climate variations, landscape topography, soil productivity, degree-of-organization parameters, storage capabilities, sociopolitical factors, etc. that affect population growth and decline; however, at least for a qualitative picture of the rationale behind different developments in the Andean world, the model equation provides a logical basis for observed activities in the archaeological record by progressive ancient societies. The use of different agricultural strategies and optimum uses of water represents steps in the technical evolution of an adaptive and successful society. The strategic decisions made by societal leadership, and the reasons for these decisions, are invariably based on some rationale for the success of one strategy over another to provide sustenance for the population on a predictive basis. It is inviting to think that similar variables used in the model were those selected for observation by the technocrats of a society and that their goal was to develop some predictive tools to measure success of their decisions. While not implying that similar methods were used, perhaps an empirical analogue made its way into the decision-making chambers of these ancient societies.

The rationale presented by the model equation may therefore represent some of the analytical foundation behind the decision-making of pre-Columbian hydraulic societies (albeit in terms and units familiar to ancient bureaucracies) that ultimately involve accounting of key variables. In this sense, the model equation provides a law derived from basic considerations for understanding both the basis for strategy decisions and the rationale for interpreting the results of those decisions in the archaeological record. Clearly, the same variables used in the model equation were of concern to the planning strategists of these societies. Some aspects of pre-Columbian hydraulic science thus far described follow a path of discovery different from Western science models and methods yet they achieved remarkable practical results over millennia of operation; this alternative path of solving hydraulics problems will certainly be a fascinating subject for future researchers investigating the history of hydraulics. It is not unreasonable to think of ancient societies making similar developments in economic models and associated predictive tools based on their analytical, empirical, accounting, and recording technology advances. Clearly these tools were developed to record some measure of productivity leading to storage, distribution, and taxation, perhaps also as a precursor to these functions some basis to manage and improve agricultural output by analytical or empirical means was present and utilized some of the variables and concepts of the model equation. While Wittfogel's (1957) controversial thoughts on the formation and function of hydraulic societies provide many avenues of socioeconomic research interest, the present work suggests that a rational mathematical/empirical observational base underlies the decision-making of these societies and that the basis of their decision-making may be found in their efforts to maximize food resources.

1.7 AGRICULTURAL STRATEGIES AND SUSTAINABILITY IN PRE-COLUMBIAN SOUTH AMERICA

Introduction

To conclude discussion of ancient South American agricultural systems, note must be taken of the climate variations that influenced the continuity of agricultural production. This section emphasizes that such considerations and their effects on the sustainability of agricultural production were firmly in the consciousness of these societies, as demonstrated by the many defensive measures to protect vital agricultural systems from the destructive effects of climate and weather variations. This section provides insight into such measures and presents an alternative model to gauge the effectiveness of different societies in protecting their vital agricultural resource base.

Loss of agricultural land is observed in the Andean landscape where abandoned planting surfaces comprise the most widespread of all archaeological remains on the continent. Throughout ancient South America, millions of hectares of abandoned farm land indicate that in some regions 30 to 100% more terrain was formerly cultivated in pre-Columbian times than at present. While cultural explanations can be formulated, the most encompassing reason for land loss is that farming was not sustainable as water supplies declined from changing climate. Studies of abandoned agricultural land suggest that agriculture was expanded many times in many different places when conditions favourable to the reclamation of new lands were anticipated by past populations. When climate trends led to less available water supplies, agrarian regression ensued (either temporarily or permanently), with consequences for societal structure.

An overview of ancient Andean civilizations reveals a wide diversity of agricultural techniques in widely varied settled areas, essentially a library of strategies for different ecological zones depending on available land area, seasonal water supply, difficulty of canalizing the area, short-/long-term climate patterns, crop types (basic staples, industrial, luxury, trade commodities), drainage methodology, temperature and humidity variations, soil fertility, and the labour input to agricultural productivity output ratio. The area-specific choices for an agricultural system's sustainability rely on a society's available civil hydraulic engineering and civil engineering skills to devise and manage complex water supply networks and to modify/adapt them to other high productivity configurations as climate and/or weather conditions changed. While shifts to a marine resource base, pasturalism, trade networks, and alternative agricultural strategies can mitigate a decline in local agricultural production due to adverse climate cycles, long-term damage to the sustainability of the main agricultural system is cause for some form of societal, economic and/or agricultural system modification. A further requirement for agricultural sustainability is the ability for administrators to record and analyse historical records for occurrence rates of potentially destructive climate cycles, weather events, and natural disasters in order to prepare defences and modifications for anticipating water supply variations. Modifications may take the form of physical alteration of existing water delivery systems and/or new strategies, with new types of agrosystems appearing. For extreme climate variations beyond a system's ability to allow defensive modifications, field system abandonment is an inevitable outcome of the failure to provide restorative answers. A sustainable agricultural base has an opposite effect: population growth, a population distribution based on agricultural settlements or urban living derived from personal choices of perceived economic advantages and a tendency towards a centralized administrative control of labour resources. Regardless of the availability of water supplies, lack of a suitable agroengineering strategy, labour force, and technical/management base can cancel societal progress. Sustainability therefore involves the ability of leadership to successfully choose an initial agricultural system design and then manage it within the envelope of expected weather, climate variations, and labour requirements to maintain high agricultural yields. This process relies on technical innovation capability to modify agricultural systems rapidly under different water supply conditions. The modification flexibility must be part of the selection process for the agricultural system's initial configuration if knowledge of prior climate/weather pattern (positive or negative) effects on water supply existed in historical records. Finally, another consideration necessary to understand agricultural sustainability is the distribution dynamics of water from an original mountain rainfall source to coastal regions. The dynamics of water delivery are a matter of hydrological principles: there is a disproportionate effect of excessive rainfall or drought in the mountainous highlands compared to that in runoff-dependent coastal lowland field system areas based on altitude-dependent rainfall infiltration, retention, transport, evaporation, and seepage loss rates. These interactive, climate-related and societal structural factors are vital in understanding the basis of the highland–lowland interaction dynamics and their possible relation to Andean historical development.

The setting: regional climate norms

The central Andean Cordillera has extended, parallel eastern and western Cordillera ranges (Figure 1.1.1). The higher elevation eastern and lower western ranges bracket lower intermontane uplands that drain mostly into the Amazon except in the far-south altiplano region and the central Peruvian Huallaga Valley/Santa Valley drainage outlet to the Pacific. Andean mountain ranges largely determine the climate, with rainfall in the eastern Cordillera Blanca coming from the Atlantic and in the western Cordillera from the Pacific. Fronting the Amazon Basin, the high eastern Andean escarpment receives abundant precipitation, creating a rain shadow to the west. The eastern escarpment flanks are exceptionally steep and therefore difficult to farm and because the eastern watershed reaches deep into the intermontane sierra, it receives and discharges approximately 90% of all moisture into the range. Sierra basins have relatively modest slopes amenable to rainfall and runoff farming. Cultivation, in conjunction with high-altitude grasslands that sustained agropastoralism, was the basis for large sierra populations in pre-Columbian times.

Biodiversity is limited in the arid Pacific watershed because this area receives and discharges only 10% of Amazonian-sourced rainfall, which supplies 60 short rivers that descend the western escarpment along steep parallel courses (Figure 1.1.1) to supply water for valley irrigation systems. Although most rivers carry water only part of the year, canal irrigation is extensive in coastal valleys where fertile flat land is abundant. Whereas rainfall farming is possible at high elevations, below 2,500 m the sierra is arid and below 1,000 m the coast is desert from northern Peru into northern Chile. Seasonal runoff valleys have more abundant water supplies than southern valleys because of a latitudinal rainfall gradient. To the south the eastern and western ranges, and the sierra uplands become progressively higher, wider, and dryer, culminating in a high-altitude (*c.* 4,000 m), 800-km long land-locked altiplano basin. Lake Titicaca occupies the northern end of the altiplano where heavy seasonal rains and abundant land support large agro-pastoral populations compared to the southern reaches of the altiplano extending into Chile, which are characterized by extremely dry desert areas that support small populations. The agricultural diversity of highland agriculture is generally limited on the basis of use of low-temperature-resistant, high-moisture-tolerant crop types. Coastal agriculture permits more diverse crop types due to fertile valley alluvial soils and smaller diurnal and seasonal temperature variations but is limited by annual/seasonal water supply variations and dispersed, limited field system land areas, which require long transport and distribution irrigation canals.

Rainfall and climate events: El Niño and La Niña

Associated with El Niño events are torrential rainfall and runoff affecting Peru's coastal irrigation systems. Beyond destructive effects on land, there are coupled effects that affect the marine resource base of coastal societies. Ocean microplants and phytoplankton form the basis of the oceanic food chain and are successively consumed by zooplankton and higher marine life forms to create the base of marine resources available to coastal populations. The phytoplankton account for half of earth's CO_2 absorption and thus climate effects that affect their ocean concentrations have new importance in global warming and greenhouse gas considerations in 21st century ecology. In terms of phytoplankton concentrations, recent research reporting (Ocean News 2005) has provided new links between El Niño and La Niña events and phytoplankton concentrations that affect the availability of marine resources to human populations. During an El Niño year, warm waters spread out over the western Pacific and upwelling subsides in eastern Pacific waters close to coastal margins. This effect causes a decline in upwelling from deep, cold waters that carry nutrients to surface waters vital for phytoplankton life. The El Niño effect results in low phytoplankton concentrations which, through the food chain, ultimately lower fish populations in surface waters. Coastal fish species in waters at their livability temperature range have been observed to migrate to northern zones and thus reduce the traditional marine resource base available to coastal populations. During La Niña events, which frequently follow El Niño events, opposite effects occur and easterly trade winds increase, causing upwelling to intensify with the ultimate effect of enriching the marine resource base. The upwelling brings dissolved iron, an important micro-nutrient for phytoplankton, to the surface, enhancing population growth. Since El Niño events depopulate fish resources in coastal zones, when La Niña events occur, the depleted fish and avian populations are not present in sufficient numbers to mitigate phytoplankton growth and thus 'blooms' occur where phytoplankton growth expands over large regions of equatorial waters. Thus, negative effects on coastal populations are not only from the torrential El Niño rains that damage irrigation systems, but also from a reduction in the available marine resources that contribute to a coastal population's food resource base. Since El Niño cycles usually last for a few years, stress on coastal populations is a regular, almost predictable, event (perhaps with a 25-year cycle for mega El Niños) and manifests itself through numerous types of defensive hydrological control systems vital to sustain agricultural production.

Climate, natural disasters and agricultural implications

Agricultural sustainability strategies depend not only on lessons learned from past climate effects on field system performance but also on additional factors. During the last decade, studies that produced proxy records of past conditions have greatly expanded the roster of natural hazards and disasters known to have affected Andean populations and their agrarian habitat. Geophysical effects affecting the agricultural landscape include volcanic eruptions, earthquake-induced landslides, uplift, subsidence, and tectonic creep resulting in land surface changes. Long, low-slope canals are particularly affected by ground slope changes that alter water delivery flow rate and thus reduce the productivity of field systems. Negative hydrological processes involve water table subsidence and river downcutting, leading to dysfunctional field systems as canal inlets become stranded. Climatic perturbations are known to cause shifts in temperature at high altitudes and be the primary cause for the protracted heavy rainfall or long-term drought observed in the archaeological record.

In the central Andes collateral natural disasters often follow from primal causes. Historically, large magnitude earthquakes occur on average every 3 years (Keefer 1994). The earthquakes that strike the Cordillera produce billions of cubic metres of landslide debris and loose material, and along the arid Pacific watershed voluminous earthquake-induced debris can lie in loose repose for years due to the normal lack of rainfall at elevations below about 2,500 m. This source of sedimentary material is entrained by runoff from strong El Niño rainfall events and can exacerbate the erosion and deposition impact of the event on valley landscapes. Strong El Niño events have occurred two or three times per century (Quinn *et al.* 1987), causing loosely consolidated debris to be swept off the landscape and disgorged into the sea to be reworked by currents to form beach ridges (Figure 1.5.14); in the presence of coastal uplift and/or aggradational sediment deposits, a series of stranded beach ridges tracks successive large El Niño events (see Figure 1.5.10).

A classic sequence of beach ridges north of the mouth of the Santa River well illustrates this phenomena in addition to numerous coastline beach ridges in north central Peruvian coastal areas. Strong on-shore winds move the newly deposited sediment and, together with aggraded sand seas, source the inland dunes and sand migrations that inundate cultural landscapes (Moseley *et al.* 1992; Sandweiss *et al.* 2009). The totality of aggradational and deflationary soil movement effects on cultural landscapes, valley topography and agricultural systems have left their mark in the archaeological record. Those societies, which are capable of defence against natural disasters and their secondary consequences through innovative modifications to preserve their agricultural systems, then preserve the story of their struggle in the archaeological remains.

Drought events

The south Andean Quelccaya ice cores (Thompson *et al.* 1985a,b, 1986, 1994), the north Andean Huarascaran Mountain (Thompson *et al.* 1995b) and Lake Titicaca sediment cores (Abbott *et al.* 1997; Binford *et al.* 1997; Ortloff and Kolata 1993; Selzer 1991) indicate dramatic climate shifts. These references show time histories of Quelccaya ice core wet/dry periods and dust maximums (Figure 1.1.24), Huarascaran dust concentration events, and Lake Titicaca wet/dry period limnological data. Ice cores extracted from the Quelccaya glacial cap in the central Andes provide a 1,500-year proxy record of past climatic conditions, and initial analysis documented a marked 25–30% precipitation decrease between 562 and 594 CE, notable for its rapid onset and exceptional severity (Schaaf 1988; Shimada *et al.* 1991). Analysis of ice cores revealed a protracted pan-Andean precipitation downturn between 1100 and 1500 CE, which averaged 5–10% below normal yearly rainfall from prior norms (Ortloff and Kolata 1993; Thompson *et al.* 1986) with notable effects on north coast Sicán, Chimú, and highland Tiwanaku societies. With the 1500 CE onset of the Little Ice Age in the Andes, rainfall gradually rose above normal by 20 to 25% before returning to long-term averages around 1700 CE. Limnological cores from Lake Titicaca have provided a 3,500-year record of lake-level variation induced by precipitation variation. These cores show early Holocene aridity, mid-Holocene lake filling around 1500 BCE, followed by drought-induced lake-level low stands at about 900–800 BCE and 400–200 BCE, as well as 0–300 CE and 1100–1450 CE (Abbott *et al.* 1997; Binford *et al.* 1997). Huarascaran ice cores show a glacial record of past climatic conditions that extend back to late Pleistocene times (Thompson *et al.* 1995) and some evidence of the drought towards 1100 CE is evidenced by dust maximums and unusual temperature excursions.

To overlay cultural change observations onto the Andean archaeological record, the Uhle–Rowe chronological sequence is summarized; aspects of this sequence have been mentioned in earlier sections primarily as a means of providing convenient names for periods characterized by various cultural shifts. The sequence begins with Preceramic and Formative Periods (*c.* 3000–1800 BCE), the Initial Period (1800–900 BCE), the EH Period (900–200 BCE), the EIP (200 BCE to 600 CE) and the MH Period (600–1000 CE). This last period, in turn, is followed by the LIP (1000–1476 CE) and then by the Late Horizon Period (LH, 1476–1534 CE) conquest of western South America by the Inka. While this classification system aids in bookkeeping events and tracking societal changes at different times in different areas of Peru, and generally categorizes periods either dominated by a single society (Horizons) or formation of different independent societies in localized areas (Intermediate Periods), it does not traditionally have any coupling to other than historical events. From Figure 1.1.24, early phases of EIP climate apparently provided adequate water resources for growth and development of canal irrigation-based agriculture of the north coast Gallinazo and Moche polities as well as the south coast Nazca and central coast Lima polities. The central highland societies of the Huarpa, the north central Recuay, the southern highland Wari, and the early-phase altiplano Tiwanaku flourished during this period, reinforcing the conclusion that water supplies from rainfall and runoff were adequate for both coastal and highland zones, although agricultural techniques varied greatly in the different locales. Towards the end of the EIP, a pan-Andean dry period apparently played a role in the decline of the Moche capital in the Moche Valley at *c.* 635–660 CE as well as the decline of north central highland Recuay, central highland Huarpa, central coast Lima, and far south coast Nazca and (Moquegua Valley) Huaricani societies. The MH saw a dramatic rise in influence and expansion of the highland Tiwanaku (and its Moquegua Valley colonies) and Wari states with highland-adapted agricultural strategies and plentiful water supplies. This is in contrast to the decline in productive land area of irrigation agriculture-based coastal states towards the end of the MH (for the reasons described in section 1.2), and expansion and colonization by highland states into coastal and adjacent highland regions (e.g. Tiwanaku colonies in the Moquegua Valley and southern valleys to the Argentine border and Wari influence on central, southern, and northern highland regions with sites at Cerro Baúl in the Moquegua Valley and Pikillacta, Conchopata, Azángaro, Viracochapampa, and Ayacucho in the central highlands, among others). Into the early part of the LIP, coastal societies, notably the Chimú and far north coast Sicán, began their ascendancy in an environment where land and water resources were adequate for expansion of field systems; this was mirrored by a continued expansion of sierra populations and agriculture until *c.* 1100 CE when a pan-Andean drought played a role in dissembling the Tiwanaku society (and its colonies), the Wari (and its colonies), as well as coastal societies. At 1300 CE (Stanish 1993; Owen 1993b) highland Moquegua Valley societies were characterized by fortified hilltop settlements and canal irrigated terrace systems (Ribeiro 1996; Conrad and Webster 1989) made possible from snowmelt runoff, rainfall, and high-elevation springs. Tiwanaku society was largely superseded by Aymara kingdoms in altiplano regions (Moseley 1992) and the Chirabaya society on the southern coast and other small regional coastal societies such as the Chancay and Ica. Thus water for agriculture provided one vector directing population and settlement patterns towards water-rich sierra environments, as evidenced by the expansion of highland terrace agriculture after 1100 CE observed by Lathrap (1970). Towards the end of the MH the decline of Tiwanaku and Wari states in the time period 1100–1200 CE may be ascribed, in part, to the effects of the prolonged drought previously commented on in earlier chapters. Significantly, the Titicaca lake cores, Quelccaya ice cores, and Huascaran dust maximums are concordant in their documentation of a decline in rainfall levels from previous averages starting around 1100 CE and indicate its long duration. The decrease in rainfall levels was gradual but the relentless, cumulative effect over many decades slowly began to alter the hydrological picture to deepen the effects of drought. The decline in precipitation appears to be the Andean expression of worldwide perturbations in rainfall and temperature known as the Medieval Warm Period in the time period from *c.* 1000 to 1400 CE. While certainly religious, political, and social upheaval characterized this collapse, it remains undecided if drought was a primary factor exacerbating conflict between different social, political, and economic classes or if longer-term problems already existed between societal elements that were amplified by dwindling food supplies. Some conflicting theories exist in this regard but rely mostly on different interpretations of circumstantial evidence.

In the LIP, Chimú, Chancay, and Ica-Chincha coastal societies sustained their agricultural base by efficient use of limited irrigation water supplies and dependence on marine resources while late kingdoms in the Altiplano (Lupaqa, Colla, and minor local groups) arose in organization concurrent with the fragmentation of the dominant Tiwanaku state. Towards the middle of the LIP, a decline in agricultural productivity in the Chimú and Moche Valley Three Pampa region is associated with sierra rainfall decline as evidenced by sequential canal cross-section area decreases and flow rates, as outlined in section 1.1. Here the ability of the Chimú to modify their agricultural systems and canals to accommodate lower water supplies, as well as population dispersal, provided sustainability in this time period. Highland societies (Wanka, Chanca, and early Cuzco) arose in this period but were of lesser regional influence compared to the north coast Chimú State, which had expanded from its base in the Moche Valley to include most north coast valleys (conquest of late Sicán society in the Lambeyeque Valley by the Chimú was completed by 1375 CE) and several valleys to the south. A shift to a wetter period towards the start of the LH (Figure 1.1.24) was followed by military and political dominance by the highland Inka state over coastal, highland, and altiplano regions extending from present-day Ecuador to mid-Chile. From this record, it is clear that finite lifetimes characterized different societies in different areas subject to specific ecological environments that responded differently to climate variations. In sections that follow, the idea of agricultural sustainability under various forms of duress as a prerequisite for a societal continuity is examined; without this element in place, probably little else matters.

The long inception and duration of the dry period starting after *c.* 1100 CE allowed coping strategies to develop over many centuries. Consequently, drought-defensive responses elicited from the archaeological record can be viewed as a measure of a society's potential for technical innovation in reconfiguring agrosystems towards greater sustainability. Clearly, rainfall farming is more efficient than canalized runoff farming (per unit water input) because surface runoff is lost to evaporation and seepage over distance by rivers and canals. As an example, in the arid sierra at elevations around 2,250 m, the Rio Moquegua flow forfeiture to these factors reaches 4% per kilometre (Williams 1997) for unlined canals (elsewhere loss rates for other systems rely on canal lining types used by different societies). Consequently, mountain runoff is greatly diminished by the time it reaches the lower coastal valleys. Coastal irrigation agriculture is therefore vulnerable and drought always has a more severe effect at coastal desert zones than in mountain headwater zones, based on water amounts available for agriculture. The potential of runoff farming, however, is far greater than that of rainfall farming because systematic irrigation produces far higher yields on average. There is therefore substantial investment in irrigation reclamation during protracted episodes of normal or above-normal rainfall when runoff is average or abundant. However, growth is not sustainable when long-term rainfall rates decline in the order of 5% or more from prior average values because runoff drops in a disproportionate manner. Consequently, over the millennia irrigation agriculture and its dependent populations have repeatedly expanded outward over arid landscapes in wet periods and then defensively reconfigured in concordance with long-term fluctuations in rainfall and runoff. This process is reflected in the ruins of vast agrarian works that blanket the Andean landscape and encode not only expansion during times of plentiful water but also contraction and system modifications during extended drought periods.

Adaption to protracted drought

The recurrence of protracted drought periods raises the probability that indigenous populations reacted to episodic dry periods in patterned ways based on prior experience and that some responses may be predictable. A very high degree of subsistence mobility characterized highland agropastoral adaptations because they are based on the exploitation of multiple, dispersed ecological zones stratified by altitude (Murra 1962, 1970, 1975). Annual hazards associated with short growing seasons and poorly developed mountain soils include erosion, erratic precipitation, temperatures below freezing, frost, and hail. Mediation requires rapid transmission of information so that agropastoral activities can be reprogrammed at short notice (Earls 1996). It also requires preserving, storing, and stockpiling of food reserves because poor harvests are frequent (Orlove and Guillet 1985). As a result, drought exacerbates many conditions that underlie human adaptations in the central Andes.

As an example of the organized drought response of an Andean society, the LH Inka provided many insights as to their procedures and strategies. As many cultural and political traits exhibited by the Inka were adaptions and borrowings from successful procedures of past societies, examination of Inka methodologies dealing with drought mirrors the methodologies of past societies and thus provides information about past procedures. Inka political formation was a slow process that began shortly after 1000 CE with the gradual consolidation of local ethnic groups (Bauer 1992). Thus, the nascent society grew principally during long time periods characterized by low average rainfall, primarily in the early LIP period. After conquest of neighbouring societies and consolidation into an empire by 1400 CE, the Inka had adapted corporate styles of art, architecture, and construction that commemorated many imperial policies on a monumental scale both in the capital region of Cuzco and in politically incorporated provinces. One policy employed corvée labour from dominated societies for large-scale agrarian reclamation of previously unfarmed or underutilized land. Initially much of the terrain was at high elevations and along the Andean eastern escarpment where terracing was required for reclamation in high-rainfall zones. This policy was an elaboration of drought response pursued at the folk level throughout the highlands. Later, as rainfall levels increased above normal in the post-1400 CE environment, corvée labour was used to reopen farming in lower, warmer elevations where conquered communities were often resettled. Certain Inka corvée policies over time may therefore be intelligible as drought adaptations.

Inka concerns with storing and stockpiling are notable in the annals of ancient civilization (Levine 1992; Bauer 1992). The monumental construction and prominent display of warehouses was equally distinctive and these masonry structures frequently surpassed the quality of more common houses. Erected in rows, hundreds, and in some cases thousands, of storage structures were strategically positioned on high hills. Although the stores were generally used for state purposes, they were also used to mitigate food shortages among the common populace (Rowe 1946). In contrast, the coastal Chimú society responded to low rainfall periods by contracting their intravalley agricultural base commensurate with lowering water supplies but also seeking new water supplies through expansion into valleys with greater river flow rates and land areas together with initiation of a large-scale intervalley canal to revitalize the Moche Valley canal systems. While canals were infilled to smaller channels during drought (section 1.1), no evidence of the reverse process is evident as LH water supplies increased because Inka policy forbade resurrection of the Chimú state. It appears that some shift from the Moche Valley centre occurred through Chimú conquest to incorporate larger northern valleys (Jequetepeque and Lambeyeque Valleys in particular) with higher flow rate rivers less subject to intermittency. This too is a coping strategy for agricultural survival as the agricultural potential of the larger northern valleys utilizing Chimú hydraulic technology far exceeded that possible in the Moche Valley. Elsewhere, Wari and Tiwanaku colonies in different ecological niches at different locations provided a diversification of agricultural systems that had different responses to drought due to different water supply conditions. This diversification provided some protection against the vulnerabilities associated with reliance on one fixed system as a drought response.

Highland agricultural stress and response

Recent work has postulated that the long-term drought initializing at *c.* 1100 CE played a role in the collapse of the Tiwanaku polity centred towards the southern edge of Lake Titicaca (Ortloff and Kolata 1993; Kolata and Ortloff 1997; Binford *et al.* 1998). This is premised on the fact that the agricultural base of Tiwanaku was anchored in raised field farming in extensive low-lying areas along lake margins. As high lake and runoff levels declined after 1100 CE, subsiding spring flows and the declining water table desiccated raised field systems and their thermal storage properties to protect crops from freezing temperatures. By the time the lake fell to its −12 m low stand as the cumulative effect of many years of below average rainfall amounts, more than 50,000 hectares of raised fields were abandoned and the urban core of Tiwanaku depopulated and dispersed around the lake in smaller rural settlements (Albarracin-Jordan and Mathews 1990; Janusek 2004) close to available water supplies. While creation of small sunken gardens (cochas) as a drought response was tenable in limited regions of the Titicaca Basin where ground water was not far below the ground surface, this was not an option in most sierra basins with steep drainages. Along the western Andean escarpment there were few means to compensate food loss in the dry sierra below 2,000 m. Here slopes are steep, ground water is deep, and natural vegetation is sparse. In this region of the Moquegua Basin, irrigation and its dependent populations declined significantly during the 1100–1400 CE dry period.

Unlike coastal valleys, where farming shifted to low elevations in pursuit of subsurface water in mahamaes and wachaques (Rowe 1969), and experienced arable land loss due to downstream migration of river canal inlets because of tectonically induced river downcutting, sierra farming shifted to higher elevations in pursuit of higher rainfall rates and water supplying the moist pasture lands that existed at high altitudes. There were many constraints on the uphill pursuit of scarce rainfall and soil moisture: progressively fewer types of crops grow at successively higher altitudes, very few domesticates are productive near the highest elevation limits of farming, and the frequency of freezing temperature, frost, hail, and erosion increases with elevation as soil quality decreases. By *c.* 1300 CE, colder, dryer climatic conditions forced a 70-m downward shift in the altitude distribution of natural vegetation zones relative to today's levels (Seltzer and Hastorf 1990; Hastorf 1993). Thus, as highland people moved agriculture and pastoralism into higher, wetter altitudes, the elevations at which plants, pasture, and crops could grow diminished. As vast areas of marginally arable mountain land exist at high elevations, drought-response farming moved from low to steep inclines. To reclaim upland mountain slopes, the construction of agricultural terraces over many generations occurred and was essential to control the loss of poorly developed mountain soils. Along the Pacific watershed and sierra zones, terracing was combined with canal irrigation to capture high-elevation runoff streams. In addition to moving farming higher, terracing was widely used to move farming eastward into the Atlantic watershed. Even during drought, this region was relatively better watered than the rest of the central Cordillera. Hence terracing allowed farming to expand into less extreme elevations where more types of crops can grow.

Over the course of many drought-influenced centuries in the latter part of the LIP, millions of terraces were built to reclaim vast areas of the Andean uplands in the eastern escarpment. Whereas agrarian productivity and populations declined along the lower Pacific watershed by perhaps 30% or more, the drop in rainfall was a major catalyst for economic and demographic radiation into the upper and eastern highlands. By about 1500 CE, large populations resided at high altitudes and along the eastern Andean slopes. As opposed to high altitudes, many more crops can grow at moderate altitudes where weather extremes are less severe. As normal sierra runoff farming produces higher yields than sierra rainfall farming, and as drought mitigated and rainfall increased in the post-1400 CE environment, farmers reverted back to lower, warmer settings more conducive to plant growth. To augment agrarian tax and tribute revenues, the Inka often forcibly resettled conquered high-altitude communities on lower terrain made more productive by increased rainfall, soil moisture, and runoff (Hastorf 1993).

Although post-LH precipitation rose above long-term normal levels, demographic decimation in the wake of European pandemics left Spanish overlords with few people to farm large expanses of arable land. Because above-normal rainfall and runoff persisted until about 1700 CE, remnants of the indigenous population were forcibly relocated to still lower farming elevations and collected into towns (señorios) for taxation and census purposes—an idea previously exploited by Inka overlords in the LH period. This facilitated political control, demographic apportioning, and religious conversion and imposed cultivation of Old World cultigens intolerant of extreme altitudes. If the drought had not broken, neither Inka nor Castillean resettlement policies would have been tenable. Thus, during the last millennium, farming, and the millions it supported, had shifted over the elevated slopes of the Andean range in accordance with long-term climate-induced changes in rainfall and runoff, all within the political boundaries of the relevant societies. The prominence of the societies occupying these ecological niches at various times is therefore tied to their history.

Regional adaptive agricultural strategies

Since climate and weather variations played a role in determining the agricultural strategies of differently located societies in ancient Peru and Bolivia, it is of interest to track the adaptive strategies of these societies to combat uncertainties in agricultural production. Of most interest are the adaptive strategies for excessive rainfall and drought over different time periods. Such strategies arise from the application of technology to defend/enhance agricultural production in the face of climatic stress. The defence strategies are specific to different geographic sectors and cultural periods, and represent active, integrated programmes to protect large investments in agricultural fields and water supply systems. Figure 1.7.1 shows many of the strategies employed in different areas of ancient South America and divides these strategies into systems (vertical axis) supplied by natural water sources (rainfall and springs for canal irrigation systems), subsurface systems (groundwater supplied), and modified water sources (groundwater collection systems typical of the Nazca galleries) and, on the horizontal axis, artificial and natural farming surfaces. For each of these major systems, defensive strategies to protect from excessive rainfall and drought are found in the archaeological record and indicate that farming was truly a science practised with considerable forethought to maintain productivity despite the many variations in climate and weather that influenced agricultural output.

While modern systems can draw produce from different worldwide climate zones throughout the year and have vast redundancy of crop types in different locations to maintain steady supplies, ancient systems possessed none of these features and had extreme vulnerability to climate- and weather-induced collapse of their systems. On this basis, the defensive measures listed in Table 1.7.1 give indication as to the concern of ancient societies to protect their agricultural systems to the degree their technology and innovative resources permitted. The catalogue of defensive measures listed gives direct evidence of memory and response to past catastrophic events and constitutes evidence of the importance of such events in shaping the technological

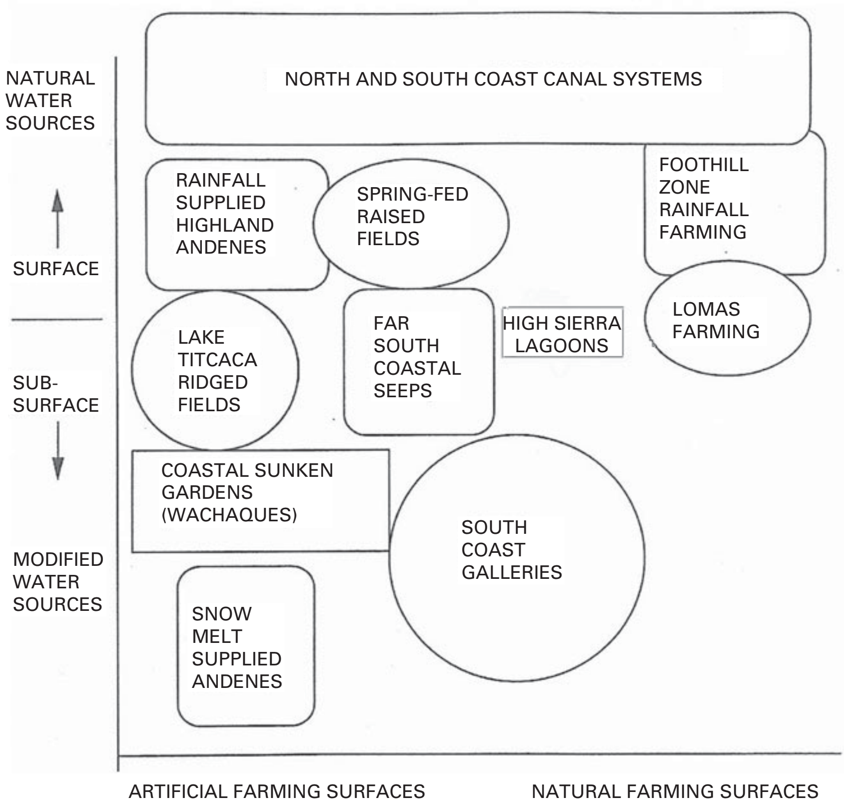

Figure 1.7.1. Agricultural strategies in ancient Peru and Bolivia indicating the library of agricultural techniques for different ecological conditions in different geographical areas.

response pattern to protect agricultural field systems and vital canal and aqueduct systems against excessive rainfall and drought in different areas for different societies. The summary of active defences against climate/weather destruction of agricultural systems for different societies in different ecological zones then points to their concern and ability to invoke technical measures to maintain sustainability of their systems.

In Table 1.7.1 the + Rainfall notation denotes the defence strategies exercised in excessive rainfall periods to protect vital agricultural systems and the – Drought notation represents drought defence strategies and innovations. Table 1.7.1 is divided into north sierra and southern altiplano regions, and the north and south coast valleys in different time periods from the EH to the LH. The numbers in Table 1.7.1 refer to the numbered list below.

Table 1.7.1. Regional and adaptive agroengineering defensive strategies

	EH (and Preceramic, Formative)	EIP	MH	LIP	LH
North sierra					
+ Rainfall					
Drought					
Southern altiplano					
+ Rainfall			2, 5, 6, 12, 14	6, 14	6
Drought			3, 4, 5, 6, 7, 8, 12, 13, 14, 19, 20	4, 6, 7, 8, 14, 16, 19, 20	6, 7, 14
North coast					
+ Rainfall	2(?), 21	1, 2(?)		1, 5, 15, 16	
Drought	4, 6, 9, 7, 11, 17, 18, 21	4, 9, 17, 18, 21(?)	4, 21(?)	1, 3, 4, 7, 10, 18, 21(?)	
South coast valleys					
+ Rainfall					
Drought		9, 10, 18	7, 9, 10, 18	7, 10, 18	10

— denotes lack of available information.

1) Canal flow rate controls and use of intervalley canals as drought remediation measures

Examples include adjustable inlet blockages at river intakes to regulate canal intake flows and canal overflow weirs releasing water from canals when El Niño flow rates exceed canal design capacity, i.e. excessive rainfall-induced canal flows activate chokes causing side overfall weirs to activate to release excess flows from canals. Examples are present in the Chimú Chicama–Moche Intervalley and Farfán–Pacatnamú canal systems (Ortloff *et al.* 1982, 1988, 1995, 1997a,b; sections 1.2 and 1.3). Mega-canal systems (for example the Chicama–Moche Intervalley Canal) represent a drought remediation measure to redirect water from a valley with a large river to an adjacent valley of political importance to restimulate canal-supplied agriculture. Elsewhere the Lambeyeque–Supe–Leche Intervalley Canal and the Lima Intervalley Canal Complex (Kosok 1953) provide extension of canals and intervalley river diversion to include more arable land area and may have a subsidiary function to redirect water to upvalley fields to limit seepage and evaporation effects as a water conservation measure.

2) Flood diversion channels

These are used mainly in the Tiwanaku and Lukurmata areas to intercept and shunt excessive rainfall runoff from hill slopes directly into Lake Titicaca by large, flood-activated canal systems (Ortloff and Kolata 1988; Ortloff 1997b;

Kolata and Ortloff 1997) that modulate ground water level with respect to planting surfaces (section 1.2). Tiwanaku drainage canals with outlet weirs direct floodwater above a given height into drainage channels leading into Lake Titicaca are further examples. There are applications of flood diversion channels to Moquegua Valley mountain region terraces (in the Wari and Tiwanaku colonies) to divert excessive rainfall runoff in terrace supply canals into downhill spillage channels draining into valley quebradas (section 1.4) to serve drainage considerations. Possible use of the EIP great trenches is observed in the Moche and Jequetepeque Valleys for flood water diversion (section 1.1).

3) Ground water recharging

North coast Chimú mahamaes (sunken gardens) and Chan Chan wells (Moseley and Deeds 1982) activated by canal water seepage from field systems (Chapters 1.1 and 1.6) are examples of recharge technology; Tiwanaku and Pampa Koani use of spring-fed canals to deliver water to local raised field water troughs to alter local water table height and nutrient chemical composition (Ortloff 1997b) are further examples.

4) Sunken gardens and wells, pukio (spring) systems

Examples of Sunken gardens include the north coast Chimú and earlier north and south coast societies' use of excavated pits dug to groundwater level (mahamaes) and pits excavated close to springs (wachaques) for agriculture in low river runoff and drought periods (Moseley and Deeds 1982); sunken garden systems (cochas) in late to post-Tiwanaku times (Ortloff 1997b; sections 1.1 and 1.6) in the Pampa Koani area to support agriculture are examples. Use of wells interior to Chan Chan (Figure 1.1.28) whose depth could be lowered to intercept a declining water table in drought periods serves as drought defensive measures. The use of canalized, pukio-supplied agriculture at Caral in the Preceramic Period that provided water to field systems throughout the year to overcome limited drought periods (Figures 1.5.3 and 1.5.4) is a further example.

5) Runoff interception and river canal shunts

An example of these techniques can be seen in the collection and channelling of rainfall runoff flows through channels directly to Lake Titicaca to limit seepage flow into groundwater and regulate local groundwater height in raised field systems. Another example are the canals used to drain excess groundwater into depressed channels to limit water height in swales to regulate moisture available to raised field plots in Tiwanaku and Pampa Koani raised field systems (Ortloff 1997b; Kolata and Ortloff 1997). Chimú use of interception trenches uphill of canal systems near Farfán (Jequetepeque Valley) to intercept rainfall runoff from mountainous terrain (Ortloff 1997a) for diversion into quebradas to limit inflow damage to major canals is a feature of Chimú defensive water control measures.

6) Terrace agriculture

Examples are post-Tiwanaku V, highland Wari, and Inka societies' use of terraced planting surfaces where agricultural zones can be moved to higher elevations to intercept higher rainfall amounts during drought periods. Use of high-altitude canals from mountain snowmelt and rainfall zones to provide irrigation water to terraces during drought periods by Tiwanaku, Wari, and Inka in the MH and LH periods are examples of drought-defensive measures. For situations where raised fields are flooded by high Lake Titicaca water levels, use of terrace systems provided an alternative to continue agricultural production. Use of multiterraced river bottomland and upper plateau canal-supplied field systems in the Caral area (Chapter 1.5) provided a defensive strategy to bottom land erosion during flood events.

7) Specialty sunken gardens

These are used, for example, by late and post-Tiwanaku V altiplano cultures to supplement pasturalism-derived food supplies; basin pits (cochas) located near streams or away from the Lake Titicaca margins where the water table remained high through dry periods from incoming groundwater from vast watershed areas. The use by the Inka to create terraced excavated pits providing a controlled environment for speciality agricultural products (at Moray) requiring temperature and humidity control (probably for growing coca varieties) is a unique example of Inka agricultural technology. Mahameas and wachaques provided exploitation of local water sources largely impervious to drought conditions. Note that a time delay exists in water supply to these systems compared to immediate river runoff sources to promote multi-cropping.

8) Agricultural reserve land and field system alternative use strategy

Examples of this include Lateral Lake Titicaca raised field agricultural zone shifts to areas with a high water table as subsurface groundwater profiles and soil moisture levels vary spatially and temporally from subsiding/increasing lake and rainfall levels. This method was applied to field systems on Pampa Koani (Ortloff 1997b) and Pajchiri. Agricultural field area shifting also allows fallowing of different field areas to increase later productivity.

9) Groundwater collection into subsurface transport channels to field systems

Underground galleries penetrating the water table collect seepage water and channel it to surface fields (south coast Nazca V galleries (probably built between early and late Nazca phases of the EIP, *c.* 500–600 CE; Schreiber and Rojas 1995, 2003)). Use of canalized groundwater pools and springs for water supplies to field systems in the Supe Valley in Preceramic times (*c.* 2800 BCE) was shown to be effective in mitigating short-term drought conditions as the water table had little variation throughout the year.

10) Canal and river water/groundwater seepage utilization

An example of this is north coast Chimú utilization of irrigation canal water seepage to recharge interior Chan Chan wells (Moseley and Deeds 1982). Moquegua Valley Chirabaya coastal groundwater seep agriculture (Clement and Moseley 1991) in the Ilo area of southern Peru based on collection of deep groundwater on cliff face troughs with leadoff canal water distribution to adjacent field plots is a further example. This system provided agricultural continuity through drought periods as the water table had a low drought subsidence rate. Also some limited raised field, north coast valley-mouth agriculture at Casma, Virú, and Moche Valleys to intersect the water table near the coastline utilized groundwater seepage for opportunistic agriculture.

11) High sierra reservoir or lagoon water storage/canal delivery to coastal valleys

An example of this is the high-altitude (>2,000 m) Cordillera Negra mountain lagoons interconnected with canals to deliver water to highland valley and terrace agricultural systems, and used to augment groundwater in coastal valleys by transfer through fault zones and/or bedrock-limited, shallow soil layers (Avila 1986). The 50-km Huiru Catac Canal (possibly of Inka construction) irrigating the Jimbe, Moro, and San Jacinto upland areas, and the upper Nepeña Valley are examples. The probable water source to the Supe Valley through geological faults transferring infiltrated sierra runoff water to coastal valley areas to create the high water table prevalent throughout the year that underwrote sustained canal agriculture for Caral and other Supe Valley sites are examples of sierra water delivery systems.

12) Canal water collection and diversion of runoff to modify ground water profiles

Tiwanaku Pampa Koani agricultural systems on the Taraco Peninsula (Ortloff 1997b; section 1.2) exemplify this procedure, which is used to regulate water table height for different crop types. Use of Pajchiri multiple canal systems to regulate the water table height for different crop types in different parts of the field system are further examples.

13) Snowmelt water collection channels directed to mountainside terraces

Examples are upper highland Moquegua Valley drainages in late and post-Tiwanaku V times as well as Estuquiña and Wari terraces that utilized snowmelt water supplies channelled to agricultural terraces are examples. This technique was used in elevated (or lowered) temperature periods associated with dry (or wet periods) as a water source for terraces; in either case, inlets were relocated accordingly as snowmelt varies in altitude and with changed temperature.

14) Vertical and lateral agricultural zone strategy shifts

Relocation of valley surface agriculture by the Tiwanaku to terrace agriculture when Lake Titicaca height excursions completely covered raised fields is an example of this. Possible reuse of very early Tiwanaku terraces during Inka occupation times by relocated, conquered populations represents a strategy shift towards use of higher level agricultural systems. The presence of terraces and adjacent raised fields in areas in close proximity to Tiwanaku offered options for different agricultural strategies in the Pampa Koani area depending on the local water table height in swales. Shifting of Tiwanaku agricultural zones towards receding lake edge areas and areas distant from Lake Titicaca where the water table profile remained relatively unaffected by drought-induced declining lake height for long time periods are further examples.

15) Canal multi-valley transport/distribution canals

The Chicama–Moche Intervalley Canal, the Lambeyeque–Supe–Leche Canal, and the Lima complex (Chillon–Rimac–Lurin canals) (Kosok 1965; Ortloff *et al.* 1985) used as drought remediation measures by river water redistribution from large rivers to reactivate desiccated field systems in adjacent valleys with smaller flow rate rivers serve as examples of this type of Canal. Use of water for field systems along intervalley canal paths when water supplies were low in extended drought periods allowed the best use of land near water sources.

16) Canal hydraulic efficiency improvement features

Chimú hydraulic efficiency improvements in canal design by infilling and cross-section change (Figure 1.1.8), elevation change, slope and wall roughness change (section 1.1) to maximize canal flow rate in drought periods with limited water supplies are examples. Use of half-hexagon cross-section canal shapes for minimum flow resistance canal sections by the Chimú serve as a technology demonstration of a water transport efficiency increase. Exploitation of the relation between wall roughness, bed slope, and canal cross-section for sub- and supercritical flows to maintain canal *Fr* value around unity (section 1.1) for maximum transport rate in intervalley canals for a given elevation head and canal geometry (section 1.1) used as a drought amelioration measure to transfer water between valleys is a further example. Use of streamwise canal shape changes to regulate water height to activate drop structures to Pajchiri field systems by Tiwanaku agriculturalists (section 1.2) and use of shunt aqueducts by the Chimú to shorten canal flow paths interior to quebradas to limit seepage and evaporation effects are also examples.

17) Lomas farming

An example of this is the fog condensation water supply to lichen pastures in coastal areas. Fog condensation starts plant growth to begin the food chain, starting with snails and their predator species. These systems existing in early time periods to provide opportunistic agricultural and plant products (Lanning 1967) for early societies.

18) Adaptations towards a marine resource base

For drought-affected regions with access to marine resources, additional emphasis on exploiting marine resources provided food supply supplements. Several Preceramic societies were initially based on a marine resource base with simultaneous development of industrial crops to support a fishing economy with later development of extensive comestible agricultural products (for example the Aspero, Bandurria, and Supe Valley Preceramic sites).

19) Adaptations towards sierra pasturalism

As a drought response, a shift from agriculture towards herding at high-altitude locations served to supplement plant food supplies.

20) Raised fields

Examples are low vulnerability agricultural systems, which are largely resistant to short-term drought.

21) Adaptive canal inlet and lead-off designs

Canal inlets adaptive to river bed shifts from varying rainfall runoff and El Niño flooding, and easily constructed fill-terrace aqueducts positioned to intercept current river position to lead water to elevated farming plateaus are typical of canals found in the Supe Valley near Caral.

The adaptive strategies shown in Table 1.7.1 indicate conscious efforts to control water supplies by a variety of technologies specific to different geographical areas and choices of agricultural systems by different societies in different time periods. While most responses were related to observance of long-term climate trends, others provided defences for short-term El Niño-related flooding (see points 2, 5, 6, 14, 18, and 21 above) and defences against drought events (see points 1, 3, 4, 6–16, 18, and 19 above). Table 1.7.1 provides a library of agroengineering responses to long/short-term climate and weather variations over many time periods and demonstrates that climate and technology development were important factors in design, operation, and administrative planning to ensure longevity of agricultural fields.

Section 1.6 presented a macroeconomic model to evaluate hydraulic societies' understanding of the basic concepts that provided the means to analyse and optimize agricultural production. The concept of 'maximizing food production' by manipulating key variables provided the basis for the design and operation of these systems. Example cases were given to show adherence to the 'laws' that govern the behaviour of advanced hydraulic societies. While the 'laws' are fundamental to understanding canal and terrace agricultural system function, they may have served, in some quantitative sense, to provide a basis for administrative evaluation of their system's productivity and suggest ways to further modify systems towards optimum use. The fact that Chimú irrigation systems operated successfully for centuries, underwent expansion in multivalley complexes, and showed innovative modifications that reflected creative engineering practice under changing environmental conditions indicated that management expertise was present to control system performance. Success cannot be attributed to random and arbitrary strategy choices but rather to engineering expertise to guide decisions on canal placement, design, modification, and operation; similar conclusions may be drawn for highland agricultural systems with their long history of successful operation.

In the discussion that follows, an alternative view of principles that underwrote administration of a hydraulic society and guided its choices is presented. The key difference between this and the prior model is that this alternative model considers climate and weather variables in the evaluative and decision-making capability of administrative classes responsible for agricultural production and brings forward concepts relevant to their observation and judgement skills. While climate variables are emphasized in this new model, many of the agricultural strategies described in prior sections have as their basis remembrance of climate excursions occurring in past centuries that influenced modifications in later, subsequent agricultural strategies and systems design.

Modelling drought stress: highland/lowland runoff ratio (R)

Several considerations related to the effects of climate and weather variations on agriculture are next introduced. These considerations are well within the realm of observability of the administrative sector of a society and form a partial basis for decisions regarding the design, operation, and construction of an agricultural system. Drought depresses crop productivity and variability differently for rainfall and runoff farming. The main reason for the difference is that soils infiltrate rainfall and retain water within their porous structure until saturation is reached; past this level, runoff occurs. Channelled runoff is further subject to evaporation, seepage, and subsurface porous-medium water retention effects through a different set of non-linear relationships than the storage/saturation effect, resulting in imbalances in the rainfall/ runoff delivery rate.

The hydrological relationship between soil saturation and rainfall runoff can be illustrated by an example from the Rio Moquegua basin (Figure 1.1.1). Here the river system is 140 km in length with headwaters reaching above 5,100 m from sea level. Similar to other Pacific drainages, precipitation is negligible along the Moquegua coast, but in the interior it gradually increases with increasing altitude. However, the quantity of rainwater only exceeds retention values in the upper 19% of the basin above 3,900 m in elevation. Between 3,900 and 4,500 m, average rainfall is about 360 mm/year, of which 260 mm is absorbed at saturation and 100 mm is available as runoff (ONERN 1976). In this zone, a 10%, or 36 mm, decline in rainfall to 324 mm decreases runoff by 36% from 100 to 64 mm. Given a specific soil type with a given retention capability, a 15% decrease in rainfall results in a 54% decrease in runoff. In the elevation zone between 4,500 and 4,900 m, rainfall averages 480 mm/year and a 10 or 15% rainfall reduction results in runoff reductions of 21.8 and 32.7%, respectively. Thus the asymmetric disparity between rainfall and runoff diminishes as precipitation increases. Comprising less than 3% of the Moquegua basin, the zone of alpine tundra above 4,900 m is principally in the form of snow and ice (ONERN 1976). The runoff contribution is unknown because an indeterminate amount of this moisture is retained in glaciers and snowfields. Nonetheless, for the upper river basin, rainfall declines of 10 to 15% result in runoff reductions of 25–40% or more. Significantly, the asymmetric relationship between rainfall and runoff also works in reverse. Increased precipitation rapidly saturates the soil, which then releases water and amplifies runoff. This effect was prevalent in the first two centuries CE when precipitation rose by 20–25% and runoff by 72–90%; this effect was also evident (Figure 1.1.24) in early MH and LH times. In drought or dry periods, rains at high altitudes may sustain agriculture in these zones but coastal agriculture derived from river runoff from the same watershed will experience a severe deficit of irrigation water. For wet or heavy rainfall periods, highland agriculture has adequate water supplies and surplus runoff will be available for coastal valley irrigation agriculture. Thus coastal societies are more vulnerable to drought, particularly in dry periods, as their irrigation systems are fixed in coastal valley environments while highland agriculture has the option to shift agriculture to higher or lower zones to capture available rainfall for terrace systems. While highland agriculture can therefore shift vertically to optimize water resources, coastal agriculture can only shift laterally to other valleys if rivers with large flow rates and arable land area are available.

Drought stress is exacerbated by the fact that once rainfall saturates the soil and excess water is released, some surface runoff is lost to evaporation and seepage. As a result of these factors, the Rio Moquegua loses about 4% of its flow per kilometre in the arid sierra at elevations around 2,250 m. Other than spring floods, a river channel does not normally carry surface flow at elevations below 1,200 m as farming in the coastal section of the drainage depends on springs fed by subsurface groundwater flows originating high in the river basin. The relationship between highland rainfall and coastal spring flow is highly asymmetrical because of subsurface flows through porous strata with varied hydraulic conductivity and saturation values. Although these properties are poorly known, there are indirect implications that coastal spring flow may have dropped by 80% during the onset of the 1100 CE drought (Ortloff 1989). These results are approximations for the Rio Moquegua basin; other soil absorption and precipitation values characterize other drainages. Nonetheless, relationships between rainfall and runoff are always non-linear so that drought always exerts asymmetrically greater stress on runoff farming than rainfall farming.

The runoff not directly channelled into rivers is diminished en route to coastal zones by further infiltration into increasingly more porous soils (adding to the local water table) as well as by evaporation losses. Coastal river hydrographs track the availability of coastal irrigation water over time and details vary between coastal valleys as functions of soil geomorphy, topography, evapotranspiration, and temperature and humidity history. The net effect then is one of a non-linear, but generically similar, relationship between unit amounts of input rainwater at different altitudes and time, and net-deliverable runoff water to coastal irrigation systems over delayed time. In terms of quantifying this runoff effect, the runoff ratio (R) is defined as the ratio of the average net runoff rate from an area divided by the average rainfall delivery rate to the same area. Here $0 < R < 1$ where $R = 0$ denotes total absorption of rainfall with no runoff and $R = 1$ denotes all rainfall transformed to runoff due to rapid soil saturation.

Vulnerability index (1 *V*)

Figure 1.7.1 shows the main agricultural strategies practised by Andean civilizations. A vulnerability index is defined as a measure of the vulnerability of an agricultural system to continue to function under excessive rainfall and drought conditions. Systems that have a high survival probability have a high vulnerability index $(1 - V)$ or, equivalently, a low vulnerability, V. From Figure 1.7.2, raised field agriculture (methodology 1), is widely practised by MH Tiwanaku III–V around the southeastern periphery of Lake Titicaca. Tiwanaku groundwater-based agricultural systems are largely invulnerable to short-term drought due to the continuous arrival of subsurface water towards the lake from earlier rainfall events originating from the immense watershed collection zone around the lake. Since groundwater transport velocities are low, and depend on soil hydraulic conductivity and porosity, arrival of groundwater from distant collection basins may originate from infiltrated rains many years earlier. Groundwater systems are largely invulnerable to excessive rainfall events due to field system drainage canals shunting water into the lake, thus limiting infiltration into the water table (Table 1.7.1, points 2 and 5). The control of the water table and swale height is vital to maintain the integrity of the phreatic zone to support different crop types with required moisture levels. As collection basin rainfall rates and Lake Titicaca depth vary with seasonal and climate-related rainfall/runoff rates, the transient water table shape shifts under field systems so that productive

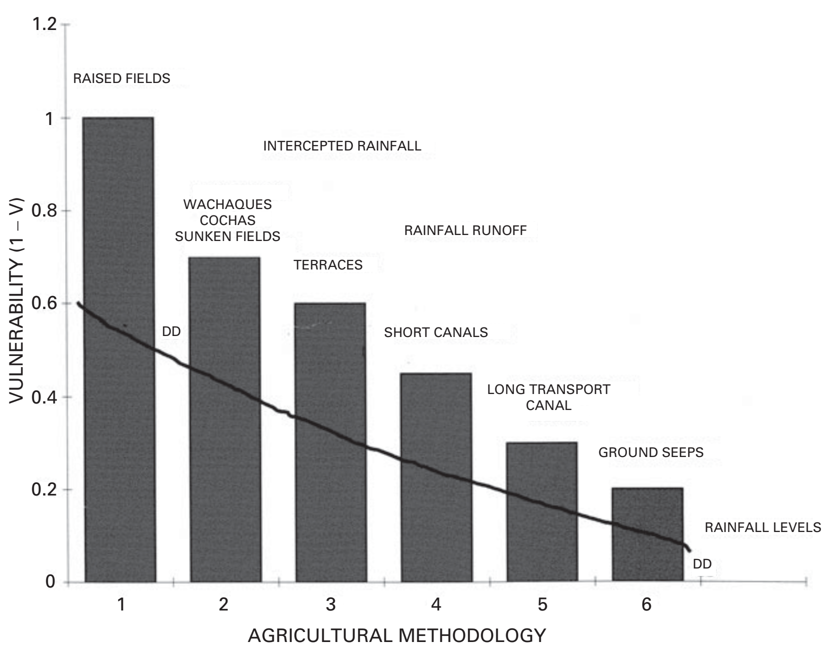

Figure 1.7.2. Vulnerability index (1 V) for different agricultural methodologies.

farming zones can likewise be shifted to follow local high water table areas (Table 1.7.1, point 14). This indicates that not all of the raised field area was farmed simultaneously but only zones supplied by spring water and locally elevated groundwater profiles. Only prolonged drought over many years could destroy the heat storage features that provided frost damage protection under diurnal and seasonal temperature variations (section 1.2) and decrease water table height to that necessary to sustain agriculture. The raised field systems can therefore be optimized to highland climatic cycles to produce high crop yields, as evidenced by modern resurrection and use of these same systems (Kolata 1996). On the basis of their defences against excessive rainfall and (short-term) drought, these systems have a high vulnerability index $(1-V)$. For raised field systems, $V=0$.

The next least-vulnerable agricultural system to rainfall variations is a variant on raised field systems: sunken gardens (mahamaes, wachaques, and cochas) (methodology 2). These systems are excavated pits to the phreatic zone of the water table or spring sources and are mostly found as a last-resort drought-response system (Table 1.7.1) when the water table has declined out of reach of root systems. Here $V=0.16$. As the water table declines, deeper excavation of planting surfaces is required to restore their function. While such systems are common in the 1100 CE post-collapse settlements around the city of Tiwanaku, similar wachaques and mahamaes are found in Peruvian north coastal valleys (Rowe 1944) in response to the pan-Andean LIP drought. While primarily a drought remediation system, these systems have no defence against excessive rainfall and groundwater level rise as no simple drainage paths exist.

The next level of vulnerability is found in terraces widely used by Inka, Wari, and post-Tiwanaku highland civilizations (methodology 3). These systems are mostly rainfall supplied and provide a well-drained agricultural system under rainy season cycles (Table 1.7.1, points 6 and 13). Here $V=0.33$. As rainfall diminishes, these systems generally become marginal for production as they depend mainly on rainfall unless supplied by channelled water supplies from snowmelt areas. As most terraces are found at higher elevations to exploit higher rainfall amounts with altitude, vulnerabilities related to cold, poor soils, and steep gradients limit the growing season and permit limited crop types.

Next in the order of vulnerability (methodology 4) is canal-fed irrigation as practised primarily by north and south coast civilizations. Such systems are only viable in the presence of highland rainfall exceeding saturation conditions. Here $0.83 < V < 0.66$. As such, if coastal agriculture flourishes, then highland agriculture most certainly has excess water supply due to the non-linear input/delivery (R) relationship. Highland agrosystems therefore demonstrate less vulnerability to reduced rainfall provided the technology to use available water is adequately developed and drainage technology to control runoff and water table height is in place.

Generally, long canals ($V = 0.83$) are more vulnerable (methodology 5) than short canals ($V = 0.66$) because of seepage and evaporation losses, tectonic/seismic distortions, and high technology demands for design, low-angle surveying, and hydraulic controls. Yet more vulnerable (methodology 6) are the coastal seeps that supply agriculture (mainly in coastal northern Chile and the Ilo area of the Moquegua Valley, Figure 1.1.1). Here $V = 1$. Such systems rely on groundwater seepage to coastal bluffs over long underground distances and are marginal compared to other delivery systems. In the presence of drought, systems that rely on a high water table extending to coastal bluffs become dry, resulting in failure of associated agricultural systems. Survival of the more vulnerable agricultural methodologies is in question past a critical level of rainfall amount (line DD, Figure 1.7.2) and extinction of high vulnerability systems is inevitable whenever reconfiguration to lower vulnerability systems is impossible by a strategy change or limits in topography and environment. In the presence of yearly rainfall and runoff variations, high vulnerability systems must have superior technology innovation/modification features to maintain agricultural production. In summary, the least vulnerable raised field systems have a zero V value so $(1-V) = 1$; the most vulnerable systems have $V = 1$, so $(1-V) = 0$.

Technology response to climatic duress

Andean agricultural systems show a long history of evolution and improvement over time. An initial choice of an agricultural system fitting local ecological conditions was initially selected; system evolution developed by observance of agroproduction changes in response to field system design changes under different climate and weather conditions. A further key factor was the preservation of the agricultural system under seasonal weather and large-scale climate fluctuations. The ability to modify an agricultural system to maintain functionality in anticipation of (previously observed and recorded) climate-related changes in water supply is therefore part of the original design conceptualization of the system. Another aspect of agricultural stability and sustainability is that agrosystem modifications must be performed more rapidly than the negative climate variation effects as system modifications are only effective if climate/weather changes are perceived and agricultural system modifications invoked in anticipation of a continuing long-term trend. The vulnerability index $(1-V)$ of an agricultural system therefore depends on its sustainability under climate variations and the ability to create solutions by restorative technology T in time t (denoted as dT/dt), faster than the rate of climate-related threats D (denoted dD/dt) to an agricultural system's survivability. The ratio of dT/dt to dD/dt is known as the response ratio. Note that many entries in Table 1.7.1 are contributory factors that increase dT/dt.

Agricultural sustainability model

So far several factors influencing agricultural sustainability have been discussed; these and other factors are next combined to produce a trend equation where increases (decreases) in each term imply a net increase (decrease) in the agricultural sustainability Q of a society. The quantities in the equation (Q, R, S, P, V, Y, dT/dt, and dD/dt) are non-dimensional values normalized to the maximum reference state for each variable. A large value of Q denotes that agricultural sustainability can be maintained while a small value denotes the opposite. Based on the above discussion, a simplified model equation, based on agricultural parameters only (excluding implied or induced social, political, or economic, governmental system effects), can be postulated as:

$$Q = S + YAR + (1 - V) + P'(2 - P')[dT/dt \div dD/dt] \tag{5}$$

where R is the runoff ratio ($0 < R < 1$). The quantity S is the agricultural storage capacity ($0 < S < 1$), normalized by S_{mx}, which represents storage excess of all non-consumed crops. Here $S = 0$ represents no food storage and $S = 1$ represents maximum storage capability to store excess food supplies over that necessary for maintaining the population. The $(1 - V)$ term ($0 < V < 1$) represents the vulnerability index. The least vulnerable methodology (raised fields) would therefore have $(1 - V) = 1$ and the most vulnerable have $(1 - V) = 0$. The term $P' = P/P_{mx}$ is defined as the population ratio, where P_{mx} is the maximum population sustainable by the in-place agrosystem. If $P' = 1$, then $P'(2 - P') = 1$ at the maximum population level balanced with the food supply (or $\partial Q/\partial P' = 0$ when $P' = 1$); if $P' = 0$ then $P(2 - P') = 0$, indicating that a very small population exists, such as may occur after a natural or non-natural disaster. This term relates to the labour available for large-scale irrigation projects or system modifications (dT/dt), which is a fraction of the total population. The term Y ($0 < Y < 1$) is the agricultural yield/unit water input multiplied by unit area, where Y_{mx} represents maximum yields possible assuming fertile soils and adequate water supplies; $Y = 0$ represents poor yields in infertile soils with little irrigation water available. A is normalized to A_{mx} and represents the amount of land farmed compared to available land area ($0 < A < 1$). The term $\mathrm{d}T/\mathrm{d}t \div \mathrm{d}D/\mathrm{d}t = \mathrm{d}T/\mathrm{d}D$ is the time rate of technology change divided by the time rate of the evolution of a natural disaster (excessive rainfall, drought, seismic and tectonic-induced effects) on agricultural production. Here $0 < \mathrm{d}T/\mathrm{d}D < 1$, where the zero limit represents a technology evolution rate not able to overcome the disaster evolution rate; the unity limit represents the opposite case. The term $\mathrm{d}T/\mathrm{d}t$ may be high by virtue of the many weather/climate defence mechanisms mentioned in Table 1.7.1 to protect field systems from damage. If $P' < 1$, then the labour force extracted from the general population to make rapid $\mathrm{d}T/\mathrm{d}t$ corrections is not available and Q decreases. If $P' < 1$ in the presence of a declining agricultural supply or storage capacity, then agricultural resources are inadequate to feed a large workforce over time to ensure rapid $\mathrm{d}T/\mathrm{d}t$ changes to increase Q. Thus only a population balanced with agricultural supply (including some storage to maintain the food supply to promote a rapid increase in $\mathrm{d}T/\mathrm{d}t$) promotes large sustainable Q values.

The relative value of Q applied to highland and coastal societies at different time intervals then gives an indication of the underlying factors behind the agricultural sustainability of one society over another based on key agricultural parameters. Overall, from the Q equation, sustainability is enhanced when the runoff ratio/water supply (R), agricultural yields (Y), land area (A), and crop storage (S) are high, a stable population is balanced with agricultural output, the system vulnerability (V) is low (or $1-V$ is high), the technology innovation rate to overcome an evolving natural disaster exceeds or equals that of the disaster evolution rate, and soil productivity/unit water input unit area is high. For coastal societies dependent on rainfall, the Q equation has immediate applicability; for highland societies dependent on terraces, raised fields, and canal irrigation, interpretation of runoff in the form of field/terrace drainage is important for system survival and is the preferred interpretation in the Q equation. In general, high Q indicates a successful, well-managed society with the foresight to maintain a sustainable agricultural base under weather and climate variations; low values of Q indicate gaps in the perception of threats that will cause an agricultural system to fail or operate in a marginal manner. Of course, for extreme, long-lasting negative climate variations such as long-term drought, Q must ultimately drift to smaller and smaller values, indicating that sustainability is no longer possible. As an example, for the LIP Chimú, all terms in the above equation are high except $(1-V)$, implying that a large sustainable population can exist except when $\mathrm{d}D/\mathrm{d}T$ is large (due to drought); for the Inka, all terms are high as large storage capacity, large land area, high water supplies, high technology, and large population all are present in the LH to sustain a large Q value. Less successful societies (from an agricultural perspective only), such as the Nazca, have generally low values of most parameters, implying that only relatively small population size can be balanced with the agricultural resource base.

Andean historical patterns

In the Uhle–Rowe chronological sequence (used to delineate time periods but not to imply simultaneity of events in different locales), each time period (EH to LH) is characterized by a dominant society (or societies) with a distinct societal and political economic structure, governmental system, architectural and settlement pattern, ceramic and religious iconography, and agroengineering practices. Frequently, one dominant characteristic is sufficient to characterize a period. For Horizons, one society is usually dominant through political, religious, and/or military achievements and exerts overarching influence over vast territories over other societies. For Intermediate Periods, dominant regional states may exert control through branching government structures capable of integrating adjacent territories into the state ideological and political template and several states may control localized areas. The EH is traditionally characterized by highland Chavin influence diffused into Peruvian north and central coast radiation centres showing similar, but locally interpreted, artistic traditions in iconographic ceramic and textile traits. Expansion of Chavinoid influence from highland sources appears to be religion based. While the importance of highland Chavin in the early part of the sequence was based on knowledge current during the construction of the Uhle–Rowe sequence, new research at the Preceramic city of Caral and contemporary coastal societies in the Supe and adjacent valleys (Shady and Leiva 2003) has motivated additions to the Uhle–Rowe sequence in terms of earlier societies than Chavin having coastal, city-based state societies with influence on highland societies.

Minor south coast societies (Paracas–Cavernas) arise in the EIP with local regional influence. The EIP sees the origin of major coastal architectural and agricultural complexes with the Moche (north Peruvian coast), Lima (central coast), and Nazca (south coast) polities as dominant societies with rudimentary centralized control structure. Minor north coast Recuay and central Huarpa highland societies arise in this period but are localized in extent and influence. The MH sees a shift back to highland dominance with the later phases of the Tiwanaku IV, V, and Wari states dominating much of the southern and central Andean coast and highland regions by political, economic, and religious influence. Large agricultural complexes in the form of raised fields (Tiwanaku) and terraces (Wari) accompany secondary administrative centres (Tiwanaku: Omo, Pajchiri, Lukurmata, Wankarani; Wari:

Pikillaqta, Cajamarquilla, Viracocha Pampa, Cerro Baúl, Wari Wilka) to define control and empire in this period. The subsequent LIP is characterized by a shift back to prominence of coastal societies with the Chimú occupying a north coast zone from the Chillon to Lambeyeque Valleys. The Chimú incorporate a complex of new administrative (e.g. Farfán, Manchan, and Purgatorio) and older ceremonial centres (Pacatnamú and Chotuna) in adjacent north coast valleys to their Moche Valley capital at Chan Chan and ultimately exert influence as far north as the Lambeyeque Valley (at *c.* 1375 CE). The idea of centrally administered, multivalley agroengineering complexes directed by satellite administrative centres sharing common political, architectural, economic, social, and religious practices appears to be a central feature of this period. Ica culture is dominant in the south-central coastal areas at this time with the minor intermediate-highland Recuay and Cajamarca societies having only localized regional influence. Military conquest and complete dominance of highland and coastal polities by the Inka state occurs in the LH period. It appears coincidentally that the EH → EIP → MH → LIP → LH chronological sequence somewhat corresponds to a geographic alternation of prominence between highland and coastal polities. Since climate influence on agricultural systems suggests a role for sustainability of different highland and coastal Andean societies in different time periods, these effects are discussed in terms of the *Q* equation.

Horizon and intermediate period sustainability and the *Q* equation

The climate change history in the Quelccaya records points to drought at late EIP times; this drought has been attributed to the decline of the coastal Moche and Nazca polities at their traditional sites even as highland Tiwanaku and Wari polities began their rise to prominence. On the coast, the lowered drought-induced runoff ratio (R) affected coastal zones disproportionately and, as the coastal canal-based irrigation systems have high vulnerability (low $1 - V$) because they are runoff-dependent, such systems were under duress in protracted drought periods. In this period, coastal food storage facilities were not prominent structures in cities (lower values of S) and population was somewhat balanced with pre-drought agricultural resources ($P' \approx 1$) before the onset of drought. Coastal valley yields for irrigation-based agriculture (Y) were high due to high soil fertility and large areas (A) were in production but could only be exploited provided R could be kept high, but this was not the case in late EIP times. Apparently the elemental hydraulic technology available to EIP Moche society (Table 1.7.1) to modify and defend agricultural systems did not develop more rapidly than the evolving drought crisis

($dT/dt \div dD/dt < 1$), implying that long-term drought at Moche sites could not be overcome by technology solutions. Estimates of drought duration are on the order of 30 years so that in combination with low *R*, agricultural decline was inevitable and large concentrated populations could not be supported indefinitely in their heartland area. While large populations can provide labour resources, unless technology is present (or can be rapidly developed) to utilize these labour resources, the large populations adapted to food supply levels developed during wet periods suddenly become a liability when drought onset is rapid and food supplies decrease.

With reference to the *Q* equation, drought in the late EIP reduced agricultural sustainability compared to pre-drought levels, i.e. *Q* decreased during drought periods for methodology 4 and 5 systems characteristic of the north and south coast areas. From geophysical effects (section 1.1) related to sand incursion over field systems in this period, the term YAR underwent a decrease, further reducing *Q*. Some migration of the Moche to northern coastal valleys after abandonment of the site of Moche and the creation of new centres in Lambeyeque is observed in late EIP and MH times indicative of the need to restore *Q* to higher levels, primarily by utilizing high agrotechnology levels (dT/dt) in combination with the canal-interconnected, higher flow rate (*R*) rivers (Jequetepeque, Zaña, Leche, Motupe, and Lambeyeque) of the northern coastal valleys. Vast irrigation systems appear in these northern valleys with Moche (later transforming to Sicán) presence as Moche Valley sites contracted to the minor site of Gallindo. Thus as key parameters reduced the *Q* value as a result of declining water supplies (which is related to the amount of land area that could be put under production) other areas were sought that promised higher *Q* values.

Highland Tiwanaku and Wari societies achieved high levels of sustainability during the late EIP and MH due to adequate highland rainfall rates at high altitudes in sierra and altiplano regions. The low vulnerability Tiwanaku raised field systems maintained ample water supplies even under incipient drought conditions because of their drought-resistant features and have high *R* (groundwater infiltrated water supply), *S*, *Y*, *A*, and $1-V$, with $P' \approx 1$ and high dT/dD. Again, due to groundwater flows from the vast watershed areas surrounding Lake Titicaca from past rainfall interception events, only a slow lowering of the water table occurred in drought periods from a 5–10% yearly decrease in previous mean rainfall levels in the post-1100 CE time period. The Wari and Tiwanaku maintained high *Q* sustainability through the MH and this apparently led to expansion and imprint of Wari and Tiwanaku highland iconographic and architectural patterns on vulnerable (low *R*) south coast polities and central highland areas, although the cultural interaction mechanism is still difficult to define, particularly in northern provinces. Highland water supplies were apparently adequate during the late part of the EIP due to low V agricultural systems so that Wari terrace agriculture flourished by exploiting higher rainfall levels at altitude. Towards the end of this period, around 1100 CE, the high vulnerability to continually lowering rainfall levels diminished the productivity of these systems although canalized water from snowmelt zones gave additional sustainability. With respect to the Q equation, highland Tiwanaku in the late EIP and early MH was characterized by low-vulnerability raised field systems, large-scale storage facilities (S), high yields (Y) from large raised field areas (A), large runoff-infiltrated water supply and drainage (R) tailored to maintain adequate groundwater levels, high $\mathrm{d}T/\mathrm{d}t$ but slowly increasing $\mathrm{d}D/\mathrm{d}t$, and a large, balanced population and workforce ($P' \approx 1$) that could be utilized to modify the location of the agriculturally productive raised field zones in the Lake Titicaca area. Use of sierra pastoralism was an adjunct to the food supply base of these societies and was amplified in drought periods. The net result was a high Q value for highland societies that indicated good sustainability through the MH until the presence of deepening drought conditions that began in the early LIP.

At the end of the MH and start of the LIP, highland polities underwent slow collapse due to long-term drought while coastal polities (such as the Chimú, Sicán, and Lambeyeque polities) appear to show increasing signs of stress from the same conditions. Although there was contraction of agricultural lands and canal flow from lowered water supplies and adverse geophysical effects, as discussed in earlier sections, their success in maintaining survival level agriculture can be rationalized by the observation that while R, S, and $1-V$ were low in coastal areas, $\mathrm{d}T/\mathrm{d}D$, Y, and P' were high, reflecting the development of advanced transport and distribution canal technologies, sufficient labour force to implement major agroengineering projects in adjacent valleys under their control, and transfer of water from intervalley sources to reactivate desiccated canal and field systems in other valleys (at least, in theory, by the Intervalley Canal) as well as activating field systems adjacent to functioning parts of the Intervalley Canal. For the Chimú, Q was maintained by expanding farming areas into different valleys with more viable water supplies in drought periods so that Q values could be maintained. While intervalley water transport had limits in terms of agricultural return per labour hour invested in canal construction, development of satellite farming communities with adequate water resources that could transport food supplies where needed was another sustainability strategy. Recourse of coastal societies to switch to marine-based food supplies (which may be looked at as 'storage') was an option that mitigated a decline in carbohydrate resources but could not wholly sustain large populations. The conquest and colonization of northern valleys by the Chimú (as well as population dispersal) provided an effective *YAR* and P' increase through the occupation and exploitation of large-area, high river flow rate valleys as a diversification measure to ensure high *Q*. Basically, the advantage of coastal valley canal systems is that they can be modified and reconfigured to be efficient, even with reduced water supplies, leading to high dT/dt as manifested by spatial and configuration changes in intravalley canals for higher hydraulic efficiency (Ortloff 1993; Ortloff *et al.* 1982, 1985, 1993; section 1.1). The development of large intervalley canal systems that redistributed water between valleys to large field system complexes and provided new agricultural areas en route provided dT/dt increases. While water supplies were adequate in some valleys under Chimú control, low-slope surveying accuracies extended canals to larger cultivable areas. When water supplies ultimately declined due to drought, canal recutting, relocating, and reshaping provided increased dT/dt potential to distribute available water supplies.

The potential to transfer agricultural zones to higher flow rate, north coast valleys may be thought of as a variant of storage capability (*S*) or simply increases in *YAR*. The sustainability of coastal societies was therefore aided by their flexibility to alter irrigation systems (technology and placement). While altiplano raised fields are somewhat modifiable as farming areas can be moved to high water table areas away from, or close to, the lake edge or near streams traversing the Pampa Koani area, this shift in agricultural zones was only a short-term fix as the water table ultimately declined under long-term drought. Settlement patterns associated with field system usage changes on the Pampa Koani (Janusek 2004) show this inland shift in late MH and early LIP times as the population centred around areas for which localized farming was possible from locally high water table zones. While the Tiwanaku raised field systems have high $(1 - V)$ with groundwater elevation distribution controllable by spring, river, and drainage systems, in the presence of extended drought, the option to lower the entire Tiwanaku–Lukurmata 100 km^2 raised field planting surface to accommodate the late MH, drought-induced sinking water table would require a vast labour input over many years to achieve marginal benefit. With time, therefore, Tiwanaku agriculture shifted into lower levels of production in portions of the raised field area formerly used at the height of Tiwanaku expansion and the basis for a concentrated population centre at Tiwanaku slowly dissolved into scattered settlements close to available water resources. Later post-Tiwanaku V Pacajes occupation of the area utilized only remnants of the former system, again near high water table areas while later Inka incursion and control of the area utilized well-known terrace and valley bottom agricultural technology in areas away from now largely defunct raised field areas.

While a large Chimú labour force on the coast can be productively employed in canal modifications, intervalley connection projects, and expansion into land areas in adjacent valleys with still-functioning rivers, the large altiplano labour force could not be effectively utilized to lower the level of large raised field areas to accommodate declining water table levels induced by sustained drought. High dT/dt was therefore possible for coastal irrigation systems because of easily modified canals and relocation of agricultural production centres and population to water-rich valleys under state control. These factors permitted the flexibility to manage lower water supplies to sustain agriculture compared to the in-place and hard-to-modify highland raised field systems of the Tiwanaku. Although highland agriculture based on terraces can move upslope in drought conditions, Y decreases due to poorer soils and decreasing fertile farming area, A. The lower R available to coastal zones could still be better utilized due to high Y from fertile, fluvial-deposited soils, more effectively utilized labour resources, and high dT/dt despite the somewhat higher vulnerability index of canal systems. Eventually, coastal systems recovered as late LIP and LH climate changes restored previous rainfall norms; however, at this juncture they were easy prey to Inka conquest with all the advantages that highland agriculture had in the late LIP and LH periods. The advantages of highland systems (large R, S, A, and $P' \approx 1$, and small dD/dt) were manifest, leading to a secure agricultural base that contributed to Inka suppression of recovering coastal states with a large, indefensible boundaries resulting from strategies of dispersion of agricultural centres.

Summary

Early MH highland Wari and Tiwanaku expansion/radiation appeared to be underwritten by low vulnerability agricultural systems and adequate rainfall, providing a secure agricultural base; late EIP and LIP periods were associated with lower average level rainfall levels than past norms and were associated with the rise of coastal societies, primarily due to superior irrigation management technology well suited to their ecological conditions. In the presence of extended drought, the ability to modify canal systems and relocate the population to different valley enclaves with water supplies (supplemented by marine resources) extended coastal population sustainability; the highland counterpart to this involved extensive use of pastoral resources at elevated altitudes, dispersion of population to colonies that exploited different ecological zones to provide specialty agricultural products, and use of extensive storage facilities. While early Tiwanaku expansion is associated with adequate water supplies and low vulnerability agricultural systems tailored for optimum productivity in a highland weather/climate environment, on transition into an extended drought period post-1100 CE, the Tiwanaku state declined. Coastal societies in this period maintained the semblance of sustainability, indicating that superior, flexible water control/management technologies combined with population dispersal were in place on the north coast under unified political control. While the Tiwanaku raised field systems were somewhat drought resistant, their modification to account for the effects of extended drought was difficult to achieve. As the fate of Tiwanaku was tied to raised field systems and agricultural production from its colonies was barely able to support the colony's population, save export to the main city of Tiwanaku, the decline of the city was inevitable due to limitations on its agricultural strategy suitable to highland zones. The Chimú, on the other hand, could alter wells within Chan Chan towards the coastline to intercept the declining water table, institute wachaque and mahamae agriculture, modify canals to accept lower water supplies, and start construction of the massive Intervalley Canal to direct Chicama River water to revitalize desiccated Moche Valley intravalley canal networks. Here their agricultural systems could be exported to other coastal desert areas in the same form without modification and this proved to sustain their survival even as negative effects of the drought increased. For the Tiwanaku, only small cocha sunken gardens, reduced use of raised fields, and pastoralism were the alternative highland survival strategies to maintain the diminished semblance of city life in the post-1100 CE period.

Highland and lowland environments offered different options for responding to drought. When highland rainfall declined by 5 to 10% from previous norms during the 1100–1300 CE dry period, runoff reaching the littoral desert declined in the order of 30–50+%. The amount of land under irrigation and agrarian yields decreased proportionally and long-term declines in population were documented in a number of northern and southern desert valleys (Willey 1953; Wilson 1988; Owen 1993a,b) with notable changes in Chimú, Sicán, and Lima polities. Although use of marine resources was intensified, there were few means to mitigate farming shortfalls. Chimú expansion into northern valleys where the population could be redistributed to areas where water supplies could support agricultural production and export activity proved a viable strategy. Reconstructing canals to make water delivery hydraulically efficient and stone-lining channels to limit seepage was undertaken in the lower Moche Valley as a defensive strategy. Diversifying plant foods to include drought-tolerant domesticates and wild species transpired in the lower Moquegua Valley (Dendy 1991), if not elsewhere. While coastal agriculture was supplemented by use of wachaques/mahamaes in this time period, highland raised field systems were not easily modified to accommodate extensive drought conditions as field excavation down to the declining water table surface was prohibitive over vast field areas around Lake Titicaca. Similarly, the productivity of the Wari rainfall-supplied terraces diminished due to the high vulnerability of these systems to drought, although some lifetime extension was possible through snowmelt water supplies through canals. Although highland populations could compensate for drought by expanding farming to wetter lands at higher elevations and along the eastern tropical watershed, this implied population dispersal; no C^{14} dates were found in the Tiwanaku capital past *c.* 1100 CE, indicating a change in city organization (Janusek 2004). Under higher rainfall conditions in the late LIP and LH periods, terraces supplemented previously abandoned fields in the Inka-dominated highlands as an agricultural strategy enhancement to provide further land areas for agriculture for an enlarging population. If terracing was first associated with the highland Wari as a response to the 562–594 CE drought (which also forced major Moche cultural and location axis changes), then this was an example of the effect of the runoff imbalance noted between coast and highlands and its consequences. Note that a temperature change is associated with the highland MH drought and that snow melt water was available through canal delivery systems to maintain terrace agriculture in some limited form, particularly in the densely terraced southern Andean region. Thus a sustainability *Q* shift among societies from highland EH to coastal EIP to highland MH to coastal LIP to highland LH appears at least partially related to climate shifts and the effect on the agricultural base of the various societies.

In the Moche Valley at least 30% more terrain was farmed in the past (primarily in the LIP) than is in production in the 21st century. Agricultural systems bear widespread evidence of disastrous destruction and initial loss of land due to exceptionally severe flooding during a 1100 CE El Niño event amid a long-term drought in the post-1100 CE period that disrupted many northern valleys (Moseley and Cordy-Collins 1990; Ortloff 1993). Although the Intervalley Canal was a strategy to resupply the northside Moche Valley irrigation system, in the presence of extended drought, neither the Intervalley Canal nor the intravalley canals could maintain sufficient water to supply field systems at previous levels over time. As part of the Chimú strategy of field dispersal to available water sources, canals from the Intervalley Canal to the Lescano as well as the Chicama Valley fields helped to sustain the Chimú Empire in this period. Although dispersal and technology sustained the Chimú, ultimately large land areas were lost as river runoff dwindled in the presence of sustained drought. Reclamation efforts in the Moche Valley shifted to low areas where sunken gardens could access ground water but this strategy could not match the volume of past field production.

In LH times, in addition to reclaiming farmland, the Inka engaged in large-scale food storage to mitigate shortages and facilitated the movement of people, produce, and information through their highway network. The Inka learned lessons from the societies they dominated and put into place ways to maximize Q by emphasis on storage S, moving conquered populations to fertile lowland valleys for farming productivity increase (YAR increase), maintaining large populations and labour forces ($P' \approx 1$) for large-scale projects and farming output increases, utilizing the technical advances of conquered societies to enhance agricultural productivity, and utilizing low-vulnerability agricultural systems, all with the natural advantage of exploiting the water-rich (high R) environment. Dominance of the Inka over the Chimú in the LH occurred during a favourable rainfall recovery period ($\mathrm{d}D/\mathrm{d}t$ small). Although the coast had the potential to recover its agricultural base, Inka political and military suppression of the area precluded a return to previous Chimú practices to administer large, complex inter- and intravalley irrigation networks.

Collateral disasters involving earthquakes and El Niños transpired during the centuries of drought. When the 1100 CE drought began in southern Peru, the Moquegua drainage was later occupied by the post-Tiwanaku Chiribaya culture. This society was focused on the coast but also extended into the lower sierra. With extended drought, coastal settlements formerly dependent on river and groundwater moved their agricultural zone to humid sierra locations above 2,250 m to exploit more abundant water supplies. Exceptionally severe El Niño flooding decimated the cultural landscape around 1360 CE, and the Chiribaya occupation was largely obliterated (Moseley *et al.* 1992; Satterlee 1993). Demographic recuperation was minimal and post-disaster population levels in the lower drainage remained 80% below their preflood levels (Owen 1993a,b). Poor recovery was attributed to continued drought. Calculations for one Chiribaya coastal irrigation system (Ortloff 1989; Clement and Moseley 1991) suggest water supplies and productivity had declined by at least 80% when dryness was at its peak during the 1320 CE period. Thus, the collateral disaster struck a population that had minimal resources for recovery. Hydrological conditions conducive to agrarian and demographic recuperation did not return to the littoral valleys until drought abated and above-normal runoff and rainfall was restored later. By this time the highland Inka had conquered the drought-depressed coast. Shortly thereafter littoral populations were decimated by the convergent catastrophes of Old World pandemics and Spanish subjugation.

Final considerations

Since many highland agricultural systems incorporated large land areas, the alteration of farming zones to subzones depending on local water supplies proved a viable sustainability strategy. As an example, Lake Titicaca raised field zones had the option to shift laterally over a portion of the entire 100 km^2 Koani area depending on climate-influenced lake height and subsurface aquifer shape. Highland terrace agriculture could shift in altitude under climate-induced rainfall changes while coastal canal-supplied fields could shift in inter- and intravalley location depending on river flow rate and then finally to subsurface mahamaes/wachaques during climate-influenced drought periods.

In terms of variables R, P, Y, S, A, V, dT/dt, and dD/dt, some underlying correlatives for the sustainability Q of different societies with different agricultural systems subject to different climatic conditions provide a partial basis for underlying factors that led to changes in cultural patterns. The temporal Q value therefore provides a basis for determining different societies' responses to sustainability problems originating from their decision-making elites and the degree to which key variables were manipulated to achieve maximization of food resources and sustainability of their agricultural base. When model parameters and Table 1.7.1 contributions are extracted from the archaeological record, new thoughts about the intelligence and organization of the management structure of ancient societies can be added to our view of their place in history. Examination of the alternation between highland and coastal society sustainability patterns, as evidenced in the IP → EH → EIP → MH → LIP → LH sequence, appears to bear some relation to known climate cycles, although environmental determinism is not suggested as many social, political, and economic factors are also in play in combination with climate-related causes.

As knowledge of details of Andean climate cycles from ice and lake core data is still in the development stage, only an approximate hypothesis can be offered at present to explain their effects on societal political/economic structure and sustainability patterns through time. With respect to Tiwanaku (and its colonies) collapse mechanisms in the post-1100 CE time frame, several theories are summarized from circumstantial evidence (Owen 2005; Janusek 2004) that suggest decoupling of environment effects on social interactions and conflicts between different classes of Tiwanaku society. It is clear from the C^{14} record that abandonment of the major portion of agricultural raised fields (due to the slow decline of springs and water table height) and core urban monuments occurred. Elsewhere, in areas north of the western shore of Lake Titicaca, similar abandonment of raised field and scattered settlement patterns was observed.

As decline of agricultural production can be a catalysing agent for social unrest in highly organized societies, depending on their social and economic structure, it is best left to specialists in this field to unravel connective effects. If current (and ancient) history is examined for the countless conflicts involving water rights and access to water in agricultural and urban contexts, then severe drought as a catalyst for conflict, economic upheaval, societal change, abandonment of failed rituals, and practices of ruling classes can be an outcome. New elites with new solutions may emerge to dissolve the inefficiencies of failed elite classes that have lost favour with civilian subjects. An object lesson in this regard was the discovery of a building block commonly used in Tiwanaku housing that, when removed, revealed an iconographic deity that had lost favour as a ritual object and now was a common (inward facing) building block. Similar instances of smashed statuary at the closing phase of Tiwanaku V reflect some drastic revision in societal outlook with causes yet to be fully understood. Perhaps as climate change influences the modern world and redistributes agricultural favours and disasters to different areas of the world, some notice will be taken that previous societies have already coped with their equivalent of these changes and found ways to alter agricultural strategies for survival. Perhaps this ancient library of solutions will again be visited as the ancient societies of the Andean world coped with many climatic variation outcomes yet to be experienced by modern-day societies.

1.8 THE MAYA CANAL AND AGRICULTURAL SYSTEM AT KAMINAL JUYU, GUATEMALA, 300 BCE–900 CE

Introduction

The site of Kaminal Juyu in present-day Guatemala City has the distinction of being a Maya transition site from early Formative (2500–1000 BCE) to late Postclassic times (1200–1500 CE). Research has demonstrated evolutionary changes in art styles, architecture, and political history throughout successive periods in the southern region of the Maya world (Shook and Proskouriakoff 1956; Sanders 1974; Michels 1979a,b; Popenoe de Hatch 1997; Popenoe de Hatch *et al.* 2002). Located in the central highlands of Guatemala, the site grew from a farming community started in 2500 BCE to a major ceremonial centre and political capital (500 BCE) in later times. By early centuries CE, it had become a centre for long-distance trade and flourished until 800 CE, when unsettled conditions created the need for a more defensible setting. The city continued its existence to Late Postclassic times (about 1500 CE) with minor occupation continuing through Colonial times. Of the initial 200 mounds initially found at the 45 hectare site, few now remain. As the site lies within the city limits of Guatemala City, only a small fraction of the original site remains as a public park area. While the political, social, and economic history of the area has been elaborated by University of Pennsylvania and Carnegie researchers over the years and a vast literature remains from these investigations, the focus here is on a unique agricultural system driven by an equally unique canal supply system dating from Preclassic times.

Excavations at the site directed by M. Popenoe de Hatch in the 1980s revealed details of a large canal (denoted the Miraflores Canal) that was supplied from a 25 hectare lake (Lago Miraflores) through a dam structure to field and urban settlement complexes within the site boundaries (Figures 1.8.1 and 1.8.2). The lake existed in Late Preclassic times (200 BCE to 100 CE) but apparently went out of existence in the Santa Clara Phase (100–200 CE) (Popenoe de Hatch 1997; Michels 1997b; Popenoe de Hatch *et al.* 2002) as a result of climate change or a deliberate drainage activity to make room for later structures. Later excavations confirmed that the canal had an agricultural function and terminated in an agricultural zone (Popenoe de Hatch 1997). The interesting question to be addressed relates to the fact that the lake level lies slightly below the agricultural fields so providing water to these fields would apparently take some ingenuity to achieve. The methodology by which this was accomplished is the subject of this section.

The results presented in this section originate from excavation activity done onsite in areas now lost to development. The results are therefore only a partial record of aspects of Preclassic Maya hydraulics accomplishment in this area and demonstrate that sophisticated aspects of open-channel hydraulics were known and utilized by early Maya societies. The canal system described has been attributed to the late centuries BCE and may be typical of Maya canal systems not yet discovered or analysed. On this basis, the results analysis provides a testament to Maya hydraulics knowledge.

Traditionally, research on Maya agriculture and water distribution systems has focused on systems utilizing rainfall runoff collection into basins for urban water supply and transfer to field irrigation systems, seasonal rainfall-driven agriculture, use of moated raised fields (chimapas and tablones) and use of wells for water supply. While investigations show creativity in various types of water supply and distribution systems, the focus in Maya archaeology is mainly directed towards art history, architecture, ceramics typology, iconographic studies, glyph translations, political and social history, kingship

Figure 1.8.1. Contour map of the Kaminal Juyu area with pyramid mound concen trations; the contoured valley B A denotes the Miraflores Canal path.

successions, social groupings and societal organization, trade networks, empire spheres of influence, and historical development studies. Here, the present work adds new details to the long list of Maya accomplishments, albeit in a little-explored field: Maya hydraulic control methods.

Research into agricultural development history is currently of interest as there may be complex social-, climate-, and agricultural-related reasons for the demise of the classic Late Maya civilization. While recent discoveries of Maya social disorder and collapse derive from warfare, competition for territory, and spheres of influence, some form of agricultural stress may lie at the origin of such developments. Complicating the long-standing issue of collapse mechanisms is the observation that collapse occurred at different times in different areas of the Maya kingdom, indicating perhaps that one central reason has different manifestations depending on local political economies, alliances, resource bases, and perhaps climate-related effects. While climate variation effects are known on the transitions observed in South and North American societies at the approximate time of the Maya collapse, the extrapolation of these effects influencing Maya collapse is speculative because there is little knowledge of their agricultural systems' response to climate variations or the magnitude of the variations. This section advances results related to Maya hydraulic skills. If the Maya were capable of creating agricultural systems ideally tailored to local ecologies, and these were newly subject to climate extremes that diminished water supply, then an assessment of their hydraulic engineering skills to provide defensive responses would then expose possible avenues of collapse of their agricultural base.

Hydraulic analysis of the Miraflores Canal

The hydraulic function of the Miraflores Canal, which runs southeast from the lake occupying the core region of the site of Kaminal Juyu, is the subject of the present discussion. The canal denoted A–B in Figure 1.8.1 is shown in detail in Figure 1.8.2 together with the excavated cross-sectional profile shapes. Excavations of canal cross-sections along the length of the canal (Popenoe de Hatch 1997, 2002) revealed details of profile shapes, bed slope (i_b), and position data (Table 1.8.1) for each of the profiles shown in Figure 1.8.2. From the profile geometric data, CFD methods were used to analyse the hydraulic operation of the canal.

For purposes of hydraulic analysis, the canal cross-sections shown in Figure 1.8.2 were approximated at each measurement station by non-symmetrical trapezoids with base widths (B) and left θ_L and right θ_R side wall angles. The results are shown in Table 1.8.1.

Starting from a reference point S (Figure 1.8.2), cross-section profiles exhibit initial steep-sided, narrow base shapes. Proceeding in the downstream direction, profiles change to wider base width, trapezoidal configurations with lower-angle side wall slopes that are generally asymmetric. In the far-downstream reaches of the deep canal (the total depth from start to finish is obtained by summing incremental depths, Δh_i, between measurement stations, Δx_i, where $\Delta h_i = \Delta x_i \cos i_b$), the profiles once again narrow in width, and side wall slopes exhibit the step behaviour characteristic of an entrenched stream. Finally, at the distal end of the canal, there is an abrupt change in bed slope in the positive (uphill) direction coupled with a basin-like catchment structure to end the canal. Essentially, the deep canal ends in a vertical wall, and past this location a wide-base, shallow secondary canal emanates from the catchment basin distal end at an elevated height and runs in the same direction as the main canal. Canal wall surfaces are unlined and cut into the talpetate (clay) layers several metres below the site surface. Based on preliminary observation, the canal appears non-functional as the distal end encounters an end wall and there the canal depth is well below the surface field systems, but here application of CFD methods proves otherwise.

The excavated profiles are labelled S, B, C, D, A, N, E, F, G, L, and H; the secondary canal profiles past the main canal end are denoted I, J, and K (Figure 1.8.2). It is noted that the slopes are steep from a hydraulic point of view and will produce a supercritical flow in the canal (Chow 1959; Henderson 1966; Morris and Wiggert 1972). The method of hydraulic analysis of this canal proceeds in a number of steps. Initially, data for the bed slope, side wall angles, Manning side, and bottom wall roughness factor and base width are tabulated from the excavation data and hydraulic calculations performed (Table 1.8.2) by several methods for verification purposes.

Calculations for specific energy and momentum were made at locations where normal and critical depths interchange local maximum values in order to predict the location of a possible hydraulic jump in the flow. Calculations of normal and critical depths were made for an assumed set of flow rates (m^3/s) to gauge the occurrence of hydraulic jumps as dependent on assumed flow rate. This set of calculations is independently made by use of one-dimensional forms for the equations governing open-channel flow, i.e. all functions depend on the streamwise distance variable only and include all the approximate trapezoidal cross-sectional profile shapes in the hydraulic model.

The results of this preliminary analysis are verified by recourse to computer solutions from the full set of Navier–Stokes equations solved in finite difference form for the given three-dimensional canal geometry. Use of a modified version of FLOW-3D included interpolated, quadratic canal profile surfaces between discrete input profiles from excavation data in order to provide smooth transitional canal sections. The CFD canal model therefore becomes a continuous, three-dimensional shape agreeing with the trapezoidal representations of excavated profiles at the measurement stations. Finally, after the one-dimensional, order-of-magnitude, and detailed computer results are compared, results verification was obtained and the influence of the canal shape on water motion revealed.

Table 1.8.1. Miraflores Canal geometric data

Canal station	Location (m)	Base width, *B* (m)	θ_L (degrees)	θ_R (degrees)	i_b (degrees)	Height (top to bottom) (m)
S	0.00	2.0	66	70	2.51	5.25
B	0.40	4.5	54	78	1.83	4.00
C	0.72	6.0	53	70	1.15	3.80
D	112	6.0	57.5	47.5	2.15	4.00
A	136	4.0	31	64	0.001	5.0
N	160	4.0e	32e	54e	1.19	4.75
E	184	4.0e	32e	54e	2.39	3.50
F	208	4.0	33	44	3.10	2.00
G	232	2.5	85	85	1.97	2.40
L	264	2.0e	25e	18e	0.001	2.30
H	272	2.0	25	18	20.0	0.00
I	306	2.0e			0.001	0.00
J	330	2.0e			0.48	0.00
K	354	2.0e			1.19	0.00

e, estimated value.

Table 1.8.2. Miraflores Canal hydraulic parameters

Station	Normal depth (ft)	Critical depth (ft)	Depth (ft)	Froude number	Specific momentum (ft^3)	Hydraulic radius (ft)	Station position (m)
S	2.01	2.88	8.3			2.72	0
B	1.60	1.99	2.5	0.85		0.48	40
C	1.23	1.71	0.5	6.74		0.39	72
D	1.00	1.72	0.4	9.79		0.37	112
A		2.21	0.4	7.80		0.38	136
N			0.6	3.62		0.51	160
E	1.23	2.26	1.0	2.45		0.85	184
F	1.13	2.25	1.3	2.51		0.80	208
G	1.99	2.52	1.0	8.11	42.4	0.71	232
Hydraulic jump appears in this region							
L	6.73	3.75	0.8 to 8.78	0.40			264

Initially, a volume flow rate is assumed to begin the calculation. The canal is presumed to function intermittently with periodic discharges corresponding to the watering interval of the field systems it serves. A release volume flow rate of 269.9 ft^3/s corresponding to a depth equal to two-thirds of the water height of the canal at station S is assumed. The velocity of this section is assumed to be 3.28 ft/s, corresponding to critical flow conditions characteristic of weir flow over a dam. Independent of the assumption of the initial velocity and depth, the flow soon becomes supercritical due to the steep slope

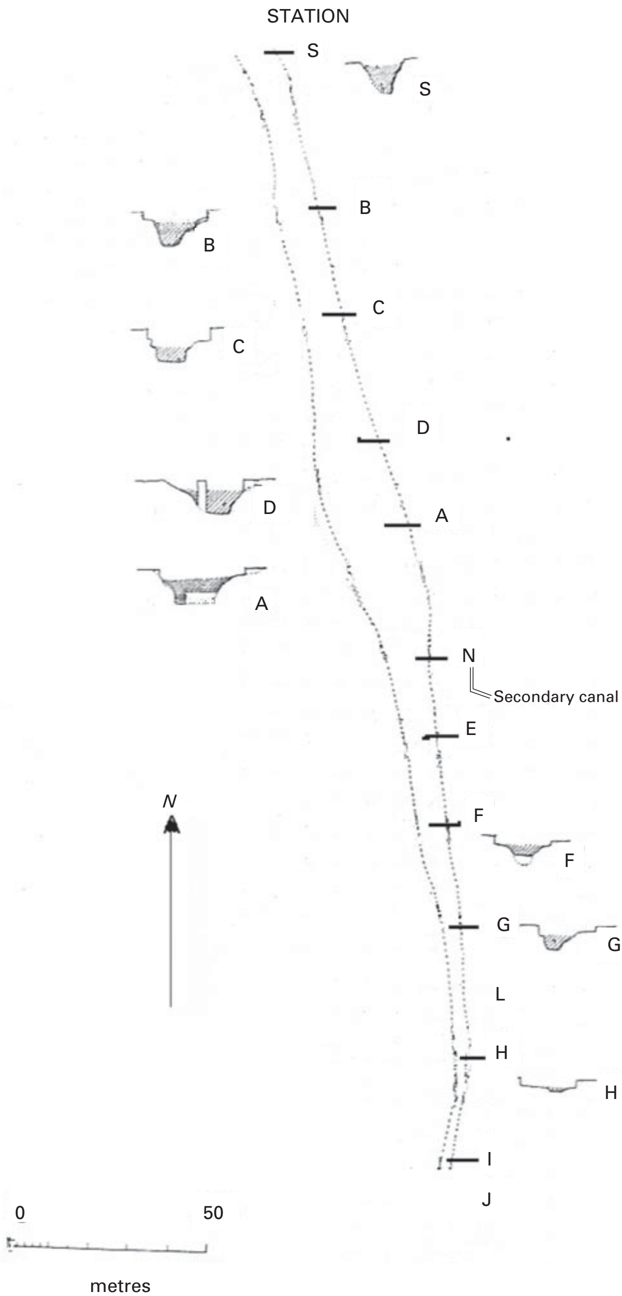

Figure 1.8.2. Canal geometry and excavated trench designations J, I, H, L, G, F, E, N, A, D, C, B, and S. Cross section geometry profiles are indicated for the trench designations.

(Table 1.8.1) in that the critical depth D_c exceeds the normal depth D_n. Use of the one-dimensional hydraulic equation (Chow 1959; Henderson 1966; Morris and Wiggert 1972):

$$L_k^{k+1} = \int_{D_k}^{D_{k+1}} \{(1 - Q^2B/gA^3)/[i_b - (nQ/1.5A_m R_m^{2/3})]^2\} dD$$

permits determination of the length L_k between depths D_k and D_{k+1} using Table 1.8.1 data. Continued numerical integration then yields the depth versus length curve for the surface of the flow passing down the channel. In the above equation, n is the Manning roughness coefficient (assumed to be 0.021 for smooth canal walls), R is the hydraulic radius (equal to the flow cross-section divided by the wetted perimeter), Q is the flow rate, B is the base width, A is the flow cross-sectional area, $g = 32.17$ ft/s^2 and the subscript m denotes a mean value between calculation stations k and $k+1$. English units are used in the numerical integration to conform to the empirical version of the Manning equation. This equation has been applied to the profile dimensions in Figure 1.8.2 and utilizes the data in Tables 1.8.1 and 1.8.2.

Shown in Table 1.8.2 are station location, the critical and normal depths (useful to obtain flow asymptotic depths), the local Froude number, and the specific momentum value (necessary for hydraulic jump location prediction). The specific momentum value at a hydraulic jump location must be matched by that at the two conjugate depths of the hydraulic jump; these depths correspond to the up- and downstream depths of the hydraulic jump and fix its location. The specific momentum is defined as:

$$M = D_{d\ c}A + Q^2/gA$$

where D_{d-c} represents the depth to the centroid of the fluid cross-sectional area. The conjugate depths D_1 and D_2 are related by

$$D_1 = (D_2/2)[(1 + 8Q^2/gD_2^3B^2)^{1/2} - 1]$$

for the special case of rectangular cross-sections (which may be used as a local approximation for an initial estimate of hydraulic jump position), and yield depths D_1 and D_2 on either side of a hydraulic jump. The head loss E_j through the hydraulic jump is given by:

$$E_j = (D_2 - D_1)^3/4D_1D_2$$

and represents an energy difference related to a fraction of kinetic energy being transformed to potential energy through the hydraulic jump.

The results of the calculations indicate that the flow is accelerating rapidly at station B (Figure 1.8.2) due to gravitational forces acting on water passing down the steep slope, as indicated by the large Froude number. At station C, the Froude number approaches 6.74. At station D, the Froude number continues to increase to 9.79 as the flow depth continues to decrease. Past station A, the canal cross-section contracts; this factor, in combination with a slope change towards a near-zero value, leads to a height increase and a lowering of the local Froude number. This trend continues to sections E and F, with increasing water depth evidenced at station F. The Froude number is 2.45 at this location and is reduced by the dual action of the contraction section and the bulge in the bed slope profile. Note that due to the complex geometry of the canal profiles and bed slope changes, the actual depth approximates the normal depth (Table 1.8.2) only in downstream supercritical locations.

At station G, the large slope change accelerates the flow to high Froude number (8.11) and reduces the flow height accordingly. The calculated specific momentum value at this location is 42.4 ft^3. Assuming an average rectangular cross-section at station G, conjugate depths of 0.8 and 8.78 ft are calculated next. Since the lower depth corresponds to the calculated depth slightly past station G and since the stream momentum yields the above conjugate depths, it is concluded that a strong hydraulic jump exists at a station between stations G and L in Figure 1.8.2. Since the calculated critical depth (for the assumed flow rate) of 3.75 ft is less than the normal depth of 6.73 ft, the hydraulic jump is expected to occur at some location between stations L and G by other considerations. For the hydraulic jump to be stationary, the mass flow into the surface secondary canal stations H, I, J, and K from the portion of the hydraulic jump exceeding the height difference between the base to surface height of the canal at station L must be equal to the input flow over the dam. Since this canal bed-to-surface height is 8.2 ft and the hydraulic jump height is 8.8 ft, the secondary surface canal is perfectly designed to drain off the overflow and produce a stable hydraulic jump. In simpler terms, the high-speed flow down the steep canal undergoes a hydraulic jump (close to the distal end wall), which elevates the flow (while decreasing its velocity) to a location where the water height exceeds the surface height, causing flow into feeder canals on the agricultural surface. These feeder canals must distribute the input volumetric flow rate to the field systems to maintain a stable position for the hydraulic jump. The feeder lines have not been excavated fully so further detail on flow to field systems is unavailable.

If the bed slope and/or distance between stations E and G were different from those shown (for the given flow rate) then the secondary canal would have to be modified to accommodate the altered overflow. Specifically, if the

Froude number at station G were higher due to a steeper slope or a cross-section widening, then the hydraulic jump would be higher, requiring a larger secondary canal cross-section and/or slope to contain the spillage.

If the slope were less steep past station F, then the hydraulic jump would occur near station N. Since the Froude number at this station is relatively low (3.62) the downstream depth of the weak hydraulic jump at this location would exceed the ground height at station N, causing non-controlled over-bank spillage. Since the assumed volumetric flow rate causes the given design to function in a controlled manner, it may be assumed that upstream controls (in the as yet unexcavated upstream portion of the canal) are in place to produce a flow rate close to the assumed value for correct function of the canal. Although there is some variability in how the flow rate is maintained by a dam at the lake edge in the vicinity of station S (no details were recorded from earlier excavations and the dam has now been destroyed by development activities), the fact remains that shortly downstream of station S the flow will approach an asymptotic depth because of the high slope. Furthermore, the assumption of a critical flow zone at S is consistent with a transition from low velocity lake flow over a weir to supercritical flow downstream of S and the weir height compared to the lake height can be set to obtain a given flow rate.

It is of interest to note that the depths of water in the canal, for it to function according to design, are relatively low. If, for example, the flow rate were three times the assumed value then although the existing design could easily contain the flow to station A, the downstream hydraulic jump would occur in a far-upstream position, causing spillage over the banks somewhere between stations N and L. It is noted that for the given flow rate the normal depth is always less than the critical depth up to station G (Table 1.8.2). The flow height will then asymptotically tend to the normal depth from flow heights either above or below this depth. Since the reach is insufficient to achieve this depth up to station E, only by means of the adverse slope at station E is there an overshoot; past station E approach to normal depth is again from below, similar to the situation from station C to E. At stations F and G flow height is again low so that approach to the normal depth is again from below.

Although the hydraulic jump is assumed to have a fixed position, in actuality the jump is probably an unsteady phenomenon with an oscillating front (Figure 1.8.3). Note that for the hydraulic jump to remain stationary and thus enable postjump water height to supply the surface canals, the flow rate into these feeder canals must equal to that into the canal over the dam. If the canal flow rate is less than this outflow value, then the initial hydraulic jump would move upstream and ultimately be drowned; then the water height would level out at a streamwise distance *L* from the end of the canal

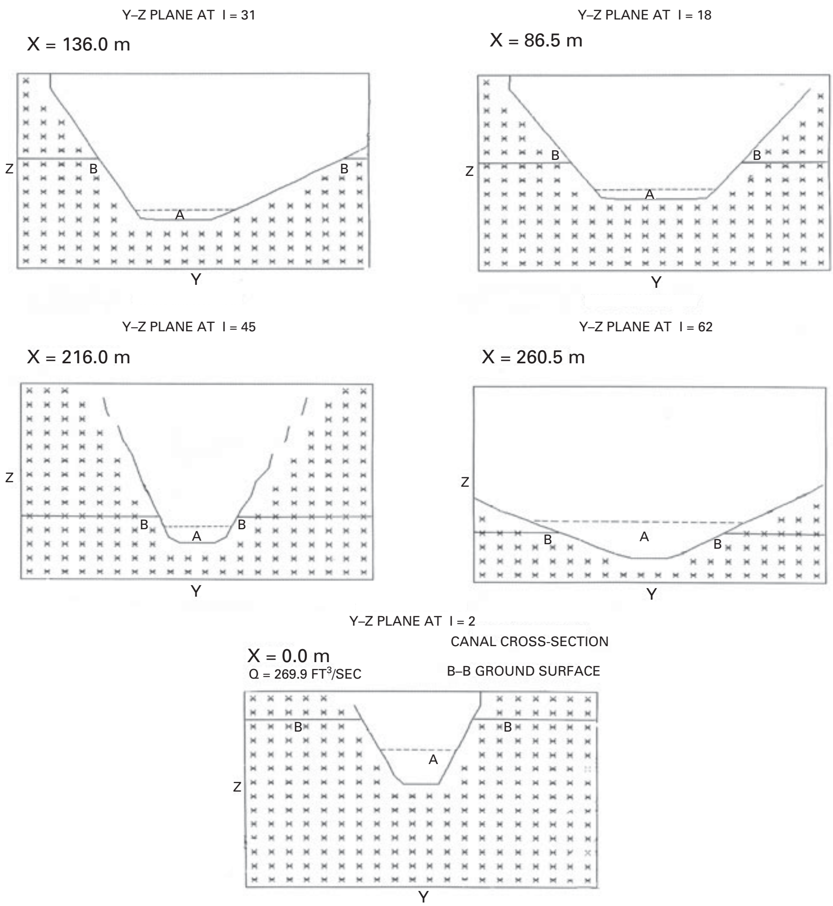

Figure 1.8.3. Computer reconstruction of canal cross section geometry at different X metre stations from station S (Figure 1.8.2). *A* is the canal water height relative to the ground height *B*.

(at depth h) such that $L = h\text{ctn}\ i_b$ and supply surface canals downstream of this distance. Both modes of operation are possible for the canal to provide water to adjacent field systems.

A further set of calculations were based on the FLOW-3D solution of the Navier–Stokes equations. This set of calculations verifies previous conclusions. Sample results are shown in Figure 1.8.3 and show canal cross-section geometry and calculated water height (A) at the various x_i metre stations shown in Figure 1.8.2. These solutions provide more detail than the one-dimensional calculations in that velocity will vary throughout the profile cross-section because of viscosity effects. This results in a velocity maximum near the one-third depth location (although this point depends on cross-sectional geometry, bed slope, local Manning roughness, and upstream velocity history). Computer calculations again predict the presence of a hydraulic jump in the region between stations F and L, which is consistent with the one-dimensional calculations.

From the results of the calculations, several conclusions can be drawn about the design of the Miraflores Canal. As the slope at station G is 1.95°, if the canal were to continue at this slope for a further 1,000 ft the depth would approach a distance some 34 ft below the depth at station G. This clearly would lead to a very deep channel. If the main purpose of this canal was lake drainage, then a deep connecting drain channel, culvert, or gully at the distal end of the canal must be in place and be lower than the secondary canal height to accept flow and successfully carry it away from the deep canal. Additionally, side wall stability at such canal depths would require shallow angle side walls, requiring considerable lateral excavation in the downstream direction for the deep-base drainage canal. At canal base depths equal to those mentioned, base talpetates would undoubtedly increase in hardness, requiring considerable excavation labour to accomplish this design. The more elegant solution is one for which the steep slope is maintained for a considerable distance then abruptly changed at the canal distal end. The creation of the hydraulic jump then provides a conversion mechanism for the high kinetic energy, low height supercritical stream to transform to an elevated height, low velocity post-hydraulic jump subcritical flow. The water height in this location then permits flow into secondary feeder canals emanating from the distal end of the canal.

The secondary canal at station N (Figure 1.8.2) may be activated by temporary insertion of an obstacle plate or barrier in the stream at N. The water depth at N is close to the surface at this location with a supercritical Froude number; an obstacle placed in the stream at this location could cause a local hydraulic jump to a height sufficient to cause flow to the secondary canal. With no obstacle in place, downstream secondary canals were only activated at the main G–L hydraulic jump location. The possibility of more than one secondary canal originating from the main canal distal end may be apparent once further excavations are performed in the vicinity of station L. If the secondary canal was blocked or its flow restricted, the hydraulic jump would move upstream from the G–L location to some point between stations L and N. As a secondary canal segment has been excavated close to station N, canal blockage could be an effective way to activate upstream inlets at elevated heights above the canal bed. The presence of a slight bulge in the canal bed

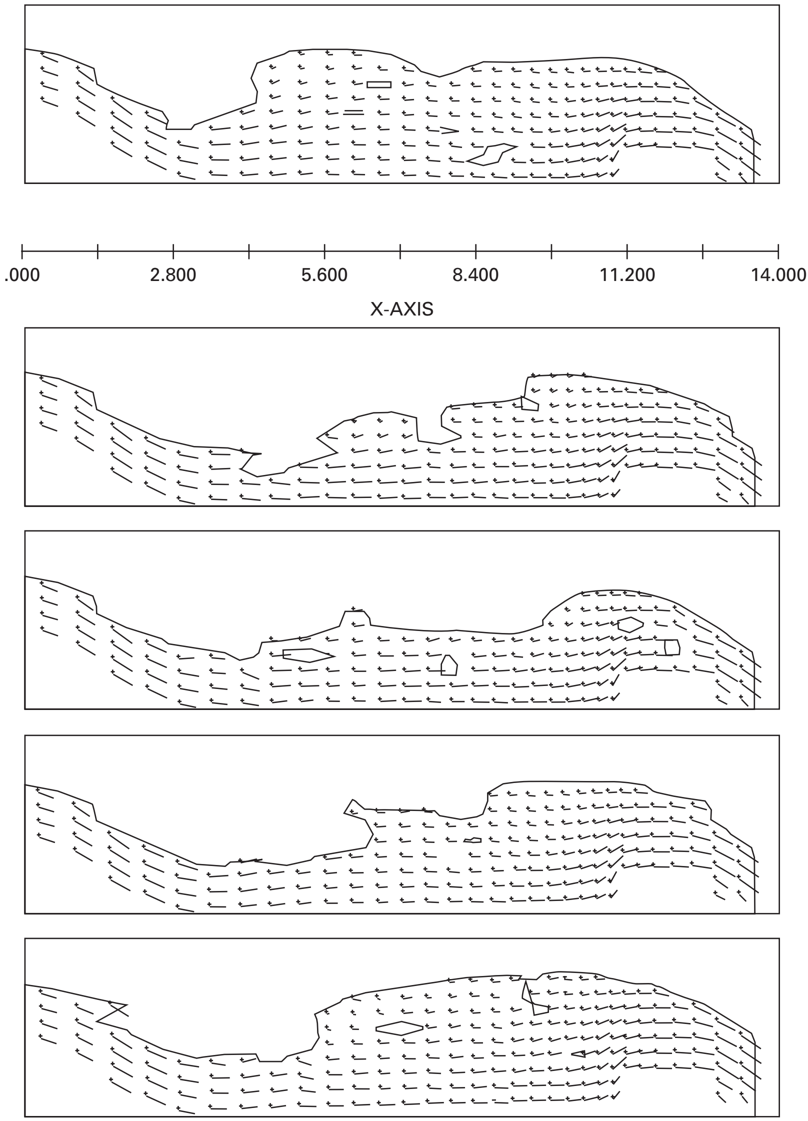

Figure 1.8.4. Unsteady hydraulic jump located at the end of the canal. The elevated water height caused by the hydraulic jump is sufficient to distribute water to surface canals supplying adjacent field systems.

from station N to G facilitates stabilization of the jump position. Although the canal may be used for lake drainage through the distal end of the main canal and the secondary canal, the use for agricultural purposes is more likely given the field systems adjacent to the urban core of the site. If a drainage use were to be the prime function of the main canal, then a shallower canal to a low-lying drainage area would be a better design. However, no connection to a low-lying drainage gully has been located as the canal ends abruptly at station K. Since post-jump water is at low velocity, a network of surface secondary feeder canals emanating from different locations off the main canal can be selectively activated to shunt water to a complex network of tertiary irrigation canals feeding local agricultural fields.

The practical operation of the Miraflores Canal design is illustrated in Figure 1.8.4. This figure shows a supercritical flow down a hydraulically steep chute encountering an obstacle similar to the end wall of the Miraflores Canal. The resulting hydraulic jump elevates the water height (as a function of the incoming supercritical Froude number) such that water can reach elevated offtakes located towards the end of the canal directed towards

Figure 1.8.5. Hydraulic jump from a supercritical flow encountering an obstacle.

agricultural field systems. Figure 1.8.5 illustrates the unsteady nature of the turbulent hydraulic jump for high Froude number flows.

In summary, the canal design indicates an elegant solution to minimize excavation labour while providing low-speed outflows to secondary feeder canals to irrigate field systems. The canal may function either as a drainage canal to maintain the lake at a prescribed height or, its main purpose, to supply agricultural water to the adjoining field areas. A blockage of the canal has been observed at station S and is related to a post-use phase of the canal. The blockage may have served as a barrier to regulate lake level to prevent lakeshore settlements from inundation during the rainy season. Since the lake has no natural outlets and collects runoff rainwater, this may be an alternative function of the canal beyond agricultural use.

The Miraflores Canal shows signs of sophisticated hydraulic control mechanisms. It represents an example of an early New World technological development well before the official discovery of similar hydraulic principles in the 19th century.

1.9 TECHNICAL TRANSFER CONSIDERATIONS

For Old World technical transfer, extensive trade networks facilitated the exchange of ideas and practical knowledge over vast distances. In this manner, technological advances from different locations were available and transferable, depending on their use to other civilizations. Other paths of technical transfer, perhaps best demonstrated by the Romans, related to state-developed technologies exported to conquered territories to demonstrate the benefits of alignment with Roman civilization. The Roman city architectural template (baths, theatre, stadium, temples, amphitheatre, fountains, gymnasia, water distribution system, market areas, and library) attest to standardized city planning exported to far corners of the empire. Yet further paths related to rapid absorption of military technologies between contesting civilizations in order to equalize chances in combat. An example from the Roman world is the origination of Roman combat fleets, where none existed before, resulting from the Punic Wars in late centuries BCE. While such transfers were related to civilizations in contact through trade, military conquest, or territorial proximity, the New World presents a different perspective: largely isolated civilizations dominating vast, but unique, ecological zones separated by natural barriers (mountains, deserts, altitude, distance) developing technologies primarily tailored to their particular needs using materials readily available within their control areas. Unlike Old World Mediterranean-based civilizations that superimposed new renovated cities and settlements on those of previous occupiers, New World cities were sited for convenience to resources, trade routes to their colonies, and defensive terrain but frequently without substantial contact to other societies outside of their domain. Sites were continuously occupied until abandonment, with architectural canons derived only from cultural phases of that society.

New World cities, therefore, present a unique record of development from successive generations of controlling ruling elites over the centuries of site occupation. When new areas were conquered, new administrative centres appeared bearing the imprint of the dominating society rather than reoccupation of cities built by the conquered society. New World civilizations, geographically distributed over the vast areas under their control, remained relatively isolated from other civilizations and each had its own sphere of influence. Each civilization apparently developed agricultural techniques specific to the ecology of the area under their control, with relative isolation from other societies. For cases for which a dominant society was bordered by militarily weak neighbours with substantial water and agricultural land resources, but without the ability or population size to defend them, the inevitable followed, with incorporation of more lands, peoples, and water resources into the expansive empire. Many examples of this exist in the South American New World: the LIP Chimú conquest of the northern Peru coastal valleys from Jequetepeque to Lambeyeque in the 12th to 14th centuries CE (Shimada 1990; Topic 1990), the EIP Moche conquest of northern and southern Peruvian coastal valleys from Nepeña to Jequetepeque in the 3rd to 5th centuries CE, the LH Inka conquest of all of coastal and highland societies of (present-day) Peru, Bolivia, Ecuador, and parts of Chile and Argentina in the 14th to 16th centuries CE, the MH Wari occupation (perhaps by conquest, perhaps by cultural assimilation) of the north Peruvian coast in the 8th to 9th centuries CE, and the Tiwanaku conquest of lands extending far from the capital city of Tiwanaku (60 km from the modern Bolivian city of La Paz) in the 6th to 10th centuries CE, among others.

Aside from incidental trade between contemporary civilizations that may share a border, technical transfer of agricultural strategies and techniques usually occurred when conquered territories contained exploitable agricultural lands similar to those of the conquerors. For these cases, agricultural technologies need only be exported rather than invented. In extreme cases related to Inka conquest of vast territories containing different ecological zones, entire segments of a conquered population were moved, under the direction of the conquerors, to newly conquered parts of the empire to expand the agricultural resource base of the empire. In this particular case, there was usually no effort to match the transferred population's agricultural technologies with their new ecological settings. Since locally tailored agricultural systems were in place for the vastly different ecological zones characterizing the Andean world (coastal valleys, dry inland and coastal deserts, rainforest zones, high-altitude altiplano zones, mid-altitude uplands, and high mountain terrain, each with different rainfall and runoff levels), few technologies applicable for one ecological zone applied to another zone. For the Inka Empire, it was more advantageous to move people from one ecological zone to another to exploit a productive agricultural method than to transfer non-applicable technologies between regions.

With this background, it appears that at least one means of technical transfer in the New World by the LH Inka was quite similar to that of the Roman Empire: the forced imposition of the template of a dominant society over the conquered territories and peoples, particularly in the creation of regional administrative centres for oversight and control of newly acquired resource bases. For the MH Wari and Tiwanaku expansion into new territories, influence appears to be spread by cultural assimilation although a military backup was certainly present as a coercive influence. While New World societies recognized they could transfer their agricultural template to similar ecological areas obtained by conquest, Old World societies were more likely to exploit the benefits of a conquered territory by maintaining existing agricultural patterns. For example, the Chimú expanded into other coastal valleys (but not into the highlands) that permitted use of canal irrigation while Roman extra-territorial expansion preferred extraction of food resources as tribute from conquered territories. Where the Inka expanded into unfamiliar ecological zones, the speciality agricultural practices of that zone were usually minimalized and the population resettled to areas to exploit highland agricultural practices. Some reuse of field systems of Inka-occupied territories is noted in coastal environments in the Lambeyeque and Moche Valleys using canal irrigation, but the post-conquest scale of reuse is much smaller than previous usage, mainly because of population resettlement and transfer of agriculturalists to other areas. A similarity between the Roman and Inka civilizations to win the minds of assimilated territories was demonstrated by increased living standards to balance the loss of autonomy, to balance tribute paid with benefits gained. This demonstration usually involved expansion of urban water resources as a well-appreciated and easily recognizable contribution to urban living standards.

With respect to technical transfer within the Andean world, 5000 BCE contour canals excavated in the Zaña Valley (Figure 1.1.1) indicate slopes in the order of 0.001. This indicates that technology was in place to survey and construct near-level contour canals in very early times, although detailed knowledge of how this was done is unavailable. Since canal technology is the basis for later expansion of irrigation agriculture on the Peruvian north coast over the next 6.5 millennia, elements of surveying that implied an understanding of angle measurement and length must have been developed from very early origins. Some transfer of angle measurement technology on planar surfaces existed in the Nazca Lines area of southern Peru (300–650 CE), where long, straight lines have accuracies of 0.1° or less over many kilometres length. Angle measurement capability existed as standard practice in later Andean civilizations utilizing canal technology, and slopes in the order of 0.001 to 0.01 were commonplace in 3000 BCE Preceramic Period Caral, MH Tiwanaku and LIP Chimú canals. It is probably accurate to say that some technical transfer means related to surveying practice occurred between Andean societies throughout the ages, although details of transfer paths and surveying devices are largely conjectural compared to Old World surveying technology, about which much is known (Lewis 2001). Canals observed in the Moquegua Valley of Wari, Tiwanaku, and, to a lesser degree, Inka origin reflect the use of precision surveying and measurement techniques. Of major interest is a Tiwanaku canal proceeding from the Tiwanaku River and flowing into raised field systems adjacent to the site of Tiwanaku. This (now destroyed) contour canal had the lowest slope encountered in all surveys over all societies in ancient Peru: the measured slope is in the order of 0.001 and the canal proceeds through excavated hills and contains fill sections over shallow gullies. The Tiwanaku canal cross-section is large (about 10 m wide), as expected for the shallow slope, and maintains a shallow parabolic cross-section of maximum width 4 m throughout part of its length. Flow in this canal is subcritical with a low *Fr* value and requires a very large cross-section to transfer water to field systems located towards its distal end. Immediately adjacent to this canal is a natural canalized quebrada that brings spring water from distant mountains into the Tiwanaku River, thus immediately adjacent canals have water flowing in opposite directions! This very low-slope canal is indicative of vastly superior surveying technology developed by the Tiwanaku probably in the 600–1000 CE time period and precedes Chimú developments on the north coast that are generally associated with slopes some 10 to 100 times higher, according to the needs of their agricultural fields system topography. As a comparison to Old World surveying accuracies, slopes of 0.0006–0.0007 have been recorded in the 324–421 CE Roman construction (with later Ottoman extensions) of the aqueduct to Istanbul over a 242 km distance (Çeçen 1996).

As for technical transfer within Andean societies, early great trench canal systems on the Peruvian north coast are found in the Moche Valley associated with the EIP Moche site and most probably derived from earlier occupations. These trenches (now existing only in segments) probably served as drainage canals to protect fields from heavy rainfall events. These canals were excavated trenches about 3–4 m deep and 10 m wide and show similarity to the Sicán Taymi and Racarumi Canals of the Lambeyeque Valley constructed and modified from early Sicán (600 CE) to Chimú/Inka occupation, terminating in 1530 CE. The excavated trench construction bears similarity to an aqueduct at Cañoncillo in the southern regions of the Jequetepeque Valley, presumably made by the Moche prior to 600 CE. Thus a trend of deep canals cut into easily excavated valley soils appeared to extend from early to late Moche EIP periods as the preferred canal system type (although aqueducted canals also appear in the Chicama Valley). Advances in canal system design appear, perhaps due to advances in surveying as well as increases in available labour for larger scale projects, in late Moche and Sicán canals. These canals are low-slope contour canals and later branches of the Racarumi also appear to be contour canals of low slope indicating that some form of surveying was common practice throughout Peru from times dating back to Zaña Valley 5000 BCE canals. The concept of interconnecting river valleys and shunting water from one river valley to another and diverting rivers to new agricultural lands was certainly established by the Taymi and Racarumi canals and the construction of other intervalley canals in the 800–1400 CE time frame and served to illustrate the massive scope of projects made possible by advances in hydraulic technology and surveying together with large labour resources. All these mega-canals have low slopes requiring large cross-sections to provide tailored flow rates to match field system irrigation requirements. Thus from early Zaña contour canals to intravalley great trench canals to low-slope, terraced canals at Caral to intravalley contour canals to massive intervalley canals extending agricultural areas within and into adjacent valleys, the path of development of canal technology appears linear with time.

With the Chimú, a revolution in hydraulics technology occurred. An apparent discovery that canals of a given average slope and cross-section can be designed to provide the maximum possible water flow rate began to dominate canal designs. Where bedrock obstacles or topographic constraints limit slope, knowledge of the relationship between bed slope, wall roughness, and canal cross-section were applied to optimize canal flow rate and flow stability by local changes in these parameters. The variability in canal cross-section and side wall roughness observed in a section of the Chicama–Moche Intervallley Canal is clearly a response to slope and topographic limitations and is directed towards maintaining Froude number in a selected range. Although the Taymi and Racarumi canals and their multiple branches are contour canals, insufficient geometric data exists on these canals to establish if the Sicán used this technological advantage in their canal designs; tectonic and seismic ground distortion is also a problem in establishing the original slope of these canals. A similar statement may be made of later Inka and Wari highland canal systems as little research data exists to conclude that coastal technical hydraulics knowledge was assimilated into highland societies that relied on canal-supplied terraces. The Wari canal to Pikillacta (outside of Cuzco) is a contour canal, contains multiple aqueducts, and maintains a low slope over a vast length and may be indicative of a technical transfer process, although further study of its characteristics remains to be done.

With Chimú advances in hydraulics technology, use of energy-dissipation structures came into use. The Jequetepeque aqueduct system is a realization that resistance elements placed into a stream can reduce water velocity: for supercritical streams ($Fr > 1$) this is manifested through a hydraulic jump that converts kinetic into potential energy with energy losses by turbulent dissipation and water height change; for subcritical flows ($Fr < 1$), wall shear and turbulent energy dominate energy loss mechanisms. Prior to Chimú use of this technology, use of boulders scattered in steep-slope chutes in the Moquegua terraces areas by Wari and Tiwanaku agriculturalists indicated the use of resistance elements to slow water flows. Use of convoluted canal paths in the uplands of Cajamarka for EH canals (the La Cumbre Canal above Cajamarca in particular) may be an example of resistance increase by successive right-angled turns in the canal to slow water flow velocity, although this canal's convoluted path is most frequently attributed to EH ceremonial functions. In the Tiwanaku region, the Lukurmata aqueduct is an example of a self-adjusting canal bed that self-modifies by streambed erosion to create an optimum, low-resistance canal profile to permit large flow rates without hydraulic jump formation. Similarly, the Pajchiri aqueducted canal has shape change effects used to produce height changes in the water stream to activate drop structures. Although there are few examples of Tiwanaku canals, the few in existence indicate some knowledge of cross-sectional shape changes on water flow heights over both subcritical and supercritical flow regimes. Although the Tiwanaku preceded the Chimú by several hundred years and no obvious connection between these cultures has been established, some diffusion of technical knowledge may have been passed along in some manner to reappear, in more sophisticated form, in later cultures.

In summary, the picture is one of very early contour canals with the earliest known (Preceramic) developments in the Zaña Valley (Dillehay *et al.* 2006) and Supe Valleys followed by great trench systems that may have early Moche, EH or EIP origins. Several great trench canals are found in the northern reaches of the Moche Valley extending towards the Chicama Valley. These canals may be a very early attempt, perhaps by EH or EIP (or earlier) valley occupants, to interconnect, or at least extend, river systems into other valleys to increase agricultural lands (or provide drainage systems to limit flood damage). While it is interesting to speculate that the later Chimú Intervalley Canal derived its basic design concept from, and is a precursor to, these earlier versions, more remains to be done to substantiate this claim. After great trench and similar large-scale canals, the Chimú advances in hydraulics knowledge permitted the tailoring of flow rates from the Intervalley Canal to match an existing Vichansao canal flow rate acceptance value. This indicates a mastery of flow rate prediction and control by some lost knowledge base. The picture then is one of a steady development of hydraulics knowledge by successive but largely independent societies increasingly dependent on irrigation agriculture to feed increasingly larger populations. Finally, later Inka developments must in some way select technologies applicable to their needs to continue agriculture in subject lands but on a smaller scale than before occupation. Inka extensions of Lambeyeque canals are probably made possible by surveying accuracies that could include more lands downhill from shallower canal slopes. While the Inka have centuries of technical developments at their disposal, more research is needed to make the necessary connections to show how technical transfer was done.

To conclude, the forward path of hydraulics knowledge through societies and centuries can only be demonstrated by the appearance of certain characteristics that seem to improve the technologies of prior centuries. While invention of the same knowledge is certainly possible in different societies, the fact that a steady improvement in techniques over societies and centuries implies that cultures interested in irrigation agriculture were keenly aware of the lessons of the past and lessons from any other successful agricultural system encountered. Even the abandoned fields of previous societies contain lessons related to the effects of climate and design decisions that helped or hurt the survival chances of predecessor civilizations. All these lessons are in the archaeological record waiting for future researchers to discover and place the South American experience into its proper place in the history of technology.

2

The Ancient Middle East

2.1 THE WATER SUPPLY AND DISTRIBUTION SYSTEM OF THE NABATAEAN CITY OF PETRA (JORDAN), 300 BCE–300 CE

Introduction

The origins of Nabataean Petra began *c.* 300 BCE from nomadic settlement origins and extended to later Roman administration of the city at 106 CE with final Byzantine occupation (Basile 2000) to the 7th century CE. Trade networks that extended throughout much of the ancient orient and Mediterranean world intersected at Petra and brought not only strategic and economic prominence but also the impetus to develop water resources to sustain increasing population and city elaboration demands. City development was influenced by architectural, cultural, and technological borrowings from Seleucid, Syro-Phoenician, Greek, Roman, and Far Eastern civilizations. The city water distribution system utilized many hydraulic technologies derived from these contacts that together with original technical innovations helped to maintain a high living standard throughout the centuries. Analysis of Nabataean piping networks indicates that design criteria were employed that promoted stable flows within piping, employed sequential particle settling basins to purify potable water supplies, promoted open-channel flow within piping at critical (maximum) flow rates that avoided leakage associated with pressurized systems, and matched spring supply rates to the maximum carrying capacity of pipelines. This demonstration of engineering capability indicated a high degree of skill in solving complex hydraulics problems to ensure a stable water supply and is a key reason behind the many centuries of flourishing city life.

Historical perspective

Because of Petra's location between Egyptian, Babylonian, and Assyrian territories, many exterior influences dominated the Nabataean cultural landscape over time. The sacred spring created by Moses, as described in Exodus accounts, has been equated with the Ain Mousa spring outside of Petra although controversy exists as to its location (and historical accuracy) with contending Sinai sites. Biblical and Koranic references to areas around Petra relate to the use of water channels and springs by the inhabitants to maintain agriculture and settlements; Assyrian texts ascribed to the Sargonic era (715 BCE) mention tent cities in this area. The earliest proto-Nabataean period (6th century BCE) is derived from Edomite agriculturalists assimilating with nomadic tribal groups familiar with caravan-based trade activities.

Although the origins of the Nabataeans remain controversial (Gleuck 1959, 1965; Taylor 2001; Guzzo and Schneider 2002), their final consolidation in areas around Petra in the early 3rd century BCE is evident from the archaeological record. Following conquest by Alexander and later division of empire, conflicts arose between Nabataeans, Antigonus of Macedonia, and Ptolemaic forces for control of the lucrative trade routes passing through Petra. With the decline of Seleucid and Egyptian influences, a Nabataean state emerged in 64 BCE after King Obodas I (*c.* 96–85 BCE) reversed Alexander Janneus' occupation of Gaza (97 BCE). Despite successful territorial wars by King Aretas III (84–61 BCE), Roman intervention began when Scaurus, an envoy of Pompey, sided with Nabatea's enemies to defeat Aretas in battle (64 BCE). With Rome declaring the province of Syria under its control, Nabataean-controlled areas were subject to Roman invasions under Scaurus (62 BCE) and Gabinius (55 BCE). Despite the tumultuous political climate over the centuries, Nabataean political wisdom prevailed to maintain the establishment of an important trading empire with Petra as the main administrative, commercial, and religious centre. A series of Nabataean kings (Aretas I *c.* 168 BCE, Aretas II 120/110–96 BCE, Obodas I 96–85 BCE, Rabbel I 85/84 BCE, Aretas III 84–61 BCE, and Obodas II 62–58 BCE) ruled in Petra with expansion of commerce and urbanization driving the city's increasing water needs. Apparently, Nabataean acquiescence to the inevitability of Roman dominance and the commercial advantages of trade made possible with territories consolidated under Roman rule outweighed any advantages that could be gained from resistance and independence. A series of post-Augustan Nabataean kings (Obodas III, Aretas IV, Malik II, and Rabbel II) next determined the history of the area with various regional alliances and wars in the period 30 BCE to 106 CE. The city experienced Roman control under Tiberius, Caligula, Claudius, Vespasian, and Hadrian with administrative consolidation and territorial status change characterizing Roman dominance. Now allied to Rome, Nabataeans under King Malichus were participants in suppressing Jerusalem (Josephus 1960) in 67 CE, ending longstanding rivalry with the Jewish kingdom. Rabbel II (70 CE) then ushered in independence under Roman ally status that permitted Petra to continue its trade-based prosperity. Following a tour by Hadrian, Petra was formally annexed into the Roman Empire under Trajan.

Throughout this period, caravan trade from Arabia, Africa, and the Far East, with Petra as a key intersection node, sustained the city's wealth and supported the construction of commercial, ceremonial, administrative, manufacturing, and water supply structures commensurate with the city's wealth and status as an emporium city. Under Roman governance of the Syrian Province, the Nabataeans enjoyed relative independence, perhaps related to the trade-based tax and tribute revenue contributions to Rome. Wealth generated from trade routes and protection taxes from caravans to Cairo, Gaza, Damascus, Palmyra, Jauf, Median, Madain-Salih, and Far Eastern locales came under the final dominance of Rome. The gradual shifting to sea trade routes (Taylor 2001) led to final reduction of Petra's status as an overland trade centre with Palmyra replacing Petra for caravan traffic from Silk Road destinations. Following Arab occupation after the collapse of the Byzantine Empire, the city faded from view until European rediscovery in the 19th century. Further historical expositions (Gleuck 1959, 1965; Hammond 1973; Browning 1982; Bowersock 1983; Homès-Fredericq and Hennessy 1986; Joukowsky 1998, 1999, 2001; Bourbon 1999; Levy 1999; Auge and Denzer 2000; Taylor 2001; Guzzo and Schneider 2002) detail the many cultural, architectural, political, and developmental influences the city experienced over many centuries of existence.

Historical background of Petra's water management

From this brief account of Petra's history it is clear that many exterior cultural, political, and technological influences coloured the history of the city. Consequently, the water supply system may be expected to reflect borrowings from the best civil engineering practices of neighbouring civilizations (Payne 1959), influences from different occupations, and innovations derived from the demands of the complex topography and limited water resource base of the area. Innovations derived from the past history of desert water conservation measures transferred to the systems required in an urban setting are to be expected given the past nomadic history of the Nabataeans. As to archaic sources of water transport technology passed along through the ages, Egyptian, Mesopotamian, Minoan, and Greek civilizations all utilized piping and open-channel systems for water supply and wastewater drainage. As examples of technologies available from the historical record, the Temple at Knossos (Crete) at 2100 BCE incorporated systems of conical, interlocking, terracotta piping elements in the main palace water system; later, the Hellenic Temple of Artemis (Turkey), dating to 800 BCE, incorporated strings of socketed, mortared-together, terracotta pipe elements (Figure 2.1.1) as well as lead pipe segments joined by stone connectors to transport water from nearby springs (Figure 2.1.2). The Hanging Gardens of Babylon, during the reign of Nebuchadnezzar (605–562 BCE), incorporated high-level reservoirs from which water was delivered to terraces and fountains through terracotta pipelines. Egyptian copper and brass piping systems associated with 5th Dynasty Temples at Abusir form part of the temple drainage systems to the Nile. Early urban Athens water supply in the 6–7th centuries BCE, as well as pressure pipe systems at Olynthos, incorporated interlocking, terracotta piping segments sealed by mortar while the Ionian city of Priene (Turkey) in the 3rd century BCE contained elaborate terracotta piping networks complete with filtration systems to purify water prior to distribution to city fountains (Ortloff and Crouch 1998). With the importation of new learning from years of trade route activity to many corners of the ancient world, many sources of hydraulics knowledge were available; the observation that archaic piping types were similar to those excavated at Petra is further verification that previously established technologies from surrounding civilizations were part of the Nabataean engineering repertoire. An initial example of the Nabataean ability to learn from prior water transport technologies was attested by the 27-km long Humeima canal from springs in the Sharma Mountains to a Wadi Rum outpost attributed to Obadas I (96–86 BCE) (Taylor 2001). This subterranean canal indicated that very low-angle surveying technology was understood in early times, perhaps a borrowing from Greek and Roman geometric traditions (Cohen and Drabkin 1966; Lewis 2001) combined with a hydraulic knowledge base from earlier sources necessary to design a canal that matched

Figure 2.1.1. 800 BCE ceramic piping elements from the Greek Temple of Artemis near Ephesos. Top holes indicate that piping contained partial open channel flow in its interior.

Figure 2.1.2. Piping elements associated with early phases of the Temple of Artemis. Lead piping segments have a wall thick ness of 6.4 cm and are joined by stone toroidals.

spring output to canal carrying capacity. These examples indicate that while knowledge of supply and drainage piping systems was widespread in archaic times, initial usage was mostly associated with elite civil and temple structures; canal building technology, on the other hand, was widespread throughout the ancient Middle East and primarily used for agricultural purposes. Gradually extension to city-wide piping networks evolved based on distribution of water to different centres of urban population—a technological advance that reached its potential in later Roman cities where branch piping extended into individual living quarters. An early technology base utilizing pipeline and canal systems as key water transport components existed well before Nabataean times and was surely available to aid in the conceptual planning and development of Petra's water system.

Contemporary with late phases of Petra's urban development, contact with cities benefiting from the Roman revitalization of water supply systems

(Crouch 1993; Ortloff and Crouch 2001) undoubtedly accelerated knowledge of city-wide water system potentialities that could be incorporated into Petra's water system design. The limited water resources (springs and rainfall capture) and the mountainous terrain of the Petra area meant that old ideas required new thinking to produce a city water system that provided constant, year-round water supplies given seasonal rainfall and spring rate variations. The story to be told here relates to the archaeological record of Nabataean solutions to water supply problems associated with large urban population demands. Again, recourse to computer simulation of hydraulic phenomena within ancient piping systems is used to reveal the engineering knowledge underlying Nabataean pipeline design and water management solutions and is instrumental in revealing their contributions to the hydraulic sciences.

The Petra water supply and distribution system

To begin the discussion of water system development and progress toward utilizing all possible water resources to meet increasing population demands, Figure 2.1.3 shows details of the supply and distribution system leading water to the urban core of Petra. Numbered locations denote the major buildings, temples, and site features listed in the Appendix. Shown are major dams (–d), cisterns (c), water distribution tanks (T), and springs (s). Dams denoted d are minor catchment structures that either stored water in mountainous areas to prevent its descent to the Petra basin and/or have channels to larger cisterns below. The superimposed grid system (A, B, C; 1, 2, 3) defines an area coordinate system composed of 1.0-km^2 grid boxes to enable the approximate location of the various features mentioned in the text. The d dams located in mountainous areas are local blockages to trap water for storage and to limit rainfall runoff from entering the lower areas; the –d dams located across streambeds are traditional barrier structures meant to hold larger quantities of water.

Petra's urban core lies in a valley surrounded by high mountainous terrain (Figure 2.1.3). Seasonal rainfall runoff passes into the valley through many canyon streambeds (wadis) and drains out primarily through the Wadi Siyagh (A2). Sources of runoff are mainly from watersheds directing water to three individual wadis: Wadi Mousa, Wadi El-Jee to the north, and Wadi Al Hudayb to the south. The combined runoff led to water flows of substantial depth entering the Siq entrance area (D1) during the rainy season. The Siq is a 2-km long narrow passage through the high mountain range bordering the eastern part of the city core area; the steep, canyon-like walls of the Siq provide nature's preface to the architectural masterpieces ahead in the city centre.

Early phases of urban Petra relied on open-channel water delivery from the Ain Mousa spring external to the city along a direct path through the Siq (Figure 2.1.3); the water channel entered into the urban core of the city before exiting into Wadi Siyagh. This early system can be observed in part as a lower

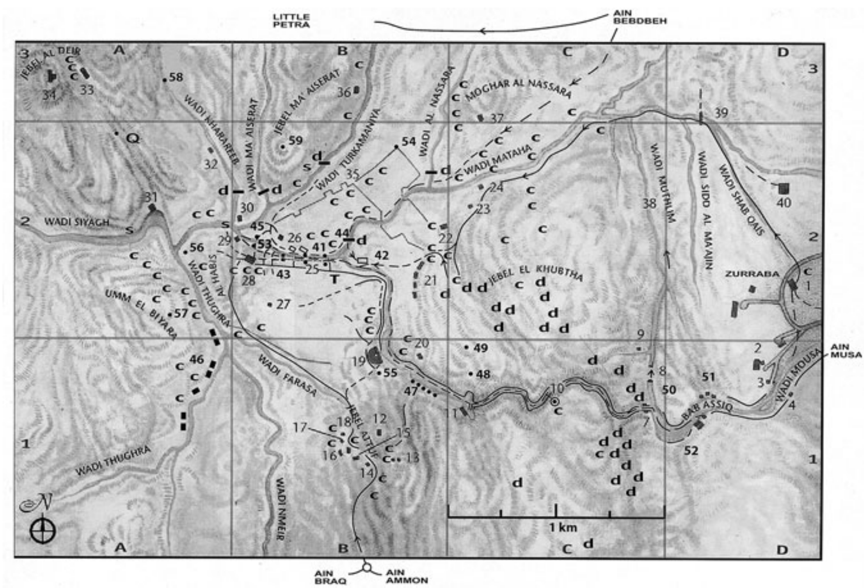

Figure 2.1.3. Map of the Petra area showing site features. 1, Zurraba reservoir (al Birka); 2, Petra forum rest house (modern); 3, park entrance (modern); 4, hospital (modern); 5, Dijn monuments; 6, obelisk tomb and triclimium; 7, entrance elevated arch; 8, flood bypass tunnel and dam; 9, eagle monument; 10, Siq; 11, treasury (El Khasneh); 12, high place; 13, dual obelisks; 14, lion monument; 15, garden tomb; 16, Roman soldier tomb; 17, renaissance tomb; 18, broken pediment tomb; 19, theatre; 20, Uneishu tomb; 21, royal tombs; 22, Sextius Florentinus tomb; 23, carmine façade; 24, house of Dorotheus; 25, Colonnade Street (Cardo); 26, Temple of the Winged Lions; 27, Pharaoh's column; 28, great temple; 29, Q'asar al Bint; 30, new museum (modern); 31, quarry; 32, lion triclinium; 33, El Dier; 34, 468 monument; 35, north city wall; 36, Turkamaniya tomb; 37, Armor tomb; 38, little Siq; 39, aqueduct; 40, Al Wu'aira crusader castle; 41, Byzantine tower; 42, nymphaeum; 43, paradeisos, market, Hadrian's gate; 44, Wadi Mataha dam; 45, bridge abutment; 46, Wadi Thughra tombs; 47, royal tombs; 48, Jebel el Khubtha high place; 49, El Hubtar necropolis; 50, block tombs; 51, royal tombs; 52, obelisk tomb, snake monument; 53, Columbarium tomb; 54, Conway tower; 55, tomb complex; 56, convent tombs, crusader fort; 57, tomb complex; 58, pilgrim's spring; 59, Jebel Ma'Aiserat high place; 60, snake monument; 61, Zhantur mansion.

open channel that appeared on the north wall of the Siq and interior portions of the city with access to the street level that existed at the time of its use (portions of this channel were reused in later times to support piping elements and many sections are buried by later road constructions and modern Siq road renovations (Bellwald 2003)). Use of this early water supply system required diversion of intermittent rainfall runoff from the Wadi Mousa River by a dam and tunnel construction (8, Figure 2.1.3) and construction of an aqueduct passing over the dam to supply the Siq channel by Ain Mousa water. Later urbanization phases revealed an integrated approach to site water system construction and management as demonstrated by new features that appeared in the archaeological record: surface cisterns to capture rainfall runoff, deep underground cisterns, multiple pipeline systems and storage reservoirs, floodwater control through diversion dams and tunnels, supply system redundancy to ensure water delivery from multiple spring and reservoir sources, and pipeline sand-particle filtration and removal basins. These later modifications reflected the need to bring potable water into the city core at higher elevations to serve hillside occupation zones above the valley floor. Since the lowest level Siq open channel ran along a path paralleling the lowest elevation Wadi Mousa riverbed, its ability to supply water to outlying urban zones above the riverbed was limited. These later changes of the Petra water system demonstrated the continual evolution of the urban water supply system through time and reflect the application of acquired technologies from archaic and/or exterior sources, integrated with indigenous hydraulic innovations, to provide for the increasing water needs of the city.

The means to capture and store a fraction of the rainfall runoff through dams and cisterns, to build flood control systems, to build pipelines and channels to deliver water from distant springs, and to manage these assets to provide a continuous, year-round water supply to the city is key to understanding Nabataean contributions to hydraulic science. While water storage is a partial key to the city's survival, springs internal and external to the city (Figure 2.1.3: Ain Mousa, Ain Umm Sar'ab, Ain Braq, Ain Dibdiba, Ain Ammon, al Beidha, and Ain Bebdehbeh) supplied water channelled and/or piped into the city to provide the main water supply to the urban centre. The complexity and ingenuity of the water supply systems in Petra was commented on in antiquity (Strabo in translation 2000) as a remarkable achievement given the apparent lack of traditional water resources available in that geographic area. Strabo's commentary '... and the inside part of the city having springs in abundance, both for domestic purposes and for watering gardens ...' reaffirms that springs were a vital part of the water resources of the city. The main Petra water supply originated from the Ain Mousa spring about 7.0 km east of the town of Wadi Mousa (D1, Figure 2.1.3) combined with waters of the minor Ain Umm Sar'ab spring; this supply still serves the modern town and the associated tourist complex (2), and administrative buildings (3) located outside of the Siq entrance (10).

In early phases of Nabataean urban development pre-dating major tomb construction and construction of pipeline systems, the main potable water supply derived from an open channel transporting Ain Mousa spring water through the Siq (D1 to C1). This channel (dashed line, 29, B2, Figure 2.1.3) extended through the urban core of the city possibly as far as Q'asr al Bint (29) with final drainage into the Wadi Siyagh (A2). Because of dam and flood bypass tunnel construction at the Siq entrance together with infilling and paving of the Siq floor both in ancient and modern times to reduce flooding episodes, parts of the channel now lie under the pavement surface attributed to construction under Aretas IV and later Roman paving efforts. Largely due to accumulation of flood debris resulting from site abandonment for many centuries, in addition to modern attempts to dam and infill the front entry of the Siq to limit floodwater incursion into the urban core of Petra from Wadi Mousa runoff events, this channel is largely buried under the current level of the road through the Siq. Recent excavations in front of the Treasury (11, C1) have revealed remnants of this early open channel as well as an early tomb cut under the Treasury, indicating its role as a mausoleum for the Aretas dynasty. Hexagonal paving slabs and a water basin existed (Taylor 2001) in front of the Treasury location in this early phase as current excavations confirm.

While this channel provided water to early, low-population phases of the city, the later concentration of urban settlement areas north and south of Wadi Mousa (B2), replete with temple, administrative, commercial, and civil structures, indicated a transition toward full city status with a developing hierarchical, stratified, and cosmopolitan society involved in trade and commerce. With demands to increase water supply and distribution to spreading urban settlement areas resulting from population increase and perhaps a desire to match the city's prosperity from trade with an appropriate elevation in symbols of success, extensive use of pipelines followed to bring larger amounts of water to areas not reachable by the old, low-elevation, open-channel system. Pipeline systems, however, introduced new hydraulic design complexities that involved knowledge of ways to maintain stable piping flows whose maximum (theoretical) transport flow rate matched (or exceeded) the spring flow rate input.

Flows in poorly designed pipeline systems are capable of a number of transient, self-destructive hydraulic instabilities (water hammer, transient pressure waves, flow intermittency, internal oscillatory hydraulic jumps, turbulent drag amplification zones, and vapour pockets), and analysis of technical solutions to problems of this type provide insight into the Nabataean hydraulics knowledge base. Equally critical problems involving reservoir and cistern water storage/release timing and an understanding of the management strategy of these assets are further paths to understand Nabataean strategic thinking. Pipeline routing from springs through rugged, mountainous terrain required technical parameters that govern the piping carrying capacity necessary to match a spring flow rate. The choice of these parameters and related ways to resolve destructive hydraulic phenomena, as extracted from archaeological survey, then decide the level of technical achievement of Nabataean engineers.

As an example of technological advances, a reservoir at Zurraba (1, D2, Figures 2.1.3 and 2.1.4) was constructed to store and transmit water along the Wadi Shab Qais (D2) around the northern flank of the Jebel el Khubtha mountain (C2) in an elevated channel (D3, 40) containing piping that continued over royal tombs to supply a large basin at its terminus. This reservoir may also have served a ceramics workshop community. The system was previously characterized (Bourbon 1999) as a supplemental water supply line into the city's urban core. Descending channels from the pipeline to multiple cisterns at the base of the mountain provided water for housing needs, workshop areas, and celebratory rituals at nearby tomb complexes. While runoff capture was one probable water supply source of the Zurraba reservoir, connection to local spring sources, including Ain Mousa, remains probable for reliable reservoir water charging in the early phase of city development. Although reservoir water could be used to supplement the Siq open-channel flow, later city phases involved shifting Ain Mousa water supplies to a Siq piping system after the earlier open channel was abandoned. In this case, rainfall runoff and spring charging enabled the Zurraba reservoir to supplement Ain Mousa sourced Siq pipeline flows when required. Although modern town construction has obliterated ancient hydraulic connections to and from the reservoir, there is no topographical constraint to a channel path to direct reservoir water into the early Siq open channel (or into a later pipeline system) to provide supplementary water supply. However, despite there being a question over the method of sourcing, the Jebel el Khubtha pipeline appears to be the main outflow path for reservoir water in the area between Jebel el Khubtha and Wadi Mataha (B2, C2). Surplus water, after cistern topping, was most certainly directed to the main city fountain (Nymphaeum 42, B2) through either a pipeline or subterranean channel. Although traces of this connection are unexcavated, some pipeline fragments in the area suggest this connection. From a systems point of view, the Zurraba reservoir served principally to maintain piping terminus, innercity cistern levels by occasional water charging by the Ain Mousa and/or other

Figure 2.1.4. The Zurraba (al Birka) reservoir made from clay bricks; the current height of the enclosing wall is 2 to 3 m.

springs while the Ain Mousa spring provided the steady water supply to the Nymphaeum by piping supported in a channel through the Siq that replaced the earlier open-channel system. The Zurraba reservoir served as a backup system for rapid delivery of large volumes of water on short notice to Jebel el Khubtha cisterns and augmented the continuous, but reduced, water supply to the Nymphaeum from the Ain Mousa spring during dry season periods. The ability to provide an 'on-demand' water supply from this backup system proved most useful to large caravans entering the city that placed a sudden demand on water supply capability.

Pipeline carrying capacity considerations: the Zurraba–Jebel el Khubtha system

While a spring produces a given volumetric flow rate, one limitation on how much can be transported by pipeline relates to pipeline technical characteristics (diameter, internal roughness, slope, supply head and outlet type (free overfall or submerged)). Piping design considerations therefore require the spring output flow rate to match (or be less than) the theoretical carrying capacity of the pipeline. Examination of Nabataean pipeline designs gives some insight into the ability to understand internal pipeline flow phenomena and construct solutions to overcome problems limiting the maximum volumetric flow rate. For an upper-bound estimate of the volumetric flow rate that the Jebel el Khubtha pipeline system could sustain, it is assumed that the surveyed mean slope of ~0.005 of the elevated channel supporting the pipeline corresponds to the critical flow angle (Morris and Wiggert 1972) and the maximum flow height within the piping is at critical depth equal to perhaps 50% or more of the piping diameter. This condition means that water flows in open-channel mode through the piping with an airspace above the water surface and provides an upper-bound estimate for the maximum flow rate possible for given diameter, internal roughness, and slope under free overfall outlet conditions. This type of hydrostatically unpressurized flow reduces leakage from the estimated 30,000 socketed joints along the pipeline length while providing the maximum volumetric flow rate possible for the observed piping design. The flow rate then is critical velocity × piping wetted cross-sectional area. For a mean channel height drop of ~40 m over the 8-km pipeline path around Jebel el Khubtha, the theoretical maximum (critical) volumetric flow rate is about 90 m^3/h for the 23-cm diameter piping, using an estimated internal roughness factor. In practice, because of the many mortared joints between exposed 0.3-m terracotta piping segments along the 8-km piping length, and assuming, for a (very) conservative estimate, a 50% leakage rate, the deliverable volumetric flow rate can be readjusted to ~45 m^3/h. While these estimates are for a critical flow system, good hydraulic practice is to run open-channel flow within piping at lower, subcritical Froude numbers to avoid flow instabilities and unsteady flow delivery (caused by joint/channel wall roughness and sinuosity resistance) and to avoid the transition from partial to full flow that may occur from wall roughness-induced flow resistance. Here lowering flow rate also helps to guarantee maintenance of partial flow conditions. Thus, the deliverable flow rate needs to be adjusted further downwards to produce stable open-channel flow within the piping. For Froude numbers in the order of 0.6–0.8 to prevent unsteady flow delivery rates, and with leakage effects included, a deliverable, conservative lower-bound flow rate ~30–40 m^3/h could then be safely directed toward the Nymphaeum through the Jebel el Khubtha pipeline.

If the Jebel el Khubtha piping system were to function in the full-flow mode typical of very low slopes (i.e. the entire piping cross-section filled), the flow rate would be somewhat less than that from an open-channel, critical flow mode due to internal wall frictional resistance. This observation was made in the early centuries CE (Vitruvius 1999) by his comment that '. . . for a supply reservoir water height, long pipe lengths (containing full-flow) diminish water transport amounts due to [cumulative] internal flow resistance effects . . .'; this statement has been computationally verified (Ortloff and Crouch 2001) to quantify Vitruvius' comment (a discussion of this effect is given in the later chapter on Ephesos). As a further consequence of a piping slope design less than that observed, larger diameter piping would be required to match the spring flow rate. For a steeper slope design, flows become supercritical due to gravitational acceleration and tend to an internal normal depth. Rapid supercritical flows, however, may be subject to intermittent zones of subcritical full-flow caused by internal-piping wall and joint roughness and curvature resistance effects (causing velocity slowing), leading to oscillatory hydraulic jumps that cause pulsations in delivery flow rate at the piping exit. Such transient effects can lead to destructive oscillatory tensile/compressive forces that weaken mortared piping joints. If flow rate pulsations developed from full-flow transient instabilities are transmitted to the supply and an assumed submerged outlet receiving reservoir, then sloshing effects amplify unstable delivery rates because of transient changes in input and exit head that further amplify transient tensile/compressive forces and induce leakage from piping joints. The best piping design to produce a large, stable volumetric flow rate is therefore a partially full (open-channel) flow at near, but below, critical conditions that empties water gently with free overfall into a terminal reservoir, thus maintaining a water surface exposed to air along its entire length. Selection of this piping design is then a measure of knowledge of the hydraulic principles required to achieve steady, high-flow rate delivery to the terminal basin (far left in C2) and explain the high elevation positioning of this pipeline that maintains a low slope around Jebel el Khubtha.

The design of the existing Khubta piping system, given other options for its slope and piping diameter, closely matches best practice as its theoretical maximum carrying capacity lies above the 20–40 m^3/h capacity of the Ain Mousa supply spring and provides the largest possible flow rate from the Zurraba reservoir to meet on-demand large flow requirements. Presumably a branch of the Ain Mousa spring could have been used to maintain the reservoir full for either contingency or continuous flow usage adding to the usage flexibility of the system. Additional benefits from the Nabataean design reside in the presence of partial flow in the piping to reduce leakage compared to a hydrostatically pressurized system. Since particles settle in the reservoir, no particle transport occurs to clog piping—this is important as access to the high-elevation piping (~20 m above the ground) on the near-vertical Jebel el Khubtha mountain face would prevent easy cleaning, particularly along piping segments that are mortared over in the rock-cut holding channel. The combination of all these positive features designed into the Jebel el Khubtha pipeline indicate that much thought and experience went into the best placement and design of this system to achieve the multiple goals that ensured not only system longevity but also rapid, on-demand water delivery capability with minimum leakage. From the Khubtha pipeline to ground-level cisterns, additional piping led to the Nymphaeum fountain to complete the Jebel el Khubtha circuit from the Zurraba reservoir. As the Nymphaeum was a major water supply to the urban core and market areas, much effort went into guaranteeing its year-round functioning from the Siq piping system supplemented, on-demand, by Jebel el Khubtha pipeline flows from the Zurraba reservoir.

Water system redundancies

A number of cisterns and dams on Jebel el Khubtha (C2) (Akasheh 2003) captured and stored rainfall runoff. Some of the upper level cisterns had channels leading to ground-level cisterns that interfaced with urban housing and field areas to the west of Jebel el Khubtha to supplement the north-eastern-quadrant water supply from the Zurraba system. Intermittent springs located on Umm el Biyara (A1, A2) were important in ancient times as the Arabic name for this mountain is translated as 'Mother of Springs'. The early Siq floor open channel was abandoned in late Nabataean phases and replaced by a Siq north wall pipeline system that extended to areas across from the theatre district (B1; Figure 2.1.5) and ended at the Nymphaeum. Thus at least two separate supply lines led to the Nymphaeum to ensure supply redundancy. The construction for the Siq pipeline system is generally attributed to Malichus II or his predecessors, Aretas IV or Obodas III, in the 1st century BCE or early in the 1st century CE (Guzzo and Schneider 2002). Since water demands south of Wadi Mousa (transecting urban Petra) were high due to the nearby marketplace, theatre, temples, and housing districts, and significant water resources were available from northside piping systems, a pipeline transfer connection from the Nymphaeum to this area was a logical use of water for development of this area. As water flow to the urban core was continuously delivered by the Siq system, it is logical that transfer of non-consumed water continued to lower elevations at the site. While a bridge or piping from the northside of the Jebel el Khubtha system in the El Hubtar Necropolis area (20, B2) across the Wadi Mousa may have existed in the vicinity of the theatre (19, B1) to carry water to the southside, traces of a bridge are lost due to extensive erosional flood damage, although platforms are in existence that may be the base of such structures.

In addition to water delivered by the Ain Braq and Ain Ammon piping system (Figure 2.1.3) north of the Siq, the theatre water source could be

Figure 2.1.5. The theatre within Petra's city limits. Capacity is in the order of 7,000 and may have been enlarged in Roman times from an original Nabataean design.

supplemented from large, upper-level reservoirs in the Wadi Farasa area, again indicating supply redundancy from multiple sources. Some of the larger reservoirs appear to function in connection with a spring supply system and are situated to collect seasonal rainwater runoff; reservoir usage, therefore, is mainly to provide water for occasional peak requirements by means of outlet water flow through piping or channel systems. Surface cisterns, on the other hand, appear to be opportunistically placed to collect rainwater runoff to supplement continuous flow sources; other than seasonal rain recharge, the numerous, widely scattered catchments appear to serve local community needs for supplemental supplies of lower quality water when piped water is not readily accessible. Over 200 cisterns of various sizes have thus far been located in the Petra archaeological zone.

Traces of the northside piping system fed by the Ain Braq pipeline and possible reservoir supplies (Figure 2.1.3) are found in front of the theatre (Figure 2.1.6). The Ain Braq system divides into two branches past the Siq exit ending with reservoirs at Ez Zhantur (61) and the Paradeisos water garden (Bedal 1998, 2000). Two parallel pipelines (Figure 2.1.6) supplied by this system continue past the theatre along the ridge (B2) above the commercial district along the Roman Cardo (25), Hadrian's Gate (43) (whose construction is attributed to Aretas IV), upper and lower marketplaces, and the Paradeisos water garden to locations above the Great Temple (Figure 2.1.13) (Joukowski 2001, 2003) where it forms part of the water supply to structures located in B2. The piping system consists of two separate pipelines that indicate one branch line to the Zantur Mansion (61) and another to the lower Paradeisos area; some extension of the upper line probably continues to Q'asr al Bint (29) through the Great Temple area to supply the Sacrificial Altar area (Figure 2.1.7), although no excavations exist to connect the multiplicity of subterranean canals below the altar to a specific water source. Hadrian's Gate (43) separates the secular commercial district from the Western sacred temple district containing the Great Temple, Temple of the Winged Lions (26), and Q'asr al Bint; the gate was reported to have had a gilded door to control traffic between sacred and secular parts of the city. The Paradeisos water garden complex west of the gate consisted of an open house structure situated on a platform island within a large water-filled basin; bridge

Figure 2.1.6. Remnants of the dual piping systems north of the theatre leading to the urban core marketplace (Cardo) of the city.

Figure 2.1.7. Part of the underground channel sys tem in the forecourt of the Great Temple. Lead piping runs at the base of the back wall towards the market place area.

structures connected the island to outer precincts and greenery added to the city's elegance as indicated by reconstructions reported by Bedal (2002). Strabo (2000) mentions that the city '... contains many gardens ...', which is consistent with excavation results. The basin walls contained overflow channels as well as supply piping that may have emanated from both the Nymphaeum piping extension into this area and water from a southside spring supply system. Overflow water from the garden was then directed to lower baths, chambers, or workshops (Browning 1982) and then to a tunnel close to Wadi Mousa before final discharge into the Wadi Siyagh and was indicative of conservation measures to use water in consecutive downhill structures.

Distributed along this piping system are remnants of elevated basins lined with hydraulic plaster (T, Figures 2.1.3 and 2.1.8) that served as receiving basins; earth-fill mound structures extended from these basins to the lower

Figure 2.1.8. Remnant of a water holding tank above the Cardo district. The tank supplied water at sufficient head to supply fountains for the marketplace section of the city.

Cardo area and served as pipeline support structures to marketplace fountains. As the basins were elevated ~15 m above the Cardo, sufficient head existed to provide pressurized pipeline water for fountains and basins in the Cardo market area as well as for the Great Temple and Q'asr al Bint.

Due to the elevation head of the Ain Braq system above the city core area, sufficient full-flow pressure was available to supply the elevated mansion area reservoir. Because the southside urban core region contains the marketplace area, water requirements were high; consequently, additional water supplies were channelled to this area by means of piping from the combined flows from Ain Braq and Ain Ammon (B1, B2) about 10 km southeast of the urban core through Wadi Farasa to the southern part of the city. Water from these springs could be supplemented by elevated cistern water from the Jebel Attuf area (B1) in one of the many high places (12, 13, B1) of the city. Water to the Lion Fountain (14, B1) and the al Hamman sacred pool area in the vicinity of elite tombs (16, 17, 18, B1) came from this supply line, which continued on to the Great Temple area and clearly indicated that a continuous spring supply was part of the system due to the presence of the Lion Fountain. A further spring at Ain Abu Olleqa (B2), originating in the Wadi Turkmaniyie, served the core area of the Temple of the Winged Lions with possible connections to the Q'asr al Bint area over a bridge traversing the Wadi Mousa stream. Large cisterns located near the Tomb of the Roman Soldier (16) (Browning 1982) also contributed runoff water supplies into this system. Details of the Wadi Farasa water system in this area (B1) have been investigated (Schmid 2002) and indicate the existence of large reservoirs and piping systems that not only served local usage, but also had sufficient capacity to transfer water further west to the Great Temple and lower urban areas. Numerous channels, pipelines, and multiple cisterns within, and leading from, the Great Temple indicate that water supplies within the temple were abundant (Joukowski 1999, 2001, 2003) and that the temple may have served as the distribution centre for lower structures. Water export lines to the marketplace area and the Q'asr al Bint region from the Great Temple served as part of the water system. Water supplied from Ain Braq, Ain Ammon, the spring in Wadi Turkamaniya, multiple cisterns as well as a pipeline that may have crossed Wadi Mousa from the northside are likely water contributors to the Great Temple and Q'asr al Bint districts. A bridge abutment (45) on the northside just west of the Temple of the Winged Lions contains some piping elements that may represent just such a connection but the total system configuration cannot be confirmed without further excavations.

Water supply system network management operations

The evolution of the water system to incorporate piping networks transformed the site to meet the demands of a large urban population estimated to reach 30,000 (Guzzo and Schneider 2000). The Nabataean water system incorporated both intermittent and on-demand supplies piped from large reservoirs or drawn from cisterns, and continuous-supply piping systems from remote springs to provide the daily requirements of city inhabitants. The contributions from these supply types were consciously regulated to meet demand fluctuations from special events in different areas of the city superimposed on constant daily requirements delivered to urban core fountains. Water supplies were brought close into population concentration areas so that all were only a few minutes' walk from fountains or supply basins.

Regulation of the system required bureaucratic oversight to manage, as decisions regarding storage/release amounts needed not only day/night but also seasonal adjustments. Efficiency dictated that no water could be wasted. As a consequence, transfer piping from northside systems (Jebel el Khubtha and Siq pipelines to the Nymphaeum) provided water that could be transferred to southside downhill locations for further usage or storage before final discharge into Wadi Siyagh. Beyond spring system supplies, other supplies from springs in the Wadi Kharareeb and Wadi Ma'aiserat north of the city were channelled as far as the Great Temple and Q'asr al Bint areas, although no detailed excavations are available to verify the total configuration of subterranean pipelines or channels. Additional water supplies were available from the spring at Wadi Siyagh (A2), and piping/channel systems from wadis to the east of the Wadi Siyagh spring probably contributed water to a large terminal cistern (A2). The Wadi Siyagh spring, even today, is adequate for the local needs of scattered rural settlements in this area.

The water system picture thus far developed is one of major springs to supply baseline continuous flow water supplies to multiple city locations by long pipeline systems, reservoir, and cistern recharge capability by spring and runoff input flows, and reservoir–pipeline systems designed so that supplemental reservoir water can be delivered to a terminal location to provide on-demand release peaks for special events and/or seasonal demand changes. Such a well-planned system required an equally well-planned management system that involved measurement of stored water resources as well as release flow rates over time intervals. While the geometry of major reservoirs made water volume calculations straightforward, measurement of piping flow rates through techniques developed by Hero of Alexandria (Ortloff and Crouch 1998) could have been implemented to provide the database related to release rates. While rainfall collection provided one source of reservoir water storage, wherever possible pipelines from springs provided yet another source of recharge of reservoirs during the night when public requirements were minimal.

To add to this complexity, water storage through the use of major, on-site dams presented a further aspect of Petra's water system. For example, on the northside of Wadi Mousa, numerous high status structures in the B2 quadrant (Temple of the Winged Lions, Royal Palace (41), North Defense Wall and Fortress (35), and Conway Tower (54)) are logically associated with some water supply system. A dam (d) at Wadi Turkamaniya (B2) may have trapped and stored runoff to provide water to the lower reaches of the Temple of the Winged Lions, although no excavation data are available. Excavations reveal that lower portions of both the Temple of the Winged Lions and the Great Temple spanned the Wadi Mousa stream by means of bridging. A nearby destroyed bridge abutment contains piping elements that may have transferred water from the south to the northside area (or vice versa). It appears then that supply redundancy derived from pipelines from different spring/reservoir sources crossing from one to another part of the city was an aspect of the Nabataean design approach. This design philosophy ensured that the water supply to any area was composed from different sources depending on variations in individual spring flow rates and reservoir/cistern storage amounts; this implied that management oversight was in place to monitor and control the system network.

While cisterns were dispersed throughout the urban settlement area, a main underground channel starting from Ain Bebdehbeh north of D3 and running toward the convergence of Wadi Mataha and Wadi al Nassara (B2), then running into the lower reaches of the northside below the temple areas, provided water to the Q'asr al Bint area. The complete channel, mentioned by Taylor (2001), has not been fully explored to verify its path within city confines but it certainly added additional supply water to the northside.

To illustrate the Nabataean mindset to utilize all water resources, a further element based on on-site dams lends further complexity to the water management picture. Local histories mention the existence of large dams: one on the Wadi Mataha (Taylor 2001), the other on the Wadi al Nassara (Figure 2.1.3). Destroyed remains are found to verify that these dams provided water storage from runoff within urban Petra. Dams were in place in other wadis to store water and limit the effect of erosion/deposition problems on the urban environment. The stored water behind these dams additionally served to amplify the groundwater height for purposes of supplying wells as backup to cisterns. While a well existed in the Byzantine church (east of 45), others may have existed as a drought remediation measure but are, as yet, not reported from excavation data. Judging from Nabataean placement of the Wadi Mataha dam (d), piping to the nearby Nymphaeum must have been an additional third-backup water source to the fountain. Since the Ain Mousa spring could also serve to place water behind the Wadi Mataha dam through the Wadi Shab Quais pipeline branch from Zurraba (in addition to seasonal rainfall runoff storage behind the dam from diversion of the Wadi Mousa stream through the bypass tunnel (8 in Figure 2.1.3), the water level behind the dam could be maintained sufficiently deep to provide water to the Nymphaeum throughout the year as well as providing water to dense settlements on either side of Wadi Mataha.

The Nymphaeum could then be supplied by contributions from stored runoff water behind the Wadi Mataha dam, a canal or pipeline from Ain Bebdehbeh, the pipeline along the western face of Jebel el Khubtha feeding ground-level cisterns and pipelines, and the northside Siq pipeline. This degree of redundancy indicated that planning for water supply variation was a foremost consideration addressed by a complex design that could tap into various pipeline-water storage resources depending on available supplies, seasonal variations, and special occasion needs. The redundancy guaranteed that if one of the multiple supply systems malfunctioned or was undergoing cleaning, repair, or modification, other elements would be in place to guarantee water supply to the urban core throughout the year. The redundant water supply sources for the Nymphaeum clearly illustrate planning to maintain continuity of the city's market and temple area water supply throughout the year. The ingenuity of the Nabataeans to maintain ample water supplies must have been apparent to visiting traders, who spread fame of the city's wealth, architectural accomplishments, and water management expertise to far corners of the known world.

Flood control, groundwater recharge, and the Great Temple water subsystem

Floodwater drainage during the rainy season was a major concern. Since heavy rainfall and flooding characterized the Petra area (even to present times), measures to divert Wadi Mousa floodwater from the Siq by means of a bypass tunnel (8 at C1, Figure 2.1.3), a low dam at the Siq entrance, and elevation of the Siq floor near the entrance provided a measure of flood control. While this strategy had proven effective in deflecting small flood events, continuous deliberate infilling and accumulating flood deposits in the Siq continued to help protect against floodwater incursion. While large flooding events had negative consequences, there were also ingenious ways to utilize the sudden water bounty: storage dams across the numerous wadis intersecting the urban core served to reduce floodwater entry into the city while seepage from the impoundments provided groundwater recharge suitable for well extraction during protracted drought. Thus a fraction of the seepage from dam storage, canals, and pipelines ultimately was recaptured and used as a groundwater defence against drought.

The same idea was used on a more localized basis for elite structures. Within the Great Temple, an elaborate south boundary wall drainage channel (Figure 2.1.9) collected infiltrated rainfall seepage and directed it to a nearby underground cistern with >50 m^3 capacity (Joukowski 2001) located within the eastern, upper part of the temple structure. A channel connected to the upper part of this cistern conducted overflow water to lower-level structures before exit to Q'asr al Bint and Wadi Siyagh. Large channels located in an upper room north of the Theatron (Joukowski 2003) of the temple indicate the terminus of a subterranean channel from the Ain Braq–Ain Ammon system (B1, B2) with water transfer access to the cistern. Some additional water sources may have been available from springs in Wadis Kharareb and Ma'Aisert (Figure 2.1.3) although piping connections await further excavations. Channel water, supplemented by cistern water to meet peak demands, was then distributed to subsidiary open cisterns located on the east and west sides of the temple then through subterranean channels under the lower,

Figure 2.1.9. Part of the drainage channel collect ing seepage water from the back wall of the Great Temple. Water led to an underground reservoir in the eastern part of the temple.

hexagonal limestone slab-paved, lower temenos platform, and then to lower-level rooms near the temple entrance stairway. Thus the cistern functioned as a reservoir within the temple, adding stored runoff and seepage water to the channel-delivered base supply—much in the same way that previously described reservoir–pipeline systems worked in tandem to meet occasional peak demand requirements. Because such a system was contained within the temple, its position of importance as a major canal terminus and water distribution node is clear from the complexity of hidden channels, cisterns, and piping thus far discovered. Perhaps the internal water system of the temple, capable of always providing ample water for rituals, had special significance to demonstrate the premier role of religion in the lives of the Nabataeans; only later under Roman rule are these supplies used for more utilitarian, marketplace purposes, perhaps indicating Roman predilection to practical concerns.

Technical innovations in Nabataean piping systems

The piping systems in the eastern vicinity of the Great Temple reflect some late-phase Roman modifications made to supply water for market and commercial structures along the Romanized Cardo (Figure 2.1.13). Sections of lead pipe running at the base of the northernmost lower temenos platform of the Great Temple continued eastward towards this area. Typically, lead piping types demonstrate Roman manufacturing techniques so that identification with Roman modifications is probable. Low-temperature-fired clays with relatively thick walls and socketed ends characterize Roman standardized piping elements. Wall thickness runs from 1 to 6 cm while piping segment lengths run from 30 to 100 cm, indicating large variability for specific applications. The internal diameter is usually 20–25 cm for most typical urban-use, mainline piping elements and, while the interior surfaces are generally smooth, the socketed end connections involve a large area constriction. Generally, Roman pipe diameter classifications (Vitruvius 1999) were standardized and used throughout areas under Roman occupation and renovation; observed Roman piping in Petra generally conforms to standard categories. In contrast, some (but not all) Nabataean piping was made from high temperature-fired clays with thin walls usually in the order of 5 mm or less (Figures 2.1.10 and 2.1.11) with piping lengths in the order of 30 cm. Because of the convoluted paths piping was often required to traverse, the short Nabataean piping segments were more easily conformed to sinuous paths with near-flush socket connections that limited leakage. For applications where piping was laid in long excavated channels (e.g. the Jebel el Khubtha mountainside and Siq walls), flush mortar infilling was used to reduce leakage. While the Great Temple is of Nabataean origin, elements of Nabataean piping types remain along with Roman piping types. Due to the many years of occupation of the site, many different types and sizes of piping elements are found, including smooth-interior surfaces with/without severe contraction zones, thin wall, short piping with smooth connection junctions, piping with/without internal rippling and lead pipe of various sizes. Excavations have revealed thick-walled Roman piping abutted into earlier Nabataean piping designed to shunt water to Roman markets on the Cardo from Great Temple sources. A further characteristic of Nabataean piping is that it is frequently placed within channels cut into stone then mortared over to yield a water seal that provides aesthetics for civil structures, while also providing security to protect supply source discovery. In combination with subterranean channels found elsewhere in

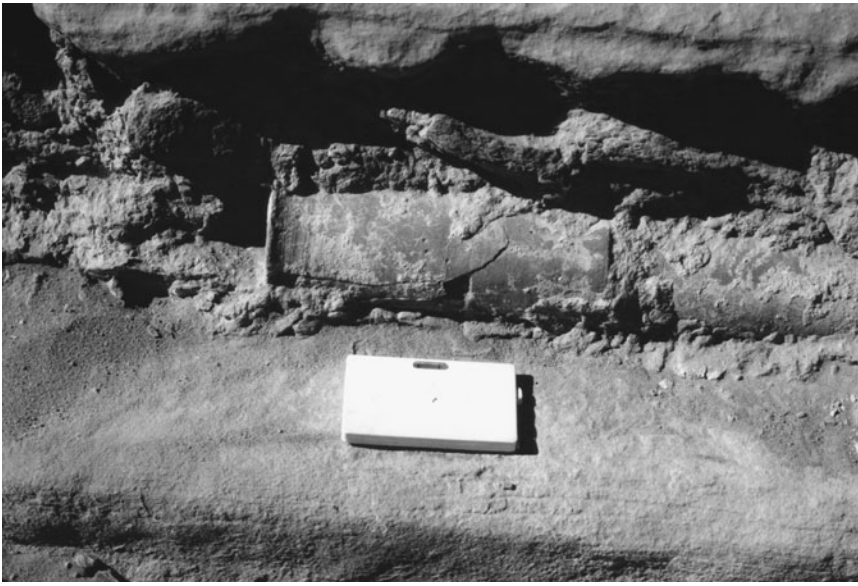

Figure 2.1.10. Nabataean thin wall short segment piping elements in the Great Temple forecourt (15 cm reference plate).

the Nabataean domain (Levy 1999), the concept of hiding water channels and supply sources served as a defensive measure to protect vulnerable water supplies from compromise, particularly for spring sources distant from the city centre.

Some types of Nabataean short piping lengths are characterized by a relatively minor area-contracted socket junction and within the piping interior sinusoidal ripple patterns appear (Figure 2.1.11A,B) with wavelengths of about 1.0 cm and amplitude of 2–3 mm from the symmetry plane. Some piping, mostly in the Great Temple area, shows rippled interior patterns of this type. *In situ* piping elements within the Siq show interior ripple patterns but also exhibit rather severe joint contraction sections that tend to increase resistance, cancelling out any benefits obtained from between-joint, interior wall surface modifications. Other piping types may have existed within the Siq from different eras but a complete chronologically sorted catalogue of these types is not available from the limited excavation data. In some Great Temple locations, piping had flush connections with smooth joint connections between rippled piping segments while other piping types, perhaps from different eras found elsewhere on-site, had severely contracted connection zones. The smooth junction piping type may represent an evolutionary step in pipeline design to facilitate hydraulic resistance decrease benefits that permitted higher flow rates for the given head, slope, and piping diameter.

Figure 2.1.11A,B. Piping elements associated with the forecourt of the Great Temple.

Experimental results (Cary *et al.* 1980; Walsh 1980; Gad-el-Hak 1996) related to flow over rippled plates indicate that shear drag reduction occurs over a wide Reynolds number range for shallow ripple geometry similar to that observed in Nabataean piping elements. The use of such shear reduction methods permitted a flow rate increase in the order of 5 to 10% for the same head compared to smooth-interior piping designs for either full or partial flow conditions. This feature may constitute the earliest empirical observation that low micro-surface roughness patterns in piping can increase the flow rate when used in conjunction with smooth connection joints. Current explanations of this phenomenon rely on changes in the near-wall turbulent eddy size distribution, which results in velocity profile changes sufficient to alter turbulent shear stress. While questions arise as to whether the ripple patterns are deliberate or a byproduct from manufacturing processes, nevertheless their appearance in conjunction with smoother joint connections apparently represents a realization of the effect of design refinements on improvement of piping flow delivery rate, perhaps revealed by empirical observation.

As examples of the Nabataean concern with high-quality water sources and innovative ways to eliminate particle clogging of piping systems, the Siq north-side piping system contained four open drinking basins capable of trapping particles with easy access for removal (Bellwald 2004). Dam systems also served to settle particles to improve water quality before delivery to fountains. Long pipelines (such as the Wadi Shab Qais system) were essentially immune to particle clogging effects as the upstream reservoir at Zurraba served as a settling tank. This reservoir appears to have multiple sections that may represent some form of internal particle settling capability; however, no detailed excavations of silt types are available. Thus water quality improvements went together with reduction of sediments trapped in pipelines and provided substantial benefits to the continuous operation of the Petra water system.

As yet a further technical innovation, note that if the piping lengths are very long, wall friction effects for full-flow conditions limit flow rate and increases in supply head do not translate proportionately into flow rate increases (Ortloff and Crouch 2001). For this reason, long pipelines, where feasible, are usually interrupted by open basins placed along their length to effectively create short piping segments between (cleanable) head basins; this system permits higher flow rates than a continuous pipeline with no intermediate 'head reset' basins. The 'head reset design' is certainly beneficial for full-flow conditions; it is also beneficial for partial-flow conditions as it largely eliminates conversion to full-flow conditions from cumulative wall friction effects in long pipelines. Although this practice is observed in Roman piping networks (Ortloff and Crouch 2001), it probably represents a pre-Roman innovation. While the northside piping of the Siq provided the main potable water supply, the southside channel system was probably meant for animal watering purposes and was supplied from a cistern atop the bluffs with a drop hole to this channel (C0, Figure 2.1.1). The continuation of this flow to southside piping systems in the theatre district is possible but excavation data are not available to verify this connection.

The Siq piping system—flow stability considerations

Some Nabataean pipeline design solutions are best illustrated by computer analyses that reproduce internal flow details. For an examination of flow stability in the Siq northside piping system, computer models were made of a 1,220-m long section of the 14.0-cm diameter piping at a -2.5° slope with and without internal roughness patterns. The -2.5° angle represents an average value while certain sections of the piping had either higher or lower slopes. Presumably, as Ain Mousa had a high flow rate, the Siq piping system represented a design that accommodated a large fraction of this flow rate. A number of three-dimensional computer runs (FLOW-3D 2007) were made (Figure 2.1.12) for velocities of 0.305 m/s (Figure 2.1.12A), 0.610 m/s (Figure 2.1.12B), 1.524 m/s (Figure 2.1.12C), and 3.05 m/s (Figure 2.1.12E), assuming full-flow entry conditions at the right boundary and the mean slope and wall roughness typical of *in situ* piping elements. Figure 2.1.12D represents a smooth-interior pipe surface at 1.52 m/s to demonstrate differences made by wall roughness on the flow pattern (a Siq piping element of this type is displayed in the on-site museum located in the tourist complex west of the Great Temple area).

One criterion for determining an acceptable design relies on flow stability (i.e. is flow smoothly delivered to a destination point without pulsations?). A second criterion asks if the flow delivered to an open basin can be successively transported into a next pipeline segment without spillage; this implies piping free surface flows that transfer water into intermediate basins without sloshing and that the output flow rate from the delivery pipeline equals the acceptance flow rate into the continuing pipeline segment. This requires that pipeline segments between basins have similar resistance characteristics, slope, diameter, and internal flow patterns and the same entry conditions. A third criterion requires that the piping flow rate can accommodate urban core water needs for a segment of the population the pipeline serves. A further criterion is minimization of leakage. For this, partial flow is preferable as no hydrostatic pressure effects causing leakage occur.

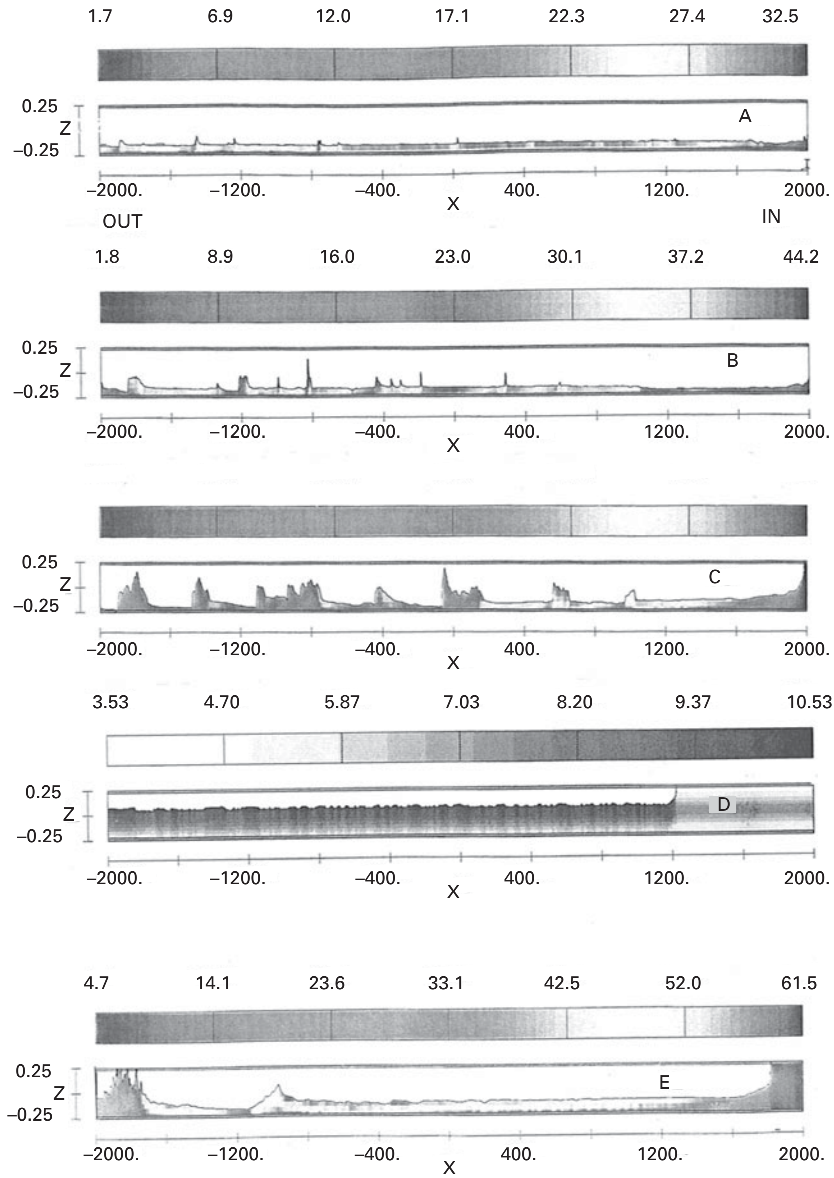

Figure 2.1.12. Centreline velocity and water free surface results for Siq pipe flows under A to E inter conditions as described in the text. Flow enters from the right.

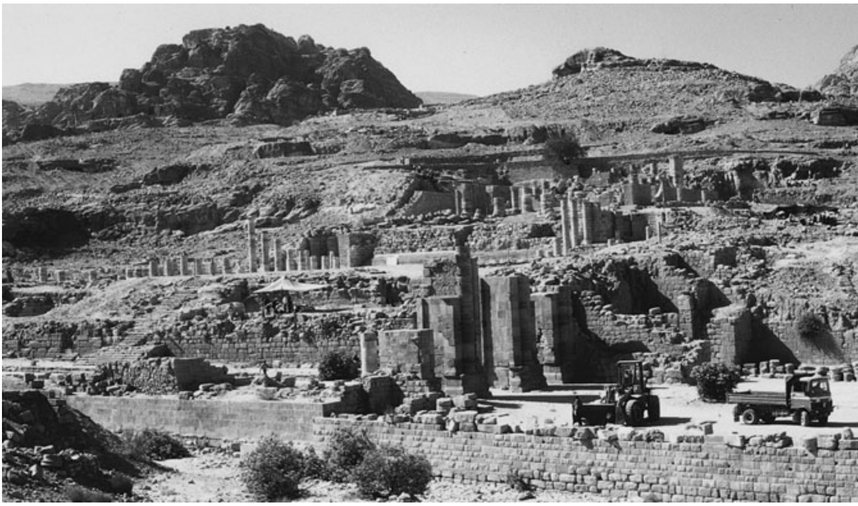

Figure 2.1.13. The Great Temple with Hadrian's Gate in the foreground.

Analysis results indicate that flow velocities up to 1.52 m/s (Figure 2.1.12A–C) with prescribed wall roughness produce open-channel flow within the piping but with an apparent unsteady delivery rate. This is manifested by random water height peaks that translate down the piping, leading to unsteady flow delivery resulting in sloshing and spillage in open basins along the length of the Siq piping. If the piping were to be made continuous with a smooth interior at this flow rate, Figure 2.1.12D indicates that a smooth delivery flow rate is achieved as compared to that for which wall roughness exists but at the expense of a longer pipeline segment exposed to full flow transition with induced hydrostatic pressure and increased leakage. At 3.05 m/s flow velocity (Figure 2.1.12E), the effects of the roughness-induced, randomly distributed water height changes disappear over much of the piping length, leading to a region of smooth free surface flow. While this high-speed flow appears to change back to a full flow after nearly 1,200 m flow length due to cumulative wall friction effects (Figure 2.1.12E), this negative feature can be removed by the 'head reset' feature so that shorter length pipe segments connecting open basins prevail and contain open-channel flows at least up to 400 m in length (this would permit at least four northside open watering basins within the Siq). Without open basins, a long uninterrupted pipeline would contain an unsteady flow, require a large downstream settling basin to trap particles (without which pipeline clogging would occur), and be subject to full flow caused by high shear resistance. The pipeline would then experience high-pressure leakage under full-flow conditions, and require a very large pressure head to provide a high flow rate (Figure 2.3.4). As confirmed by recent excavations (Bellwald 2003, 2007), four drinking basins existed along Siq northside piping to provide clean water as well as a solution to a complex flow stability hydraulics problem. The basins imply that the 'head reset' design principle was employed by Nabataean engineers. For both full-flow and partial-flow conditions, head reset has benefits: for full flow, it increases head-flow rate dependence and permits high flow rates; for partial flow, it largely eliminates conversion back to full flow by cumulative wall friction effects, thus enhancing system flow rate and stability.

From calculations (Ortloff and Crouch 2001) for full-flow conditions, piping lengths in the order of those between basins represent maximum values where relatively minor head values influence piping flow rate; beyond this length, increases in head have progressively smaller influence on flow rates (Figure 2.3.4). Thus even if the piping were to function in a near full-flow rate condition (perhaps due to sinter build-up), the multiple open basin design approach would still make the piping system operate in a reasonably stable mode. However, the piping system, at least in early usage phases before significant sinter build-up occurred to alter the 'effective' piping diameter, supported a supercritical open-channel flow due to the hydraulically steep slope. If the lower-slope piping length that continued to the outer Siq (past the Treasury on an elevated side wall channel) is considered as an extension of the inner Siq system, then partial flow continued in this line to the Nymphaeum, thus eliminating leakage. With sinter (calcium carbonate) build-up, resistance increased creating full flow conditions, thus increasing leakage due to hydrostatic pressure build-up. It has been observed (Bellwald 2003, 2007) that when large internal sinter build-up occurred, Siq piping was chiselled open at the top, thus converting to open-channel flow conditions to extend the usefulness of the Siq piping to provide water to the urban core.

As water velocity in the order of 3.0 m/s was adequate to prevent major instabilities, and considering that the supercritical flow filled about 25% of the piping cross-sectional area (at normal depth) and that a (very conservative) 50% adjustment was related to connecting joint leakage, spillage, and evaporation, the deliverable Siq volumetric flow rate approached 36 m^3/h—well within the maximum Ain Mousa spring flow rate. As the on-demand Wadi Shab Qais water supply capability was in the order of 30–40 m^3/h, the maximum peak, total northside water supply that could be carried through these two piping systems is estimated to be about 60 m^3/h, but it is more like 30–40 m^3/h if only the Ain Mousa–Siq system is used. Obviously, control over entry flow rates into each piping system must have been in place together with consideration as to the storage/release function of the Zurraba reservoir, considering seasonal spring/runoff supply variability. Seasonal spring variability as well as climate cycle variability are further considerations that alter spring output and thus piping system flow rates, indicating that the design must have encountered some variability in performance. Flow rate delivery predictions therefore reflect conservative estimates of the maximum values possible with the observed design with somewhat lower flow rates possible at different times.

Preliminary estimates of Zurraba full capacity and the pipeline maximum flow transfer rate from the reservoir yields about 50–75 h of delivery time at maximum transfer rate—and more time at lesser flow rates. The predicted $\sim$35 m^3/h for single-source Siq piping flow rate is consistent with recently observed, modern Ain Mousa spring supply flow rates (Markoe 2003) of 20–40 m^3/h (depending on climate history, seasonality, and rainfall infiltration rates), although past rates cannot be known with certainty.

The Siq and Jebel el Khubtha pipelines are of different designs and demonstrate the wide technology base available to Nabataean engineers to produce designs for different purposes. Note that while the Jebel el Khubtha and Siq piping systems have a 7 $\times$ slope difference (the former by selective design, the latter dictated by topography), the presence of head reset basins for the Siq system permitted use of short piping lengths to maintain low flow resistance to sustain a high-flow rate for both full and partial full flow regimes. Although Siq flows are supercritical due to the steep slope, there is no possibility of achieving near-critical maximum flow rates given fixed piping slope, roughness, and diameter limitations. The net result is a Siq piping design that meets design criteria for an adequate flow rate with delivery stability. As can be observed from scant piping remnants along the northside of the Siq channel, sinter deposits appear to be deposited within the piping from many years of use, resulting in cross-sectional diameter change. While some hydraulic benefit may be gained by smoothing the junctions and walls by deposits, the net effect is negative as flow rate diminishes as diameter closure and local build-up regions further increase flow resistance. As some highly sintered piping segments appear to indicate, top breakage of the piping was instituted to ensure an open-channel flow to at least capture some further use of the piping. At present, there is no accounting for how many different types of Siq piping were used at different times or their removal and replacement by different types—only some elements remain *in situ* to give a snapshot of at least the last phase of piping system development.

The subtlety of hydraulic design differences for these two pipeline systems indicates that different design options were understood for different flow problem types. The fact that few Roman additions to the water supply situation occurred was an indication that the Nabataeans had already exploited all available water sources and that Roman technological improvements could not significantly improve on existing Nabataean technologies.

Petra per capita water availability compared to Roman standards

For estimates of total water volumetric flow rate into the city, conservatively assuming about a third of the northside supply rate for the southside rate as a result of less robust southside springs, and assuming a combined flow rate for the Siq and Wadi Shab Qais reservoir release lines of about 40 m^3/h, the city could receive at minimum an estimated 50 m^3/h from these sources. While additional sources (Ain Braq (0.8 m^3/h), Ain Dabdebeh (2.5 m^3/h), Ain Ammon, and Ain Siyagh (<1.0 m^3/h)) add to this estimate, released storage water and additional springs add further capacity to arrive at a higher flow rate, perhaps to 100 m^3/h in total if less conservative leakage estimates are used. For 30,000 inhabitants of the city, at least 0.04 m^3/day (40 litres/day) would be available on a per capita basis, which is the minimum required to maintain hygienic standards for an urban population. Considering public use in the form of fountains, watering troughs, baths, domestic usage, water gardens, and workshops, per capita water availability is well within the urban water usage rate in Rome of 0.6 m^3/day per person (Butterfield 1964) according to one estimate. Considering hot climate survival water intake per person of about 0.003 m^3/day, the surplus water beyond human consumption/survival rates was available by these estimates. The estimate for water storage from dams and cisterns on Jebel el Khubtha alone (Akasheh 2003) is 0.36 m^3/person; for a personal consumption rate of 0.003 m^3/day, considering evaporation losses, about a 2-month emergency supply is available through Jebel el Khubtha cisterns alone. A similar calculation shows that the Zurraba reservoir contained about 3 weeks' emergency survival supply, and additional cisterns and dams on-site, particularly those of the Wasi Farasa system (Schmid 2000) add further reserves totalling several months' supply. Water from the many additional cisterns, perhaps up to 200, clearly provided adequate reserve water resources for inhabitants and transitory populations. While per capita water supply for Petra is somewhat lower than Roman city standards, the amounts supplied to the city on a continuous basis are more than sufficient to maintain high-quality living standards.

As the city underwent major construction in the 50 BCE to 100 CE period during the reigns of Obodas II (III) and Aretas IV (construction of the Treasury, Monastery, Q'asr al Bint, Temple of the Winged Lions, and Theatre), Roman/Greek technologies most probably influenced water system design.

The availability of advanced Roman surveying techniques for aqueduct system design would be particularly useful in constructing long-distance lines of prescribed slope to and within Petra to maintain near-critical, open-channel flows in piping to match spring flow rates. While the design capability to achieve such balances still remains elusive due to fragmentary knowledge of ancient hydraulic practices, some hints of water flow rate measurement capability exist (Cohen and Drabkin 1966; Ortloff and Crouch 2001) through works of Hero of Alexandria, which may have found use in later hydraulic planning applications of the Nabataeans, particularly in matching spring flow rates with piping flow rate capacity.

Nabataean overall water system design strategy

Early use of spring-fed pipelines in Hellenistic cities in Ionia, mainland Greece, and the Greek colonies (Crouch 1993) as well as contemporary Roman cities indicated that pipeline transport technology was well developed in many parts of the ancient world and available for assimilation into Nabataean water system designs. The Nabataean systems, however, were unique in that water conservation was practised on a much larger scale and intermittent supplies from seasonal rainfall constituted extra storage capacity to sustain the city through low spring flow rates in dry seasons. In essence, the Nabataeans utilized all possible above and below ground water supply and storage methodologies simultaneously. While water storage in contemporary Hellenic cities also emphasized cistern water storage for household use, the Petra systems advanced this technology to citywide systems with elaborate dam and cistern systems that served both water storage and flood control purposes. Water storage in groundwater aquifers was also practised by multiple dam system storage; this allowed for the possibility of constructing wells as a backup system should other supply systems decline due to long-term drought effects. Provided a cistern could be made deep enough, its resupply could result from intersection with the groundwater profile; a technique well known in ancient Bronze and Iron Age cities of the Middle East.

Summary and conclusions

A comprehensive water supply system consisting of dams, cisterns, channels, pipeline networks, and groundwater storage exploited multiple spring supply systems as well as rainfall runoff storage. While borrowings in water technology were inevitable from contemporary cities within the extensive trade network, the limited water resource situation at Petra, in combination with complex topography, led to innovations in the use of water storage methodologies on a citywide scale where stored runoff water provided a sizeable fraction of yearly requirements and served as backup supply to the many continuous springs that supplied the city through pipeline systems. Examination of design characteristics for two different pipeline systems with very different slopes and delivery requirements (one on-demand, and the other continuous flow) indicates that technology was in place to provide different design options that minimized leakage, maximized flow rate, minimized pipeline particle ingestion to prevent clogging, and eliminated the transient flow instabilities that caused system vibration and prevented steady flow from developing. Further Siq pipeline advances were related to water purification by four settling basins whose positioning eliminated a complex flow stability problem characteristic of pipeline supercritical, open-channel flows transitioning to full flows due to large internal pipeline roughness. The totality of solution options to produce well-functioning systems confirms that a hydraulic design methodology was in place and applied with great skill and experience to solve complex hydraulic engineering problems.

While it is traditional to look for Roman technical advances that improved the in-place Nabataean system, few have been found, indicating that Roman engineers perhaps viewed the Nabataean system as near optimum. In this case, it is likely that the library of water management techniques observed by the Romans served to increase their library of water conservation and management techniques as applied to Roman desert cities and outposts. While details related to technical transfer and hydraulic engineering practice of ancient societies is still a matter of research, it is certain that the success and longevity of Petra based on its innovative water system design constituted a vital chapter in the history of technology and water management in the ancient Middle East.

2.2 THE INVERTED SIPHON AT ASPENDOS, TURKEY

The city of Aspendos in Turkey has, as its main water source, a Roman siphon system. The remains of the siphon structure contain many enigmatic features that, once analysed by modern fluid mechanics methods, begin to reveal an unexpected level of knowledge by Roman engineers of that period. This section details the results of this investigation, which add to our knowledge of the Roman contributions to the history of hydraulic science.

Inverted siphons were well known to the ancient Romans as a way to overcome water transport problems caused by deep valleys, which are not practical for large, multi-tiered aqueduct structures due to their large height and potential structural instabilities under seismic loading. Extreme examples of the use of this technology from the archaeological record include a siphon that connected the Claudia Aqueduct to a reservoir in Domitian's Palace (81–96 CE); here a 1-inch diameter lead pipe carried water through a 133 ft deep valley and sustained a maximum hydrostatic pressure of 60 psi. The most extreme usage occurred at Alatri, 50 miles east of Rome, where in 134 BCE a 340-ft deep valley was traversed by a 3.9-inch diameter lead pipe of 0.4-inch thickness sustaining a maximum hydrostatic pressure of 150 psi; the piping hoop stress (0.06 kpsi) is well below the yield stress of lead in this case (1.45 kpsi). While further examples of Roman siphon water conveyance technology and long-distance water lines can be found in the literature (Hodge 1983, 2002; Ceçen 1996), analysis of their dynamic operation under transient filling modes, as presented in this section, represents a source of new results and revelations about Roman technology.

The city of Aspendos, located about 50 km east of Antalya and 12 km north of the southern coast of Turkey, was initially founded as a Hellenic colony (Akurgal 1985) of the Argives and was already known as Aspendos by Greek historians Thucydides and Zenophon in their lifetimes. In 133 BCE the city came under Roman rule and extensive urban development followed, accompanied by a water delivery system in the form of a large inverted siphon system (Figures 2.2.1, 2.2.2, and 2.2.3). The importance of the city derived from its commanding position on the Antalya–Side–Pergammon–Sillyon–Selge and Pisidian commerce routes as well as its position on the Eurymedon River with Mediterranean access. The city's role as an inland port city and commerce centre was noted by Strabo, who commented on the exports of salt, wheat, wool, and oil that gave prosperity to the city in Roman times.

Characteristic of the importance Rome placed on its eastern economic outposts, which served as conduits for resource transfer to central state authority, major state-sponsored building projects were instituted to demonstrate dominance and the benefits of integration into the empire's economic structure. As such, the siphon system would be expected to incorporate the highest hydraulic technology available to Roman engineers because of its daunting size and length. The siphon represents an exercise of a technology base that, when analysed, provides insight into Roman civil engineering practice. Through surviving Roman administrative and engineering texts related to water management and distribution (Herschel 1973; Evans (on Frontinus) 1994; Vitruvius 1999), prescientific notions survive related to

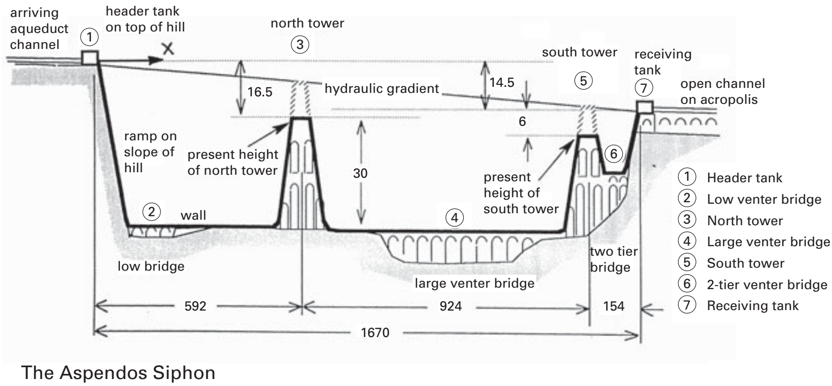

Figure 2.2.1. Geometric details of the Aspendos Siphon in southeast Turkey. Dimen sions in metres (after Kessener 2000).

aqueduct and siphon engineering details; however, it is likely that much more was known, but not recorded, by Roman civil engineering practitioners.

Since scant descriptive material is available from ancient sources, the next recourse to discover ancient civil engineering practice is by use of CFD and modern analysis methods (Wylie and Streeter 1998) to investigate transient siphon hydraulic behaviour. By such analysis, insight into the unwritten

Figure 2.2.2. Field view of the Aspendos Siphon with the South Tower in the foreground.

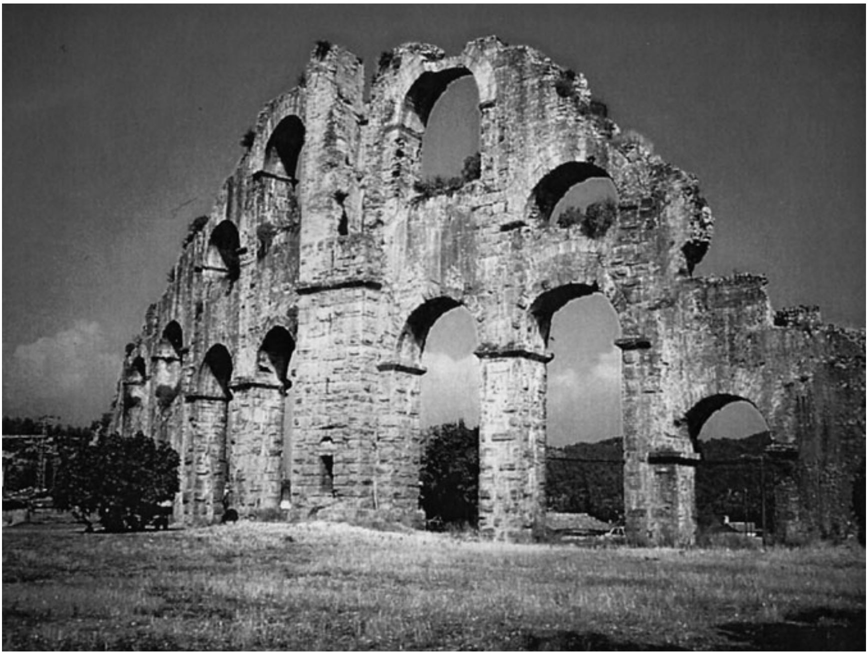

Figure 2.2.3. One of the two towers supporting open tanks of the Aspendos Siphon.

accomplishments of Roman engineers can be extracted from their surviving engineering works. From a survey of the Aspendos system (Kessener 2000), precise measurements of siphon dimensions were available and served as the basis of technical analysis.

The Aspendos siphon system (Figure 2.2.1) consists of three main siphon legs (2, 4, and 6) joined by (non-surviving) elevated tower basins (3 and 5). A header tank (1) accepts water from a channel originating at a distant spring while the distal end of the siphon system contains a receiving tank (7) leading water to a distribution centre within Aspendos. From Figure 2.2.1, a horizontal venter (bridge) (2) supported the siphon crossing to the north tower (3) (Figures 2.2.2 and 2.2.3) whose surviving height is about 30 m. The siphon then crossed a wide valley over a second venter (4), then up to the south tower (5), then on to the receiving tank (7), leading water to the city over a bridged channel.

The receiving tank (7) is 14.5 m below the header tank (1). Based on the hydraulic gradient line, the original height of the north tower is about 46.5 m and the height of the south tower is 35 m. From the dimensions shown in Figure 2.2.1, the total siphon system length is 1.67 km, with 1–3 and 3–5 lengths of 0.592 and 0.924 km, respectively. The use of elevated, single, or multiple tier venters to support horizontal siphon pipeline segments and elevated tower constructions was notable in the Aspendos siphon design. A top view indicates that angle changes occur at the elevated towers (16° north at tower 3; 55° north at tower 5). Views of the system are shown in Figures 2.2.2 and 2.2.3.

The piping system carried by the support structure consisted of joined 0.8-m^3 stone blocks with a 30-cm diameter cylindrical bore. The block ends were cut to form socketed attachments and a sealant was used to cement adjacent blocks together to render joints watertight. It is estimated (Kessener 2000) that about 3,200 blocks originally made up the total pipeline length. Interestingly, several of the blocks contain 3-cm diameter perforations from the cylindrical inner bore to the outside surface with an unclear hydraulic function. While contemporary authors attribute these perforations to cleaning/drainage holes (Hodge 1983), other authors (Smith 1976; Fahlbusch and Peleg 1992; Kessener 2000) assign hydraulic functions variously related to entrained air release, pressure relief, and programmed leakage to regulate head. The function of the elevated tower open basins is also controversial—firstly, because they are conjectural (as the physical remains no longer exist) and secondly, because the hydraulic function of the elevated basins is unknown. To add further controversy to the understanding of Roman siphon engineering practice, Vitruvius (1999) mentions that 'colliquiaria' were vital to successful siphon usage, although the meaning of the Latin term is not provided. The word 'colliquiaria' occurs nowhere else in Latin literature and the technical meaning of the word is lost. Additional Vitruvian cautions relate to the slow filling rate required in initiating siphon flow to avoid large force oscillations. As Vitruvius describes hydraulic phenomena in Latin prescientific terms, further controversy as to the meaning of colliquiaria exists as modern translations are undecided as to whether colliquiaria refers to hydraulic devices or principles. Since these mysteries persist to the present, this section seeks to address these issues with new results from hydraulic analysis of the siphon.

Hydraulic analysis

The basic equations governing water flow in the siphon are:

$$\begin{aligned} \mathrm{d}H_T/\mathrm{d}t &= (Q_{\mathrm{in}} - Q_{\mathrm{out}})/A_T \\ p_T &= \rho g H_T \\ \mathrm{d}Q_{\mathrm{av}}/\mathrm{d}t &= [A(p_1 - p_2)/\rho] - fQ_{\mathrm{av}}^2/4RA \end{aligned}$$

$$p_1 = p_{T1} + \rho g z_1 - \rho z_1 f Q_{av}^2/4RA^3 \sin a_1 - \rho(z_1\ dQ_{av}/dt + Q_{av}\ dz_1/dt)/A \sin a_1 + \{\rho Q_1[2g(z_{1,mx} - z_1)]^{1/2}/A\}$$

$$p_2 = p_{T2} + \rho g z_2 + \rho z_2 f Q_{av}^2/4RA^3 \sin a_2 + \rho(z_2\ dQ_{av}/dt + Q_{av}\ dz_2/dt)/A \sin a_2 + \{\rho Q_2[2g(z_{2,mx} - z_2)]^{1/2}/A\}$$

The geometric variables are shown in Figure 2.2.4. Here ρ is the water density, g is the gravitational constant, A is the pipe cross-sectional area, Q is the flow rate, R is the pipe radius, H is the head, f is the Fanning friction factor (Knudsen and Katz 1950; Benet and Meyers 1974; Wylie and Streeter 1978; Welty 1994), and p is the pressure. The subscript av denotes average values and T relates to open basin values. The subscripts 1 and 2 relate to entry and exit values from and to adjoining siphon legs. Q_{in} and Q_{out} apply to each siphon leg individually. Here the output flow rate for one leg (Q_{out}) is the input flow rate (Q_{in}) for the subsequent siphon leg.

Note that this equation set is applied to each siphon leg individually with coupling at the elevated basins that join adjacent siphon legs. Numerical solution of this equation set then provides the dynamic water motion in the siphon from start-up filling to final steady-state behaviour. Since there are water free surfaces within the siphon legs during start-up as water

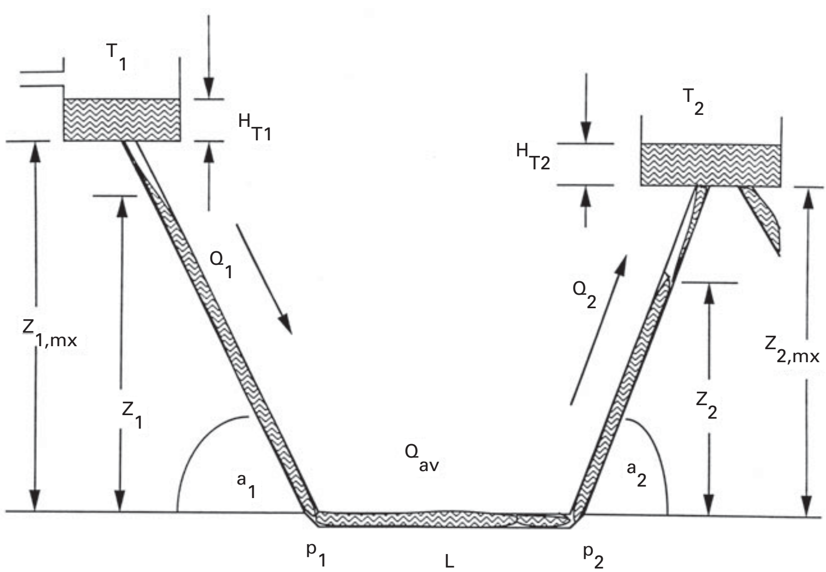

Figure 2.2.4. Nomenclature for a siphon leg used in the differential equation set to describe the fluid mechanics behaviour of the siphon system.

transfers from one leg to another through the open basins to initiate water motion in successive siphon legs, transient behaviour is expected to be highly non-linear.

During start-up, incoming water from the header basin (1 on Figure 2.2.1) impacting water present in the first siphon leg (assumed to be at the water level of the receiving basin (7)) serves as a driving force to start first leg oscillations. As more water enters leg (2) of the siphon, water spills over into the next partially filled siphon leg (4) by transfer from the first open basin (3) and then onto successive siphon legs through successive basins. A complex non-linear oscillation process occurs in each (spilled-into) siphon leg coupled at the elevated basins and internal damping due to frictional effects determines time until steady-state operation is achieved. Numerical solution of the above equation set then predicts water transfer dynamics as a function of time as dependent on water physical properties, geometric properties of the siphon, and the piping roughness factor.

Results

The steady-state inlet-to-outlet pressure difference Δp in circular cross-section piping is usually described in terms of key parameters in a Fanning chart (Figure 2.2.5). Here $\Delta p = f(L/D)(\rho/2)U^2$, where f is the Fanning friction factor, L is the pipe length, ρ is the water density, D is the pipe diameter, and U is the average flow velocity. Re is Reynolds number $= UD/\nu$, where ν is the water kinematic viscosity ($\upsilon = \mu/\rho$) and μ is the fluid absolute viscosity. The friction factor f is also dependent on ϵ, the root-mean-squared wall roughness height. For an ϵ/D value, Figure 2.2.5 gives empirical relationships to relate the Reynolds number to Δp (from the above expression) from which the piping low rate ($\pi U_P D^2/4$) is determined. Note that Figure 2.2.5 applies throughout a wide Reynolds number range incorporating laminar and turbulent flows. To gain insight into siphon hydraulic behaviour for different ϵ/D values, transient flow velocities and pressures were obtained for the siphon geometry shown in Figure 2.2.1 (Ortloff and Kassinos 2002) using the above equation set.

While $\epsilon/D = 0.001$ represents a smooth internal siphon wall, medium range $\epsilon/D = 0.01$ values are representative of the hand-manufactured, chipped, interior wall roughness found in sample on-site piping (Figure 2.2.9). Figure 2.2.6A shows the progression of flow rates in successive siphon legs 1, 2, and 3 (corresponding to legs 2, 4, and 6 in Figure 2.2.1) for $f = 0.010$ given a header tank input flow velocity of 1.0 m/s (in the turbulent Re range) as a function of start-up time. Flow rates Q' are normalized to an input flow rate of

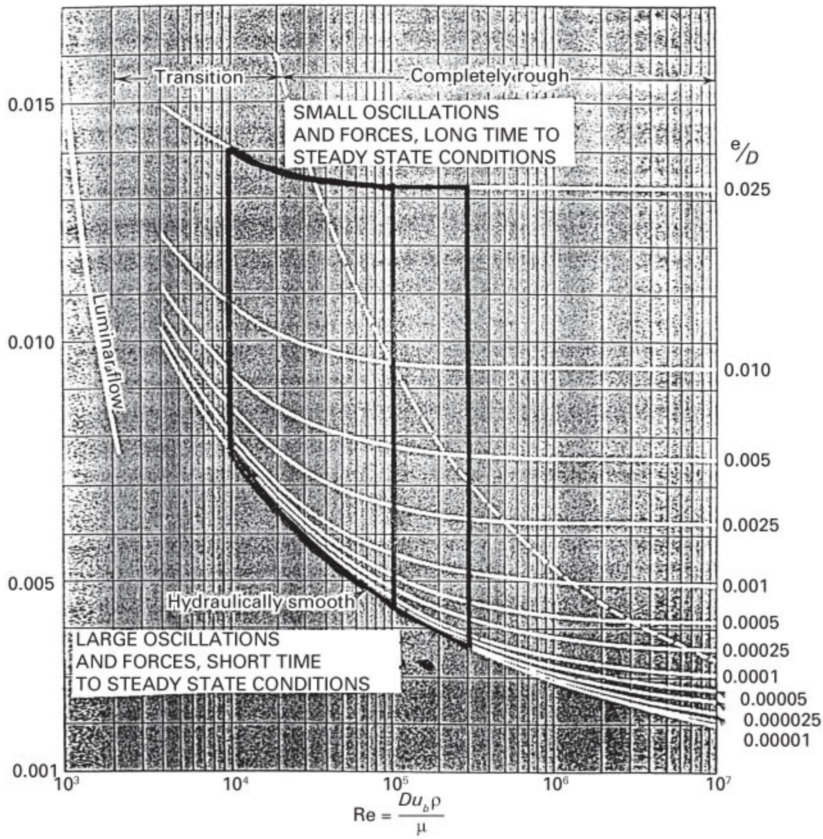

Figure 2.2.5. Friction factor (f) diagram for Reynolds numbers $10^3 < \text{Re} < 10^7$ for various internal piping mean square roughness height to diameter ratios (ϵ/D). The bold outline is the siphon operating range during start up and steady state operation.

$Q_1 = 1.0\ \text{m}^3/\text{s}$. Figures 2.2.6A and B represent the transient flow rate behaviour given impulsive flow into the siphon leg 1 given a water level in each leg equal to the water height in the receiving tank (7) with the north and south elevated basins empty. Figure 2.2.6B represents the same scenario but for $f = 0.006$. As water pours into successive siphon legs through spillage transfer from the elevated tower tanks, it begins impulsive motion of water in these legs hence the time delay in water movement from leg 1 to leg 3. For increased wall roughness from 0.006 to 0.01, the wall roughness fluid-friction damping effect slows water velocity, thus eliminating the velocity overshoot seen in Figure 2.2.6B. Note that while steady-state Re is nominally on the order of 2.0×10^5, the start-up local Re values can vary somewhat due to varying transient velocity in the different legs. The f values are relatively constant for typical $\mathrm{Re} > 10^4$ values as a result of turbulence induced by large wall roughness ($f > 0.005$) and are used in the analysis as representative of the internal chipped bore surfaces. Portions of these curves exceeding the normalized input flow line indicate an additional delivery from an upstream siphon leg to a downstream leg as a sudden water delivery surge alters the flow rate through the connective elevated tanks. Similarly, sudden transient declines in flow rate (curve 1 in Figure 2.2.6A) indicate temporary resistance to flow from an oscillatory backflow cycle from a downstream elevated tank. Cases may exist for which impulsively started, but time delayed, oscillation frequencies in each leg are in phase, out of phase, or partially out of phase, leading to complex transient start-up behaviour dependent on the piping internal wall roughness. The overall picture is one of initially oscillating flows in each leg driven by spillage from successive open tanks that sometimes either add to or subtract from flows through legs depending on oscillation frequency and amplitude in each leg; as expected, after oscillations are damped, a steady flow ensues.

Since three elevated, open surface basins (3, 4, and 7) separate siphon legs 2, 4, and 6, the output flow rate into each successive leg is indicated in Figure 2.2.6 to show the influence of the internal siphon wall friction factor, f. Clearly the impulsive start-up is highly non-linear due to open-basin coupling and the impulsively induced oscillatory flow in successive legs of the siphon. For very low fluid-wall friction $f \sim 0.001$, large oscillations and a long time to achieve steady-state conditions occurs as there is small shear resistance to promote damping from fluid-wall frictional effects. Midrange or low f values, in combination with slow ramping of the header tank (1) input flow to the first siphon leg from 0.0 to 1.0 m/s, represent the best working methodology to limit start-up fluid oscillations. These fluid-wall friction values limit flow resistance while permitting a large flow rate for the given head. The outline polygon shown in Figure 2.2.5 represents the typical transient siphon operating Re range and f boundaries. The best start-up operating conditions are achieved at some central location within the polygon. However, as excessive wall roughness limits the achievable steady-state flow rate and requires larger input tank head to achieve, f and ϵ/D should remain in the mid-to-lower half of the polygon as a practical design option. Figures 2.2.6C and D represent what happens for a gradual start-up ramping of the input velocity from 0.0 to 1.0 m/s over a 1,800 s (1/2 h) time period for different f values. It is assumed that sufficient head exists in the supply tank (1) to maintain this flow rate and this assumption holds for all f values considered. Here oscillations are damped with increasing f at 2,000 s to achieve steady-state flow conditions for the first two cases while for $f = 0.015$ (Figure 2.2.6E) start-up oscillations are largely

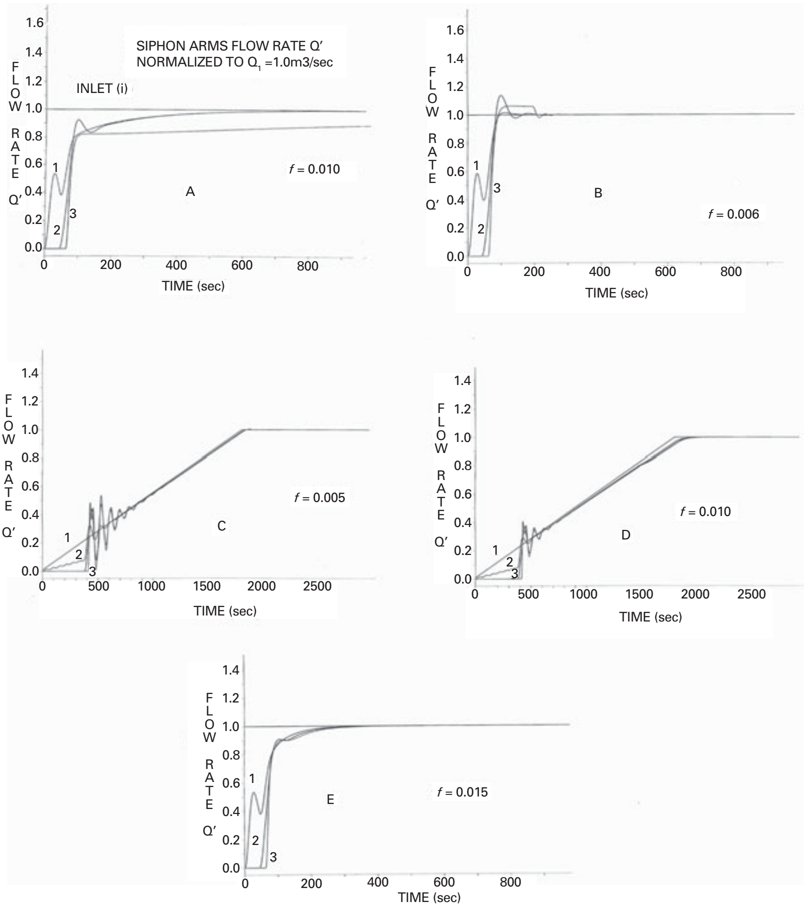

Figure 2.2.6. Flow rate Q (m^3/s) in siphon legs 1, 2, and 3 for $f = 0.010$ (A) and $f = 0.006$ (B) as a function of time for impulsive start up at $t = 0.0$ s. Flow rates are normalized to Q1 = 1.0 m^3/s. Flow rate Q in siphon legs 1, 2, and 3 for $f = 0.005$ (C) and $f = 0.01$ (D) as a function of time from ramped start up at $t = 0.0$ s. Oscillations are damped rapidly for slow siphon infilling. E, Flow rate Q in siphon legs 1, 2, and 3 for $f = 0.015$ as a function of time for impulsive start up at $t = 0.0$ s. For impulsive start up, increased f rapidly damps water column oscillations but lowers flow rate due to increased wall shear resistance effects.

absent. Use of Vitruvius' advice to limit header tank inflow rate '. . . the water is to be evenly and sparingly admitted from the fountain head . . .' (Vitruvius 1999, translation) to eliminate pressure and velocity surges is well founded as present results indicate. Clearly the slow-filling-rate has a beneficial effect in limiting start-up oscillations from developing as the low momentum of entering fluid interacting with stationary fluid within the first siphon leg precludes large oscillations from occurring, thus reducing an energy source to initiate fluid column oscillations. The limiting of oscillations and pressure surges during start-up is particularly important to maintain the integrity of the siphon-block joint seals, particularly when considering that these joints are already experiencing large hydrostatic pressure from as much as 40 m of hydrostatic head. Most probably, several failures of other siphon systems that were impulsively loaded gave rise to Vitruvius' cautions.

The pipe flow discharge flow rate Q, represented in terms of the Reynolds number as $\mathrm{Re} = 4Q/\mu D\pi$, is proportional to the pressure gradient Δp for laminar flows for $10^3 < \mathrm{Re} < 10^4$ depending on wall roughness ϵ/D and free stream turbulence levels. For fully developed turbulent flows, Re is found experimentally to vary as $(\Delta p)^n$ where n lies in the range between 0.5 and 0.6 depending on ϵ/D. Laminar and turbulent regions intersect around $\mathrm{Re} = 10^3$ but the gradual transition between curves occurs well above $\mathrm{Re} = 10^3$. When the discharge rate is increased slowly from zero, the first departures from laminar conditions are observed at an upper Re value as high as 10^5 for smooth walls ($f << 0.001$), no local roughness disturbances, and a rounded inlet shape—otherwise for non-smooth walls, laminar-turbulent transition occurs about $\mathrm{Re} = 4{,}000$. When the discharge rate is reduced from a high value, laminar flow is not fully restored until Re falls to a value close to 2,300. Within the siphon legs, flow rates vary during start-up and Re transitions with different internal wall shear effects occur, causing flow intermittency. The source of the intermittence may be near the entry region where the flow becomes locally turbulent and reaches the upper critical Re value and then spreads downstream forming a 'turbulent slug' or a zone of highly concentrated turbulent flow. From mass continuity, the mean velocity must be the same in the slug as it is in front of the slug, where the flow may be moving under laminar conditions. This implies that the pressure gradient is larger in the slug than in front of it and thus, if the pressure drop along the pipe is constant once a slug has formed, the pressure gradient in the laminar fluid must be less than it was previously. The slug therefore locally reduces Q and U within itself and these parameters continue to decrease as long as the slug is increasing in length. When they have decreased such that Re is only about 2,300, relaminarization occurs near the entry zone. The slug may continue to increase in length if the velocity U_F with which its front (downstream) end travels exceeds that of its far end, U_R. Provided the slug is expelled from the pipe, the initial conditions are reset and the process is repeated. For cases for which piping lengths are large and roughness varies along the length and elevated open surface basins occur along the piping, multiple translating, interacting slug zones occur that can emanate pressure waves; these waves propagate and reflect throughout the system and can lead to chaotic discharge rates. Complications arise at the interfaces of laminar and turbulent flows, for example at $\mathrm{Re} = 4{,}000$, $U_F > 1.5U$, and $U_R > 0.7U$ (Faber 1995), which is intermediate between the zero wall U value and the pipe axis $2U$ value. The U_R/U ratio falls steadily towards zero for $\mathrm{Re} > 4{,}000$ while U_F/U remains relatively constant, indicating growing turbulent slug length. For $\mathrm{Re} < 4{,}000$, U_R/U rises while U_F/U falls and at the lower critical Re value both become approximately equal. Below the lower critical value, the flow is laminar because turbulent slugs shrink rather than grow. Thus transitions from laminar to turbulent flow (and the reverse) can occur in patches (slugs) within flow passageways, causing a further source of localized flow resistance and unsteadiness that then necessitates interruption of the siphon length with open basins to mitigate pressure surges.

While steady-state Re values for the Aspendos siphon are estimated to be no less than 5.0×10^4, local ϵ/D roughness can vary along the piping length (at cemented-block junctions, for example), leading to local friction factor changes and, ultimately, local internal pressure changes. In combination with transition effects arising from turbulent slug formation in the critical Re range, the possibility of non-steady discharge rates is high without an active damping mechanism. For $f = 0.01$, fluid transfer from successive basins to the receiving tank shows little oscillatory behaviour and large damping effects. The basins therefore serve as 'accumulators' to damp the successive transfer of fluid energy between siphon legs by limiting the upstream propagation of pressure waves and providing fluid energy absorption mechanisms through sloshing. For $f = 0.001$, oscillatory behaviour in siphon legs occurs with little energy absorption by wall-fluid friction effects and limited energy absorption by open-tank sloshing effects, resulting in chaotic delivery rates to the receiving tank. Values of $0.010 < f < 0.006$ typical of chipped interior surfaces appear to result in adequate damping between siphon legs and promote rapid transition to steady-state flow rate conditions from an impulsive start. Slow filling at similar f values further reduces oscillatory and backflow effects. It appears that deliberate internal wall roughness was maintained to promote damping of oscillatory fluid behaviour.

The source of fluid energy to initiate siphon leg oscillations during start-up may come from: (1) a supply flow rate to the header tank exceeding the acceptance flow rate to individual siphon legs (this may be mitigated by the in-place header tank overflow weir observed by Kessener), (2) the momentum imparted to water partially occupying a siphon leg from inflows, (3) inflow from successive open basins to successive siphon legs during filling imparting momentum to water already in the siphon legs, and (4) open-channel flows in steep angle siphon leg segments, resulting in an upstream-moving hydraulic jump that drowns the inlet then proceeds to re-establish the open-channel flow in an endless oscillatory cycle—this cycling results in piping flow rate changes and head/elevated tank time-varying head. While this latter effect may be somewhat reduced by backflow drainage from the supply basin overflow weir, head tank surges can still drive oscillations. Many of these effects can occur in successive siphon legs with upstream/downstream interactive feedback through open basins that drive fluid column oscillations through complex interactive effects. Clearly, from the discussion presented, siphon flow behaviour during start-up (and to a lesser degree during steady-state operation) can be a major source of problems for the structural integrity of the siphon system due to oscillatory force generated on piping sections. Also of note are steady-state forces at piping angle changes (Figure 2.2.1) of the siphon system under steady-state conditions as well as during start-up. These forces result from momentum vector orientation change between incoming and outgoing flows at the angle-change bend joint. They are directed outward from the piping bends and, as Vitruvius notes, '. . . a [hard] red stone is to be used at the base at the junctions to anchor the piping . . .' presumably to limit any deflection that would cause the siphon blocks to come apart and leak in these junction zones. Inclusion of water inertial effects would reduce oscillation frequencies somewhat from those shown, but tracking the changing water column heights and their inertial effects with time in all siphon legs would add substantial complexity and not change the qualitative picture of the dynamic behaviour of the system during start-up.

To observe fluid behaviour in the open tanks, a FLOW-3D siphon model was made with Figure 2.2.1 dimensions with the same inflow conditions as the analytic model. Figure 2.2.7 shows that when backflow occurs at the header tank (which may occur during start-up), air entrainment (as noted from the entrained air bubble) and sloshing are possible, which further vary input head and alter the oscillatory water column behaviour. Such flow patterns may be the source of Vitruvian comments about '. . . air pockets forming within siphons . . .'. Additionally, Figure 2.2.8 for $f = 0.006$ shows that the northside elevated tank (with geometry consistent with Figure 2.2.1) acts to promote further damping to limit transmission of pressure and velocity surges through sloshing energy absorption. The open elevated tanks therefore serve as 'accumulators' to damp energy transfer between siphon legs and limit oscillations is verified from the CFD results.

The next question considered is the possible meaning of the Vitruvian term 'colliquiaria' and its relevance to the hydraulic behaviour of the siphon. Colliquiaria can possibly relate to: (1) the function of observed transverse holes leading from the piping core to the outside atmosphere, (2) pressure relief valves to limit pressure excursion values, (3) drainage holes to facilitate cleaning, (4) release openings to let entrapped air escape from the system, (5) elevated head tanks to reduce siphon leg water column oscillations, and (6) overflow weirs in the supply tank to limit input flow rate. This list is not inclusive as further fluid phenomena may be included in possible meanings. While the presence of the elevated open basins may serve to satisfy points 4 and 5, and many of the other suggestions have practical merit, research was drawn to the ubiquitous nature of transverse holes. Since the formation of turbulent slugs and oscillatory fluid column behaviour characterizes siphon start-up and increases the time to achieve steady-state operation, some mechanism to reduce pressure and velocity oscillations in the siphon legs would certainly help induce steady flow. If small transverse holes are present in some of the blocks, then some additional leakage can occur. This implies that although some leakage was permitted from the small diameter holes (which also provide for entrapped air to be forced from the system on long horizontal stretches of the siphon), the leakage can help to reduce the local Reynolds number to modify the formation of turbulent slugs and thus reduce one contributor to fluid column oscillations. While some drainage leads to head loss and minor water loss within the siphon piping, it can also limit pressure excursions to diminish fluctuating forces acting on the block joints, thus limiting leakage. The leakage loss also promotes relaminarization as the Reynolds number decreases, thus reducing wall friction forces. Only a few small holes are required on occasional blocks to achieve these benefits as the (overpressure) turbulent slugs and/or pressure waves ultimately travel past

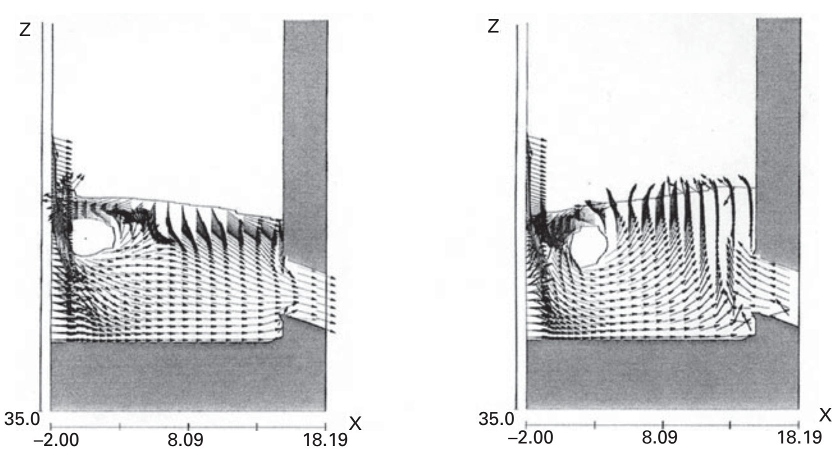

Figure 2.2.7. Reverse flow in the inlet basin from a backflow event can create an entrained air bubble transfer into the first siphon leg, adding complexity to the water motion.

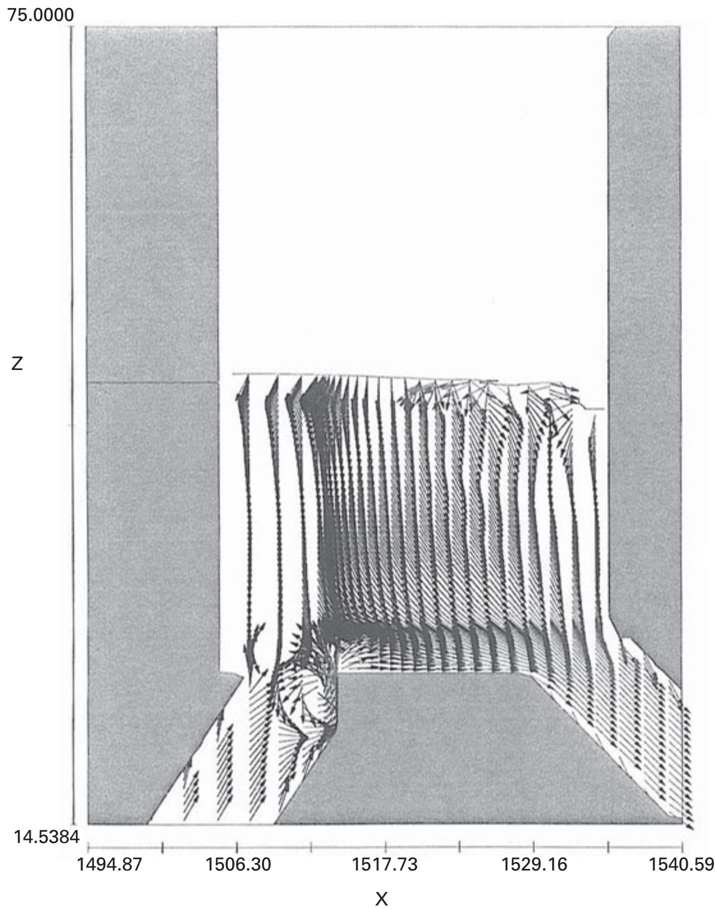

Figure 2.2.8. Water motion in the north elevated open basin during start up with $f = 0.015$. Tank sloshing occurs to damp transfer of energy between siphon legs during rapid start up.

dispersed open holes and diminish intensity by a head change adjustment. Field observation allows the conjecture that accumulations of sinter deposits noticed on the siphon superstructure away from the open basins could arise from occasional transverse hole leakage effects. In essence, the transverse holes may 'fine-tune' the siphon flow rate to achieve low start-up oscillations and steady flow rate at minimum supply basin depth. While conjecture on the role of the holes and their placement on siphon lines (and if they relate to colliquieria) may be made, some experimental results may clarify their function.

Figure 2.2.9. Internal wall roughness of a typ ical siphon block elem ent. The hand chipped interior surface rough ness limits oscillatory water column behaviour by increased frictional shear resistance.

Start-up tests were run to duplicate the Re range of the siphon using clear tubing and an adjustable leakage valve placed near an adjustable input head and flow rate source. In addition to results verifying the above conclusions as to their function, several new effects were observed to explain the transverse leakage hole function. It was observed that air bubbles originating from the header tank inflow (Figure 2.2.7) were effectively purged by outflows from the leakage holes placed downstream to the header tank (1) on the first siphon down-leg, limiting their further travel in the piping. Secondly, it was observed that for cases where an elevated tank head temporarily exceeded that in an upstream tank (as can occur during oscillatory start-up), the holes released a burst of water and thus served as an additional damping mechanism to limit upstream propagation of water column oscillations. In this case, a downstream tank head increase served to increase backpressure resistance, causing temporary water bursts from the leakage holes to exceed the nominal leakage rate. The leakage effect limited tank sloshing and helped to promote steady-state siphon behaviour. A third effect related to cases for which the siphon may operate with partial flow in some of the downward-angled legs. As long as a positive head is maintained between the upstream piping water level and the next elevated tank, the siphon will transfer water. As flow resistance is low for internal-piping segments supporting partial, supercritical flow (which terminates in a hydraulic jump to set the downstream full-flow water level), some savings in friction head loss can be achieved. This (probably non-optimum) operating condition then relied on the transverse holes to admit air into the air space above the partial flow region to help eliminate partial vacuum regions and flow surging.

In summary, fluid mechanics models describing the transient hydraulic behaviour of the Aspendos siphon system have shown that internal piping wall roughness is a key parameter to determine the steady-state flow rate and start-up oscillatory behaviour. For large wall roughness ($f = 0.01$) and impulsive start-up, small amplitude start-up oscillations occur and siphon leg 6 reaches steady-state conditions only after a long time; additionally, large wall roughness limits the flow rate unless additional head is available at the input tank. For small wall roughness (e.g. $f < 0.004$), large start-up oscillations and forces occur but the time to reach a steady-state flow rate is much shorter, probably because of the high flow resistance induced by the high velocity surges. This suggests that an intermediate f value about equal to the internal wall roughness occurring during hand-chipping manufacture ($f \sim 0.006$) represents a design optimal strategy, perhaps achieved fortuitously. While these conclusions are based on a start-up strategy of admitting water into the header tank impulsively at a given velocity with an initial water height in the siphon equal to that of the receiving basin, further calculations made assuming a slow, ramped entry velocity yielded interesting results. At a slow entry velocity ramped from 0.0 to 1.0 m/s in approximately 1/2 h, steady state is achieved in about 500 s for $f = 0.005$ and 200 s for $f = 0.01$. This indicates that slow filling largely reduces the time needed to achieve steady-state conditions and confirms Vitruvius's observation. Apparently the thought that rapid filling would lead to rapid onset of steady-state behaviour was recognized as a fallacy even by ancient hydraulic engineers. The elevated tower basins served as ultimate release points for trapped air, energy absorbers to limit water oscillations, and as accumulators to damp the transmission of pressure waves during impulsive start-up. The shallow header tank with an overflow weir at 1.0 m height served both to limit the entry flow rate, and head and damp backflow-caused sloshing head changes that contributed to oscillations. Since open-tank oscillations occur at their natural frequency, an automatic frequency interrupter mechanism was in place to reduce coupled leg oscillations. For cases where water column oscillations occur, and both orifices to an elevated basin experience an inflow, the water height change represents a potential energy change subtracted from the flow. This again has the effect of damping sympathetic oscillations at the same frequency within the siphon legs as the natural frequency of the water in the tank is different to that of the legs. The damping of oscillations within the siphon system was a vital consideration to limit tension-induced cracking between cemented siphon blocks and this was one of the main functions of the elevated tanks. A further reason for the multi-leg siphons can be attributed to Figure 2.3.4, which shows that cumulative flow losses in long pipelines alter the relation between head and flow rate. By using individual, short siphon legs with 'head reset' basins before each siphon leg segment, high flow rates could be maintained. Thus, 'head reset' in this manner follows Vitruvian advice to limit pipeline length if high flow rates are desired with limited available head. For slow-filling and an intermediate f value, the Aspendos siphon design was able to limit the duration and magnitude of oscillatory start-up tension/compression forces on siphon block joints to limit leakage and system breakage. By use of slow, ramped infilling, an f value consistent with a rough, chipped interior surface of the siphon blocks, and use of various damping systems, oscillation problems were minimized and steady-state flow achieved in a relatively short time.

In conclusion, defences to counter transient fluid mechanics problems appear within the Aspendos siphon. This revelation advances the scope of knowledge of Roman engineers although this knowledge probably came from empirical observation of faults and cures in early attempts to optimize siphon operation. Given the source of knowledge to design this system, the technical accomplishments of Roman engineers demonstrated in the design and operation of the Aspendos siphon must certainly be added to the history of hydraulic science.

2.3 THE WATER SUPPLY AND DISTRIBUTION SYSTEM OF EPHESOS, TURKEY

Settlement history

Occupation of the Ephesos area (Figure 2.3.1) on the western coast of Turkey (Ionia in ancient times) began from rural settlements in the third millennium BCE through Mycenaean occupation in the second millennium and continued into Hellenistic and early Roman periods of the first millennium BCE. Occupation continued into the Imperial Roman and Byzantine eras, with site architectural modifications made according to the religious and civil templates of the occupiers. Settlement continued through the Turkish and Selucid occupation beginning in the 14th century CE, with final abandonment resulting from military collapse of the eastern Roman Empire at Constantinople. The political and cultural history (MacKendrick 1962; Foss 1979; Karweise 1995; Koester 1995; Scherrer 1995; Wiplinger 2006), architectural history (Miltner 1958; Alzinger 1972; Lessing and Obrerleitner 1978; Bammer 1988; Rogers 1991), and geological history (Kraft *et al.* 1985; Crouch *et al.* 2002) of this site are well documented. Continual changes in site architectural details (Akurgal 1975) occurred through site relocations over time, the effects of silt deposition of nearby rivers (Greek settlements lie some 10 m below the later Roman city), and the effects of hostile invasions, occupations, and earthquake destruction episodes with periods of abandonment, modification, razing, and rebuilding according to the architectural and defensive preferences of successive occupiers. The shoreline of the bay on which Ephesos stood frequently shifted due to silting from the nearby Kaystros (ancient Meander) and Klareas (ancient Marnas) rivers. Changes of shoreline and sea level caused relocation of settlements to different locations on the general site (Crouch *et al.* 2002). The earliest occupation was a Mycenaean trading post (1699–1400 BCE) located north of the archaeological site in the area of the castle outside of Selçuk. No later than the 8th century BCE the nearby Sanctuary of Artemis (Artemesion) drew pilgrims from throughout the ancient Near East and eastern Mediterranean world, becoming a huge temple complex in the 6th century BCE with rebuilding episodes noted several times during the following centuries. (Site number descriptions corresponding to Figure 2.3.2 are given in the caption.)

The Sacred Processional Way passing through Ephesos was important for all periods of Greco–Roman culture and was a focus of religious processions that extended from the Artemesion on the north–northeast, around both sides of Panayir Dag Mountain to the village of Ortygia in the coastal mountains southwest of the city. Commercial activity centred at the Tetragonos Agora (Figure 2.3.2, 61) from early through to Byzantine times and its buildings stood on successively elevated sites as river-deposited silt accumulated over the centuries.

Pre-archaic settlements near the Artemesion gave place in the 6th century BCE to a small town on the northside of Panayir Dag. Before 300 BCE, Lysimachus, a successor to Alexander the Great, moved the urban population to the southside of Panayir Dag (Figure 2.3.2) and built surrounding defensive walls (11) encompassing Panayir Dag and on Bulbul Dag to the south. When Asia Minor came under Roman rule *c.* 130 BCE, new buildings (16, 18, 21, 22, 30, 59, 61) were constructed in the population centre between the two mountains and in new areas at the western foot of Panayir Dag on natural and artificially filled land (41, 92, 93, 94, 95, 96). New port facilities were added (87, 88, 89, 90) and both the theatre and stadium (75, 104) enlarged. Four major supply aqueducts (Figure 2.3.3) and fountains (17, 101) were added in the Roman period. Temples and elite houses completed the Romanization of the site so that its character largely reflected the Roman Imperial template. At this stage, Ephesos had achieved status as the Roman capital of Asia and was the central administrative seat of the eastern provinces. Some buildings were transformed in the 4th century CE into Christian churches (95, 96) and auxilliary buildings. By this time the shoreline had changed radically (Crouch

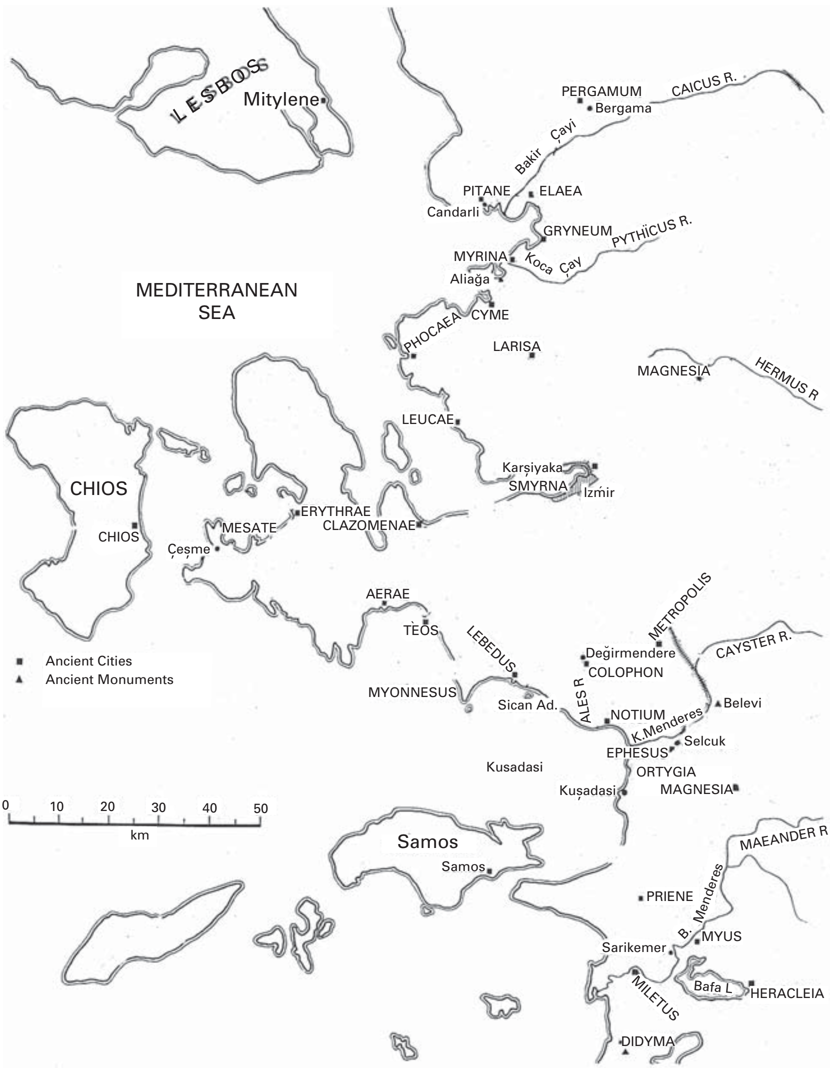

Figure 2.3.1. Map of the Ionian coast of Turkey.

et al. 2002) so that new buildings stood on new land to the northwest of earlier sites that had been abandoned after a major earthquake in the 4th century CE. The effort to maintain port status was abandoned in the 7th century because of alluvium filling the harbour. Byzantine–Turkish struggles during the following centuries were evidenced by new ramparts (77) enclosing part of the city. Ephesos ultimately lost importance as a religious

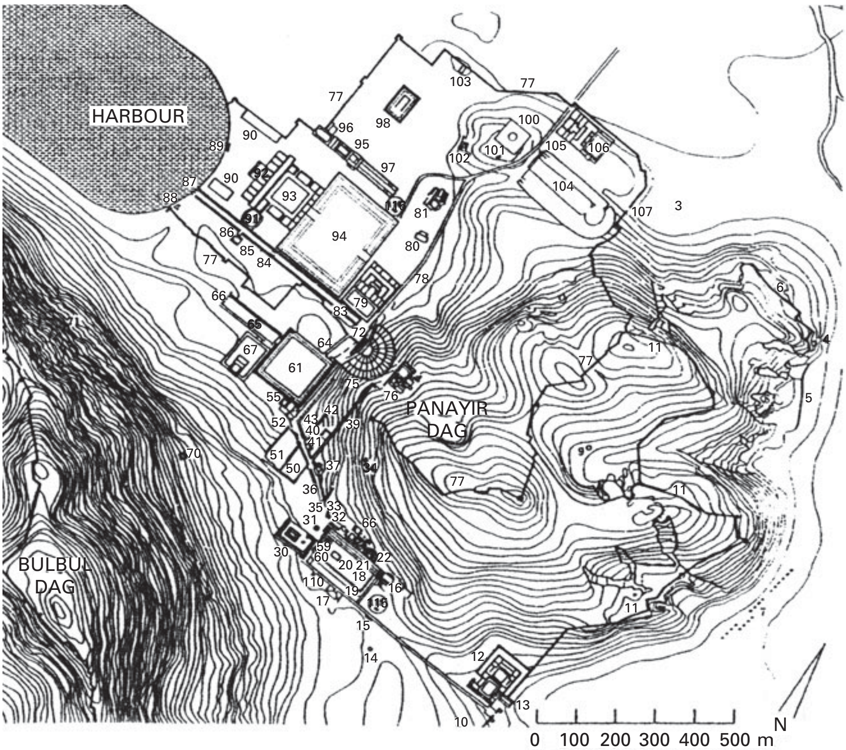

Figure 2.3.2. Site map of Ephesos showing key (numbered) architectural features (Austrian Archaeological Institute, Vienna, Austria). 10, Magnesia Gate; 11, Hellen istic city wall; 12, east gymnasium; 15, fountain on road to Magnesia Gate; 16, upper gymnasium; 17, fountain house; 18, state agora; 20, Temple of Divus Julius; 21, Basilike Stoa; 22, Bouleuterion; 30, Temple of Domitian; 32, Memmius Monument (Nymphaeum); 35, Marble Street; 36, Embolos/Kuretes Street; 37, Fountain of Trajan; 40, Varius Baths/Scholastikia Baths; 41, Shrine/Temple of Hadrian/Olympeio; 43, latrinae; 50, slope house I; 51, slope house II; 52, Heroon of Androcles (Byzantine fountain); 55, Library of Celsus; 59, Pollio Fountain; 60, Bassus Laecanius Fountain; 61, Tetratragonos Agora; 66, Prytaneion; 67, Sarapeion District; 69, east gymnasium adjunct; 70, Magnesia Gate; 72, theatre plaza/fountain; 75, theatre; 76, upper palace east of theatre; 77, Byzantine city wall; 78, theatre gymnasium; 83, Arcadian way; 87, 88, 89, harbour gates; 90, warehouses; 92, harbour baths; 93, harbour gymnasium; 94, courtyard of 93 (Xystoi); 95, 96, Church of Mary; 98, Temple of Hadrian Koressian District; 100, Macellum; 101, late fountain; 104, stadium; 106, Vedius gladiator gymnasium; 107, northern gate.

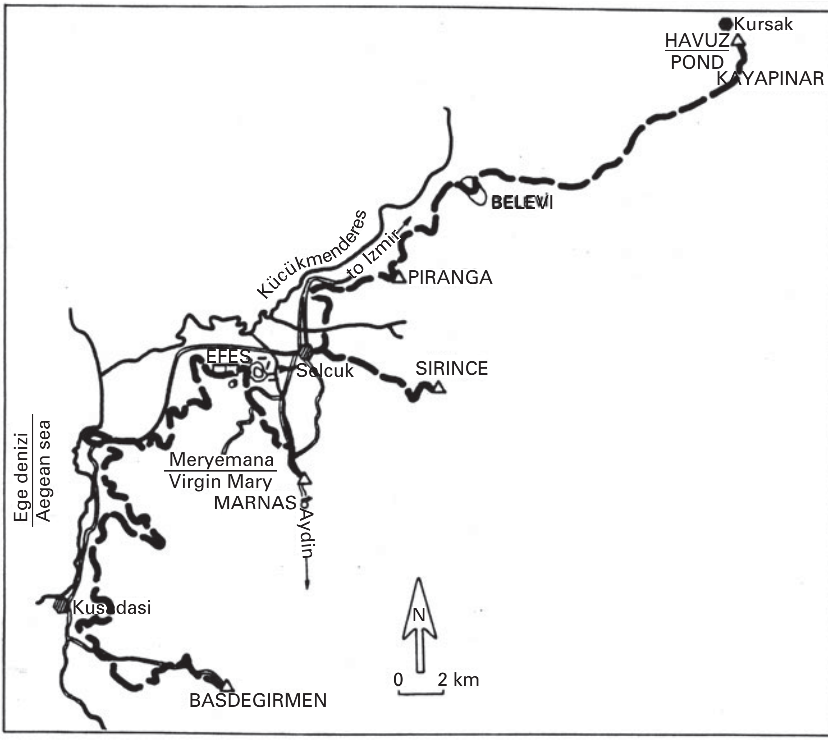

Figure 2.3.3. Major aqueduct systems providing water to Ephesos through spring sources. The Meryemana system originates from springs in the House of Mary area located towards the top of Bulbul Dag Mountain (Özis *et al.* 1997).

centre but had sufficient Turkish population to warrant a mosque built near the Artemision made of the materials taken from the building. The Crusader period castle at the north end of the Ayasoluk hill (4 km east of Bulbul Dag) was associated with incursions of Arabs and Turks from the east and south countered by crusading armies of Franks and Europeans from the west and north. Finally, Ephesos survives as a historic site centred in an agricultural zone around the modern city of Selçuk, immediately east of Ayasoluk.

Engineering history

Less well known than the political, economic, and architectural site history is the civil engineering history of Ephesos related to the urban water supply, distribution, and drainage systems that served ceremonial and state structures, baths, fountains, elite and common housing, as well as temples and domestic quarters. Each of the occupying civilizations left traces of their civil engineering practices in the archaeological record. Since the exposed urban core of the city mostly dates from Roman occupation, the water supply and distribution system visible today reflects Roman civil engineering practice in early centuries CE. Some understanding of water distribution systems and associated hydraulic sciences in Roman times is provided by the written records of Frontinus (Bennett 1925; Herschel 1973; Evans 1994) and Vitruvius (Morgan 1960). While these works give insight into the administrative and design methodology of water supply systems of that period, they also reflect pre-scientific views of hydraulic principles. One hypothesis is that the archaeological remains of water supply and drainage systems, once analysed, demonstrate that more was known than the fragmentary literature revealed and that the Roman engineers had deeper hydraulics knowledge than these literary works attest. While theoretical developments and codification of physical laws are not evidenced in the surviving literature, much in the way of empirical knowledge gained from trial and error probably constituted a substitute methodology for major construction projects. Civil engineering expertise manifested in surviving aqueducts and urban water supply systems must then be rediscovered by field survey, excavation, and analysis in the absence of ancient text descriptions to test this hypothesis.

To attempt to understand Roman engineering practice more fully, field investigation of physical remains of water systems were combined with analytic and CFD methods to determine to what level Roman designs contained an understanding of basic hydraulics principles. This section examines the hydraulic engineering problems faced by Roman engineers using piping system details obtained from site archaeological field data. Then, as now, many aspects of hydraulics knowledge came from empirical observations translated into practical working principles. Years of experience (good and bad) probably generated a working set of rules whose physical form can still be discovered in the archaeological ruins of Ephesos.

Water supply elements

Water was continuously supplied from aqueducts to distribution structures composed of multi-compartment collection tanks (castellum) at high points within the city; each compartment had a number of terracotta exit pipes originating from compartment sidewalls or bottom areas leading to various destinations: baths, fountains, domestic neighbourhoods, theatre, agora, temples, etc. Following text descriptions by Vitruvius (1999), each individual water compartment and its outlet piping system set served a different purpose: one set may supply baths and other public buildings, another set residences, and another set, the fountains and public water basins. Yet as Hodge (1990) indicates, no system divided exactly like this has yet been discovered in the Roman world although the system at Pompeii contains elements of flow division by means of three weirs placed at different heights to direct flow rates to different destinations from a constant head tank.

One (as yet unexcavated) castellum (17) is a multi-compartment design incorporating principles similar to those described by Vetruvius, as may be observed from the cleared top part of the structure. Each of the individual water compartments maintained a different water height necessary to produce the required flow rate through the outlet piping to supply specified destination buildings. Different water heights in individual compartments were maintained by either top ledge overflow weirs or water surface-level piping that shunted water between compartments or into adjoining public basins by fountain discharge. For applications requiring delivery of a given amount of water over a given time (for example to baths or pools), a compartment needed to discharge intermittently rather than continuously, implying storage and manual control of release time within a castellum compartment. While most pipelines ran directly from a particular castellum compartment to a designated destination, field observation indicated occasional use of drain piping connecting successive downhill basins to extend the utility of potable water sources.

The supply elements of the Ephesian urban water system are long-distance water pipelines and open-channel aqueducts tapping distant springs (Özis *et al.* 1997; Wiplinger 2006: Figure 2.3.3), onsite springs with collection basins, wells and cisterns, castellum structures at the terminus of aqueducts, distribution pipelines to fountains and housing areas, and gutters and sewers to provide site drainage. Roman period piping elements are usually composed of standardized terracotta socketed segments in the Vitruvian class of 100 centenaria (20 cm inner diameter) or 120 centenum vicenum (22 cm inner diameter)—variations may exist in piping wall thickness because of repair insertions. Typical straight piping element lengths are in the order of 40 to 60 cm with occasional exceptions found associated with repair elements or special high-pressure sections. Use of hydraulic cement at pipe joints provided watertight connections.

Pipeline hydraulic design criteria

The physics of pipeline flows, as detailed by modern hydraulic theory, are applied to analyse Roman systems. From Roman pipeline network and open-channel delivery system design, questions arise that relate to the hydraulic criteria necessary to deliver precise flow rates, or finite water volumes over time, from castellum compartments. The key parameters determining the flow rate in a pipeline are slope, internal wall roughness, diameter, pipeline length, pipeline inlet shaping, outlet configuration (submerged or free-overfall), and the hydrostatic head at inlet and outlet. Subsidiary design criteria relate to piping pressure losses, flow Reynolds number, pipe venting to the atmosphere, flow stability, internal piping flow rates for full-flow (entire cross-sectional area full) or internal open-channel flow (cross-section partially full), head reset by open basins on pipelines, and flow rate maximization. All of these considerations are vital to successful pipeline design and can best be analysed by CFD techniques. The degree to which Roman pipeline design reflects knowledge of these design principles gives insight into aspects of Roman civil engineering practice.

Some aspects of pipeline design are now discussed. Figure 2.3.4 shows the limiting full-flow rate obtainable through a pipeline length L for 1.0 and 3.0 m inlet head (H) with inclination angles from 2 to 6° and at atmospheric pressure with a free-overfall outlet. Calculations for a 22-cm inner diameter (D) pipe, typical friction factor $f = 0.05$ for socketed, constricted joint piping elements, Reynolds number $\mathrm{Re} \sim 5 \times 10^5$ and a rough piping interior surface at $\epsilon/D = 0.02$ are shown. Here Re is defined as the pipeline average velocity V times the diameter D divided by the water kinematic viscosity. From this figure, a 50-m pipeline at 2° slope with $H = 1.0$ m inlet head reaches a limiting volumetric flow rate of 0.083 m^3/s; increasing the head by a factor of three to 3.0 m for the same slope increases the flow rate to 0.115 m^3/s. Therefore a three-fold inlet head increase only produces a 27% flow rate increase for the 50-m pipeline. For a 6° slope, the increase in flow rate is only 15%. For pipe lengths >200 m, the flow rate at a 2° slope for 1.0 m head is 0.072 m^3/s, while at 3.0 m head, the flow rate is 0.080 m^3/s. Increasing the inlet head three-fold for pipe lengths ≥200 m in the slope range from 2 to 6° therefore does not substantially increase flow rate due to the cumulative frictional flow resistance. The length L of the pipeline therefore affects the flow rate due to the cumulative effects of wall-induced frictional shear on fluid velocity. From these results, it appears that pipelines over 200 m long approach limiting flow rates dependent on slope and these rates are not linearly dependent on input hydrostatic head. Piping lengths less than 120 m, however, show a significant dependence on inlet head. For example, a 20 m pipe section at 2° slope shows a 40% flow rate increase if the inlet head is increased three-fold (to 3 m) and a 20% increase at a 6° slope. Clearly the head-flow rate angle dependence is more pronounced at short pipeline lengths. The magnitude of the dependence is largely influenced by the pipe internal wall friction factor f value, which depends on the ϵ/D wall roughness magnitude. While calculations show that cumulative resistance effects affect long pipelines by a non-linear head-flow rate relationship, this effect was noted some two millennia earlier by Vitruvius (1999).

While entirely partial and entirely full flow may be subcritical ($Fr < 1$), supercritical ($Fr > 1$) or critical ($Fr = 1$), the determination of streamwise transitions between full and partially full pipeline flows (or partially full and full flows) is a complex function of flow rate, cross-section geometry, internal roughness, exit conditions (exit flow height should be less than the critical depth), piping inclination angle, and local *Fr* values. For unsteady flow conditions that may involve moving hydraulic jumps within pipelines, the transitions are more complex so that recourse to CFD methods is necessary to determine flow patterns. Totally supercritical ($Fr > 1$) open-channel flow can be sustained within low wall roughness piping under conditions where pipe slope is hydraulically steep, a free-overfall outlet exists, and the inlet supply compartment head to pipe diameter ratio (H/D) is below a critical value (H^*/D) necessary to create weir flow at the piping inlet (typically H^*/D is 3 to 5).

The full-flow results shown in Figure 2.3.4 contain restricted regions of applicability, particularly for low head and steep piping angles, as further considerations apply to determine piping internal flow patterns. For certain flow conditions, results indicate that the full-flow rate can be less than that

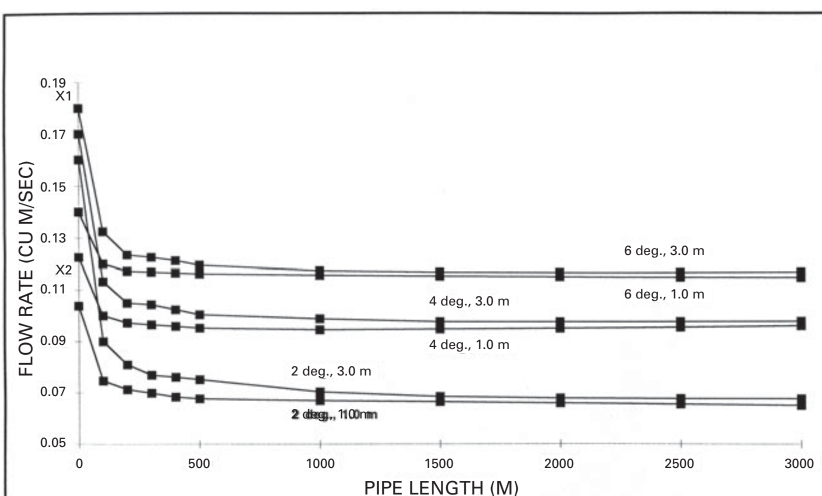

Figure 2.3.4. Flow rate through a 3,000 m piping length for various inclination angles and water inlet heads. Cumulative viscous flow resistance limits flow rate despite increased head values and piping angles past ~250 m piping length.

from open-channel flow within piping, for example, for the same head, open-channel flow conditions in piping (for a flow rate 0.125 m^3/s, designated as X2 in Figure 2.3.4) can lead to greater flow rates for all of the 3.0 m head and most of the 1.0 m conditions compared to full-flow conditions for 5° slopes. Complex situations of this type are examined in later sections; results of such analyses explain water flow problems related to a particular pipeline design likely to be encountered by Roman engineers. Examination of the methods to resolve problems resulting from internal pipeline flow type changes give insight into the level of hydraulics knowledge practised by Roman engineers.

Hydraulic analysis of piping systems

To address complex transient internal flow conditions within pipelines, it has been shown (Ven Te Chow 1959; Morris and Wiggert 1972) that the full-flow rate (Q_{ff}) is greater than the (partial flow) open-channel flow (Q_{ocf}) provided:

$$S_b \geq (H/L)[C_c^2(1 + K_i + fL/\mathrm{D}) - 1]$$

where L is the pipe length, S_b is the piping slope, H is the hydrostatic head (for example in a castellum compartment), C_c is the contraction coefficient for sharp edge inlets, K_i is the inlet loss coefficient, f is the pipe internal wall friction factor, and D is the pipe diameter. For example, for a pipeline length of $L = 200$ m and $C_c = 0.62$, $K_i = 0.4$, $f = 0.05$, $H = 3.0$ m, $D = 0.23$ m, then $Q_{ff} > Q_{ocf}$ only for pipe slopes $S_b \geq 13.9°$. For a 1,000 m pipeline, with $H = 3.0$ m, $S_b \geq 13.9°$ for the same result. For similar conditions but for a 2° slope and $H = 3.0$ m, $Q_{ff} = 0.077$ m^3/s while $Q_{ocf} = 0.197$ m^3/s; therefore the piping open-channel flow rate is 2.5 times (2.5×) that of the full-flow case. For a 50 m pipeline length and $H = 3.0$ m, $S_b \geq 12.5°$ so that the open-channel flow rate multiplier is 1.72×; for a 200 m pipeline, the flow rate multiplier is 1.23×. For $H = 1.0$ m, $L = 200$ m, and a 2° slope, then $S_b \geq 4.64°$ and the open-channel flow rate multiplier is 1.46× over the full-flow rate. This exercise demonstrates that open-channel flow piping flow rates are higher than full-flow rates for the same inlet head at typical field-surveyed, low piping slopes <5° at typical f values and are desirable design objectives to achieve. Another advantage of partial flow conditions is that the piping system is non-pressurized, thus reducing leakage possibilities. However, other conditions hold for full-flow to be maintained in piping at hydraulically steep angles. Figure 2.3.4 therefore contains restricted regions of applicability as further considerations apply to determine internal flow patterns.

To explore the conditions that determine the type of internal pipeline flow, if the entire pipeline can be maintained at full flow for a castellum compartment head $H > H^*$ (H^* is a reference head equal to about 3 to $5D$), then the full-flow rate (Q_{ff}) is given by (Ven Te Chow 1959; Morris and Wiggert 1972):

$$Q_{ff} = A[2g(H - mh + S_b L)/(1.4 + fL/D)]^{1/2}$$

where h is the effective free-outlet height and $m = 0.30$. If open-channel flow can be maintained within a pipeline, then the flow rate (English units) is:

$$Q_{ocf} = A[2gH/(2.6)]^{1/2}$$

where a typical orifice coefficient (0.62) has been assumed for the inlet and A is the cross-sectional area of the flow. Presumably, some empirical version of the relationships shown was available to Roman engineers to determine flow rates in pipelines for different applications. Once flow rate totals for different pipelines of different lengths and slopes emanating from castellum compartments at different head values were known, then efforts to match that total to an aqueduct supply rate (which was designed to match the spring supply rate) form the basis for a system design. This process is complicated when water requirements at different destination locations are prescribed in advance of supply system construction. The fundamental design and laying angles of pipelines rely on knowledge to achieve either full- or open-channel conditions within pipelines due to the sensitivity of the flow regime and flow rate to head and piping slope. Design errors can lead to problems that render water supply inadequate for its intended purpose. Clearly for low-angle pipeline designs, it is possible to achieve high-flow rates if an open-channel flow can be induced and maintained throughout the piping length.

Up to this point, a number of design features observed in Roman Ephesian pipeline designs appear to follow basic tenets in accordance with the hydraulic principles thus far discussed:

1 Long pipelines originating from distant springs or emerging from a castellum compartment reach a limiting full-flow rate after only a few hundred metres of pipe length for given head, f value, diameter and slope; steep-slope, parallel piping system bundles were occasionally used to increase the total delivery flow rate to a destination point. The recently discovered four-bundle piping system on a hillside road cut near the Marnas aqueduct that brings water to the city from either the spring system located near the House of Mary (HM) high up on Bulbul Dag Mountain or from a Marnas River inlet is evidence of this concept. Where open-channel delivery

systems are not practical or desirable (for example in the use of buried pipeline systems for defensive purposes), multiple piping bundles were used to increase flow delivery. No evidence of larger diameter pipelines, beyond standard sizes, are found at Ephesos. Long, hydraulically mild slope pipelines of slope $S_b < S_c^*$ (where S_c^* is the critical slope related to maximum flow rate conditions) are likely to be near-full-flow conditions due to wall frictional effects (lowering velocity and thus increasing flow cross-sectional area to maintain the same mass flow) if submerged outlets are in place.

2 Since most Ephesian pipeline angles have $<5^\circ$ declination, open-channel flow (partial flow) conditions characterize most observed piping systems; this strategy enables higher flow rates over those obtainable for full-flow conditions (particularly if near-critical flows can be obtained) and limits leakage under pressurized, full-flow conditions. Open-channel flow occurs at castellum outlets (pipeline inlets) for castellum compartment water levels $H < H^*$ and can be maintained for hydraulically steep, short piping lengths. For compartment $H > H^*$ and hydraulically mild slopes, pipeline flow can be maintained in full-flow mode provided submerged outlets exist.

3 Open-channel flow delivery (by aqueducts or large masonry-lined, contour-following channels) is an optimum strategy for large volume flow rates as opposed to multiple pipeline bundles of equivalent cross-sectional area because of their low flow resistance. Open-channel flow in piping is a better strategy in that flow rates can be higher than full-flow systems provided critical or steep-slope design conditions can be met by precise surveying. While open-channel, masonry-lined systems are used for aqueducts and channels with large flow rate demands (theatre, baths, stadia, etc.), pipeline bundles may be used if topographic constraints (or defensive considerations requiring underground systems) rule out open channels. Both design strategies are found at Ephesos.

4 Roman engineers avoided piping designs incorporating a large main trunk line from a castellum compartment from which multiple branching piping networks originated; preference was given to multiple, individual pipelines originating from castellum compartments to designated usage locations. Full flows that originate from a single large pipe and branch into successively smaller diameter piping branches can result in unsteady flow rate delivery, particularly when end-point usage varies. For this reason, the design strategy of individual short pipe lengths (with deep submerged inlets $H >> H^*$ originating in a castellum compartment) to a destination structure whose flow rate is regulated by compartment head levels is the preferred design, although such designs do not necessarily yield maximum flow rates. Full-flow rates can be associated with short piping lengths,

$H >> H^*$, and hydraulically mild slopes ($S_b < S_b^*$); flow rates can be regulated by head level H in castellum compartments (e.g. for $L = 20$ m, 4° slope, full-flow rate can be increased 30% by increasing head from 1.0 to 3.0 m). Such designs were preferred for carefully monitored flow rates but large flow rate applications required open-channel flow either within piping or in open masonry channels. Even for $H >> H^*$, pipeline supercritical, partial flow may develop provided a hydraulically steep slope exists, the outlet water height is above the critical depth, and flow resistance is sufficiently low (short piping lengths, smooth inter wall surfaces, and smooth joint transitions are required). For $H \leq H^*$, the partial vacuum region created by a submerged critical weir pipeline entry zone from a castellum compartment can create a vortex string, funnelling air into the inlet region from the water top surface as a means of relieving pressure imbalance; therefore $H \leq H^*$ compartment water level designs are usually avoided as unsteady flow results. Roman practice options included use of short, mild slope piping associated with full flow from a given castellum compartment using a specified head to precisely regulate flow rate to key structures; the head was maintained by continuous aqueduct inflow distributed to the compartments. For high flow rate applications (rapid filling of baths or large water supplies to nymphea fountains) a further design option was compartment $H > H^*$ with short, hydraulically steep piping providing high-flow rates. Since the Ephesos castellum has not been fully excavated, inner structure details remain unknown; however, many individual pipelines are observed to emerge from the castellum on their way to different destinations with different water demands, implying different compartment head conditions.

5 When a piping length at hydraulically mild slope continues on to hydraulically steep length and causes a transition from full to partial flow, top air holes on pipes in the partial flow region are required to mitigate the partial vacuum regions created as the flow height decreases in the partial flow region, particularly if the outlet is submerged. Top air holes in many Ephesian pipelines are an indicator of such conditions. Under opposite conditions, in which a supercritical partial flow changes to full subcritical by means of a hydraulic jump (caused by a piping slope change from steep to mild and/or wall frictional flow resistance in long pipes and submerged outlet), the hydraulic jump position will oscillate back and forth within the pipeline and periodically drown and recreate partial flow entrance conditions, causing periodic flow rate variation. This causes castellum compartment water to slosh, creating variable head and further flow rate unsteadiness. Although partial flow can exist at hydraulically mild slopes, this implies trickle flow

rates of little practical use. Flow rate instabilities are avoided by using short piping lengths and avoiding slope changes from steep to mild, particularly when free exit piping exists, causing air incursion to migrate upstream to connect with partial vacuum regions and resulting in unsteady flow delivery. Problems of this type can be solved by submerged outlets. For all these possibilities, Roman engineers show awareness of design solutions.

6 Roman engineers recognized that the fastest delivery rate of water in low slope pipelines is achieved by having a pipe containing near-unit Froude number (critical) open-channel flow (or slightly below critical to avoid instabilities) where the critical height is close to the top of the pipe, i.e. the flow resembles near full flow but is open-channel flow at critical velocity and height. The presence of piping top holes may have an additional function to observe if standing V-waves are formed by a rod inserted into the flowing water; by this, the flow regime can be established as supercritical. If these waves are not present, the flow is subcritical. While the *Fr* value can be determined from the V-wave-included angle by hydraulic analysis methods, at least this sight determination by Roman engineers could be used to determine where the flow transitioned from one regime to another or if the pipeline maintained supercritical flow throughout its length for a given pipeline slope. As transverse holes are found in many pipelines as well as in T- and L-joints, this qualitative 'sight' method may have been used to fix downstream slopes to maintain the desired flow regime throughout the total piping system. If oval standing wave shapes are created about the rod probe, then critical flow exists—as this condition produces the maximum flow rate, this observation would be of use in setting pipeline angle to a critical slope.

To determine the slope (S_c^*) needed to sustain a critical open-channel flow rate (Q_c), the critical depth (y_c) in pipes of diameter D is approximated in English units (Ven Te Chow 1959) by:

$$y_c = 0.325(Q_c/D)^{1/3} + 0.083D$$

Then if the top surface of water at critical depth in the pipe is a leg of a triangle with the two other arms as radii with an internal angle $(2\pi - \nu)$ radians, then the angle ν is given by solving the transcendental equation:

$$y_c = (1/8)[(\nu - \sin\nu)/\sin\nu/2]D$$

The critical flow rate in terms of the ν angle is given by:

$$Q_c = 0.251D^{5/2}(\nu - \sin\nu)^{3/2}(\sin\nu/2)^{1/2}$$

and the determination of the pipe slope (S_c) that supports the critical flow rate is found from the Manning equation (English units):

$$S_c = (Q_c n/1.49)^2 A^{\ 2} R_h^{\ 4/3}$$

where n is the Manning roughness coefficient, A is the cross-sectional area of the pipe and R_h is the hydraulic radius $= (1/4)(1 - \sin \nu)\nu^{\ 1} D =$ flow cross-sectional area/wetted perimeter. This equation is used to determine the approximate pipeline slope needed to sustain critical open-channel flow. Based on these equations, a sample (smooth pipe interior) calculation shows that for Q_c values of 0.010, 0.025, 0.050, and 0.075 m^3/s, the S_c^* angles are 0.032, 0.389, 1.357, and 3.016°, respectively. The corresponding y_c/D values are 0.344, 0.565, 0.848, and 1.0 (full-flow), respectively. This indicates that for typical pipeline flow rates ($<1.0\ m^3/s$), internal open-channel flow can be maintained at low pipeline slopes and no hydraulic jump will be triggered past the entry region for short pipeline lengths at these low slopes. Note that if an internally rough pipe were used, full flow due to velocity slowing may be induced and increase the critical angles. The flow rates and slopes described imply that near-critical conditions apply for relatively shallow slopes for which open-channel flow rates are maximized for typical pipeline diameters.

In summary, most field-observed, low-slope pipelines emanating from castellum compartments support high-flow rate, open-channel flows, as evidenced by top air holes. Since small piping angle changes can easily alter flow regimes, the presence of top air holes provides an 'observational fix' to understand the flow regime and alter the piping angle accordingly. The flow rate can be maximized by setting the piping angle to S_c^* but this requires some knowledge of the flow rate. At least for flow rates $<1.0\ m^3/s$, only shallow angles are required, such as those typically observed on-site. It may be surmised that Roman engineers observed the dependency of the flow regime and flow rate on piping angle for different head conditions and that some form of empirical table was utilized for specific design purposes. As much of the piping at Ephesos shows lengthwise angle changes, it is interesting to speculate if these changes were deliberate and resulted from monitoring flow to be as close to critical as possible (by observing wave patterns in the water flow through top holes) or just made to follow topographic contours.

As the discussion indicates, many types of internal piping flow transitions can occur. If internal pipeline flow suddenly switches from full to open-channel flow mode due to piping slope change, then a partial vacuum region can occur. If an initial supercritical open-channel flow suddenly switches to full flow due to a slope change and/or viscous flow and roughness resistance effects, an internal hydraulic jump will be created. The position of the jump may be oscillatory or stable depending on downstream conditions. Both types of flow contain unstable partial vacuum regions that shift and alter the flow rate, leading to highly non-linear flow patterns. Based on the preceding discussion, Roman high flow rate (preferably near-critical), partially full pipeline designs of any length (preferably short) should have top air holes (Figures 2.3.5 and 2.3.6), free-overfall exit conditions, and low slope ($<5^{\circ}$); these conditions can be met over a large range of castellum compartment head values. While regularly spaced top holes on each pipeline element, particularly for Greek pipeline systems excavated in the Athenian Agora (Lang 1968), functioned as hand-insertion holes to smooth mortar at internal joint connections, they may also have served a cleaning/blockage removal function as well as hydraulic purposes. Roman pipeline systems at Ephesos demonstrate neither hole positioning regularity near pipeline joints nor a top hole size sufficient for hand insertion, perhaps indicating the test-and-observation hypothesis as a reason for their existence. The conclusion that the pipeline top holes served hydraulic purposes is therefore a logical surmise given the low slopes of the piping around critical and the changes in flow regime that can result. High-slope piping in the order of 60°, as can be found at the Roman site of Morgantina in Sicily (Crouch 1993), demonstrates that air holes are a regular Roman feature of steep-sloped piping as the internal flow is supercritical, open-channel asymptotically approaching the normal depth, and stability considerations dictate access to atmospheric pressure through top holes. Similarly, Roman steep-slope, cored-block pipeline systems at Laodicia in Turkey (Figure 2.3.7) show use of this same technique for similar reasons. Unless oscillatory pressures caused by an oscillatory hydraulic jump at a steep slope–mild slope transition pipeline junction is relieved by top air holes (as air pressure is also affected particularly when flow originates from a $H > H^*$ tank), flow instabilities result, causing forces that weaken cemented joints between piping elements. An alternative strategy for precision delivery of a prescribed flow rate utilizes short pipeline lengths and full-flow conditions maintained with a hydraulically mild slope with no top holes. Examples of each of these design types are found in Ephesos.

In summary, for large Fountain House compartment head values and short piping lengths between source and destination, full flow can be maintained provided piping segments have hydraulically mild slopes and submerged outlets or free outflow outlets if the flow rate is sufficiently high. In this mode, flow rate can be tailored by varying compartment head according to Figure 2.3.4 with short (<100 m) pipe lengths. The same compartment head can induce a near-full, critical flow provided a critical piping slope continually

Figure 2.3.5. Roman construction piping elements leading from the Castellum. Top holes, some plugged and some open, are indicative of partial flow conditions within the piping.

Figure 2.3.6. Further piping elements at Ephesos.

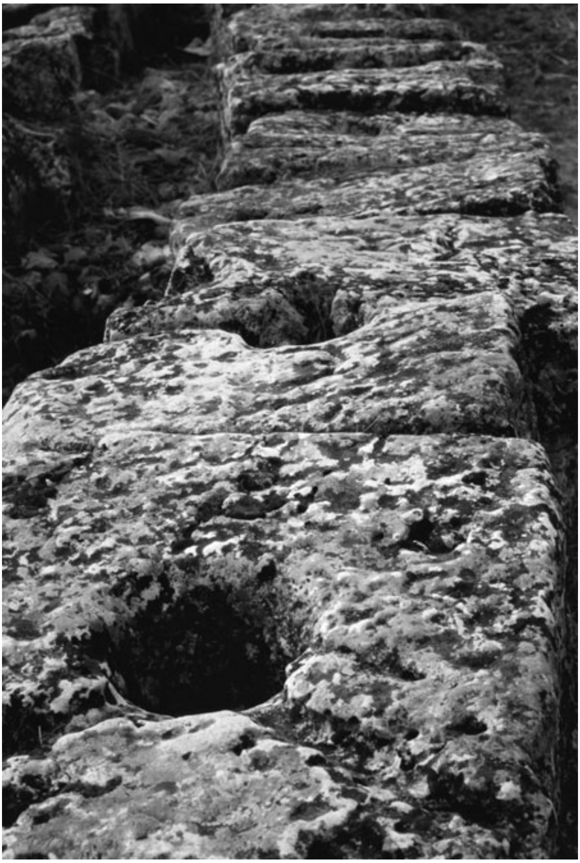

Figure 2.3.7. Top holes in the Laeodocian piping system. The top holes let air into the piping to al leviate partial vacuum regions that result from the contracted water (normal) depth in the steep downhill piping supporting supercritical flow.

exists downstream of the castellum outlet and wall friction is low; such conditions will produce a maximum flow rate for the same head. For $S > S_c{}^*$, $H > H^*$, and short piping lengths, flows are hydraulically steep and can be maintained supercritical throughout provided a free-overfall outlet occurs and the friction factor is low to prevent subcritical full flow from developing. For long pipes with full subcritical flow in the entry region but with a local slope change from mild to steep along a given pipe length, the supercritical partial flow region may revert again to subcritical full flow when rough wall frictional effects lower velocity or a slope change back to mild occurs. Here top holes provide benefit in the supercritical region to alleviate partial vacuum regions that disturb flow stability. If a downstream slope change from mild

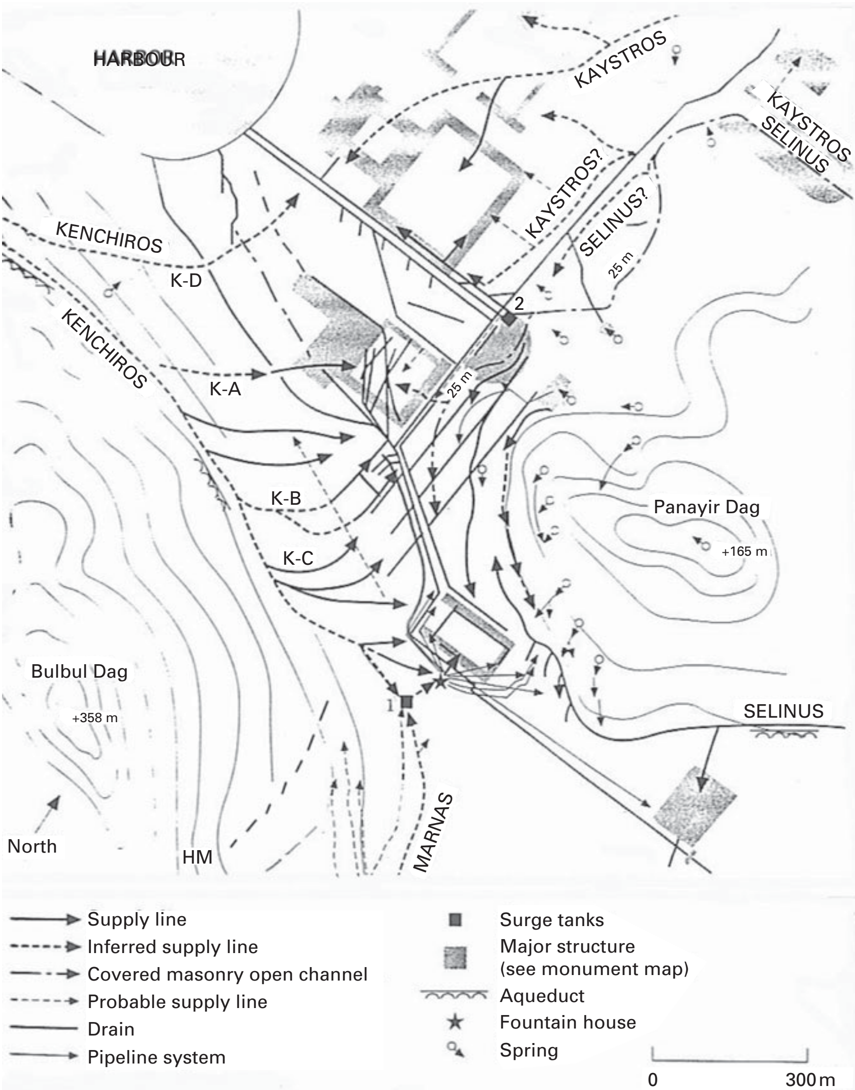

Figure 2.3.8. Main inner city aqueduct/piping network water transfer paths (indicated with arrows) within Ephesos. Shaded lines represent drainage and sewer systems.

to steep occurs and the downstream supercritical flow rate exceeds that of the upstream full flow, the upstream full flow is drained back to the castellum inlet and flow patterns in the castellum compartment and piping are altered to accommodate the faster supercritical flow rate. Piping top holes are used to ensure steady flow delivery when partial vacuum regions caused by local isolated transitions to supercritical open-channel flow regions with lowered water height occur; entrance air relieves partial vacuum regions that create flow unsteadiness as they alter induced pressure gradients within the piping. Also, as top holes permit sight assessment of flow regime, their use to set piping angles is important to alter flow rates. Since piping open-channel flow rates for low head, hydraulically steep piping may exceed those for mild-slope, full-flow cases under certain conditions, castellum compartment designs probably incorporated a variety of high and low head tanks to achieve tailored flow rates depending on destination requirements. Many of these strategies appear frequently in the Ephesian piping network, as shown in Figure 2.3.8.

For long pipe lengths (>100 m), increasing the compartment head only marginally increases the flow rate for full-flow conditions (Figure 2.3.4). The options to deliver higher flow rates are therefore: (1) limit piping length to take advantage of the head full-flow rate relationship, (2) induce open-channel flow within hydraulically steep piping while maintaining a short piping length to limit friction-induced hydraulic jump formation and reversion back to full flow, (3) create a piping system at S_c* to induce critical flow or (4) connect sequential open basins for 'head reset' that effectively creates short piping segments. This is effective for full-flow conditions but also has some benefit for partial flows that may experience conversion to full flows due to wall frictional resistance. For (4), head is essentially reset in full-flow pipeline segments by intermediate sequential open basins, therefore flow rates can be kept high as the system is essentially composed of short piping segments with strong head-flow rate dependence. Very long, full-flow lines were avoided because of flow rate limitations, but to satisfy large water demands for public assemblies in the theatre, stadium, or gymnasia large masonry open-channel systems were used; where pipeline use was unavoidable, pipeline clusters were used, albeit at low water transport efficiency.

CFD pipeline flow analysis

To investigate the complexity of pipeline flows, recourse to CFD methods is made. A sequence of transient calculations at 15, 25, 35, 45, and 55 s (Figure 2.3.9) for water-free surface shape at the centre plane of a pipeline is

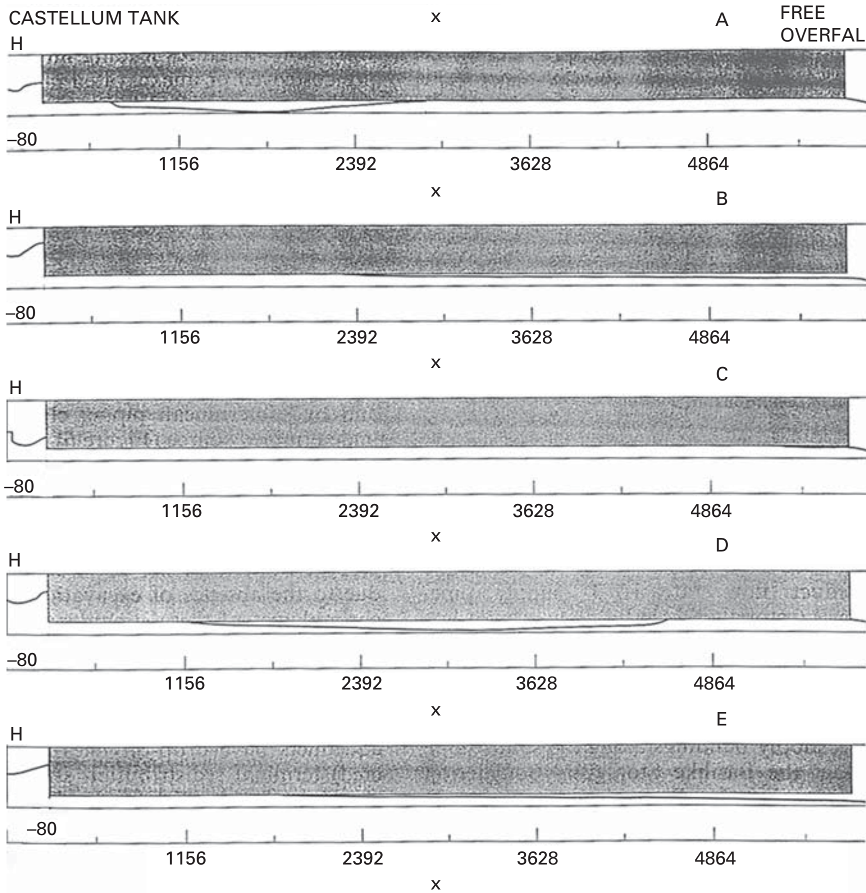

Figure 2.3.9. Sequence (0.0 to 55.0 s) of piping centreplane free surface shapes within a 60.0 m, 22.0 cm diameter pipeline with $f = 0.05$ friction factor and 2.5 m supply head.

shown for a hydraulically steep 5° slope, $L = 60$ m, $D = 0.22$ m, $f = 0.05$ roughness, $H/D = 2.7$ pipeline with free-outlet conditions. This parameter set is characteristic of pipelines running from the castellum (Figures 2.3.8 and 2.3.10). Panel A indicates an initial partial vacuum space created near the inlet. Incoming air moving upstream from the free-overfall exit joins the downstream-convecting partial vacuum region causing flow rate change (Figure 2.3.11) amplified by supply tank sloshing in panel B. The hydraulically steep pipeline causes supercritical open-channel flow to form initially

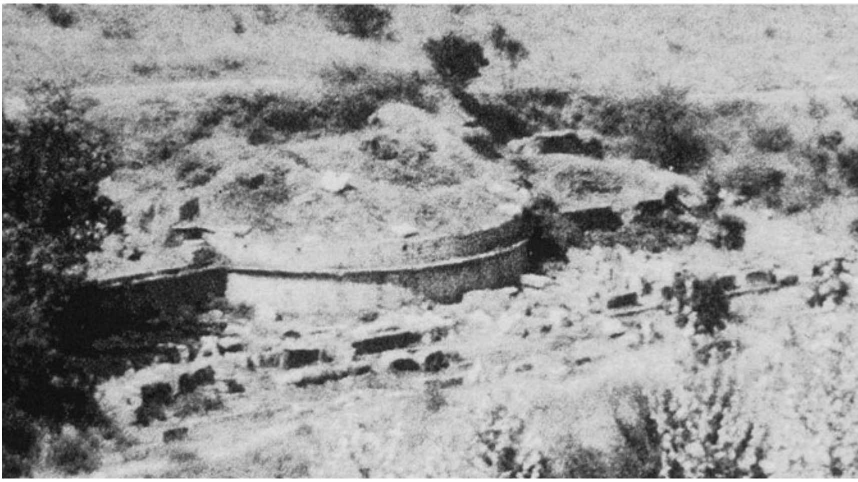

Figure 2.3.10. The Castellum (fountain House) in its present unexcavated form.

while wall friction causes full flow to form further downstream. As the hydraulic jump moves upstream over time, the inlet is flushed (panel C), temporarily increasing the flow rate. The far downstream flow (panel D) then reverts to supercritical open-channel flow near the pipe centre but downstream flow resistance causes full flow to develop, trapping a partial vacuum region. This region merges with air from the outlet (panel D) and the cycle repeats, causing flow rate variation with time. The sloshing compartment head varies with time, further complicating flow patterns. In this sequence, flow resistance changes from time-varying, fluid-wall contact area and variable tank head oscillation as Figure 2.3.11 indicates flow rate changes.

In summary, computer analysis of low-angle pipeline-internal flow patterns demonstrates the complexity of transient, non-linear effects. Complex fluid mechanics phenomena appear in long pipelines but are not present in shorter pipelines primarily due to cumulative wall frictional effects and localized slope changes, which influence flow regimes. While top air holes help alleviate some of the slugging phenomena present in long, internally rough wall, hydraulically steep pipelines, flow rate stability can be improved by use of short pipeline lengths under full-flow conditions with hydraulically mild slopes or lower *H*/*D* compartments with short lengths of hydraulically steep pipeline that maintain high open-channel flow rates, both with submerged outlets. Both types of pipeline designs are found within Ephesos. For

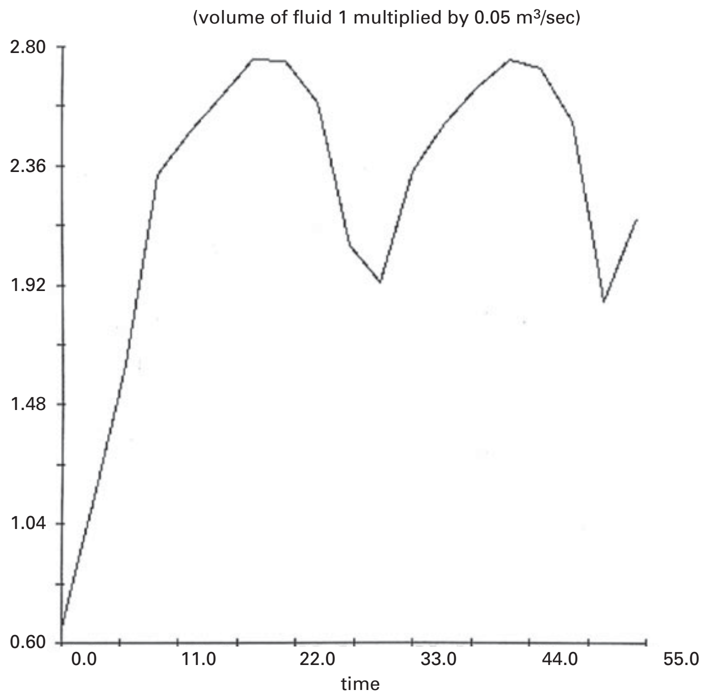

Figure 2.3.11. The unsteady delivery flow rate from internal flow patterns shown in Figure 2.3.9 in the presence of partial vacuum regions.

cases for which periodic flows are delivered to a destination point, a settling tank is usually in place (the Byzantine Fountain on Kurates Street, for example) to dampen oscillations before ultimate flow delivery.

The Ephesos Fountain House

The Fountain House (17, Figures 2.3.2 and 2.3.10) is a major feature of the Ephesos water system. Since it is not excavated, the exact internal details of the structure are not available. However, from preliminary clearing and inspection, some details of the original Roman structure are apparent. From the visible remains, the castellum appears to be compartmentalized into discrete tanks (Figure 2.3.12 shows a possible representation). The outer north wall of the structure (Figure 2.3.10) has an elevated row of ten (extant) multiple openings at ~2.5 m height above the front basin bottom surface; the

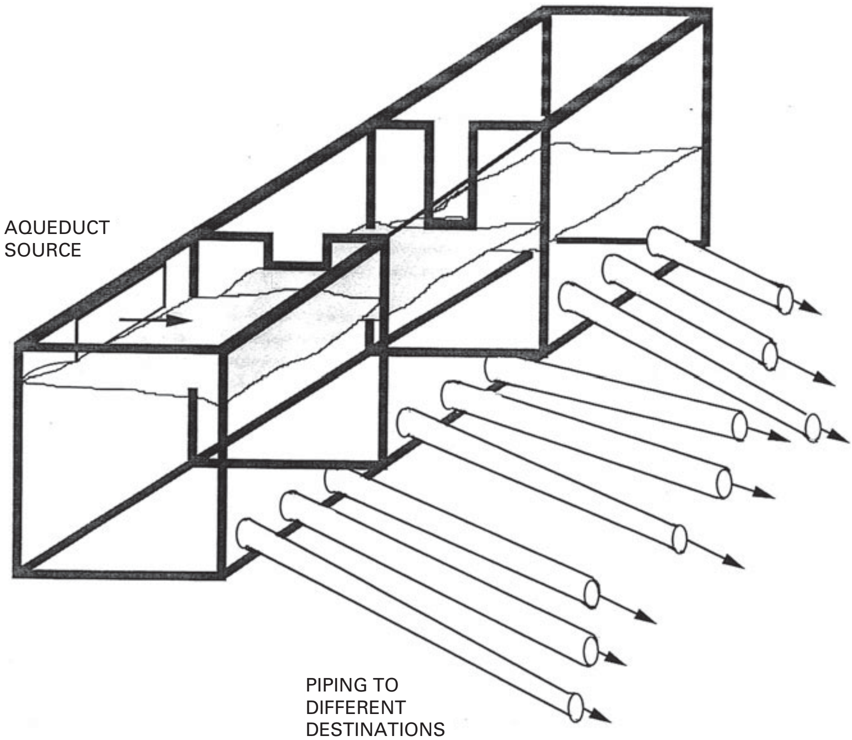

Figure 2.3.12. Theoretical Fountain House internal construction detail. Multiple pipelines emanated from individual compartments with different heads to produce different flow rates tailored for different applications.

openings serve as free-overfall fountain streams, depositing water into a lower basin enclosure in front of the structure for public use. Another basin is set along the back of the building. The rear and front basins have overflow weirs on the basin walls to direct overflow water to subterranean drain channels just outside the basin-enclosing walls.

For an estimate of head H within a compartment supplying the fountain free-overfall openings above the front basin, consider that streams projecting from the orifices must impact the basin water surface close to the back wall to prevent splashing onto basin users. The shape of a free jet issuing normally from an orifice located at $x = 0$, $y = 0$ is $y = -(1/2)(x^2/2H)$ where H is the constant head in the supply tank measured above the $y = 0$ line and x and y are the horizontal and downward (negative) vertical coordinates measured from an exit jet origin. This calculation assumes head losses from the compartment-to-pipeline orifice and that frictional loss effects are negligible. For jet impact onto the basin water surface 2.0 m from the back wall after a fall of -2.0 m, the head (H) is 0.5 m above the outlets; this provides an estimate of a minimum height of a compartment above the outlets (note that the topmost castellum compartment supplying the fountain outlets no longer exists). Assuming that the pipeline distribution outlets (Figure 2.3.12) originate above the tank bottom (to eliminate silt transfer to pipelines) the maximum head H available within the castellum is $\sim$2.5 m (if the fountain streams derive from the top part of the maximum depth compartment). Based on the $\sim$2.5 m maximum head available to a main compartment, $H >> H^*$ and a full-flow rate could be matched to requirements of a high-priority destination (such as the nearby Nymphaeum) using mild-slope, short-length piping.

The ten active, 4 cm diameter, fountain orifice openings have a total area of 0.0128 m^2 so that the volume flow rate is 0.038 m^3/s for the given 0.5 m head. Since the Kenchiros aqueduct estimated flow rate is 0.018 m^3/s and the Marnas aqueduct flow rate is 3 (supply pipelines) $\times$ 0.08 m^3/s (estimated from full-flow rates at low slope), then the fountain streams are estimated to consume about 15% of the total aqueduct water supply. The (fountain stream supplied) basin water height was maintained by drainage to the frontal open drainage channel, decoupling it from castellum tanks, which had other specific supply functions. The remaining flow was directed into at least eight pipelines that emanated from the base of the Fountain House (more may have existed but were removed in earlier excavations) into and across the State Agora to supply buildings along the south slope of Panayir Dag: the Basilike Stoa (21), Bouleterion (22), and the Prytaneion (66), nearby baths, the Gaius Laecanius Bassus Fountain (60), the Nymphaeum in front of the Domitian Plaza, and rooms of the Slope House (50, 51). Additional water supplies from the Kenchiros were tapped into lines K–D, K–A, K–B, and K–C (Figure 2.3.8) to supply the Slope House district at the terminus of K–B and K–C as well as the western parts of the Agora (61) to account for the remainder of the Kenchiros water supply. Based on the $\sim$2.5 m maximum head available in a main castellum compartment (other compartments have lower head and flow rates), flow from five pipelines emanating from this compartment can average about 0.06 m^3/s at $<2^\circ$ slope for a total continuous flow of $\sim$0.3 m^3/s (plus contributions from remaining pipelines). Since 85% of the available flow can be directed into active pipelines for a flow rate $\geq$0.26 m^3/s and the input flow rate is $\sim$0.36 m^3/s (Özis *et al.* 1997), an approximate input–output water balance for the Fountain House is at least qualitatively established.

Several compartments supported different head and flow rates to piping elements emanating from compartment sides. Most pipelines originated full flows with downstream-increased slope changes inducing partial flow conditions, as indicated by top air holes. Apparently the transition region from sub- to supercritical partial flow stabilized at a distance where top holes begin to appear in piping some tens of metres from the castellum. Several piping lengths from the Fountain House do not have top air holes, indicating that a variety of flow regimes were employed. Careful balance of compartment head H with flow rate was apparently necessary to avoid Figure 2.3.9 instabilities—this also involved along-the-length piping slope choices to achieve flow stability. Clearly many of the pipeline placements and lengthwise slope changes underwent iterative solutions to achieve stable, designated flow rates to different destinations. A vertical pipe set at the edge of one of the compartments supplying the rear fountain has an opening to maintain water level in that compartment at $\sim$1.4 m; this indicates that water levels (head) varied in different compartments. Vertical piping segments are noticed in the vicinity of the compartments; these may be related to the overflow drains needed to maintain constant water heights in different compartments. Large segments of aqueducts structures leading to the Fountain House have been destroyed or unexcavated, making associations difficult at present. Additionally, later modifications of the Fountain House to include a grain-grinding overshot wheel appeared in Byzantine times, probably resulting in some internal compartment changes.

Aqueducts

Ephesos was supplied by four main aqueducts: Kenchiros from the southwest, Kaystros from the north, Selinus from the east, and Marnas from the southeast. It was served by subterranean piping clusters originating from spring systems in the HM district south of Bulbul Dag (Figures 2.3.3 and 2.3.8) and/or from the Marnas River. A further aqueduct (MacKendrick 1962) runs from springs high up on the Bulbul Dag Mountain to the southeast of the city and passes in a northwesterly direction to Luke's Tomb, located at the base of Bulbul Dag Mountain below the upper level House of Mary (which contains extensive piping elements) then on to the Magnesia Gate region and nearby baths. Some remnants of the outer-city aqueduct and piping systems remain, but the aqueduct-to-intra-city connections to piping systems through other possible castellum structures remain unexcavated or have chronologically unsorted piping remnants. Large Byzantine settlements in this area further complicate pipeline chronologies and origins. While the castellum (17) has

Marnas and probable Kenchiros connections, other castella are unknown, with the exception of fragmentary remains near the Vedius Gladiator Gymnasium (106) and stadium that may lie at the terminus of the Kaystros and/or Selinus aqueducts. An interesting drop structure on the K–D line of the Kenchiros aqueduct (Figure 2.3.8) is formed by a branch canal that free-falls water into a grotto-like nave structure ~15 m below. This structure forms a basin with exit piping to downhill structures and settlements, and may be considered a variant castella structure.

The aqueducts have sufficient remaining structure to constitute the basis for at least a partial reconstruction of Roman civil engineering practice. The 43-km long Kenchiros aqueduct system (Özis 1997; Wiplinger 2006) supplied water to sites on the southwestside of the city. This 1st century CE system originated at the Degirmendere spring east of Kuçadasi, the Keltepe springs somewhat further north (Figure 2.3.3), and additional springs en route. The aqueduct takes a coastal route west of Bulbul Dag, turns east along the north face of the mountain, and runs directly into the Fountain House area. Many bridging structures occur along the open-channel path to maintain the slope of the system and a tunnel has been discovered as part of this system. Flow rate estimates (Özis *et al.* 1997) are 0.06–0.07 m^3/s, with a second downstream source contributing 0.02 m^3/s. The 6-km long Marnas system originally conveyed water from the Klareas (Marnas) River by a series of four pipes routed along a contour and possibly over an aqueduct bridge structure. Some early version of the conveyance system may have connected to the Pollio Aqueduct southeast of Ephesos in the river valley, then northward along the hillside above the Magnesia Gate (70), although the Pollio Aqueduct probably connects to the spring house at Sirinçe to the east through an underground channel. This aqueduct mainly supplied water to the Fountain House and then to the State Agora/Government Centre (18), and sites along Kurates Street (36) to the district near the Celsus Library (Figure 2.3.13). The Selinus aqueduct system collected spring water near the village of Sirinçe, with channels passing through the town of Selçuk towards Ephesos. The aqueduct may have been built originally to supplement the water supply of the 6th century BCE Artemesion and fountains on the Sacred Way. The water system probably extended onto the northern and eastern slopes of Panayir Dag later, bringing water to urban housing and the East Gymnasium (12) in the southeast edge of the city as well as to the northern Koressian district (98), and later Byzantine structures on the northwest sector. Estimates by Özis *et al.* (1997) of an aqueduct flow rate of 0.002 m^3/s provided water for both domestic and public uses. In the northwest

Figure 2.3.13. Curates Street, leading to the Embolos District in front of the Celsus Library. Marble Street to the right leads to the main agora, theatre, coliseum, and baths.

sector of the city and along the westside of Panayir Dag, its waters probably combine with those of the Kaystros aqueduct.

The 40-km long Kaystros system originating to the north at the Kayapinar springs was supplemented 10 km from the city by Pranga spring water. Its many bridges and channels have been traced in the area north of Ephesos (Özis *et al.* 1997). The subterranean open-channel segment in an underground tunnel behind the funerary monument at Belevi is part of this line, which also passes Asayoluk Hill (near Selçuk) into Ephesos. This aqueduct contributed to the open-channel supply system for the Stadium (104) and Theatre District (72) as well as the western and southwest slope urban housing region of Panayir Dag (below 34). A separate branch over a still-standing arcade probably provided water into parts of the Harbour Baths (92). No estimates are currently available for the flow rate but it must have been on the order of 0.1 to 0.4 m^3/s to supply public demand. The aqueduct from springs originating at upper levels of Bulbul Dag Mountain as yet has no estimates of flow rate but certainly could have additionally served dense settlements (perhaps Byzantine) in the valley and on the slopes to the east of the old city.

The urban water supply system

The Kenchiros aqueduct (Figure 2.3.8) originated from springs near Kusadasi (Figure 2.3.3) and had many downhill branching piping off-takes to populated areas in the western parts of the city. The K–D branch consisted of supply pipes to the urban district and fountains southeast of the harbour district, as well as settlements on a mountain spur west of the main city (Figure 2.3.8). Several fountains along the Arcadian Way (83) have basins supplied by this piping system. The presence of large covered drainage systems along the Arcadian Way, as well as drains passing north under the Serapeion district (67), are strong evidence of a water supply system in this area. The K–A branch is an underground tunnel system fed by piping from the main aqueduct. This system supplied the Serapeion district and the later phases of the Tetragonos Agora (61), where the covered channel splits to serve the north and southsides of the agora. Some vertical piping segments incorporated into Serapeion walls indicate an uphill collection basin to supply the temple's internal system of basins and fountains. A further set of pipelines (K–B) appears to enter Slope Houses 1 and 2 (50 and 51); some pipelines branch into smaller lead and terracotta piping systems to serve the household and hygienic needs of these structures, with many decorative fountains in evidence. Further pipelines run adjacent to the main Slope House structures to supply fountains on Kurates Street as well as the Domitian Temple (30), Memmius Monument (32), and the Pollio Fountain (59), with probable aqueduct termination in the Fountain House. Pipelines K–D, K–A, and K–B all had steep downhill slopes supporting open-channel, supercritical flow and many of these pipelines had top air holes to maintain atmospheric pressure in the airspace above the water free surface. A hydraulic jump will occur within piping upstream of a steep-to-level piping angle change and its position is affected by the roughness resistance of the level section; the hydrostatic head at the jump position largely determines the system flow rate and if this piping is connected to a fountain, the available head. Top air holes prevent air pressure changes in the confined air region space above the partial flow region from influencing the jump position.

The Marnas aqueduct system (Figure 2.3.8) was an additional supply line to the Fountain House. Numerous pipe fragments occur on the eastern reaches of Bulbul Dag indicating offshoot piping to urban structures on the unexcavated hillside. Remnant foundation blocks and partial walls of a large surge tank, much destroyed, lie at the end of the Marnas line uphill from the Fountain House. The Kenchiros, Marnas, and upper Bulbul Dag spring-fed aqueduct and pipeline systems therefore appear to supply the southern and western parts of the city, sections west of Kurates Street, and along the Magnesia Gate to the State Agora road. In all cases, branches from the main supply lines appear to distribute water for the maximum area coverage as no urban structure appears to be more than a few minutes' walk from an available public fountain or basin within the city.

From Kaystros–Selinus sources, water is directed to the Bassus Laecanius Fountain (60) in the west end of the Government Centre with contributions to the Pollio Fountain on the lower plaza. Fountain House water goes into the State Agora region as well as contributing to the Upper Gymnasium baths (16), the Basilike Stoa (21), and the Slope Houses on a northward running pipeline connection. These two latter structures also received water from the pipelines and springs on Panayir Dag. Kaystros supplies from the north are directed to the Trajanic Fountain (37) area. Both aqueducts supply public basins and fountains along Marble Street (35), providing basin water for residents of the downhill area. Kenchiros and Marnas aqueduct water supplies to lower Bulbul Dag zones near the Fountain House, Kuretes Street, and areas on the south slope of Panayir Dag constituted an instance of overlapping water supplies from branches of the Selinus and Selinus–Katstros aqueducts as dual aqueduct sources were available to provide water to these regions (Figure 2.3.8). Redundancy of water supplies to the same area from multiple aqueduct and spring sources allowed for repairs and cleaning of pipelines without total interruption of water supply and lessened the probability that earthquakes would simultaneously interrupt both lines. Particular care was taken in supplying water to the baths. One of the larger Fountain House compartments probably accumulated water overnight for this purpose. As water was transferred, compartment and bath pool water heights equalized and the flow transfer automatically ended. Use of short supply and drainage piping segments to and from baths to maximize supply and drainage rates as well as careful surveying for the automatic shut-off feature was then integral to the design of the Fountain House.

Short pipelines at hydraulically steep slopes reduced pipe-interior surface-induced wall frictional resistance to limit conversion of partial to full flow. For cases involving long and steep pipelines, the height of the interior hydraulic jump location sets the hydrostatic pressure available to downstream fountains. Thus, a variety of control mechanisms were available to regulate head to fountains depending on the aesthetic requirements of the design. For certain cases, short lines between successive fountains reset inlet head for the next line segment to maintain high flow rates. Major fountains on Kurates Street contain tanks set to maintain constant head to the fountains and thus promote steady flows. A head tank located behind the Byzantine Fountain (52) on Kuretes Street indicated that piping coming from the residential slope house to the area behind the fountain was conducted to a 1.2 m $\times$ 0.45 m rectangular head tank (with a depth of about 40 cm) with a drainage overflow weir upstream of the fountain delivery outlets to maintain a low head and a steady delivery rate to the fountain spigot. Here the Reynolds number could be adjusted to produce a steady laminar jet of high aesthetic appeal by simply adjusting the pipe length (L) from the head tank to the exit orifice to ensure laminar flow; in modern terminology, the Reynolds number ($\mathrm{Re} = V\ L/\nu$) should be kept less than ~2,000 to ensure this condition.

The Kaystros–Selinus aqueduct's large masonry open-flow channel system is part of the water supply to the Stadium and Theatre districts (104 and 72). The channel base width is about 0.6 to 1.0 m, which is commensurate with the large water demands of the Stadium. Some Stadium open-channel sections were used for drinking water and animal watering troughs. A subterranean open-channel extension of the Selinus Aqueduct around Panayir Dag entered the theatre through a covered channel about halfway up the rows of seats from the stage and continued on to the housing sector on the south slopes of Panayir Dag (Figure 2.3.8). A separate branch over an arcade probably provided water for the northwest sector of the Harbour Baths, but whether this branch belonged to the Kaystros or the Selinus line is unknown. Water for the Macellum (100), Temple of Hadrian Olympios (98), Harbour Gymnasium (93) and its courtyard (Xystoi, 94), baths (92), and (lower) Church of Mary (95, 96) in the Koressian District was supplied by the Kaystros channel. Deeply buried and near-surface lines in this area probably connect to the Kaystros system. There may have been intermediate water distribution centres (not yet excavated) to connect this supply to piping distribution networks. The water supply to the Harbour baths probably required intermittent nighttime supply with daytime diversion to public fountains. Exploration of the Harbour Bath area shows multiple pipelines supplying basins near the Arkadian Way (83). One section of the Selinus aqueduct system may supplement the Kaystros supply of water to the Koressian district and Olympeion (41) as these two aqueducts seem to jointly supply the whole northwestern sector of Ephesos. It has not been determined from excavations whether this overlap is contemporary or sequential. No estimates are currently available for flow rates but they must be in the order of 0.1 to 0.4 m^3/s to supply the demands of major public events in the theatre and stadium.

The Selinus aqueduct's path to its presumed source at Sirinçe is lost under several metres of alluvium in the plain deposited by the Kaystros and Klearos (Marnas) rivers. However, details of the intra-city Selinus pipeline system (which may join with the Kaystros aqueduct) can be inferred from remaining stone channels, pipeline fragments, and reservoir locations. Many sections of this line have been found on the slopes of Panayir Dag in an underground tunnel maintaining a low slope (<3°) at 25 m elevation (Figure 2.3.8). Most of the water continued through an open masonry channel between the Stadium and the Theatre to housing, fountains, and public areas on the mountain's western reaches. Some part of the Selinus supply system continued along the south face of the mountain above the Bouleterion and Prytaneion, and led to an underground reservoir on the southern slope of Panayir Dag. On the southeast, the Selinus aqueduct reached the East Gymnasium (12), passing through a near-level subterranean tunnel structure immediately behind the Magnesia Gate (10). Further water supply came from springs on Bulbul Dag located near the upper level House of Mary that supplied piped water to urban development areas in the southern part of the city; this spring supplied piped water to the Tomb of Luke and water transfer between later holy sites may have had some religious significance.

In addition to the aqueducts, cisterns, reservoirs, and domestic wells, springs made an important contribution to urban water supply. The total intracity spring-fed supply easily constituted the equivalent of a further aqueduct's yield. Numerous karst springs originating on Panayir Dag immediately behind the Basilike Stoa (21) and Upper Gymnasium contributed water supplies to these structures; others at higher levels were equipped with storage basins and supplied local piping systems for residential hillside areas. An intact high-level piping system and scattered piping fragments exist above the East Gymnasium zone. Extensive spring systems associated with the Palace (76) above the Theatre collected and distributed water to piping that supplied theatre fountains, a small bath north of the Palace, and a meeting hall to the south. Additional piping passed around the eastern slopes of Panayir Dag through the upper tiers of the Theatre. Some pipelines at 55 and 80 m elevation from the spring system that circled Panayir Dag above the Theatre conveyed water from mountaintop springs that, at one time, filled the reservoirs and provided water to palaces and military installations on the Panayir Dag's summit. The pipelines at the 80 m contour extended from the northern to the southern face of the mountain in a counterclockwise direction and provided spring water to houses and the many downhill fountains and reservoirs at lower levels. Some buried pipeline sections and rock-cut channels that appear south of the Theatre in areas northeast of Kuretes Street indicate supplemental supplies for the Scholastica Baths (40), Latrinae (43), Trajan Fountain (37), and the Shrine of Hadrian (41). That large water supplies were available on the northern slope of Bulbul Dag may be a key reason for placing houses and public buildings on these slopes. Additional spring systems at the northwest corner of Panayir Dag above the stadium supplied water and could amplify Kaystros–Selinus aqueduct water supplies to the Vedius Gladiator's Gymnasium. Some of this spring system's water supply was diverted to the west to supply, in later Byzantine times, the church structure in the Koressian District, the nearby Bishop's Quarters, and baths within the Byzantine Wall (77). A steep transport channel located on the hill slope and exiting near the Late Antique Fountain (101) on the street to the Stadium served as a flow rate regulator to the open-channel Kaystros–Selinus canal, draining off excess flow above a certain height. This link may also have served to provide water for the shops, fountains, and structures that lay along this street.

It has been noted that several sets of pipelines are not presently attributable to any aqueduct. Some of these are the untracked, buried pipelines running underground through the Magnesia Gate Plaza, which may originate from a branch of either the Selinus and/or Marnas aqueducts and/or from springs near the upper level House of Mary; some of these water supplies probably connect to the Fountain House. Other deeply buried pipelines are found in the Olympeion and eastern Koressian districts, where they underlie later Byzantine constructions. Deeply buried pipelines in the Tetragonus Agora are Hellenistic, associated with structures dating from that period. The supply may be from Kaystros and/or Selinus aqueducts or from springs on Panayir Dag but conformation is not available. Long-length piping systems (Kenchiros feeder lines to the Slope Houses, for example) were hydraulically steep and required top holes to limit flow instabilities and partial vacuum regions that disturb steady flow delivery. For most piping system branches supporting flow rates $<0.075\ m^3/s$, calculations indicate critical values for slopes, verifying the internal partial-flow conditions within piping networks.

The urban drainage system

Since the drainage system (Figure 2.3.8) must accommodate the continuous spring and aqueduct-supplied water as well as rain runoff, the drainage channels must of necessity be large masonry open channels. Drain water from all complexes was directed by open channels to drainage systems exiting downhill toward the harbour west of the Arcadian Way. Starting from the southern reaches of the city, a large masonry open channel runs from the East Gymnasium underneath the paved entry immediately behind the Magnesia Gate; some (as yet undiscovered) connection to a main open-channel drain exists along the road from the gate to the Fountain House. This drain is positioned to collect rainwater from both mountains as well as wastewater from adjacent urban areas. The Fountain House adds overflow water from the front- and rear-facing public basins into this drain system. The covering plates of this drainage system are sufficiently separated to allow rainwater inflow additions to fountain basin spillage. A further extension of this drainage channel runs along the southern edge of the State Agora east of the Pollio Nymphaeum to collect non-consumed Fountain House water directed to agora buildings. Proceeding downhill from the Fountain House in a northwesterly direction, the drainage channel is in the form of a masonry tunnel ~1.9 m high running northward toward the agora from the Fountain House drain network. The channel next turned across the State Agora and entered a brick-vaulted tunnel that ran east–west underneath the Basilike Stoa. The open-channel drain on the northeastside of Kuretes Street collected drain water from the Upper-Bath Gymnasium (16), Stoa (21), Bouleterion (22), and Prytaneion (66), and combined drainage flows into the tunnel that runs under Kuretes Street. As this vaulted tunnel entered the southwest reaches of Kuretes Street, open-channel drains on each side emptied into it. Drain water from the Slope House district connected into a second sewer system on the southwestside of Kuretes Street.

The steep slopes of Panayir Dag posed special drainage problems. As high retaining walls lined the southern downhill sides of three streets to the northeast of Kuretes Street, provision for drainage from the karst mountain interior and uphill springs was necessary to stabilize the mountainside. This was accomplished by drainage slits in the retaining walls that directed drainage water into channels below the staircases on the streets on the western side of Bulbul Dag. Wastewater from basins, fountains, streets, and seepage channels from the hillside and urban structures on the unexcavated southern-side of Panayir Dag was channelled downhill to the main southeast drain channel along Kuretes Street. Brick vaulting was found underneath some of the hillside streets as both mountainsides and some of the hillside walkway steps on the western part of Bulbul Dag show open slots that functioned as drainage openings from the subterranean vaulted rooms. The northern slopes of Bulbul Dag at one time supported additional housing across from the Slope House area, although this vaulted area is unexcavated. The underground drainage branch on the southwestside of Kuretes Street served as a drain channel for the Slope House district as well as the Byzantine Fountain and shops that lined the street. The total extent of the underground vaulting on the slopes and the connection to drainage passageways to collect rainwater and urban wastewater remains to be determined from excavation. Both sewers on opposing sides of Kuretes Street converged to the Plaza in front of the Celsus Library (Figure 2.3.13), while additional drain pipes ran from the Serapeion District to contribute to the drainage channels that led out from the Plaza. Exploration of the subterranean drainage tunnels in the Embolos district revealed the presence of channels that pointed south of the library to the harbour district as well as other subterranean drainage channels that crossed the Tetragonos Agora towards the harbour. The tunnel draining the Plaza area is about 3 by 4 m in cross-section, indicating that considerable drainage was required from the uphill and urban zones. Many reconstructions and modifications occurred in this area during the long occupation period of the city (Scherrer 1995), making it difficult to date the various branches of the drainage system. Additional removal of terracotta piping in the Tetragonos Agora, Library, and gate area during early reconstruction of the Library Plaza has lessened possibilities of further defining the piping networks in this area.

A further large, open-channel sewer under Marble Street ran towards the Harbour District with connections to the lower, southern-side channel along the Arkadian Way. The paving of Marble Street has numerous gap openings to accept rainfall runoff water from the southwestside of Panayir Dag. Some large feeder sewers from Panayir Dag may join this sewer from uphill structures and baths, as may be determined from further excavations. Further north, large drainage canals appear on both sides of the Arkadian Way draining toward the harbour. Some drainage connections from fountains on this street, as well as from unexcavated urban areas to the northeast and southwest, are evident. The large basins of the Harbour Bath had exit piping that led toward the main drains on the Arkadian Way.

At the eastern end of the Arkadian Way, another drainage channel originating in the area of the Stadium and the Vedius Gymnasium ran past the Theatre district towards the harbour. This northern channel from the southern edge of the Koressian District main street came to the Theatre Gymnasium, where these two drainage systems joined via a diagonal connecting branch under the Theatre Gymnasium. This drainage channel, with many openings between cover stones, helped to protect the low-lying Agora from rainfall runoff from Panayir Dag. The Latrinae located on the northern reach of Marble Street appears to be supplied from the Selinus system passing through the theatre; this system had a continuous flow to flush the waste material into the adjacent sewer system and then into the main drain tunnel to the harbour. As aqueduct water supply was continuously provided, most water destinations were continually provided with 'new' water, facilitating the continuous flushing to sewer systems and thus contributing to hygienic conditions in the city.

Given typical bathwater heights, bathwater head H is much larger than the pipe diameter D as drainage initiates. As water height diminishes to $H < 3D$, a vortex appears, entraining air down to the drainage outlet. This hydraulic event tends to cause discharge fluctuations but as soon as the water height falls below the outlet pipe diameter, open-channel flow resumes with a steady flow rate. The bath drainage sequence is therefore an interval of full flow for $H >> 3\text{D}$ followed by an interval of unsteady flow for $H < 3D$, with the last stage becoming open-channel flow for piping with a free-overfall drain outlet to a sewer system. If the system was designed properly, the final emptying stage involved piping with a near-critical or supercritical flow rate. Use of a short drainage pipe length supporting fast partial flow prevented formation of a roughness-induced internal-piping hydraulic jump, which would severely reduce the emptying flow rate as well as cause pool oscillations. All these considerations were part of bath pool piping design to ensure rapid drainage. As several hours were required to heat large bath water volumes, daily rapid filling and emptying strategies were a design priority. The time to drain was lessened by placement of bath buildings close to drain channels; if supply Fountain House compartments or reservoirs were close to the baths and supply lines short, then rapid filling could be maintained by pipes supporting near-critical or supercritical partial flow. The Selenius supply to the Eastern Gymnasium and the Fountain House and spring water supply (from the hill above) to the Upper Gymnasium Baths utilized the height advantage to maintain rapid inflow conditions; the drainage to low-lying sewers likewise permitted rapid drainage. An alternative strategy was the use of masonry open-channel flow supply to major baths, which required large water supplies over short times. This strategy was evident in the recently discovered Theatre basin supplied by the Kenchiros–Selinus aqueduct to the Theatre Gymnasium baths. The basin behind the north retaining wall of the Theatre was able to release 250 m^3 of water through a 1.0 m^2 outlet orifice at $H >> H^*$ to rapidly transport water to the Theatre Gymnasium and the Harbour Baths. This type of masonry channel supply system was appropriate for very large bath systems but multiple piping supply systems were also common at Ephesos. It may be concluded that the bath facilities were deliberately located as close as possible to water supply sources and drainage channels to facilitate rapid water exchange.

Modifications were made to pipelines during the many different occupations to meet new utilization demands. While some of these lines represented different design styles from different time periods, different wall thickness pipe segments were occasionally inserted into a line of another wall thickness. This may arise from a repair episode where some of the original thickness pipe segments cracked due to local ground subsidence or pedestrian or transport vehicle loading. No published statistical studies have been done on Ephesian pipeline thickness and style types so the correlation of style type to hydraulic function is unknown. Some shorter but thicker piping elements have been observed associated with the Domitian Temple and Serapeion districts, which may imply thick wall pressure piping associated with the Kenchiros aqueduct.

A full flow may be induced at some elevation within a hydraulically steep line by an internal hydraulic jump caused by a downstream constriction. The hydrostatic pressure resulting from this column of water could be used to advantage for spectacular fountain displays or multiple orifice release displays such as the Bassius Laecanius Nymphaeum or other fountains in this zone. If the supply system was entirely composed of full-flow piping, hydraulic transients may arise from the opening and closing of taps; such a system would require numerous accumulators or pressure surge dampers to eliminate damaging internal pressure excursions. For the Ephesian intra-city system, the numerous interconnected fountains and open basins (such as those along Kuretes Street) serve as 'virtual accumulators' to accomplish this end.

The Theatre water tank

Recent discoveries have uncovered a 250 m^3 internal basin behind the northern wall of the Theatre supplied by the Kaystros–Selinus aqueduct. The basin has dual symmetric contoured-block outlet structure (leftmost structure shown in Figure 2.3.14) on the lower side walls, leading to the exit orifice intended to deliver large volumes of water to the downhill Theatre Gymnasium

Figure 2.3.14. Detail of the left most, dual ovoid symmetric structures flanking the rectangular discharge opening within the internal water tank at the north end of the theatre.

and Harbour Baths. The basin structure is shown as a FLOW-3D computer model with the exact dimensions of the internal tank and outlet structure (Figure 2.3.15); the model shows the front-wall orifice exit structure but excludes vertical side walls. Typical of Roman channels, some filleted quarter-rounds were placed along the bottom edges of channels and basins to limit leakage and (perhaps) perform some hydraulic resistance decrease function. To determine the possible hydraulic function of the shaped-outlet structure, the computer model was used for outlet flow rate calculations. A later flow rate comparison was made using a model without the shaped-outlet structures to gauge the differences in flow rates and patterns between the two designs. Two cases where the exit orifice ran either into a steep slope open channel or through piping to downhill structures were investigated. By filling the tank for each model to a prescribed water depth and computing

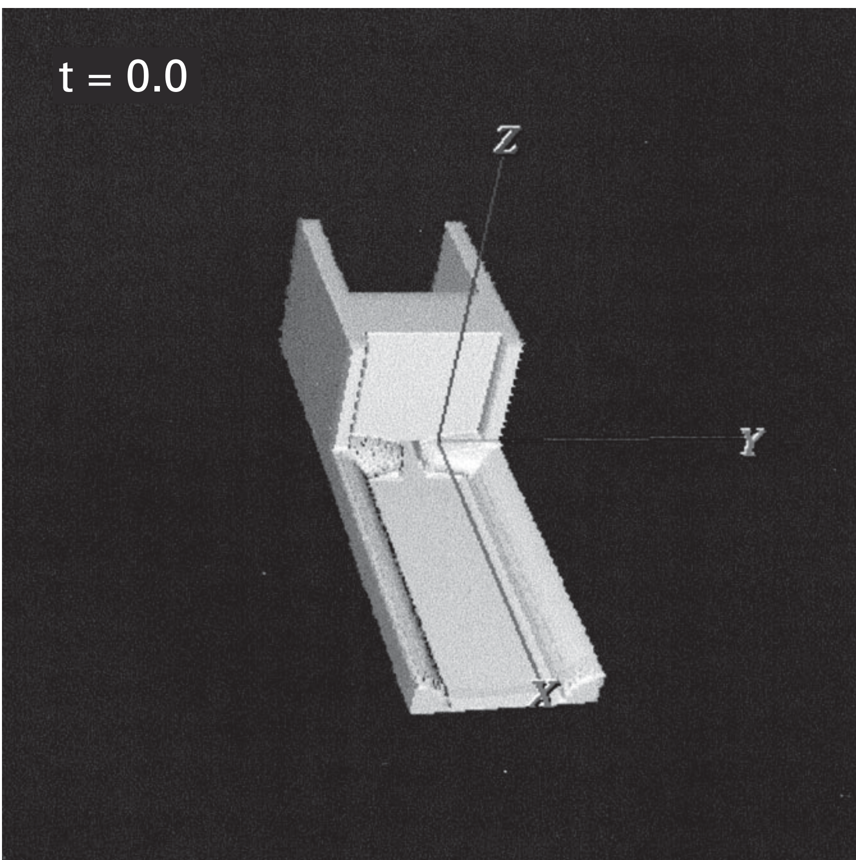

Figure 2.3.15. FLOW 3D computer model of the internal water tank within the theatre (side containing walls not shown) at actual tank dimensions.

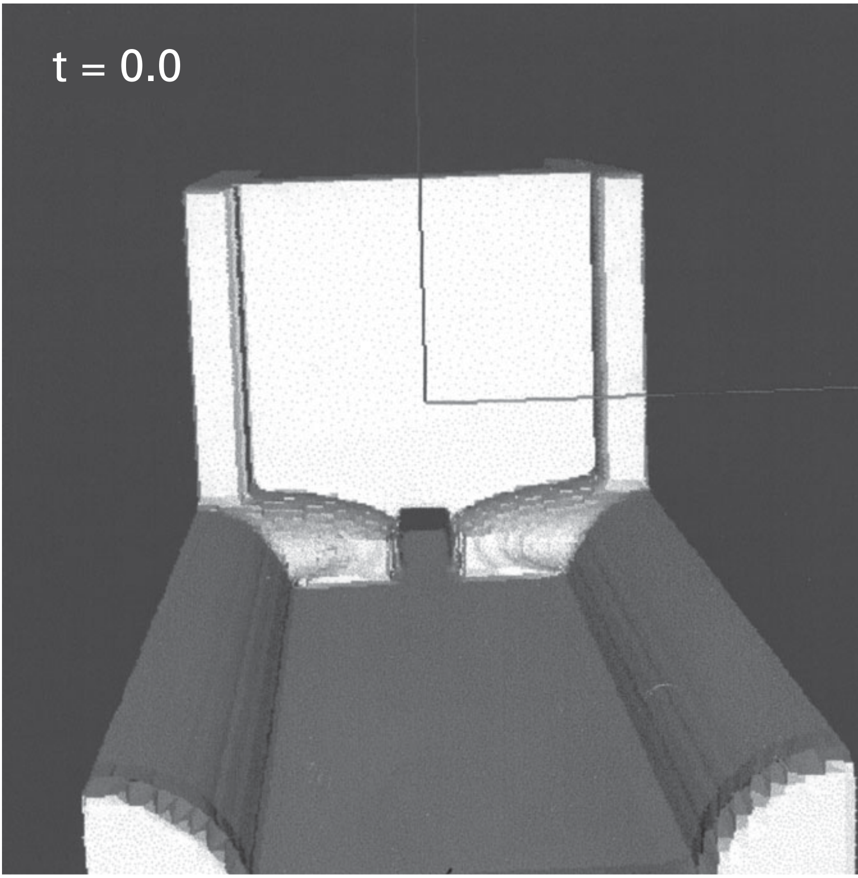

Figure 2.3.15. (Continued)

the individual drainage history times, the hydraulic function of the exit orifice shaping was determined.

Calculations for the outlet flow rate for each model revealed a slight advantage in drainage flow time for the shaped-outlet structure (e, Figure 2.3.16) compared to a flat wall opening without these structures. It appears that while the shaped-outlet orifice has a low resistance coefficient due to its 'streamline' shaping, the increased surface area of the shaped orifice increased flow resistance. The flush wall rectangular outlet case indicated creation of a toroidal vortex around the interior perimeter that served to decrease flow resistance as the vortex streamlines create a virtual outlet orifice with a low resistance coefficient (but with a lower exit area). While the discharge times

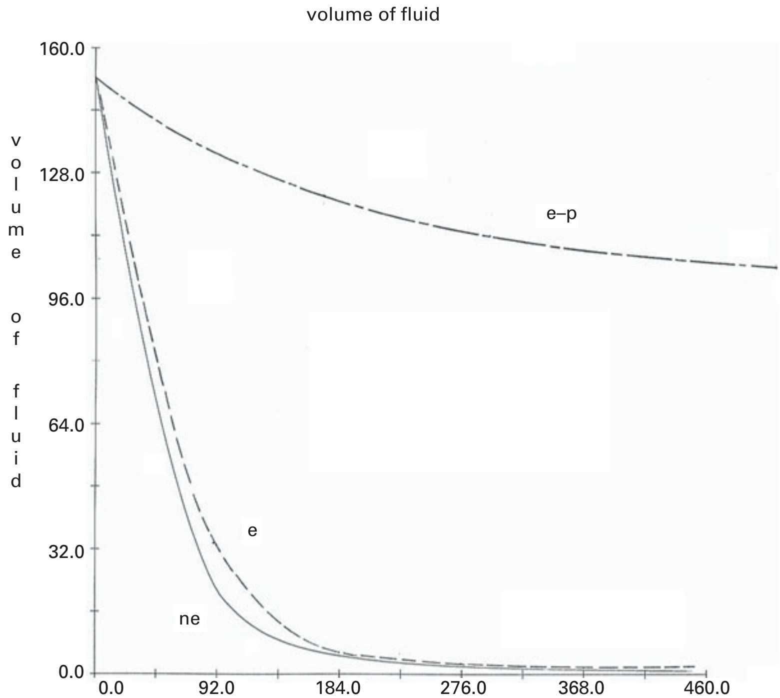

Figure 2.3.16. Computer results indicating full tank discharge history through 23 cm piping with different exit region geometries: ne, no ovoid structures present; e, ovoid structures present; e p, an open channel of the same base width as the rectangular exit.

for each design were similar, the fillet and curved outlet structures may serve to seal the edges of the tank against leakage and provide wall structural support. The e–p curve in Figure 2.3.16 represents flow through a 20-cm pipeline downstream of the inlet (which was a later change from the channel open–channel outlet design), and, as expected, restricted the flow and vastly increased drainage time.

Some reasons other than drainage time for the streamlining structure may be seen from Figure 2.3.17. Results indicate water agitation at low water depths compared to the smooth exit flow of the ne design. This served to agitate sediments that would be carried into the tank by the supply canal and keep them in suspension during the sudden water release into the exit channel (presumably some provision for a gate to block the exit orifice was in place during water inflow and could be raised or lowered from above). The vector distributions indicate highly agitated flow induced by the orifice shaping.

This effect eliminates tank cleaning (which had limited access) but required easy-access sediment traps downline. Due to a later earthquake, the basin apparently lost its function as the Theatre reconstruction precluded clearing of a large number of tumbled wall stones from the tank interior. The outlet opening and downhill subterranean lead-off tunnel were not cleared after the earthquake but a single piping element was found deep within the tunnel, perhaps indicating some additional limited function to carry water to the front of the theatre for fountains and street use. Additional piping elements found in front of the Theatre may connect to this reservoir but excavations are needed to verify this connection.

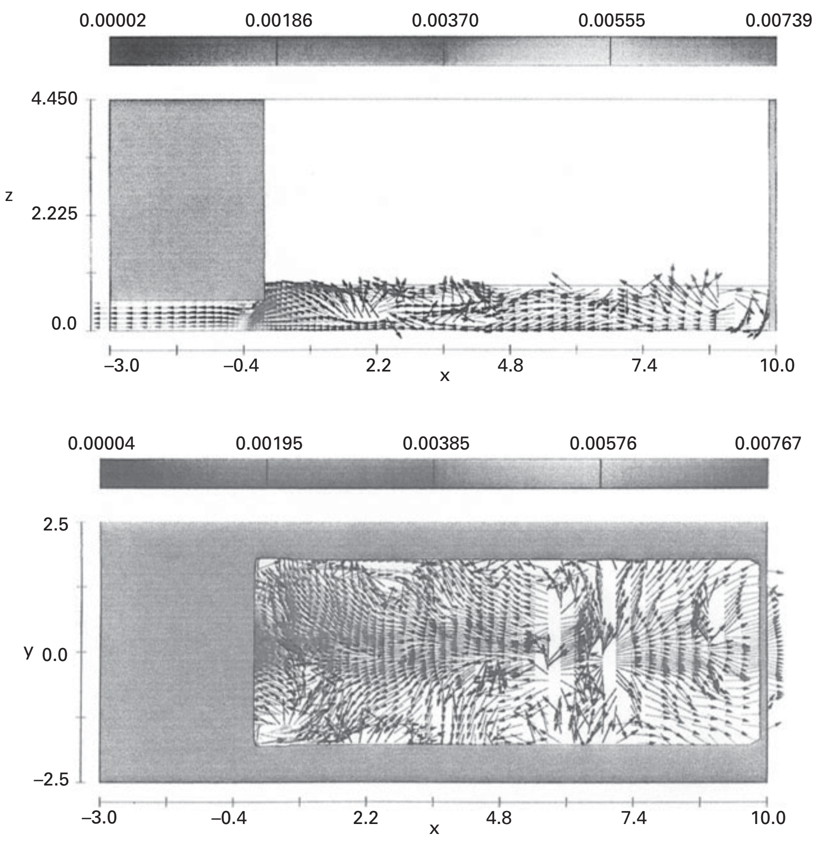

Figure 2.3.17. Velocity vector patterns corresponding to case e. Chaotic flow patterns occur at low water levels to agitate and prevent silt build up in the internal water tank.

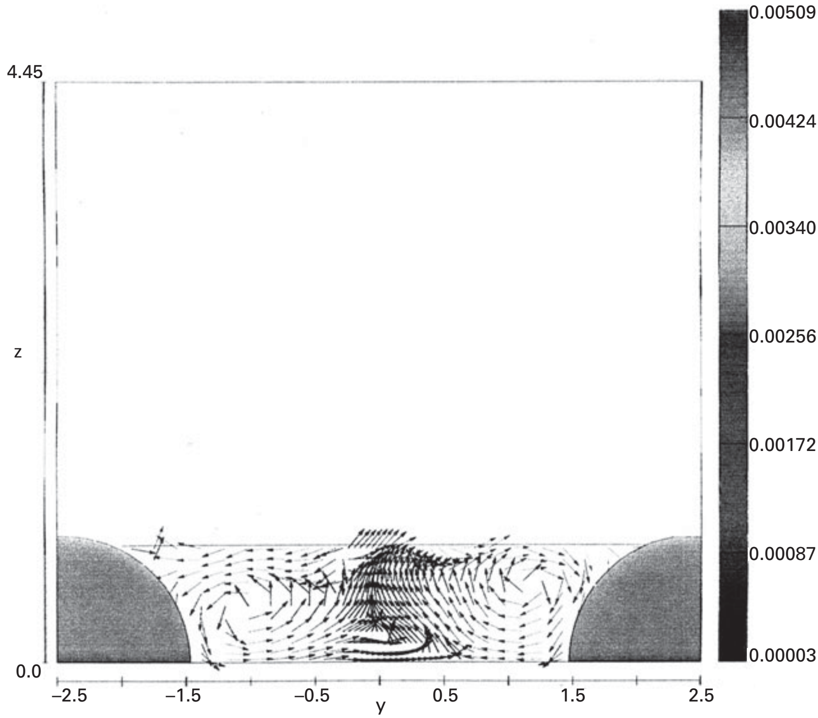

Figure 2.3.17. (Continued)

Conclusions

A complex distribution network of supply piping and drainage channels has been mapped within the city limits of Ephesos. From four major supply aqueducts, incoming piping bundles from springs, cisterns, a high-level spring-sourced aqueduct within city limits, and local karstic springs emanating from Panayir Mountain water was redistributed by overlapping piping networks to provide water supply redundancy for all city areas. Within the city, many of the piping systems functioned in open-channel mode. This design permitted large flow rates while eliminating pressure-overload pipe breakage, leakage, and pressure wave surging from rapid flow cutoff. For typical Fountain House compartment head values and short piping lengths between source and destination structures, precise flow rates could be maintained provided piping had hydraulically mild slopes and was continually supplied through the sourcing aqueduct. While this water transfer mode could be sustained by specialized castellum compartments, several other piping elements supported high flow rate partial flows. By use of piping top air holes for partial flows, the effects of partial vacuum regions on flow stability were reduced.

Since complex flow patterns that alter steady flow delivery occur for long pipelines where flow regimes can switch from sub- to supercritical (and vice versa), depending on streamwise slope changes, input head, internal pipeline roughness, exit conditions, and flow rates, long pipelines were avoided whenever possible. The piping system layout at Ephesos appears to reflect a variety of strategies intended to achieve the best designs for transport and distribution efficiency depending on topography and function. For longer pipe lengths between castellum source and destination, increasing castellum compartment head marginally increases the full-flow rate. The options to produce a desired large flow rates were: (1) limit piping length to take advantage of the head-full-flow rate dependence for short pipe lengths, (2) induce partial flows within hydraulically steep piping while maintaining a limited pipe length to limit friction-induced hydraulic jump formation, which causes unsteady flow rates, (3) introduce sequential open basins on pipelines to reset head for each sequential pipe segment, (4) use multiple piping bundles to increase flow delivery, (5) design piping angle near S_c* to get the maximum, low angle, partially full-flow rate possible, and (6) use masonry open-channels for very large flow rates over long transport distances (aqueducts and the intra-city Kaystros channel, for example). Ephesos contained examples of all these design options, which indicates that a large engineering solution repertoire was available to Roman hydraulic engineers.

The chronology of the various pipeline systems is usually associated with the structures utilizing their supply. This correspondence is, however, tentative because of the many reuses, modifications, repairs, abandonment cycles, and partial reconstructions in time as well as the problem of undiscovered segments of piping segments. Since this section primarily deals with Roman systems, its conclusions are regarded as a survey of Roman hydraulic engineering practices and the solutions available for urban water systems given the varied hydraulic phenomena that can exist within piping systems. The piping systems observed at Ephesos reflect observational knowledge of many hydraulic phenomena; the observed solutions reflect responses that indicate a more detailed knowledge base than that implied from the ancient literature.

2.4 WATER CONTROL DEVICES IN THE HELLENISTIC CITY OF PRIENE (TURKEY), 300 BCE–100 CE

Introduction

The late-classical Hellenistic city of Priene on the Anatolian west coast of Turkey (Ionia in antiquity) lies about 65 km south of the city of Izmir (Figure 2.3.1). Occupation of the city extended from Greek presence in the 4th century BCE with later Pergamese and Roman presence, then a final building phase extending into early Byzantine times. The city's political and architectural history is well documented (von Berchen 1979; Akurgal 1985; Crowther 1996). Excavations (Wiegard and Schraeder 1904; Koenig 1983) have revealed a Hippodamean grid-network planned city (Figure 2.4.1) with an integrated

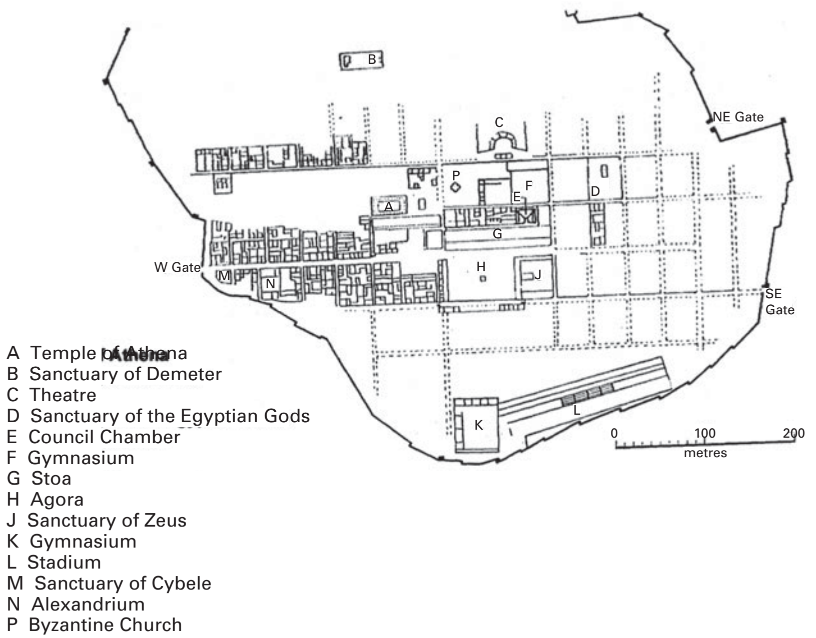

Figure 2.4.1. Ground plan of the site of the Hellenic site of Priene in Turkey. A, Temple of Athena; B, sanctuary of Demeter; C, theatre; D, sanctuary of the Egyptian gods; E, council chamber; F, gymnasium; G, stoa; H, agora; J, sanctuary of Zeus; K, gymnasium; L, stadium; M sanctuary of Cybele; N, Alexandrium; P, Byzantine church. The West Gate drainage channel (Figure 2.4.2) runs west from the agora through the western city wall.

Figure 2.4.2. The West Gate (Figure 2.4.1) drainage channel run ning downhill in the east west direction interior to Priene.

municipal water supply system. Sited on a low terrace of a mountain, Priene overlooked a Mediterranean bay in ancient times before silt deposited in the bay from nearby rivers, altering its status as a port city. The city was planned at its inception, as seen from the placement of underground water supply piping originating from a system of reservoirs and elaborate channel drainage systems (Figure 2.4.2) to carry waste and rain water out of the city. It would be expected, based on the large number of elite public structures and urban housing concentrations, that the most advanced urban water control technology available at the time was utilized consistent with the wealth and status of the city. The continual water flow through the drainage canals to prevent debris accumulation was therefore important to maintaining the cleanliness, health, and hygiene of the population. The water supply system represented Greek technology as the site does not have a Roman overlay. Thus, insight into the state of Greek hydraulics technology existing in late centuries BCE is possible. As the city had elite status, as observed from its architecture and temples, it is a window into the highest Hellenic water system technology level at that time.

One reason why the site was selected by early Greek settlers is its access to karstic water supplies from springs in the adjacent high mountains above the city (Crouch 1993, 1996; Güngor and Alkan 1994; Dilamarter and Csallany 1997). Water led down from mountain springs to reservoirs uphill from the urban terrace settlement, then down to house and public buildings through networks of underground terracotta pipelines (Wiegand and Schrader 1904; Fahlbusch 1982, 1996; Tanirover 1984; Radt 1993; Crouch 1993). Drains were provided for rain and wastewater by means of masonry open channels (Figures 2.4.1 and 2.4.2; West Gate Street from the Agora to West Gate) along main streets and thoroughfares within the city. As early as the 6th century BCE, Greek builders supplied water to cities by long-distance lines that ran up to 100 km (Graber 1888) and/or tunnelled as much as 1,600 m through mountains (Giebler and Graber 1897; Kienast 1995). Excavations on the Athenian Agora (Lang 1968) revealed 5th century BCE great drain systems similar in construction detail to the West Gate masonry-lined drainage channel at Priene. While Priene contains a catalogue of Greek water system innovations, the full details of Greek water engineering technology are only now being revealed by the study of such systems.

Hydraulic engineering achievements at Priene were representative of the Greek accomplishments of the 3rd and 4th centuries BCE. Book 8 of the later 1st century BCE Roman writings of Vitruvius (*Ten Books on Architecture* (Morgan 1960), Chapters 1 to 8) dealt with the water engineering of cities; among the topics were finding water, properties of water types, tests for good water, aqueducts, and wells and cisterns. Such statements as '... if the spring's bed is not polluted by debris of any sort but has a clean appearance, these signs indicate the water is light and wholesome in the highest degree...' indicated an awareness of cleanliness of urban water supplies as key to city hygienic conditions. Since Vitruvius's book is a summary of what was known about building practices, his ideas about water supplies and hygiene were commonly available and probably had earlier precedents.

This section begins by looking at the discovery of an unusually shaped drainage outlet located at the distal end of an open-channel drain (Figure 2.4.2) under the West Gate of the city. The drainage structure is a complex-shaped passageway with an S-shaped channel (Figure 2.4.3) and a left-side blind passage. The outlet structure has a doubly contracting, rectangular cross-section

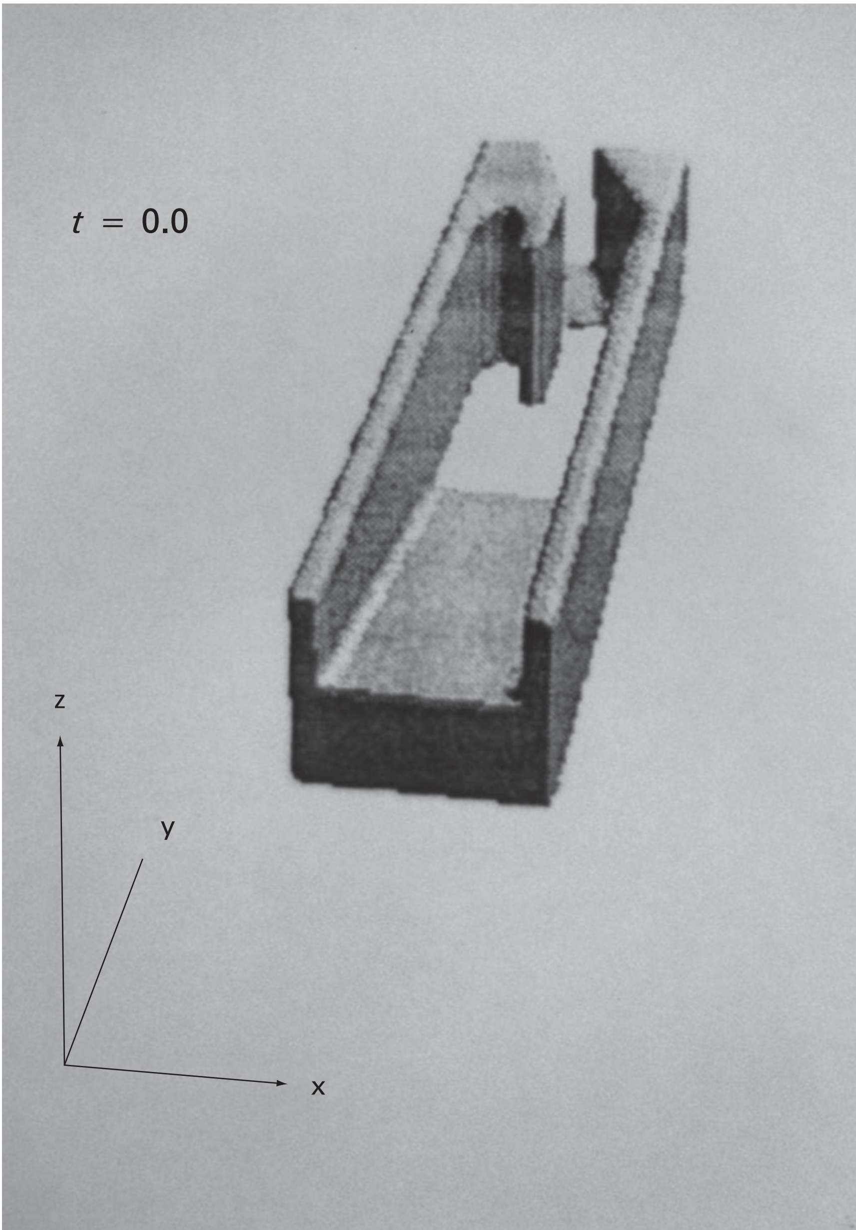

Figure 2.4.3. FLOW 3D computer model of the exit structure at the end of the long channel (Figure 2.4.2) passing under the city wall at the western end of West Gate Street.

and dual-ramped bottom geometry and is supplied by a steep-ramped, rectangular open channel. Because of topography, some drains leading from adjacent houses along West Gate Street did not contribute to the drainage channel, but instead led to other drainage channels exiting at different points in the city peripheral wall. The major effluent contribution to the West Gate drain came from channels leading from uphill housing: 11 housing complexes with surface channels crossed West Gate Street and emptied into the main drainage channel. For the central part of the city, other drains ran directly downhill on the southside while for the eastern area of the city, drains were found under two streets that ran steeply down to the eastern gates. Outflow to the sewer system contained debris that could easily accumulate and clog poorly designed systems, leading to overflow spillage in urban areas. For example, if drainage channels have too low a slope and flow rate, debris settles and accumulates in channels and causes system dysfunction by clogging drainage outlets. The waste disposal problem, as acute in ancient as in modern times in city environments, was addressed by unique channel design and hydraulic control measures, as described in the following sections.

Analysis results

The long open channel running east to west along West Gate Street and terminating at the West Gate of the city wall served as the drainage system for the central part of the city of Priene. An examination of the West Gate revealed that under the now destroyed gate, a carefully designed and constructed subterranean drainage outlet existed at the distal end of the downhill rectangular cross-section drainage channel, as shown in the FLOW-3D computer model (Figure 2.4.3) without its top-covering masonry slabs. The dimensions of the model correspond to field data measurements. The drainage channel captured rainfall runoff from uphill house roof/spout systems adjacent to the channel while shallow, covered canals along the length of the channel added additional wastewater contributions from adjacent urban housing areas. The channel flow volume was composed of a steady-state component equal to a fraction of the external water supplied to the city through long-distance piping and directed to urban housing near the main drainage canal plus intermittent flow rate contributions originating from rainfall events. From the domestic and urban centre, including the agora, additional debris-laden wastewater flows were directed to the West Gate drainage channel. Wastewater was then carried by the channel via the drainage structure through the city wall under the West Gate. For hygienic and safety reasons it is of paramount importance to avoid the potential for the channel and drainage structure to clog from accumulated debris, resulting in overspillage into the adjacent urban housing areas during rainstorms.

Flow leaving this structure through a rectangular exit port flowed downhill outside the city wall into a ravine for drainage to an adjacent bay that existed during the occupation of the city. A small preserved portion of the road leading to the West Gate remains on the steep hillside outside the city walls and curves to the north. This road is without steps and was used for animal cart traffic to and from the city. The direction and velocity of the discharge stream from the outlet structure was controlled so that it did not obstruct the steep road; this was accomplished by discharging water away from the road. It is of interest to examine the unusual design of the outlet structure by modern computer analysis methods to determine the civil engineering expertise available for Greek water management in that time period. By numerical solution of the governing equations, the influence of the outlet structure's internal shaping on the internal flow patterns is examined to determine the function of the outlet structure.

Slope measurements of the channel (Figure 2.4.2) before the outlet structure indicate a lead-in slope of about -10°. Due to the slope and 70 m upstream length of the lead-in channel, the channel flow approaches normal depth (D_n) asymptotically on an S-2 profile (Henderson 1966) before entry into the drainage outlet structure. Practically, this means that the water depth and speed approach constant limiting supercritical values after a long transit distance down the drainage channel. Although some additional debris-laden water is added to the channel en route from downstream urban structures along the channel, most of the total volume flow proceeds from major civic structures and the market agora area located at the upstream head of the channel from piped water supplies to that area.

The channel flow height boundary condition before the drainage outlet structure must be consistent with a velocity (V) determined from the Manning equation, given the channel cross-section geometry and channel Manning roughness value. This follows from the fact that the Manning equation describes the empirical normal depth relationship between hydraulic depth, wall roughness, and water velocity. From prescribed boundary conditions on flow height and velocity at the entrance to the drainage structure, calculations were performed to show the influence of the unusually shaped internal geometry of the outlet structure on the flow. Typical sample upstream boundary conditions for flow velocity and D_n are summarized in Table 2.4.1 on a plane normal to the upstream channel leading to the drainage outlet structure to determine their influence on the flow patterns. These conditions relate to the different volumetric flow rates that the outlet may experience under normal to extreme conditions involving large rainfall

Table 2.4.1. Boundary condition data related to the inlet channel (Figure 2.4.2)

Normal depth (ft)	Hydraulic radius (ft)	Volume flow rate (ft^3/s)	Flow velocity (ft/s)	Froude number, *Fr* $V/(g\ h)^{1/2}$	Critical depth, D_c (ft)
0.1	0.093	1.829	6.44	3.59	0.23
0.3	0.247	10.51	12.34	3.97	0.75
0.5	0.369	22.88	16.12	4.02	1.26
1.0	0.587	62.26	21.93	3.86	2.46
1.5	0.729	107.9	25.35	3.65	3.55

events. The outlet boundary condition for the free jet emanating from the drainage structure is the ambient atmospheric pressure.

The supercritical Froude number ($Fr > 1$) is consistent with $D_n < D_c$ in the upstream channel (Ven Te Chow 1959; Henderson 1966; Morris and Wiggert 1972;) because of the steep slope of the supply channel and the long upstream channel length. In Table 2.4.1, g is the gravitational constant, D_n is the normal depth, D_c is the critical depth and h is the depth of water in the rectangular cross-section channel. A number of Table 2.4.1 trial cases were examined to determine the behaviour of the outlet structure under varying flow rate conditions. Two of the five cases of the D_n, V input data pairs in Table 2.4.1 were then used to generate solutions within the drainage structure to assess the effects of internal geometry on steady-state flow patterns and determine the maximum flow rate that can be accommodated within the channel-outlet system without overflow. Calculations for Case 2 ($D_n = 0.0914$ m) and Case 4 ($D_n = 0.3048$ m) were run to determine the steady-state free surface height, internal flow velocity, and streamline patterns within the drainage outlet as well as the maximum contained flow rate of the channel/outlet system.

For the normal depth case of 0.0914 m (Table 2.4, Case 2), 0.297 m^3/s flow rate, an internal velocity vector pattern indicates that a rotational circulation pattern exists within the flow on constant *x*-planes centred towards the end of the inclined inlet ramp. On a *z*-plane parallel to the bottom floor, the velocity vector pattern indicates further rotational circulation cells (Figure 2.4.4). Figure 2.4.4B shows a plot of the streamlines originating from points on a plane associated with the inlet boundary conditions and their development on passage through the drainage structure. The streamline patterns confirm large imbedded circulatory flow patterns existing in the region between the bottom of the inlet ramp and the structure's internal floor, and that the blind passage zone is effective in creating a localized secondary mixing zone with a clockwise rotational cell in the *z*-axis direction. Additionally, the flow exhibits

A

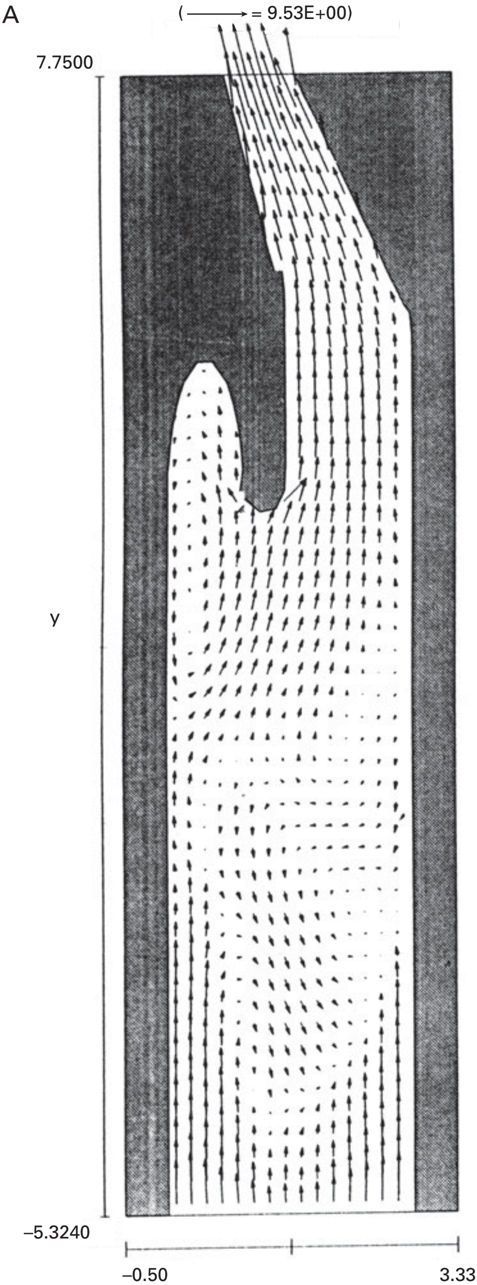

Figure 2.4.4. A, Top view velocity vector pattern at mid depth within the exit structure (Figure 2.4.3). Complex vortex regions are apparent as flow passes though the structure. B, Streamlines originating from the channel entry flow showing complex 3D vortex regions within the exit structure. The vortices agitate debris and facilitate self cleaning.

B

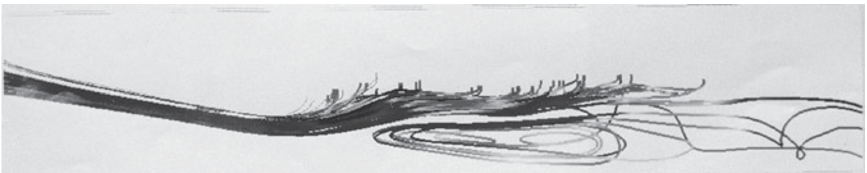

Figure 2.4.4. (Continued)

a twisting motion along the *z*-axis. A weak hydraulic jump also exists ahead of the inlet structure as the flow changes from supercritical to subcritical. The drainage outlet internal shaping is therefore effective in creating large, three-dimensional, imbedded turbulent mixing zones to agitate and keep in suspension any debris while the stream discharges through the outlet. The drainage structure internal shaping creates a 'self-cleaning' system that eliminates, through induced multi-vortex, three-dimensional fluid motions, any accumulation of settled debris that could cause clogging of the outlet orifice. The velocity of the many internal rotational zones is high with respect to the outflow velocity therefore guaranteeing capture of debris particles into the outflow stream. Accumulating mud/sludge on the channel floor would likewise be slowly transported downstream by the shearing action of the rapid water flow; as this viscous mass reached the discharge structure, the turbulent water motion initiated by the hydraulic jump and associated downstream circulatory flow patterns would entrain debris particles back into suspension and transport them out of the exit orifice.

Given that entry Froude number is supercritical and the bed slope partially transitions from steep to level within the discharge structure, a hydraulic jump exists before the entry zone to the outlet structure. The internal shaping of the drainage structure is not only effective from a self-cleaning perspective but also has high turbulence levels typical of a hydraulic jump, aiding particle entrainment. The complex curvatures of the contracting cross-sectional area drainage structure tend to increase flow resistance, leading to an increase of water height above that produced by the weak hydraulic jump; this back resistance moves the hydraulic jump further up the inlet ramp. The S-shaped, contracting area feature of the outlet structure therefore produces internal secondary flow patterns that help limit the possibility of channel overflow at relatively small flow rates and high Froude numbers; this is due to the reduced stream height amplification resulting from a downstream area contraction and curvature effects modifying the flow structure behind the hydraulic jump. The circulatory flow behind the hydraulic jump tends to lessen the magnitude of the hydraulic jump height as the stream surface below the circulatory fluid structures serves as a 'virtual floor', lessening the effective curvature of the bottom of the channel. This follows from the observation that a stream surface is equivalent to a bounding wall for flows where viscous effects are largely negligible, as in the present case. Without the effects of downstream internal wall curvature and energy dissipation through multi-vortex creation, a strong hydraulic jump induced by a straight-through but contracting outlet would amplify the height of the water surface before the structure and lessen the flow rate that can be contained within the vertical dimensions of the structure.

Based on calculated exit velocities, the exit stream should carry a metre or two past the exit plane before impacting the steep hill slope beyond the city wall. As the structure also deflects the discharge stream to the left, the stream avoids flowing onto the steep north-running road. The hydraulic overview of the design is then one of creating internal water flow patterns within the structure to provide for self-cleaning features while simultaneously decreasing the possibility for channel overflow at high flow rates by internal geometry effects reducing the water height behind the hydraulic jump and allowing for flow containment within the structure.

The question of the maximum flow rate supported by the drainage structure is next addressed. A calculation based on a normal depth of 0.3048 m (Table 2.4.1, Case 4, 1.763 m^3/s) is made to provide an answer. The criterion for the maximum flow rate without channel overspilling is based on containment of the weak hydraulic jump within the top cover plate that lies over the forward part of the drainage structure. If the flow is at the cover plate height, any further increase in flow rate will cause overspillage into urban zones, defeating the purpose of the drainage structure. The bottom surface of the covering lintel lies 0.97 m from the bottom surface on the lead-in channel and about 0.45 m ahead of the U-shaped projection (the lintel or covering plate in the lead-in channel before the outlet structure is not shown in Figure 2.4.3 but is in place on-site).

Calculations for Case 4 show that the height of the drainage structure is exceeded by the free fluid surface. Although the internal circulatory patterns still exist at this higher flow rate, overspillage occurs due to the flow rate exceeding the drainage outlet's capacity to contain and transmit this increased amount of flow through the outlet. The net capacity of the drainage system is therefore about 0.425 m^3/s. Since the city water supply originates from a number of local and distant springs supplying pipe transport systems to intra-city reservoirs, the 0.425 m^3/s drainage canal capacity is a lower bound for steady-state water supply to the city from reservoir supplies but an upper bound for the channel system capacity. Spring-fed water supply piping systems towards the northern side of the site and spring systems on the city acropolis have been identified as part of the supply system, but their flow rates have not been estimated nor have all of their drainage paths been identified. Since storm runoff and capture flow rate into the drainage channel could easily exceed the steady-state flow rate capacity, it may be speculated that the city water supply piping system may have been curtailed during periods of heavy rainfall to permit efficient city rainfall drainage through the drainage network.

It is of interest to note the possible methodology used to size the lead-in channel to the drainage structure. It has been noted that the system designers tried to maximize the amount of contained flow by minimizing channel overspillage; this was done by weakening the hydraulic jump through discharge structure shaping effects. From Hero of Alexandria (as quoted in Cohen and Drabkin 1968), '. . . it is to be noted that in order to know how much water a spring supplies, it does not suffice to only find the cross-sectional area of the flow. It is also necessary to find the speed of the flow for the swifter the flow, the more water the spring supplies. One should therefore dig a reservoir under the stream and note with the aid of a sundial how much water flows into the reservoir in a given time and therefore calculate how much will flow in a day. It is therefore unnecessary to measure only the area of the stream as the total amount of water delivered will be determined also by the passage of time . . .' This statement is equivalent to the modern concept that volume flow rate is equal to average flow speed times the cross-sectional area of the stream and is equivalent to a one-dimensional, integrated form of the continuity equation of fluid mechanics. Based on this knowledge, a reservoir at the end of a trial design for a sloped channel could have been used to determine the volume flow rate for a steady supply flow. If the supply spring's flow rate is known from the same measurement procedure, then a basis for a channel design change is in place. This procedure would then aid engineers in specifying the channel design (depth and width) to contain the spring flow rate. Since spring-fed reservoirs supply water to the agora and West Gate Street housing, then the geometry of the long channel down West Gate Street could have evolved according to this procedure, as opposed to trial-and-error reworking of the channel. Since the channel and outlet appear to have sophisticated flow controls and ideally suit the flow situation, this implies application of some fluid mechanics principles such as those known to Greek theoreticians. Since the lead-in channel slope is hydraulically steep, it must have been observed that the water depth decreases to an asymptotic normal depth as it accelerates downhill in the channel. Therefore, an estimate of the station-to-station velocity magnification could be obtained by simply noting the station-to-station water height decrease down the rectangular cross-section channel. On entry of the low-height, high-velocity water into the exit structure, a hydraulic jump occurred and the internal exit structure geometry caused both weakening of the jump and a water height increase within the structure. Water was safely contained within the structure and steady-state discharge maintained provided the total flow rate is kept below the 0.425 m^3/s limit that caused the jump to move ahead of the inlet and overflow. It therefore appears that such well-designed drainage systems were installed for urban areas where flow rates could be estimated; other urban areas in the city must have individually tailored supply–drainage systems to provide adequate water for local needs. (A similar system may be in place for the street immediately north of West Gate Street but excavations are required to verify this observation.) The division of water supplies can be done by dividing a main supply flow into individual reservoirs, each of which acted as an individual source for different parts of the city, or by tapping local springs to supply individual reservoirs for individual supply–drainage systems. In this manner, individual drainage systems were tailored for the expected flow rates they discharged. It appears, to the best knowledge currently available on the city water system, that a mixture of both of these supply methods was employed.

Summary

In summary, the outlet drainage structure appears to incorporate a self-cleaning hydraulic function to keep the system free from debris accumulation. This feature operates continually at all flow rates up to a maximum value of 0.425 m^3/s. Flow rates exceeding this value, which may occur from rainfall runoff adding to the continuous-supply from the reservoirs, caused channel overspillage, flooding adjacent urban structures within the west wall of the city. It is postulated that the water supply may be purposefully limited by pipeline flow blockage (resulting in increased cistern and reservoir storage) during rainfall events to prevent intra-city flooding. The net effect of the drainage structure at the end of the drainage channel is to provide a hydraulic mechanism to create a self-cleaning, maintenance-free outlet to prevent the system from clogging under day-to-day usage conditions. In addition to large-scale vortex and turbulent mixing effects to keep debris in suspension, the wall roughness of the internal masonry structure and vortex formation on concave surfaces aid in promoting smaller-scale turbulent agitation of the stream near the walls where boundary layer velocity is low. The hydraulic features of the outlet drainage structure demonstrate that Greek city planning expertise extended not only to details based on water supply and distribution systems but also to drainage and waste elimination systems. No detail was apparently overlooked to promote the efficient drainage of the elite status city by maintenance-free systems using creative hydraulic practices. Since waste accumulation may occur in improperly designed channels (too low a slope and flushing water supply, constrictions and bends that accumulate debris, etc.), the Priene waste management system and drainage outlet design incorporated health benefits to the populace in terms of rapid flushing of waste water and debris through covered channels within city walls with small likelihood of spillage. No flow control device of this type is known from any other Greek city of the same era. There are three possible explanations: none were built, none survived, or none have yet been discovered. Although knowledge of Greek hydraulics practice is fragmentary, it is suspected that empirical observation from nature formed the basis of some of the constructions. Perhaps observations from natural occurrences were translated into engineering designs; in this respect, an observation of Seneca in the 1st century BCE (quoted from Seneca in translation 1932) may be pertinent to this hypothesis: '. . . we may ask why a vortex occurs. In the case of rivers, it usually happens that as long as the river moves along without obstruction, the channels flow uniformly and straight. When they run into some boulder projecting from the side of the bank, the waters are forced back and twist into a circle with no way out. Thus they are swirled about, folded into themselves and form a vortex . . .' Greek engineers in earlier times, by observing stream flows with curved obstacles on side or underwater boundaries, were able to observe the motion of debris particle trajectories and the associated debris accumulation patterns. The empirical observations quoted could be reflective of earlier observations and then codified as the basis of drainage outlet designs to duplicate the same phenomena. It is therefore suggested that the Seneca quote serves as an observational basis underlying the use of created vortices in water engineering; the application to drainage outlet design is the next step in Greek genius and creativity.

2.5 THE RESERVOIR AND MULTIPLE SLUICE GATE WATER RELEASE SYSTEM AT ROMAN CAESAREA (ISRAEL), 6 BCE–300 CE

Introduction

The ancient city of Caesarea lies on the Eastern Mediterranean coast of Israel halfway between Haifa and Tel Aviv and is located around the (ancient)

Sebastos Harbour. While the political history of Caesarea is well known (Josephus (in translation) 1960; Negev 1967; Holum *et al.* 1988) and many city constructions are attributed to Herod and Roman occupiers from 6 BCE when the city was the seat of the Roman procurators of Provincial Judaea, aspects of its water supply history remain to be explored given the reliance of the city on adequate water supplies for its large population. As the seat of Roman administration of the Palestine territories and headquarters of the 10th Roman Legion, further expansion of the urban core of the city continued into the 2nd and 3rd centuries CE with elaboration of its water supply system. Water supplies to the city were largely through an aqueduct (Figure 2.5.1) and bedrock-cut channels built in the Herodian Period and expanded in later times from canalized springs at the foothills of Mount Carmel about 12 km distant. The main aqueduct originally contained one channel but was later repaired and enlarged to include a covered, ground-level channel in response to the growing population and elaboration needs of the city. A supplemental water supply that connected into the main aqueduct system came from a reservoir supplied from a nearby river and/or channels from spring and rainfall runoff from nearby mountains. The reservoir basin located within Kibbutz Migan Michael appears to cover about 3–5 ha in area but its true bottom depth remains unknown pending excavation. The deeper end of the silted-in reservoir is bounded by an elevated ashlar wall (Figure 2.5.2). The wall contained a bridged opening over an exit passageway that contained two gates whose open height regulated the amount of water released into a guide

Figure 2.5.1. The Roman aqueduct at Caesarea in northern Israel.

Figure 2.5.2. The dam front wall of the reservoir supplying water to Caesarea with ~8 m height.

basin. The guide basin had multiple channel intercepts leading off to the long elevated aqueduct to Caesarea; other channels remain unexcavated, destroyed, or incomplete, suggesting multiple uses for the stored water supply. Some of the multiplicity of exit channels at different levels may be earlier channels superseded by later designs but left in place without access to reservoir water.

The use of two parallel gates is evidenced by dual vertical guide channels cut into the passageway sidewalls (Figures 2.5.3 and 2.5.4). The dual-gate arrangement suggests safety precautions to control leakage and/or failure of the gates to hold back reservoir water. The design poses the question as to whether some additional technology application is suggested by the dual-gate design and to what degree the dual gates provided a safety margin beyond a single gate configuration. While elevation of the gates was presumably provided by dual winches located to the sides of the gates, basic questions remain as to why the design incorporated two parallel gates separated by about 1.0 m as well as the winching method to lift the gates. The gates, presumed to be wooden structures about 5 m high and 14 m wide to fit passageway dimensions and of sufficient strength to withstand hydrostatic pressure, are no longer in existence but their presence is assured by the dual vertical guide slots (Figure 2.5.4) remaining in the side walls. While the provenance for the

Figure 2.5.3. Detail of the dam outlet region leading to the dual gate passage. Dual vertical grooves are apparent on the side walls.

Figure 2.5.4. Detail of the symmetric vertical groove structure carved into the walls in the exit region of the dam. Wall height in this area is *c.* 5 m.

reservoir is certainly within the Roman period (the adjoining aqueduct contained a plaque attributing construction to the 10th Legion), there may be modifications attributed to earlier and later Crusader occupiers in the 9th to 12th centuries.

The first consideration arises from the weight of the gates and effects of the hydrostatic forces acting on them. For example, for a $4 \times 12\,m^2$ (516 ft^2) gate holding back a 4 m water height in the reservoir, the hydrostatic force on the gate would be ~211,300 lbf (96,000 kg). This force, distributed onto two opposing side wall slots, adds a vertical frictional resistance force (dependent on an assumed gate-wall friction coefficient, contact area, and lift velocity) to be added to the gate weight, which would require considerable effort to elevate by a winch/pulley system. For an assumed wood gate thickness of 0.30 m (~1.0 ft) and for typical water-logged cedar, an additional ~12,900 kg (28,400 lbf) weight can be added to the frictional resistance force. If the gate is fully submerged, this buoyant force is ~14,600 kg (32,200 lbf). The total lifting force therefore far exceeds the buoyant force. Of course, no buoyant forces exist when water is only on one side of a gate. It remains to be determined if the multiple gate design can be utilized in some way to reduce the lifting force required.

Hydrostatic forces

Since the gates no longer exist and no information exists as to their mode of operation, materials, or construction details, some speculative reconstruction of their function is advanced to explain a possible reason for the dual-gate configuration. In the proposed arguments, the first gate facing reservoir water is denoted Gate 1; the gate immediately behind is Gate 2. Initially the force needed to lift Gate 1 would have been high, considering the frictional lift forces against the guide channels from hydrostatic pressure loading as well as weight forces. Speculating that a small plate held in vertical flanges covering an opening through closed Gate 1 were to be lifted (assuming a $0.092\,m^2$ (1.0 ft^2) plate located in the centre of Gate 1 about 1 m down from the gate top), the upward force required to move the plate is about a 107 kg (236 lbf) normal force times a friction coefficient distributed over the contact area between the plate and gate face opening edge. On opening the plate, water begins to enter the space between Gate 1 and (initially closed) Gate 2. As the water level in the gap rises, the hydrostatic pressure on the reservoir side of Gate 1 becomes somewhat balanced by the hydrostatic pressure of the rising water behind it supplemented by an increasing upward buoyancy force due to the rising water. As the water continues to rise in the gap between gates, the force required to elevate Gate 1 decreases. Gate 2, during elevation of Gate 1, begins to experience increasing hydrostatic pressure as water begins to fill the gap between the gates. If Gate 2 begins to be elevated after Gate 1 reaches a certain height and both continue to be elevated (as can be arranged by suitable cabling to the winches), as Gate 1 elevates (and water continues to pour through the plate opening and under Gates 1 and 2), the gap water height stabilizes below the reservoir water height and the force required to lift Gate 2 is approximately its own weight plus some friction force from minor hydrostatic pressure from the small gap water height. The combined winch/pulley force required to elevate both gates (but to different opening heights) would then be approximately the weight minus the buoyancy force on Gate 1 (which would be low) plus the weight of Gate 2 as frictional uplift forces on Gate 1 are largely absent and Gate 2 experiences only a small friction force contribution from hydrostatic force from the low height gap water. Thus two heavy gates could be lifted further with the force required to lift Gate 2. For closure, the small plate on Gate 1 is closed, gap water drains under Gate 2, and Gate 2 begins its descent due to its weight. With the small plate on Gate 1 now opened, hydrostatic pressure equalizes on both sides of Gate 1, reducing friction force values, and Gate 1 descends as its weight exceeds the buoyancy force. This system therefore works to reduce opening forces and provides an easy closing mode.

A variant on this procedure may be envisioned. If Gate 2 is initially set with a given fixed bottom opening and Gate 1 initially closed, then, as the small Gate 1 plate is opened and Gate 1 is lifted, a fixed flow rate through the gate system is established by the height of the Gate 2 bottom opening and the hydrostatic head of the reservoir. With the small plate on Gate 1 open, the gap water height then stabilizes and the hydrostatic forces on each side of Gate 1 are somewhat balanced, reducing the lifting friction forces. Additionally, the buoyant force on the partially submerged Gate 1 decreases the lift forces on Gate 1. Thus, the height opening of Gate 1 can be easily adjusted to fine-tune the flow rate through the dual-gate system to any fraction of the maximum flow rate set by the fixed Gate 2 opening. Again, closing proceeds by closing the small Gate 1 plate opening, draining gap water between the gates, allowing Gate 2 to close by its own weight, opening the small Gate 1 plate, then closing Gate 1 by its own weight. This operating system results in reduced lifting forces and is easily controlled by operating the winch/pulley systems on either side of the gate. When Gates 1 and 2 are fully lowered, a double gate seal exists to prevent water seepage from the reservoir with a safety margin to ensure flow containment should one gate develop leakage or breakage failure.

Additional variants involving the gate lift sequence and small plate size, small plate position on gates to regulate between-gate water height, and the number of small plate openings are possible. The most probable methodology involves the idea that if the space between gates can be temporarily flooded with water to a given height, then lift forces on Gate 1 can be reduced by buoyancy and reduced sliding friction. In general, the smaller the flow rate through Gate 2 and the larger the plate opening in Gate 1, the higher the gap water level between the gates; this translates into lowered lift forces for Gate 1 due to a balance of weight and the buoyancy forces with reduced frictional forces. Presumably, with the ideas advanced by the designers of the system, trial variations were made to improve operation to minimize the forces necessary to lift and close the gates.

Computer investigations

A number of FLOW-3D computer models were made to investigate aspects of the gate lift process. For a single plate opening near the top of Gate 1, water begins to fill the gap prior to Gate 1 lifting; Gate 2 is set at a fixed height to give an upper limit to the flow rate. In addition to buoyancy effects, the hydrostatic pressure in the gap helps to reduce the friction force on Gate 1 reducing lifting forces. A variant to this design may incorporate an opening near the bottom of different size (Figure 2.5.5A and B) where Gate 2 may be opened a small distance from the bottom prior to Gate 1 being activated. As a

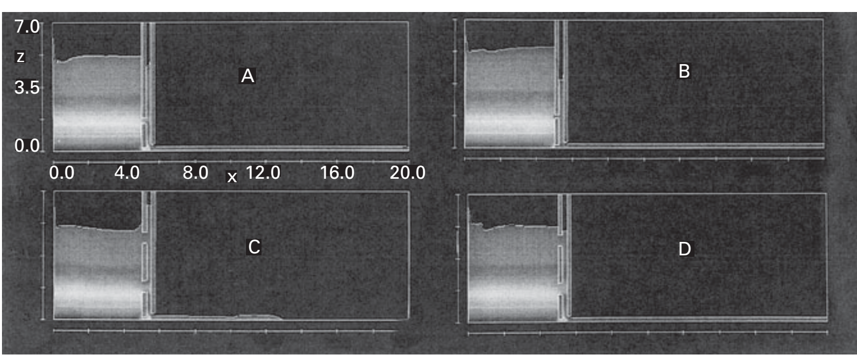

Figure 2.5.5. A, Dual gate flow pattern 3 s after Gate 1 opening, indicating hydraulic effects reducing lifting forces on Gates 1 and 2. A small plate on Gate 1 opens, allowing water inflow with Gate 2 partially open. B, Flow pattern 10.0 s after the small gate on the lower part of Gate 1 is opened. C, Flow configuration with two small openings on Gate 1 activated by small withdrawn plates and the flow pattern 1.0 s after activation. D, Flow configuration with two small openings on Gate 1 activated by withdrawn plates; the flow pattern is shown 6.0 s after activation.

secondary plate on Gate 1 is opened, Gate 1 can be easily lifted further to allow passage of water through the Gate 2 bottom opening. The additional hydrostatic pressure on Gate 2 then fixes its position and prevents motion that could affect the flow rate. Closure of the system then involves lowering the small plate over the opening on Gate 1 and lowering Gate 1; then, as water drains from between the gates under the bottom of Gate 2, Gate 2 is lowered by its own weight.

An innovation may be envisioned by placement of two secondary plates at different heights on Gate 1 (Figure 2.5.5C and D). Prior to lifting Gate 1, two plates are opened, letting water rapidly enter the gap between the gates. A reduced Gate 1 lifting force results from buoyancy, now rapidly increasing due to the rapid and higher infilling of the gap between gates coupled with the hydrostatic pressure balance that somewhat cancels the Gate 1 gate-wall slot frictional force. Again, Gate 2 has been initially opened a small distance from the bottom prior to plate openings on Gate 1. This case may represent the easiest mode of operation of the system requiring minimal lifting forces. While many different plate locations and opening sizes may be envisioned to facilitate reduction in Gate 1 lifting forces, the Gate 2 bottom opening may be initially set by lifting Gate 2's weight without hydrostatic forces. Once Gate 2 is set at a fixed height, lifting Gate 1 for a fine adjustment to Gate 2's flow rate can be done with relatively little lifting force. Although configurations involving wooden frames over the channel width and counterweight pulley systems may be envisioned to aid in gate lifting, the observation that any such system will work better if the forces involved are lessened by hydrostatic aids constitutes a key factor in reducing the complexity of the lifting structure, and the methodologies mentioned do this. Based on the winch and pulley systems common on Roman architectural constructions, the generation of forces of the magnitudes mentioned is well within the capability of Roman technology. While the probable main function of the dual gates is safe containment of reservoir water, the methodology described is also suitable for reducing the lifting forces on the gates to achieve precise outflow control.

3

Ancient South-East Asia

3.1 THE BARAYS OF ANGKOR WAT, CAMBODIA, 800–1432 CE

Geographical background

Cambodia is situated in southeast Asia on the coast of the Gulf of Thailand and shares borders with Vietnam to the east, Thailand to the west, and Laos to the north. Lake Tonle Sap occupies ~2.5% of Cambodia's land area and plays a vital role in the rice agriculture of the country. The total cultivatable area is about 2.1 million hectares, of which 1.8 million is devoted to rice agriculture. The growing season is largely coupled to the monsoon cycles: the bimodal wet season starts in May and ends in October with peaks in June and September/ October resulting from different rainfall origins. Rainfall levels vary around the country: although average levels are about 1.5 m, amounts vary from about 1.0 m at Svay Check in the western province of Banteay Meanchey to nearly 4.7 m in the southern province of Kampot. The Tonle Sap River reverses flow twice each year: from July to October, water flows into Tonle Sap Lake from branches of the Mekong River, swelling its area from 2,600 to 10,500 km^2; in November when the flow rate of the Mekong River decreases, the Tonle Sap River reverses flow and water flows into the Mekong once again. Since 85% of Cambodia's land area is included in the Mekong River basin, river water levels coupled to groundwater levels play a role in agricultural systems. The dry season from November to April requires irrigation to support rice agriculture making water storage and high groundwater levels important. Based on recent research (FAO 2005), the net renewable water balance (volume inflows minus volume) is equal to about 120 km^3 with about 18 km^3 stored in groundwater reduced by 13 km^3 per year by river drainage. Of the total amount of water withdrawal per year (520×10^6 m^3), about 94% is devoted to agriculture; given the dependence on rice farming through the ages, it is likely that a similar percentage was used for agriculture in ancient times as now to support like-sized agrarian populations.

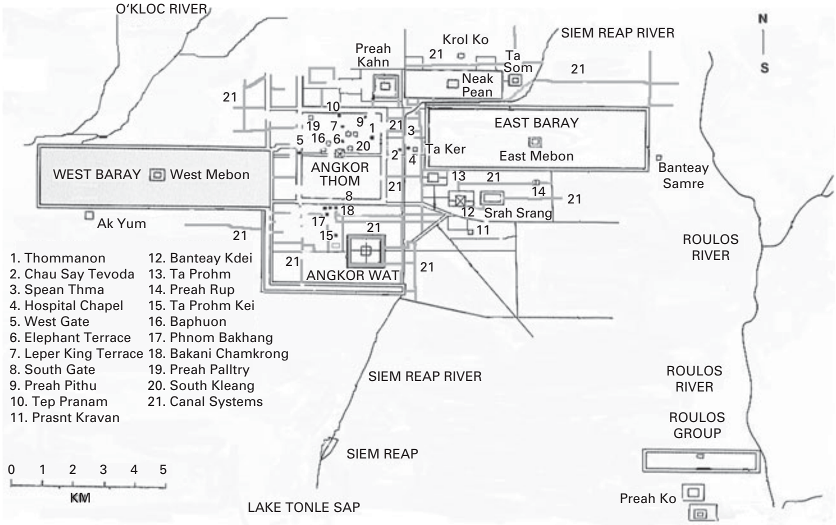

Figure 3.1.1. The Angkor temple complex showing large reservoir structures (barays) in the northern part of the city and structures surrounded by moats. 1, Thommanon; 2, chau say tevoda; 3, spean thma; 4, hospital chapel; 5, west gate; 6, elephant terrace; 7, leper king terrace; 8, south gate; 9, preah pithu; 10, tep pranam; 11, prasnt kravan; 12, banteay kdei; 13, ta prohm; 14, preah rup; 15, ta prohm kei; 16, baphoun; 17, Phnom bakhang; 18, bakani chamkrong; pereah palltay; 20, south kleang; 21, canal systems.

In the 10th to 14th centuries CE, Angkor's water supply system was based on four (baray) reservoirs (not all functioning simultaneously) with a total capacity of $100–150 \times 10^6$ m^3. The reservoirs were supplied from nearby rivers (Figure 3.1.1; grey lines represent interior canals; solid lines berms) with further input from rainfall over their surface areas. This amount of water had the capacity to irrigate about 15,000 hectares through a variety of different irrigation methods, which can be divided into flood recession farming (typical of the system still in place as Tonle Sap recedes in the dry season), controlled release from water reservoir systems, wet season rainfall agriculture, and excavated bunded land plots (i.e., soil removed to lower a field area and mounded into bordering retaining walls) that retain water from seasonal rainfall and high water table. Different rice varieties (floating rice-straw lengths up to 4 m; deep-water rice-straw length up to 1–2 m) further complicate the agricultural picture as different water requirements demand flooding to maintain basin water height for different rice crop types. All these methods rely, however, on the maintenance of a high water table throughout the year to sustain multi-cropping wetland farming and the relationship of reservoir water to these different agricultural techniques is vital to understand Khmer water control methodologies.

Historical background

The Cambodian Khmer Empire was ruled between the 8th and 12th centuries CE by a series of kings whose capital was centred in Angkor after several other capital city locations were successively built and abandoned in different areas of the country. The Angkor capital, once one of the ancient world's largest urban areas centred around temple complexes, was intensively engineered over time to suit the empire's practical and religious needs. During this process, land was continually reshaped into an image of the celestial city (Mount Meru) of the Hindu and Khmer gods with Angkor's earthly reflection ruled over by human incarnations of the gods. While the political, religious, architectural, and economic history of the site is well known (Rawson 1967; Kostof 1991; Chandler 1992; Englehardt 1995; Freeman and Jacques 1999; Laur 2002; Highham 2003; Coe 2003; Rooney 2003; Roveda 2004), and substantial research on the water systems has been accomplished (Goodman 2000), much remains to be done to clarify its functional elements. In particular, the function of the barays and canals within the city remain controversial to this day despite many years of research. Use of stored water from rainy season inundations for rice paddies, municipal water systems, and transportation canals are certainly among the most probable uses, but the usage strategy and details of the distribution system remain research topics.

Originating with Jayavarman II's consolidation of competing states, the establishment of a prevailing government structure with a Hindu religious foundation started with proclamation of universal kingship at Phnom Kulen in 790 CE. After pacifying rebellious states that enlarged the dominance of Jayavarman II's central rule, the first capital city was formed at Roulos (Figure 3.1.1) over a pre-Angkorian settlement. A further transfer of the capital to the Kulen Mountains, under Jayavarman III, then a return back to the Roulos area in 802 CE with the capital renamed Hariharalaya occurred. This city served as the base of empire until Jayavarman II's death in 850 CE. Elaboration of the capital at Roulos was subsequently performed by his successor, Indravarman III, in 880 CE with a series of dedicatory temples to Jayavarman II's memory as well as ceremonial structures rich in Hindu iconography. Among the structures derived from his kingship was the first large baray (reservoir) at Roulos. Accompanying the Roulos Group was the large rectangular East Baray (Figure 3.1.1), built by Indravarman's son Yasovarman I at the site of Angkor, whose construction and type was to characterize all future Khmer capitals. This baray is attributed to Yasovarman I, who proclaimed on the foundation stone of Preak Ko in 879 CE, '... five days hence, I will begin digging ...'; this promise was kept and another inscription proclaims '... He made the Indratataka, mirror of his glory, like the ocean ...'. The baray measured 3,800 by 800 m and was supplied by runoff streams from the Kulen Hills and a canalized channel from the Roulos River. Additional structures south of the baray, Preah Ko, and the Bakong had moats supplied from baray waters. The northern dike and the Lolei Temple (mebon) in its centre were completed by his son in later times. Indravarman III's son, Yasovarman I, subsequently moved the capital to Yashodarapura, near the current site of Angkor, and is credited with the construction of the first major temples (Phnom Bakheng and Phnom Krom) in 893 CE. For the next 500 years, with one major interruption, the capital remained at Angkor and experienced further elaboration with construction of many monuments and temples reflecting the earthly version of the Hindu paradise and incorporating architectural renderings of multi-towered Mount Meru, the seat of the Hindu gods. A transfer of the capital under Jayavarman IV 100 km north to Koh Ker was followed by a final return to the Angkor area, now centred at Pre Rup rather than Phnom Bakheng (Figure 3.1.1). With the final move to Angkor and the final military dominance of the area under King Rajendravarman, a monumental building programme commenced with the construction of Ta Keo, Banteay Srei, the Baphuon, and the East Mebon, under Jayavarman V in the 950–980 CE time period. Previously, the East Baray had been constructed under Harshavarman in *c.* 920 CE and the East Mebon temple in the centre of the baray completed under the kingship of Rajendravarman II in 952 CE. The West Baray was built during the reigns of Suryavarnan I and Udayadityavarman II in the 1025 CE time period, presumably after the East Baray became dysfunctional due to silting-in problems. A baray trace, Banteay Choeu, located in the southwest lower corner of the West Baray but never completed, may be associated with the construction of the West Baray or form an earlier version of a baray system in that area. A later baray, the North Baray (Jayatataka), was constructed under Indravarman III in *c.* 1220 CE with Neak Pean as its central monument, and again subject to silting-in problems and abandonment. Kings Suryavarman I and II further expanded the empire to include portions of modern-day Thailand, Laos, and Vietnam in the time period from 1050 to 1150 CE. King Suryavarman II, in the early 12th century CE, led the empire to its political and economic golden age and construction of Angkor's most spectacular monuments, including Angkor Wat, Thommanon, Banteay Samre, and Beng Melea. A large South-East Baray trace located south of the East Baray and Sras Srang and Pre Rup, planned during the reign of Suryavarman II, was never completed but nevertheless indicated the intention to create many reservoirs within the city urban core. After a period of invasion from eastern and western countries accompanied by internal unrest and rebellion, Angkor was occupied by the Cham, now associated with a region in present-day North Vietnam, until liberation by Jayavarman VII about 1181 CE. Associated with this period is a conversion of the state religion to Buddhism and construction of monumental structures that largely defined Angkor over the next 40 years. Jayavarman VII's major works include the Bayon, the royal compound Angkor Thom (built between 1181 and 1219 CE), Ta Prom Kei, Ta Som, royal terraces and promenades, Banteay Kdei, Preah Khan, Neak Pean, Srah Srang, Krol Ko, Preah Pililay, Prasat Sour Prat, and hundreds of ceremonial and civic structures (such as hospitals, monasteries, sanctuaries, and temples). Following this kingship and a reconversion back to Hinduism under Jayavarnman VIII, subsequent invasions from the west forced abandonment of the capital and relocation to the Phnom Penh area. The architectural remains of the Khmer Empire at Angkor now constitute a World Heritage site, which is spread over 400 km^2, and are a final tribute to the creativity, energy, and glory of the rulers that created, presided, and guided their people.

The barays

The West Baray is an 8-km long and 2.8-km wide reservoir with an initial depth a few metres below the surrounding ground level (Figure 3.1.1). A wide perimeter dike 15 to 20 m high rings the baray, allowing water to accumulate to depths of 2 to 5 m above the (current) bottom from rainfall, groundwater seepage, and a river inlet in the northeast corner of the baray. Although nominal water height in the baray is that of the supplying river at the inlet to the baray at the height of the rainy season, additional baray water storage may be attained by excavation below ground level. Due to silting-in, the original baray depth remains undetermined.

Many authors (Coe 2003, particularly Chapter 7) have proposed reasons for baray construction. The explanations range from '. . . no-practical function, only ceremonial use . . .' to '. . . some relation to agriculture . . .' to '. . . an essential component of the hydraulic city's irrigation system . . .', but none of the conjectures are backed by convincing arguments or field data. The controversy between Groslier (1979) and Dumarcay (1997), with their vision of a hydraulic city whose barays supported agriculture through canal distribution systems, and Van Liere and Acker, whose research demonstrated that only a miniscule fraction of Angkor's population could have been sustained from channelled waters originating from main barays (Higham 1991, 2003), sustain the controversial function of the barays. The fact that no ancient inscriptions or commentaries mention the barays being directly related to irrigated agricultural fields by distributive canals, but rather emphasize their ceremonial function in connection with Mebon temples at their centre, further clouds interpretation of their purpose (Coe 2003). In addition to identification of the barays with a near-baray irrigated field system by earlier investigators, some dispenser canals off the West and East Barays into distribution canals, moats, and field systems have been recently discovered. Here modern development has led to the placement of a surface irrigation canal network originating from a dam on the West Baray southern bank that may trace older canal paths used for irrigation agriculture except for one outlet canal in the southwest corner of the West Baray. One such canal from the West Baray runs 40 km east until it reaches the 25 km Damdek Canal, which could have provided water to lakeshore farming areas as Tonle Sap flood waters receded. The presence of the Tonle Sap Lake to the south is a vital consideration for the agricultural base of the city. This lake is the drainage basin of western Cambodia, draining the Cardoman Hills to the west and the Dangrek Mountains to the north. From monsoon water from the start of the rainy season in May/June and ending in November, lake inflows originate from cumulative rainfall amounts, runoff drainage from the western Cambodian basin, numerous runoff streams, and the Mekong River to the east. Subsequent summer monsoon water arrives from the Mekong swollen from snowmelt from sources in Tibet further amplified from flows originating from the vast catchment areas of southern China, Laos, Thailand, Myanmar, and Cambodia. While outflow from Tonle Sap occurs early from rainfall accumulation, later water inflows from Mekong reverse the outflow and increase inflow into the lake, causing its level to rise 7 to 9 m at peak flood levels. The silt accumulation onto lake margins and floodplains provides a source of fertile soil that had played a vital role in the agricultural base of Angkor (Goodman 2000) and made this area ideal for multi-cropping over floodplain areas as well as providing fish and marine resources. The distribution of Khmer settlements around lake margins from Banteay Chhmar to Angkor also supports the premise that agriculture was largely based on usage of the fertile floodplain of Tonle Sap. Use of recession agriculture (i.e. rice farming on lands exposed by the receding lake) is still practised today as in ancient Khmer times.

The site of Angkor, based on high ground and showing signs of fill areas underlying compound areas, had immediate access to floodplain agricultural areas as well as the perennial Siem Reap River, which drained the Phnom Khulen to the north and provided transport access from the city to the lake's fisheries and agricultural zones. This river was augmented with waters from the (canalized) Puok River in the 10th century CE under the reign of

Rajendravarman I to provide water for the many moats, reservoirs, and canals within the capital city. While the vast natural floodplains of Tonle Sap seem to provide sufficient land area to support a vast population's food needs, the question of the function of the barays becomes even more problematic as the amount of agricultural land it could influence (by some form of timed water release) is relatively small compared to the Tonle Sap floodplain area available for agriculture. Nonetheless, it would be expected that all available land and water resources be utilized for agriculture given the continual needs of the large population of Angkor and its environs, which is estimated to range from 500,000 to 1,000,000 inhabitants.

One purpose of this section is to present reasons for the existence of barays as they were obviously a main feature of Angkor and Roulos from early to late times and required much labour to construct. Angkor contains at least three major barays built at different time periods: the 8×2.8 km West Baray (1050 CE); the 7×2 km East Baray (890 CE), and the Neak Pean (Jayatataka) Baray (1200 CE) to the northwest of the East Baray (Figure 3.1.1). Total stored water maximum volumes for the barays are

West Baray 48.0×10^6 m^3
East Baray 37.3×10^6 m^3
Jayatataka Baray 8.7×10^6 m^3
and Indratataka Baray (at Roulos) 7.5×10^6 m^3.

Additional pools (e.g. Sras Srang, Neak Pean, Ta Prohm, Bat Chum, and Preah Prei) and moated compounds (Angkor Thom, Angkor Wat, Banteay Kdei, and Ta Phrom) characterize Angkor as do the many open-channel canals taken off the Siem Reap River and barays that flow through the site to supply pools and moats. Canals fed by the East and West Barays ran through the city (Rawson 1967) and also irrigated areas outside walls where commoners lived in villages. Groundwater pools and open-channel water distribution systems interlaced the commoner quarters to provide water needs. The multiplicity of water systems was obviously a part of the city design to serve the practical needs of its inhabitants as well as maintaining the ethereal and aesthetic nature of religious ceremonial structures. The Neak Pean Baray shows complete infilling due to siltation from its supply river. The West Baray still maintains some capacity to store water, although its eastern region is fully silted-in. Some water supply to the West Baray still occurs from the O'Kloc River to the north (and some contribution from the Siem Reap River before baray siltation limited this source) during the rainy season, and depths of around 2–3 m have been recorded in non-silted-in zones of the baray as late as 2004. During low rainfall years, the West Baray can remain dry westward past the West Mebon and retain small amounts of water in its far western reaches. As the dry season (November to April) progresses, much of this water is lost to evaporation and groundwater transfer, leaving only shallow pools in the western reaches.

Some rivers draining Angkor show entrenched meanders, indicating that some form of river downcutting was occurring during city occupation; tilting along a northwest–southeast axis has progressed over the last 1,000 years so that some riverbeds are now entrenched about 6 m below land surfaces and well below the levels of 10th and 11th century reservoirs, canals, and moats. As channels continued to lower with respect to land surface, there was an apparent lowering of the water table and waterwheels were in place to lift water to the surface to maintain canals and reservoirs (Englehardt 1995). As an example, the remains of the Spean Thma bridge that crossed over the Siem Reap River at the main approach to Angkor Thom are presently about 6 m below the footing of a 14 arch span bridge, giving testament to the downcutting/uplift/subsidence effects that have occurred over the last 1,000 years. This apparent lowering of the water table was problematic both for agriculture and the foundation stability of the many structures within the city and may suggest a reason for the barays. Prior to baray construction, long transverse dikes were built to trap rainy season runoff in the zone north of Angkor to the Kulen Mountains to provide water for multicropping of the rice fields. As a later construct, high walls were built around these dikes to enclose a rectangular basin structure that could hold large quantities of water. Parts of these earlier systems were incorporated into later urban planning. For example, the old moat from an earlier version of the city (Yashodarapura) was used as a spillway to channel excess water from the Western Baray into the Siem Reap River south of Angkor Thom to both limit the height of water in the baray and prevent excess water from causing flood damage.

To understand the function of the barays, a three-dimensional FLOW-3D model showing the major water features of the Angkor site was constructed. The model surface extended from the Tonle Sap Lake north to the Kulen region and included the area from the West to the East Baray. All water features (moats, pools, barays, and rivers) were included at their approximate depths and locations as well as the perimeter dikes encompassing the barays. Porosity and hydraulic conductivity values were estimated from soil samples taken south of the West Baray. Use of model soil capillarity allows for effects that create a phreatic zone above the water table where the fraction of fluid:

$$(0(\text{dry soil}) < f < 1\ (\text{saturated soil}))$$

denotes moisture content. The model is composed of a porous medium representative of the soil properties and includes angular tilting of the landscape observed from contour maps of the area (ANSIRO 1993). The porous soil is assumed to be unsaturated to a depth of 20 m with a saturated layer extending below this depth. Computations made from this idealized model enable the groundwater footprint penetration to be qualitatively determined as a function of time and depth below the ground surface. For the first calculation set, the West Baray is assumed to be full at a 4 m depth at the end of the wet season and at the start of the dry season; the resulting calculations show the time-transfer of baray water to groundwater. Note that for each 1 m drop in West Baray water height, 12.0×10^6 m^3 of water is released into the aquifer. The purpose of the calculations is to show the extent and shape of the subsurface groundwater profile around the initially full West Baray as it discharges its water into groundwater during the dry season.

Analysis results

Figure 3.1.2 shows the groundwater penetration ($z = 0.0$ is the ground surface) from the initially full West Baray along a mid-baray plane cut (constant x) through porous soils after 5 months 'leakage'. Figure 3.1.3 shows groundwater penetration at different times after the start of the dry season. The subsurface footprint is mainly north–south of the baray due to ground slope with some side groundwater flow evident. Darker shading denotes fully saturated soils ($f = 1.0$) with lighter shades denoting partial saturation ($f < 1.0$). With increasing time, the subsurface penetration zone increases in length toward Lake Tonle Sap.

The groundwater top surface lies 2–3 m below the ground surface in areas a few kilometres north and south of the baray, with some localized surface

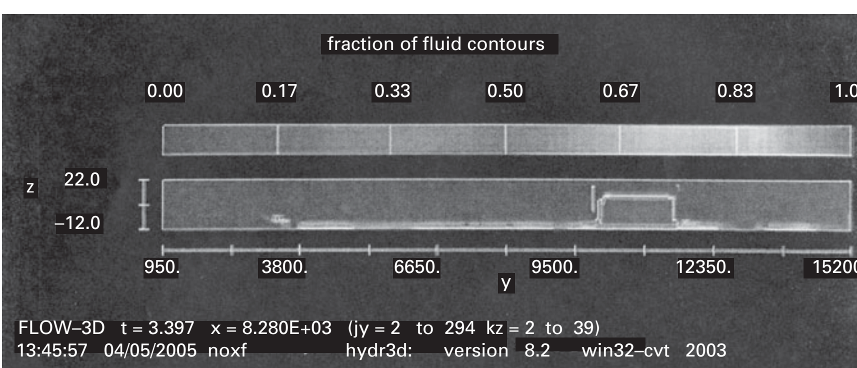

Figure 3.1.2. West Baray groundwater seepage patterns into porous soils 4.5 months after the rainy season ends. The rectangle between 9,500 and 12,350 m is the high walled West Baray at 6.0 m water depth above the Z = 0.0 m ground surface.

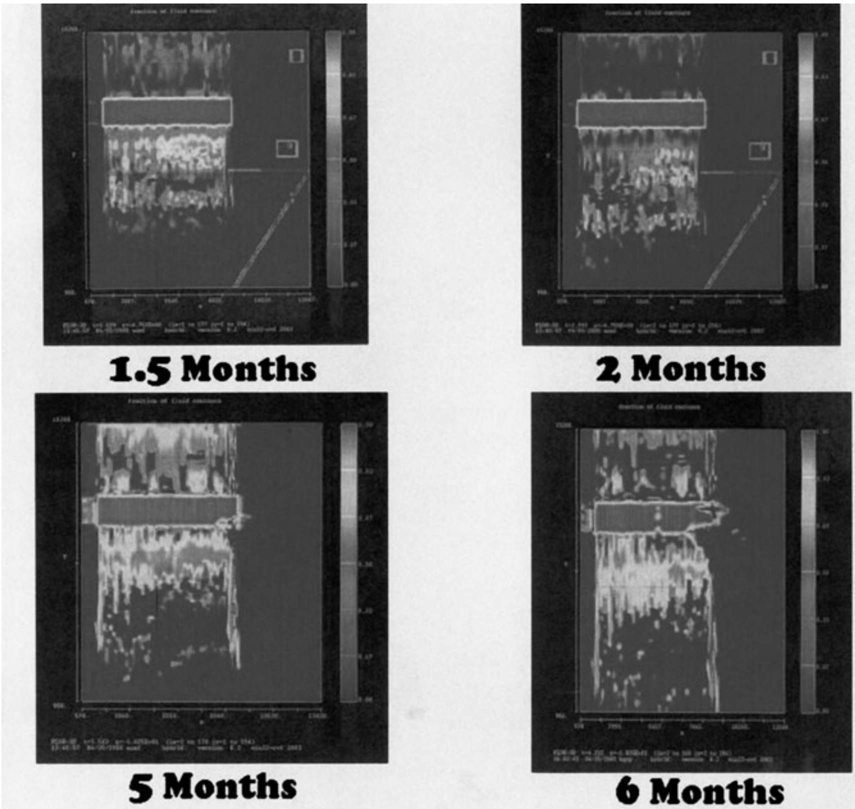

Figure 3.1.3. Top view of West Baray groundwater seepage at various shallow depths from the ground surface at scaled times of 1.5, 2.0, 5.0, and 6.0 months after the wet season ends.

penetrations due primarily to capillary action and local ground slope change. For the Figure 3.1.3 time scale, the ratio of actual groundwater velocity to computed velocity indicated a scale factor of 1.15×10^{7} for the same input head and soil properties, therefore 1 second of computational time corresponds to about 2 months of real time. A ~1.0 m drop in baray water height leads to a ~8 km southern extent of the subsurface footprint shown on a *z*-plane 2–3 m below the ground surface after 6 months' real time. Some ground surface penetration occurs at the leading edge of the footprint. Later months show an expanded footprint with the groundwater top surface ~1.0 m below the ground surface. For full discharge of the West Baray into groundwater during the dry season, land areas 25 km from the baray are affected in the north–south direction with groundwater reaching Lake Tonle Sap. Of course, the height addition to the existing groundwater level will vary with distance and time from the baray and depend upon local soil properties; additionally, the diminishing pressure head of decreasing baray water height in the dry season will influence the transfer rate into the aquifer. The net result of the baray water storage transfer function is therefore to launch a timed pulse of groundwater to amplify the existing groundwater base in the dry season to maintain agriculture, site stability, and ceremonial water usages in on-site moats and pools. Although the full three-dimensional shape of the groundwater volume varies with time and the graphic sequences are not shown, a mass flow balance between water leaving the baray and that transferred into the groundwater volume is maintained in the calculation methodology.

The West Baray was initially excavated below the ground surface with a large height southern dike. The baray was intended to sustain a high groundwater base in the dry season from May to November to which wet-season infiltrated rains would add 1–2 m of water table height. Without this sustained dry-season groundwater base, later rainfall-infiltration additions to groundwater would not be able to support flooded-field rice cultivation as rains would continually infiltrate until they encountered a low groundwater level. As excavation of bunded areas further lowered the ground surface towards the water table, the excavation depth decided the moisture level necessary for different crop types. Few major temple structures existed north and south of the West Baray, indicating that this area was devoted to agriculture and/or ponded-housing settlements. In combination with lake recession agriculture in dry periods, large areas around Angkor could be productively farmed due to the high water table induced by the baray. Satellite images (Coe 2003) of these areas confirm a complex network of many individual canals and ponds consistent with exploitation of the high groundwater levels for urban and agricultural use north and south of the barays. Equally as important, the high water table provided by the barays maintained the water levels of the many pools, moats, and canals within the city throughout the year, giving the city functional constancy independent of seasonal weather variations.

The soils surrounding the barays are relatively porous and have substantial thickness above an impervious clay base layer estimated to lie about 20–30 m below the ground surface. With wet-season water stored in barays, the water table was kept high throughout the year. For successive dry years, followed by a few rainfall-intensive years, the dry surface soil may absorb water but limit aquifer recharge due to evaporation. In this case, agriculture may be limited to surface depressed zones where rainfall provided sufficient moisture for limited crop varieties over a short time period. Observations of the modern-day water table height fluctuation in plains south of the near silted-in West Baray indicate about a 2–5 m groundwater drop at the height of the dry season.

A modern channel leading from the south berm of the West Baray provides water to field destinations to maintain localized water table height for rice agriculture. The observation that fields supplied by groundwater from the northern Kulen area and fields south of the West Baray were used in antiquity to support agriculture and ponds for housing is evident as only minor temples exist in this area (Prean Kas Ho, Prean Ta Noreay, and Preah Repou). The West, East, and North Barays served additional purposes related to maintenance of a year-round high groundwater level: foundation stabilization of monuments and maintenance of water levels in ponds and moats by limiting seepage. It is known that water table fluctuations change the strength properties of the foundation soils supporting monuments, leading to deformation and destabilization. For this reason, the East and North Barays would be particularly critical to support monument stability over the many centuries of Angkor's existence.

Many open channels led water into the city from transecting rivers and barays, and supplied the moats, pools, and urban housing within and around Angkor Thom and elsewhere throughout the city. Although the water table could be maintained locally high by river flow and baray water leakage effects, urban concentration areas may have required fill elevated areas to facilitate a hygienic septic system. Excavations within Angkor Thom in urban areas indicate subterranean channels from barays and pools were in place, but excavation of these archaeological remains is in a preliminary stage so the total water system remains to be defined.

Siltation from rivers constituted a problem as heavy highland rains carried and deposited silt in the lower slope portions of rivers passing around and through Angkor. Progressively, the East Baray, the Northern Baray, and a major part of the West Baray fell from use as river-borne silts deposited within the barays led to abandonment and decline of the city's water resources. Even today under dry season conditions many of the city moats and pools are dry, reflecting the loss of function of the barays. Silt transport into barays may have been amplified by deforestation to support urban housing concentrations for an expanding Angkor population. From observation of effects of present-day deforestation of areas around and north of Angkor, silt transport by rain runoff and by rivers has been greatly amplified to demonstrate possible origins of high silt transport rates.

As observed by the Chinese visitor Chou Ta Kuan (1296–7 CE) to the royal court at Angkor, the area was capable of 'three to four rice crops per year'. This may have been achieved by a combination of a floating rice crop on the rising waters of the flooding Tonle Sap, an upland dry rice crop near Phnom Khulen, a wet-season rice crop at the edge of the floodplain to the upland rice-growing area boundary, a rice crop on the dry-season receding margins of Tonle Sap, and agriculture associated with regions south of the barays utilizing their heightened groundwater level. Thus rice-growing areas were well-distributed geographically to take advantage of localized water availability from rainfall and groundwater sources. Since successive rulers of Angkor established privileged administrative court families that, through land grants and favours, maintained centres around and distant from Angkor for the purpose of expanding the empire and its dedicatory temple complexes (Higham 1991, 2003), rice and valuable commodities were part of the taxation system to provide resources directly back to the capital for return favours. Thus satellite cities and temple complexes under grants from the king provided additional food supplies to augment the capital's prosperity. Many towns and villages under the political control of kings were charged with providing resources to specific temples within Angkor to guarantee their prosperity and function. In this light, dependency on local rice supplies was reduced as different parts of the empire, governed by different ecologies and water regimes, balanced and augmented the decreased supply from any local source.

Since limited agricultural areas could be served by the baray's water functioning as canal water supplies, crops derived from canal irrigation were insufficient to maintain a large population according to Goodman (2000). Other functions for the barays beyond surface irrigation are therefore strongly suggested. Noting the dry-season release of baray water to maintain groundwater height subsequently amplified as the rains started, an overall picture of the baray's function in agriculture, water supply to housing, and monument stabilization begins to emerge. From Coe (2003), the presence of many reservoir-pools, as observed from AIRSAR remote sensing photographs and ground survey north and south of the West Baray, indicated an intense concentration of field systems and house plots such as would be associated with localized rice farming and the support population to maintain the fields (Coe 2003, particularly his Figure 94). This finding is consistent with the north–south groundwater footprints (Figure 3.1.3) that support high groundwater levels in these areas.

The presence of the Great North Channel (Coe 2003) indicates that supplemental water from the Kulen Hills was available to support agriculture and urban water supplies in regions north of Angkor Thom by open-channel distribution networks and amplification of groundwater levels. The presence of the main southeast-running canal to Indratataka from the southwest corner of the West Baray indicated that this canal may have served to distribute water to distant field systems by surface transfer. Thus the barays supported some of the agricultural base near the urban core of the city, limited seepage from moats and pools within the city, helped stabilize the groundwater base under city monuments, and provided water to pools and moats to maintain their levels on a year-round basis.

The urban core water supply network

The main water source to the open channels that threaded through Angkor were the Siem Reap River and the northern O'Klok River, both of which originated from highland rainforests in the Kulen region. Multiple channels, some sourced by the barays, formed the intricate water artery network supplying the multiple moats, pools, farming zones, and urban water supplies of the city (Rawson 1967). The Siem Reap River was the primary water source to the West Baray until siltation limited this supply resulting in use of the O'Klok River as the new supply. The Siem Reap River was then diverted into an artificial north–south channel to serve other channels to the east and returned to its original bed south of the site. A number of height additions

Figure 3.1.4. The Banteay Srei water temple. The central temple (mebon) within a water filled basin is surrounded by four adjacent basins with individual ritual functions.

to the West Baray perimeter dike were made in response to silt deposits raising the bottom level. This required a northern entry point of the O'Klok River and/or a higher northern canal takeoff point from the Siem Reap River. Use of these river sources indicated that the West Baray still retained its function with the inlet shift, albeit in diminished capacity. The river diversion enabled some minor reactivation of the southwest corner of the Eastern Baray and provided water through canals to the temple and reservoir areas south and west of the East Baray from a diversion canal from the Siem Reap River. As the Eastern Baray became dysfunctional, the Neak Pean Baray (or Northern Baray) with the Neak Pean temple as its centre was constructed (Figure 3.1.4) and supplied from a combination of rainfall and river flow north of the baray. With monument construction and the need to supply water to the temples and urban concentrations at Angkor Thom, the outlet channel from the East Baray was cut and abandoned, signalling the end of water transfer capability from the East Baray which, at that time, was largely silted-in and near abandonment. The Neak Pean Baray is associated with the adjacent Preah Khan temple, which served as a temporary residence of royalty during the construction of the permanent government seat at Angkor Thom. While this system served the Preah Khan complex, the perimeter dike at the Western

Figure 3.1.5. Piping detail between the central basin and an adjacent basin. The laterite piping is carefully inserted into the surrounding block structure with sealant to eliminate leakage.

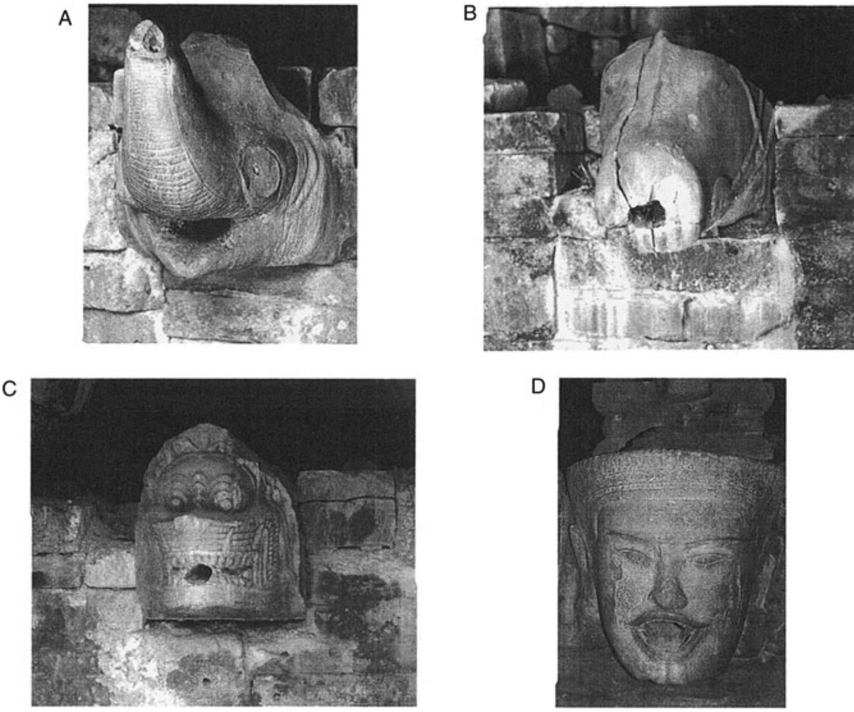

Figure 3.1.6. Elephant (A), water buffalo (B), demon (C), and human head (D) fountains in the four adjacent basins supplied by pipelines from the central basin. Water exits through mouth openings.

Baray was further raised, indicating that the function of the West Baray was distinct from that of supplying temple complexes and served primarily to supply agriculture and population housing water.

The temple complexes of Ta Prohm and Banteay Kdei included the Sra Srang reservoir as an integral part of the religious landscape. Water from the Siem Reap River was again the major supply through the north–south diversion canal. With the continual silting-in of the Western Baray and the use of the O'Kloc River as the main water supply, elevation in the perimeter dikes, evidenced in the Neak Pean Baray, pointed to the river's continual use as siltation raised its bottom level. The Neak Pean Temple was centrally located in the Northern Baray and centred in a walled-pool structure surrounded by four symmetrically placed basins. Separate laterite pipelines (14 cm outer diameter; 11 cm inner diameter, Figure 3.1.5) connected the central pool to each individual side pool and led water into small temples at

Figure 3.1.7. Khmer bridge of 15 m height built with corbelled arch construction and still in use in modern times.

the inner wall of each pool. Each temple contained an individual monument (stylized elephant, water buffalo, demon, and human head (Figure 3.1.6A–D)) with a mouth spigot supplied by piped water from the central pool. The Neak Pean Temple pool complex is a replica of Lake Anavatapta, a sacred Himalayan lake with curative powers to absolve human sins. Each of the four temple stations, according to popular accounts, provided water to cure certain diseases and thus had a ritual function.

The presence of Neak Pean pipelines (and some evidence of pipeline use at Banteay Srei) indicates that the technology of piping manufacture was known and may have been incorporated into other structures within Angkor, as further excavations may reveal.

The Northern Baray was the last baray construction. Past this point, gated bridges composed of narrow corbelled arches were used as dams (when openings were blocked) that backed up Siem Reap River water to feed distributive canals. For example, a bridge/dam between the south dike of the Neak Pean Baray and the north dike of the Eastern Baray was used to impound the Siem Reap River. The Neak Pean Baray thus incorporated a dam when a corbelled-arch bridge was placed in its south dike wall. While such structures were used to trap water, water seepage through dike fill structures reduced soil coherence under hydrostatic pressure and posed a failure mechanism. A flood event due to dam collapse was recorded in the area east of Angkor Thom; the area was apparently flooded in antiquity as a new channel was carved by floodwaters through a dike that bypassed the bridge. While some low bridges were used in this manner, the 87-m long, 20-m high bridge at Spean Prap Tos near Kompong Svay south of Angkor (Figure 3.1.7) functioned solely to provide passage over a river.

Summary

Angkor's water system partially derives from Siem Reap River's waters channelled into the urban core of the city and barays that provided the groundwater base for agriculture, housing basins, site foundation stability, and watercraft transport. The water system included gate controls regulating storage, release, and transfer functions for the city water supply from river, groundwater, and rainfall contributions. Outlets from the West Baray to the Angkor Thom moat served to maintain the moat at a constant water level throughout the year by surface and subsurface water transport in keeping with its sacred function and appearance. Here water input was regulated through supply/drainage canal controls to balance evaporation losses and keep moat levels constant throughout the year. Water transfer from the Angkor Thom moat to the southeastern part of the site (north of Roulos) through canals provided site drainage by returning water back to the Siem Reap River. Since the groundwater release from barays was slow compared to open-channel release, groundwater was maintained high as the rainy season transitioned into the dry season. Thus as an integral part of the water management structure at Angkor, the timed water release into groundwater, played a key role in maintaining the agricultural and water base of the city. Ideas advanced by French researchers Groslier and Dumarcay characterizing Angkor as a 'hydraulic city' with an intricate surface canal and irrigation networks sourced by barays now may be viewed in a widened perspective as the barays served additional functions to support the hydraulic infrastructure of the city's moats and pools, provided ground stability for monuments, and contributed to the agricultural and housing water infrastructure on a year-round basis. Regardless of the accuracy of Groslier and Dumarcay's picture of the surface hydraulic infrastructure of the city, the new dimension of groundwater manipulation as a vital part of maintaining the city's vitality must now be added.

Finally, no picture of water systems in Khmer lands would be complete without some emphasis on the ceremonial uses of water beyond practical applications. Figure 3.1.8 shows linga structures covering a long expanse of a

Figure 3.1.8. Under water river bed in the highland Kulen area. Individual carved figures represent linga fertility blessings to water used for agricultural purposes in downstream locations.

riverbed at a site in the Kulen Hills. Clearly deep within religious practice of the Khmer is reverence of water as a special benefit bestowed on humans by the gods, as riverbed fertility symbols indicate. Water from this river source, thus blessed with passage over fertility symbols, increased the potential for a bountiful growing season. Thus a combination of practical and religious expression came together in Khmer society to form a harmonious balance that water, in its various aspects, provided.

3.2 THE IRRIGATION AND TERRACE RICE CULTIVATION SYSTEMS OF BALI, INDONESIA, 1500–2005 CE

Chapters 1 and 2, which detailed the water systems of the Old and New Worlds, stressed the underlying engineering basis for system development. There is an assumption that, although religious practices on state and local levels were present in ancient societies, beneath the reliance on divine providence to influence nature to produce positive outcomes in personal and state matters there coexisted a rational engineering basis to handle practical matters. This posits groups or specialized individuals close to governmental and managerial elites that advised on civil engineering projects and provided successful results through their expertise. Provided benefits accrued to the society, confidence in governmental and religious structures was reinforced and acceptance of governance reassured. If civil engineering success was embellished with religious trappings, then this proved that the religious establishment was included in the success story to enhance their prestige as communicators with and receivers of divine benefits and blessings. But, as every engineer (ancient and modern) knows, some divine or otherwise providential intervention (sometimes called luck) can make the difference between success and failure, particularly if some scientific or engineering phenomena are overlooked in analysis, test, design, and construction phases of a project. Often failures are termed 'learning exercises' as they can deepen engineering knowledge to benefit future generations. This picture is certainly a western perspective of the rational scientific basis for progress that de-emphasizes religious providence while increasing the emphasis on science and engineering to produce project success. In earlier centuries where technology was less certain and gods were thought to be in charge of human endeavours, reliance on both tracts was an understandable strategy. Observing Chimú technical achievements in irrigation system design and operation over several centuries and their coexisting exotic religious and ceremonial practices, it would be reasonable to assume that some coupling of these two viewpoints on how to achieve success existed in that society although direct proof from the archaeological record can only be surmised. Given this perspective, it may be possible that a religious system based on codified engineering practices can occur as religious rituals and practices may symbolically contain practical engineering rules. Alternatively, a strong belief system can appear to be behind any ideas that work so that progress can be characterized as proceeding from divine origins. This perspective has new relevance in the 21st century in the form of 'intelligent design', which offers an alternative explanation of how complexity can arise from chaos in a manner other than evolutionary processes.

While it is reassuring to think of western societies developing from rational bases with a strong tendency toward science and engineering as mechanisms of progress, it is reassuring to find a 21st century society functioning outside of this model with strong dependence on ancient religious-based rituals that produce a harmonious society and provide all that is necessary for a well-balanced lifestyle. This society emphasizes cyclic rituals that provide practical life needs in harmony with religious rituals; such a society may be described as being in a 'cultural vortex' where all spiritual and practical needs are met so that further progress is not required. This society is found in rural Bali, where western influence has been encountered but not absorbed as traditional societal practices and rituals are deemed closer to the true nature of divine intent and thus require no change. Investigations of Bali irrigation systems

(Lansing 1991, 1995) have uncovered aspects of the complex irrigation system that interweaves religious and practical considerations and provide the basis of the discussions that follow.

The irrigation system

The main source of irrigation water for rural Balinese field systems is the high-elevation Mount Batur volcanic caldera, which contains a deep 2,000 ha surface area fresh water lake that serves as the source for springs and streams supplying water to lower elevation farm plots. Sufficient water is available from this and other volcanic crater lakes for irrigation during the May through September dry season. Seasonal monsoons supply rainfall to recharge the lakes on a periodic basis to provide water into the dry season. Associated with this lake are Hindu–Buddhist deities syncretized together with ancient Malayo–Polynesian deities who are worshipped as providers of life-sustaining water for rice terraces to sustain village life. Numerous water temples (Figure 3.2.1) are strategically placed throughout the irrigation system to monitor water flows into the different sections of the system controlled by different tempeks (farmers' associations with land on a common canal) and propitiate the gods that provide water for the rice terraces (Figure 3.2.2). All the tempeks using water from a common dam form a subak of about 200

Figure 3.2.1. Water temple typical of the Balinese countryside. Rituals performed at temples by priests and subak members ensure the favour of the gods overseeing agriculture.

Figure 3.2.1. (Continued)

members, which usually controls about 80 ha of farm land. Typical organizations drawing water from Oos and Penanu Rivers originating from high-elevation lakes support about 200 subaks of about 100 members, each controlling about 50 ha. A main temple (Temple of the Crater Lake) placed at the headwaters of the Mount Batur Lake maintains 24 priests that serve not only religious and sacrificial functions as representatives of the Goddess of the Lake but also staff a council centre to both mediate problems between subaks competing for water resources and provide an overall water management strategy for the entire irrigation system. While religious rituals at the main temple ensure that the water gift of the Goddess of the Lake (Dewi Danu) continues, local temples along the water distribution network associated with different subaks provide meeting places to share problems and discussions, and are centres of worship of the deities that provide their munificence

Figure 3.2.2. Terraced field system for rice production typical of the Balinese countryside.

(Wermasubun 2000; Lansing 1991, 1995). Behind the ritual lies much in the way of hydrological practicality and knowledge to determine flow measurements, dry and rainy season water control, equal water allocation to villages, placement of weirs to direct water into canals that supply rice terraces, wet and dry season water allocation, crop fallow periods, rice plot dry periods to control crop pests, nutrient delivery cycles, wet–dry phase control of microorganism and pest populations, nitrogen-fixing algae populations to promote soil fertility, the phosphorus and potassium levels necessary for rice growth as a function of dissolved minerals delivered by sudden field flooding, flood and/or dry phases for field systems, planting dates, harvesting dates, rotation schedules for subaks growing different crops with different water requirements, and the number of crop cycles and excess water rerouting back into the supply stream, all of which are vital to the survival of the community.

All tasks are interwoven into the function and capacity of major components of terrace ecosystems, including lakes, springs, rivers, weirs, major canals, irrigated terraces, tunnels, and fields. To illustrate the technical basis under which these activities are organized, initially fields are flooded for most of the 105-day growing cycle. Gradually fields are dried out for harvest and left dry so that grasses can grow and decompose, and then plowed in to supplement the nutrient base. Next flooding and drying introduce a cycle of anaerobic/aerobic cycles with various microorganisms, blue-green algae, nitrogen, and mineral constituents introduced during the cycling. The cycling excludes competing plants from dominating while grasses have deep roots that introduce leached minerals from the soils when allowed to decompose. These cycles, which are related to water distribution and allocation, govern the schedule of planting and harvesting between subaks and are prevalent during the 4-month growing season. The scheduling activities are coordinated and synchronized among subaks by a network of water temple festivals coordinated by calendar to achieve optimum production level. Subaks meet at mountain and lake temples to perform rituals and make decisions about lower-level planting, water scheduling rotations, and harvesting activities. The sum of these considerations indicates that beyond rituals lies a profound technical base managed to sustain the rice terrace and field systems, and that this role is largely performed by decisions made within the water temple associations. Thus an integrated hierarchical decision apparatus governing the function of the entire irrigation network has emerged with centuries of successful experience in managing the agricultural system.

Coordination between the subaks governing different field plots along a watercourse is very important. For example, if a percentage of fields associated with different subaks is flooded or burned in an effort to reduce pests, then water allocation for crop production in the remaining fields must be synchronized to maintain a stable production rate. It is clear that the strategies put in place by the subaks acting through temple assemblies can be looked at as a form of 'game theory' in the sense of optimization of agricultural production. If, for example, all subaks plant at the same time, then insufficient water resources are available for all, particularly for downstream fields; if a fallow period is instituted for all farmers, then pest control is ineffective. If pest losses are low, upstream subaks may want to plant simultaneously to minimize crop damage while downstream subaks may want to stagger plantings so that they will receive available water. Further considerations arise if rivalries, competition, and non-cooperation characterize relations between subaks located at different stations along a watercourse. These may take the form of subak subgroups operating outside of overarching main temple control. The more interconnectedness and communication between water networks in the total system (usually comprising hundreds of subaks and watercourses), the more mutually satisfactory option combinations can be exploited for the benefit of the totality of all subak communities. Obviously, a global optimum lies within a cooperative, well-coordinated combination of localized strategies. As concluded by Lansing's (1991, 1995) analysis, the water temples play a vital role in finding the balance between water sharing, crop timing, and pest control—this balance proceeds from the multi-century database utilized by the priest-technical/social advisors in the water temple complex to maximize agricultural yields for the entire subak community.

Ultimately, learning processes institutionalized into temple rituals can be compared to a neural network. A neural network process, mimicking human decision processes based on learning experiences with results towards or away from a desired goal, self-corrects itself to ultimately provide a decision path to achieve a desired goal—here good and bad experiences have equal weight to provide this path. Given that a fixed number of independent agricultural-productivity parameters need to be arranged by a decision sequence to produce a global productivity optimum, there are many possible combinations. If certain decisions can only occur in certain combinations and some must follow after others, and certain decisions have variances (i.e. can only be expressed with a certain degree of certainty), then the multiplicity of possible decisions is high. Only through trial-and-error cases observed over many centuries can a smaller subset of positive choices be made; this is the knowledge base that the water temple advisors encode into their oversight functions. Similar to the model results of section 1.5, which were based on maximization of food resources, a 'bottom-up' system ultimately evolves into a 'top-down' system where overriding managerial control provides the logic for maximum production. For this, a system for which each subak tries to maximize its own production independent of, and with no consideration for, the other subaks ultimately leads to non-optimum production of the entire system. The 'top-down' system represented by the water temples is a representation of a final-evolved stage-making decision based on viewing the agricultural complex as a system rather than individual subsystems that benefit individual groups. Only by individual groups ceding privileges can a central management system evolve that demonstrates that through its controls more agricultural output is available for all. This result was demonstrated for Tiwanaku-raised field systems (sections 1.2 and 1.5), where increased population requiring increased yields over fixed agricultural land areas led to conceptualization of agricultural lands as a system for which a top-down master plan of operation transcended an individual's vision of how best to manage small unit operations.

4

Hydraulic Engineering and Water Management Strategies of Ancient Societies

Societies of widely different social, economic, political, religious, and technical innovation characteristics in opposing world hemispheres developed urban and rural population centres with water and agricultural systems to maintain stable economies and expanding populations. Despite vast historical, cultural, and world view differences between these societies, one common thread united them: the necessity for mastery of engineering skills to provide water for cities and agricultural systems. Although it may be thought that the technical basis to support water engineering practice is accompanied with pre-scientific concepts, many recent discoveries reveal the contrary: sophistication in the concept, design, and execution of water supply and distribution systems indicating knowledge of hydraulic principles beyond the scant hydraulics literature that survived the centuries. In the absence of ancient treatises on hydraulics practices, archaeological analysis of hydraulics works coupled with modern analysis methods provides a way to understand their technological accomplishments through 'reverse engineering' methodologies involving computer modelling techniques. Thus computer methodologies play a role to uncover the design intent, functionality, and operation of ancient water systems to provide insight into ancient engineering practices and their theoretical/empirical basis.

4.1 OLD WORLD, NEW WORLD, AND SOUTH-EAST ASIAN COMPARISONS

In South American archaeology, the large variation in ecological conditions and landscape barriers provided the stage for the rise of civilizations and largely determined their agricultural practices. As an example, the Chimú civilization (800–1480 CE) occupied Peruvian coastal regions extending 500 km from the southern Chillon Valley to the northern Lambeyeque Valley. The desert coastal zone extends only a few kilometres inland from the Pacific Ocean before being bounded by the Cordillera Negra mountain chain. Agriculture was possible in coastal alluvial valleys through networks of canal systems originating from intermittent seasonal rivers. The temperature near the equator is near constant throughout the year while coastal rainfall averages about 2 mm/year; occasional massive El Niño events which can deposit up to 150 cm of rainfall in a few days occasionally break this pattern and cause extensive flooding and field erosion. Clearly, hydraulic practices related to the control of limited (and sometime excessive) water resources were vital for survival. Defensive measures to protect fill aqueduct structures against excessive El Niño rainfall and flooding events are expected to appear in the technology base as flood control was vital to sustainability.

Applied hydraulics technology was used in the design and construction of the mega-canals that shunted water between valleys and whose operation depended on the knowledge of the hydrograph for each river as well as the agricultural land and water resources in each valley. One example of this is the Intervalley Canal, which required a design to transport water at a precise flow rate into a pre-existing Moche Valley intravalley canal network. Knowledge of open-channel hydraulic relationships between bed slope, wall roughness, and canal cross-section were required to make the required flow rate the maximum that the canal could sustain. This was accomplished by use of near-critical flow designs that produced a maximum flow rate given the inlet–outlet altitude height difference and indicated an evolution of hydraulic technology to high levels. Where bedrock limited the construction of a given canal slope, variations in canal cross-section and wall roughness were made to keep the canal Froude number in a near-critical range to induce flow stability. The Intervalley Canal placement observed from the archaeological record led to a minimum length, minimum labour-input configuration as subcritical, lower-slope designs would be longer and need a much larger cross-section to support a high flow rate while a supercritical design (a high-slope canal design originating in the highlands of the Chicama River Valley) would be impracticable due to its steep path and the many aqueducts and fill terraces required through rugged Cordillera Negra terrain which would need high-labour-input in remote locations and a long construction time. The final design selected, among the many placement and design options, ensured that the mean canal slope and canal cross section produced the maximum flow rate possible (near $Fr = 1$) and that this flow rate matched that of an intravalley canal it was designed to reactivate.

The Intervalley Canal design used contracting canal cross-sections placed ahead of major aqueducts. The aqueducts were usually unconsolidated long-fill structures crossing deep and wide quebradas. Here canal width contraction ahead of an aqueduct served to convert super- to subcritical flow by an induced hydraulic jump. The kinetic energy of the incoming fast, low-height supercritical stream was converted to a low-velocity, high-height subcritical stream crossing an aqueduct, thus limiting velocity-dependent aqueduct inner wall surface erosion. Suitable levelling of an aqueduct maintained subcritical flow over its length consistent with the low-erosion design intent. For the Jequetepeque Farfán canal system subjected to occasional El Niño-induced large (over-design) flow rates, a narrow gap between boulder pairs imbedded in a canal served to create a hydraulic jump upstream of the gap, enabling a side wall overflow weir to drain away a portion of the flow above the height of the weir. The reduced flow rate resulted in lowered erosional damage to a downstream aqueduct as a result. Thus the use of chokes and channel constrictions to control supercritical flows appear in the Chimú hydraulic repertoire to serve protective hydraulic functions. Surveying skills to measure slopes between 0.01 and 0.25° were present in Moche Valley canals, indicating a mastery of low-angle surveying techniques. At Peruvian 5000 BCE Zaña settlements, 3000 BCE Caral and later 800–1532 CE Chimú and Inka sites, canal slopes of around 0.01° were found, while at Tiwanaku, canal slopes of 0.001° were noted. Thus surveying and canal technological development over millennia enabled inter- and intravalley canals to extend their reach to outer valley margins to increase the cultivable area and permit intervalley water transport canal development. It may be said that canal and surveying development, as evidenced by 6,500 years of successful and continuous operation, gained a premier place for South America in the history of agricultural and hydraulic science technologies.

An alternative technology base was in place in the altiplano area in western Bolivia—the heartland of the Tiwanaku civilization in the time period 300–1100 CE. The Tiwanaku controlled central Bolivia in the vicinity of Lake Titicaca and established a highland empire that extended from southern and eastern Bolivia to mid-Peru, and maintained colonies occupying different environment zones along southern Pacific coastal regions. At 4,500 m altitude in the Andes nights are frequently below freezing and the rainy season lasts several months. Soils are poor and farming conditions harsh yet this area was the seat of a major civilization with a major city of 50,000 inhabitants and a total combined rural/city population of a million people (Kolata 1997). Clearly, a novel agricultural technology and water distribution system existed to maintain this population size (while only a few thousand people maintain a marginal existence in the same area today). Their key to survival was the invention of raised field agriculture on the lacustrine environment around Lake Titicaca and the development of ~100 km^2 of raised fields adjacent to Tiwanaku's urban centre. The raised fields were formed by excavating trenches about 3 m wide into the ground and mounding up excavated soil into randomly oriented islands about 100 m long and about 2 to 4 m wide. Because the water table is high around the lake, the excavated troughs contained groundwater pools augmented by spring water emanating from nearby hills.

The special aspects of raised field agriculture permitted crops to survive the cold altiplano nights in subfreezing conditions destructive to root and surface crops. The raised field systems served as heat sinks: the sun's radiation was absorbed by dark organic matter on the bottom of the water troughs raising its temperature—even on a cold day, water temperature is about 10°C. The combined heat from the trough water plus radiative heat absorption from the sun into moist soils provided stored heat within the mound structures during the day. As night temperatures fell, heat was lost due to ground surface reradiation and convective cooling. However, the rate of heat loss within the mounds was sufficiently low to maintain above-freezing temperature and was well below the latent heat of freezing to prevent root crops from damage. Tests in reconstructed fields (Kolata 1986; Kolata and Ortloff 1989a; Kolata *et al.* 1996) verified frost prevention capability to preserve agricultural yields in the harsh altiplano climate. To regulate groundwater height, elaborate systems of branch canals were activated when the water height in the main drainage canals exceeded a given height and served to shunt excess water rapidly into Lake Titicaca, thus controlling drainage to keep constant water levels in troughs. While this canal system network was primarily used to intercept and drain excessive rainwater streams entering the Pampa Koani to limit groundwater over-charging, the system also worked to redistribute water in the dry season to maintain groundwater height. The success of the raised field system design is attested by the fact that it functioned over many hundreds of years under normal weather and climate variations. Drought response was mitigated by the low subsidence rate of groundwater as water supplies originated from an immense watershed collection zone supplied by the rainfall interceptions of past decades. As groundwater profiles shifted and decreased due to extended drought, portions of the field system retained sufficient groundwater height to sustain agriculture, particularly in areas close to the lake, far from the lake, and around channels and spring-supplied portions of the raised fields. Thus, the flexibility to counter the drought shrinkage of field systems by transferring agriculture (and population) to different locations was another advantage of raised field agriculture.

Around elite quarters within the Tiwanaku ceremonial centre, large trenches were dug to intercept and drain groundwater into the lake by canals—this maintained dry soil foundations within city boundaries to limit structural subsidence and sacred precinct exclusivity through a surrounding moat. A subsurface system of large pipelines consisting of slab walls underlay most of Tiwanaku. These large pipelines (at least two parallel systems are currently known), which drain into the nearby Tiwanaku River, were fed by a network grid of smaller cross-section, slab constructed pipelines lying above and perpendicular to the underlying pipelines and were connected to this lower system by stacks of perforated stone disks. Water from temple and palace structures was led through basins to these lower piping networks to complete the drainage network. Such well-conceived systems show that water control for urban settings was paramount in city planning. As an example of the planning required, the moat depth around the sacred precinct needed to be set sufficiently low so that the water table height within the precinct was below the underground piping network for drainage to work properly.

For the Chimú, mastery of canal technology led to near-total usage of all available farming areas reachable by limited irrigation water. For the Tiwanaku, water control was primarily required to sustain agriculture and maintain control over the field system water table height by drainage canals as high rainfall and overly high water table conditions were detrimental to agriculture. Control of raised field water table height was necessary to maintain heat storage effects to prevent root crop freezing. As a further example of Andean hydraulic technology innovation, Supe Valley agriculturalists at Caral utilized multiple canalized springs that maintained year-round, near-constant water levels for valley bottom agriculture that permitted multiple crop cycles each year. This agricultural base, in combination with marine resources provided by coastal sites at the valley mouth, provided an integrated, self-contained economic base for societies distributed at the many interrelated Preceramic sites (19) within the Supe Valley that flourished for many centuries. The example cases given here, as in previous chapters, indicate an adaptive knowledge base was available to coastal and highland Andean societies that provided agricultural solutions for dry coastal environments dependent on highland, rainfall-runoff, river-fed irrigation canals, subsurface mahamae/wachaque pit farming, coastal valley/sierra high water table farming, highland environment farming using control of surface and groundwater for raised field systems, and highland terrace farming. Other examples from Wari, Tiwanaku, and Inka societies demonstrated terrace agriculture operational flexibility as agricultural zones could be moved in altitude to accommodate changing rainfall levels and utilize snowmelt water supplies as climate change occurred. Here changes in air temperature that accompanied climate change played a role in setting the snowmelt altitude, which in turn influenced available water supplies to lower elevation field systems. The picture derived from several Andean societies is thus one of adaptability in meeting the challenges of different ecological conditions to sustain an agricultural system of minimum vulnerability to climate/weather variations. Each system incorporated relevant technical innovations and defences in response to the challenges present in the different environments. While these systems were successful for many centuries, and their success relied on modifications and innovations in the course of their development, extreme and sustained climate variations would prove their undoing as no system could survive extended drought.

Much research has been devoted to the description and analysis of Greek and Roman hydraulic structures. One missing factor is the effect of weather/climate extremes on the design of hydraulic structures, i.e. apparent defensive measures to protect structures from water flow rates exceeding design limits. Old World structures are usually designed for 'average' conditions as Mediterranean climate extremes and ecological zone variations are less extreme than those found in New World areas. Greek and Roman engineers had the option to select urban sites that had access to aqueducts from spring systems as one basis for site selection; once water supply systems were in place, the designs could be relied on to function to their design intent for many years, barring intervention of natural (or human-inspired) disasters. Sites were selected for their access to water supplies and drainage characteristics meeting the requirements of a functional urban water system. Many sites (e.g. Ephesos, Corinth, Siracusa, and Priene) contained natural springs to add to the aqueducted water supply. For the case of sites located in dry desert areas with concentrated rainfall duration, although reliance was mainly on spring-supplied water supply, additional water resources were required in the form of reservoir water storage and dams from seasonal rains. The site of Petra exemplifies water resource conservation on a city-wide scale not found in New World sites. The difference in strategies lies in the fact that many Middle Eastern inland desert sites were subject to short-duration, heavy rainfall-runoff episodes with little water infiltrated into groundwater for well extraction and thus dams and cisterns were key water storage elements.

In contrast, rains for New World, high-altitude sites (Tiwanaku on the Bolivian altiplano and highland Wari sites) were more intense with long duration. As a result, runoff was intense and the main problem was drainage (rather than storage) to maintain proper soil moisture for crop growth. Consequently, drainage canals characterized the high-altitude agricultural landscape characterized by heavy rainfall amounts and dry season water storage does not occur in highland environments except as groundwater. Here terrace systems characteristic of highland agriculture were ideal as the high slopes upon which they were constructed provided gravity drainage to regulate the moisture levels necessary for different crops. For coastal environments, water supply was by mountain watershed, runoff-supplied rivers to fertile fluvial valleys bordering the Pacific Ocean. Here coastal water supply was from the highland rainy season and snow melt supplies to coastal rivers; the Peruvian coast normally receives only 2–3 mm rainfall per year and agriculture cannot be sustained on this basis. Coastal water storage was in the form of seepage from rivers and canals to groundwater and was exploited for agricultural purposes by wachaques/mahamaes to provide moist planting surfaces as well as for walk-in wells within city limits (in Chan Chan, for example) for urban use. As the water table rose or declined depending on yearly and cumulative highland rainfall amounts, sets of wachaques/mahamaes positioned at different locations in from the coastline were sequentially used to follow the change in water table profile following changes in the runoff supply. River hydrographs indicate a significant time lag between a river's maximum flow around March and the maximum height of the water table between June and September. Thus, one water source could be used to supplement another to provide for two agricultural cycles that could mitigate variations in individual crop output. Typically, most mahamaes are found close to the shoreline where the water table begins to form a lens over the salt water ocean penetration zone. Thus Old and New World water storage technologies are fundamentally different as a result of different ecological and climate/weather conditions.

New World sites are subject to a great range of seasonal water availability, extreme high rainfall and drought events (El Niño and La Niña events), and extreme and seasonally influenced weather patterns at different site locations. In the Andean world most sites are characterized by being in regions too dry, too wet, too cold, too hot, and too remote from water sources with few if any 'perfect' conditions immune from climate and weather extremes. This reality manifests itself through the flexibility to shift from terrestrial to marine resources, use of pastoral activities to supplement the food base, creation of colonies in different ecological zones to widen the food resource base and supply constancy, development of import/export of resources between groups occupying different ecological zones, flexibility to redesign and relocate canals according to water resources, construction of intervalley canal networks to transfer river water between valleys, design and construction of defensive hydraulic measures to protect fields, canals, and aqueducts from flooding, construction of groundwater-based agricultural systems that are drought resistant, construction of terrace systems that permit transfer of agriculture to higher rainfall zones under drought conditions, utilization of snowmelt zones during climate warming periods to provide water to field systems, and design of canal systems to achieve maximum flow rates to transform virtually all arable land into agricultural production. In essence, a library of different agricultural solutions for different ecological zones and climate/weather conditions existed, all of which optimized societal sustainability given the available water resources. The variability and vulnerability of New World systems led to civilization growth and collapse cycles under natural forces that differed considerably from Old World civilization collapse cycles, which were largely driven by political control, imperial control, and dominance objectives.

In summary, the effects of extreme nature were more evident in the success or failure of New World civilizations compared to the political (and sometimes climate change) effects that dominated Old World historical processes. This is not to say that political and military effects on civilizations were not evident in New World ancient civilizations and military conquest was absent from the record (particularly the later Inka conquest of areas in present-day Peru and Bolivia and earlier Chimú conquest of northern coastal valleys as well as Wari expansion into highland and coastal areas far from their capital city), but, in reality, the scale of this activity is generally confined to later stages of Andean civilizations as earlier stages show mostly isolated societies located in different ecological zones more concerned with maintaining their own economic survival than achieving the conquest of others. As such, water supply and continuity of a civilization is a precarious business in the Andean world as the variability of nature on agriculture and water supply is a constant problem superimposed on the political and military challenges for survival. While ecological changes were evident in terms of silting-up of bays, silt overlays of sites and groundwater incursion ruining sites (Ephesos and the nearby Artemesion, for examples) and earthquakes, tsunamis, floods, drought, and sea-level changes causing modifications, collapse, and power-balance changes between competing societies of the classic Old World, history shows no favouritism in providing challenges to Old and New World societies. In tribute to our ancient forebears, their innovation and determination to overcome all obstacles, either human or nature inspired, and invent new technologies to this end is the story of humankind and its progress into the present world.

The ancient Andean landscape was transformed into vast hydrological complexes: in coastal valleys, vast networks of intravalley and intervalley canal systems were in place in major Chimú-controlled valleys in the mid-to-late centuries CE. In the highlands, many thousands of square kilometres of raised fields and mountain terraces were constructed from early centuries BCE well up to the time of the Spanish conquest in the 16th century to take advantage of groundwater and rainfall-supplied agriculture. The main enterprise of New World civilizations was agriculture and specialized techniques to optimize production given the ecological advantages and constraints of an area. The knowledge base observed in the many hydraulic constructions was commensurate with the high degree of concentration on agricultural productivity, particularly defensive measures to ward-off the effects of destructive weather/climate extremes by construction of low vulnerability systems. Of the examples cited, the conclusion is that a high degree of hydraulic and agricultural technology existed in the New World. Because early descriptions of New World archaeology were primarily art historical in nature, agroengineering technology was little explored. Only in recent times has the library of agroengineering solutions been acknowledged and become part of the world knowledge base. The effects of paleoclimate on technical innovation and societal political economy are quite new to New World studies and can now be seen as related to the technical innovations of ancient agroengineers.

The full scope of the technological accomplishments of the Old and New World civilizations has not yet been fully explored. While New World civilizations excelled in agroengineering technology tailored to ecological niche considerations and developed specialized techniques to maintain production in the face of climate adversity, Old World civilizations excelled in the scope and boldness of their engineering works, which were based on a predictable, constant climate/weather environment as dramatic change in climate conditions and water supply was not anticipated in their hydraulic constructions. Roman cities required extensive aqueducts, distribution centres, and piping systems to supply water to urban residents; New World cities, such as Chan Chan, relied on 80 wells dug into groundwater for the urban water supply. If drought came, Roman cities would feel the effects sooner as spring water output would decline; the inhabitants of Chan Chan would merely dig deeper into the receding groundwater aquifer to maintain their water supply. Roman masonry aqueduct structures could be immobilized by earthquake destruction and water supplies threatened; Chimú canal systems, also subject to earthquake and tectonic groundlevel change effects, could easily be modified, repaired, and strategically relocated as they were constructed on sand and gravel bases. Chimú canal systems provided a defence against over-design flow rates by hydraulic control mechanisms; Roman systems have yet to show these hydraulic features but rather present a philosophy of designing a system to match a constant spring flow rate output. If the spring source failed, then the transport system probably followed suit and was abandoned. The Chimú organized all coastal valleys under their rule into integrated hydrological units for agriculture with local administrative centres to monitor activities and production; Roman agriculture had a large import quotient as tribute and thus large demands and focus on enlarging and militarily protecting the empire to incorporate other subservient economies into their own. Both Old and New World civilizations developed elaborate surveying methodologies, data recording, and some ability to perform calculations to support water supply systems; while Roman technology is well known, the New World systems must wait for a key to understand the quipu and yupana's function in surveying and hydraulics technologies.

The unique irrigation and water management strategies of Bali developed over many centuries and show a deep knowledge of hydrological principles, land and crop management techniques, effects of climate cycles, and profound horticultural knowledge only obtainable by many cycles of observation and corrective actions to achieve an optimum strategy given island ecological specifics. Implementation of a 'top-down' strategy run by temple priests using ritualized, but sound, agro-engineering principles acceptable to dispersed community groups (subaks) was possible as the benefits of group cooperation under high level guidance was shown to produce mutual economic benefits for all, thus 'top-down' cooperative management evolved from 'bottom-up' non-cooperative origins by mutual recognition of the economic benefits for all concerned. The Balinese system exists to the present day (with an unfortunate intermission from Dutch colonial occupation that introduced 'western' agricultural techniques with disastrous consequences) and serves as a model to show how 'top-down' systems evolve by mutual agreement between parties that recognize that cooperation under intelligent, time-tested rules provides greater economic benefits than disparate, competing, non-cooperative systems, and similar evolution of 'top-down' systems is seen in all of the 'successful', well-organized societies discussed in previous chapters. In this system, knowledge of individual farmer's experiences over the years is channelled into a bureaucratic organization that manages projects with command state authority to enlist labour, provide engineering guidance, provide administrative support, and produce results beyond the capacity of unguided masses with disparate ideas about what constitutes an optimum strategy. In this sense, Old World, New World, and South-East Asian societies seem to share a common universal principle that cooperation (either obligatory or voluntary) usually produces a better setting for the growth and stabilization of a society. While many examples of a wise and controlling bureaucracy underwriting the stability and sustainability of ancient societies exist, this management structure still applies in present times and separates First- from Third-World societies. In final consideration, South American and South-East Asian societies exhibit profound adaptability in utililizing and modifying water usage and conveyance constructions that recognize climate and extreme weather variations in water supplies and permit innovative defensive measures to ensure their continuance (except in cases where extreme drought cancels all possibilities for adaptability). In contrast, Old World water conveyance structures appear to not prioritize climate and weather variation water supply concerns in their constructions but rather assume climate constancy that permits permanent constructions. Old World technical innovations appear to embellish the quality of life through luxury usages of water, always assuming adequacy of supply. This contrasts with New World and Asian concerns that stress conservation and back-up measures that can respond to large water supply variations. For all ancient societies mentioned so far, technical innovation is always present as a key to more efficient use of water. Here, many lessons from ancient societies, when learned and appreciated, still prove valuable in maintaining growth and stability in present-day societies provided the necessary wisdom underlies the decisions made and that these decisions reflect the economic well-being of the entire society rather that that of individuals.

In summary, Old World, New World, and South-East Asian societies independently invented many technologies and management strategies necessary for their cities and farms to flourish although under quite different ecological conditions and extremes. Although much was done in the ancient past by empirical observation, the intriguing concept remains that ancient engineers possessed alternative ways of solving fluid mechanics problems by an as yet unknown or undiscovered methodology. The example of the Chimú Intervalley Canal is a case in point as investigation has revealed the use of a technology invented many centuries later in the Western world. Similarly, the Roman siphon system at Aspendos, the baray systems of Angkor, the Tiwanaku-raised field systems, the pukio systems at Caral, the water systems at Petra, the Balinese water and land management systems, and the use by the Maya of hydraulic jump-activated irrigation systems at Kaminal Juyu in Guatemala all point to refined concepts of water resource management in the ancient world. Although few traces of the ancient systems presently exist or in use in present times (the Balinese systems being the exception), they nevertheless provide an evolutionary step in development of the technical and management methodologies necessary to proceed to civilization status. The new research layer, which looks at ancient technology and management strategies, as perceived by different societies in different ecological surroundings to enhance the lives of its members, presents a further level of fascination underlying archaeological hydraulics works and societal structures. Although many questions remain unanswered awaiting modern analysis techniques for resolution, the revelations to come in the future will undoubtedly provide greater appreciation of the depth of knowledge of our ancient forebears.

5

Environmental and Climate Perspectives on New World, Old World, and South-East Asian Societies' Achievements in the Hydraulic Sciences

5.1 FINAL REFLECTIONS

The foregoing chapters detail the many technical innovations in water supply, distribution, and management for several Old World, New World, and South-East Asian societies. For most of the New World's societies, basic water resource problems evolved around securing their agricultural base given the unique environmental and water resource conditions prevalent in their locations. Diverse New World societies occupying different environment niches from dry coastal margins to wet highlands, often subject to vastly different average temperatures, crop types, and water variation cycles, were shown to devise different approaches to the development of their agricultural bases. While rainfall runoff from mountain watersheds sourced the many rivers of coastal Peruvian valleys and provided the basis for canal irrigation, excessive rainfall and cold in Andean highland locations allowed groundwater-based farming using raised fields that had thermodynamic advantages based on conservation of the sun's heat to prevent root crop destruction during freezing nights.

The presence of varying climate cycles (excessive rainfall and drought) was seen to influence modifications in coastal canal systems. Alterations in canal size and placement to accommodate reduced-water supplies were evident in intravalley coastal systems where modifications were relatively straightforward in sandy environments. Intervalley water transfers through massive canal systems were a further characteristic of a flexible response to maintain the water resource base and this often involved the transfer of river water from one valley to another depending on agricultural, economic, and political priorities. With increased need for more agricultural lands to meet population demands, increasingly lower slope canals were surveyed to include further downslope lands. Here technical innovation was a key factor in providing surveying expertise to maintain low-slope contour canals. While such canals are found at very early Formative and Preceramic sites, surveying techniques became more refined in time to permit greater use of land areas reachable by low-slope canals. Here both Old and New World societies share their dependence on surveying technology to meet water transfer demands. While Roman surveying favoured the most direct aqueduct routing necessitating long, linear aqueduct structures interspersed with siphons and multi-tier aqueducts structures where appropriate, New World surveying was different in that canal designs following landscape contours were prevalent and, in some cases, optimized to produce specific and/or maximum flow rate designs. Specific measures to create hydraulic control structures to defend against El Niño destruction are evident in the New World archaeological record indicating an active, innovative engineering response to climate and weather-induced disasters, probably based on the memory of prior destructive events. While coastal canals were built on the presumption that river water was a reliable source of irrigation water with acceptable seasonal and long-term climate variations that could maintain a stable food supply, the use of mahamaes excavated down to the phreatic zone of the water table indicated that backup agricultural systems were in place to combat drought. Even if severe drought set in, the mahamaes could be excavated yet deeper, as could wells within the cities of north coast Peru. A sequence of mahamaes outside of Chan Chan, each dug to a given depth, can be found with the final pits close to the coastline. This sequence demonstrated the implementation of the strategy of using coastward sunken garden facilities that followed a declining water table that become increasingly more prevalent in the archaeological record as drought set in in the 10th to 14th centuries CE. In subsequent centuries, highland Inka rule was underwritten by the restoration of climate norms that brought increased rainfall to their many highland terrace and canal agricultural systems. Inka conquest of coastal and highland societies from Ecuador to mid-Argentina brought the conquered territories' varied agricultural systems under unified Inka control to exploit the well-adapted agricultural solutions of these societies to state benefit. When it proved more advantageous to maximize the food resource supply, entire conquered populations were relocated to areas deemed more productive by the Inka hierarchy. Thus the benefit of total political control through conquest was an additional method to exploit all available ecological niches of conquered societies and guarantee the sustainability of the Inka Empire through time.

Based on the model of maximizing food resources as the logic behind observed trends in the archaeological record of New World agricultural development, evolutionary canal system designs, development of surveying technologies, and food storage technology appear to conform to this principle and follow modern engineering precepts based on advanced system management techniques that integrate technical innovations to improve productivity. For Tiwanaku society, different agricultural strategies applied. The raised field systems demonstrated invulnerability to short-term drought as their function depended on groundwater delivered to field systems from a vast watershed that provided water from prior centuries of rainfall events. Severe, long-term drought ultimately proved fatal to even this seemingly invulnerable system as vast raised field systems could not be lowered synchronous to the declining water table without massive labour input beyond the Tiwanaku society's capacity to execute. In terms of section 1.7, if the rate of disaster evolution exceeded the rate of overcoming the problem by technical means, then the decline of a society was inevitable. A further model (section 1.6) associated with coastal canal systems indicated that food resources can decline exponentially with $(\text{time})^2$ in the presence of severely declining water supplies. This condition led to the declining cohesiveness of a society whose reasons for collective, cooperative activities rapidly dissolved as organized societal structures changed from diminished food resources. Thus Peruvian north-coast societies in the 13th century CE may have presented opportunities to the Inka for later conquest based on their apparent vulnerability. Early Middle Horizon (MH) paleoclimate records indicated adequate water availability (following an Early Intermediate Period (EIP) drought that collapsed the Moche V presence in the Moche Valley) then a gradual decline up to Late Horizon (LH) times— all of which begins to explain the multiplicity of canal variations (section 1.1) seen in the north coast archaeological record. In contrast, the highland civilizations in this same period appear to flourish as water resources from high-elevation rainfall are plentiful for crop and pasturalism activities. In the presence of the extended drought that characterized much of the Andean world in the ~1000–1300 CE period, many civilizations disassembled from past urban concentrations in cities and reverted to rural roots while others continued innovation and intervalley construction projects and/or extension of the agricultural base to more water-rich areas and valleys. As an example, the abandonment of Tiwanaku accompanied by reduced use of the raised field systems is clear from the archaeological record as no C^{14} dates appear within Tiwanaku past late MH times. New occupation settlement patterns (post-Tiwanaku V, Pacajes phase) centred close to available high-water table zones, runoff streams, and cochas appear in this time period away from Tiwanaku proper coupled with the appearance of eastern-slope Amazonian, post-Tiwanaku settlements to exploit higher rainfall zones. The post-Tiwanaku V, Pacajes phase sees a shift to less numerous, sparsely populated 0 to 1 and 1 to 7 ha sites further inland near rivers and lake edge wetlands where the water table remains viable for farming compared to the more numerous 7–20 ha sites more widely dispersed in Tiwanaku IV times (Janusek 2004; Owen 2005). This indicates that Pampa Koani population levels decreased from earlier times and relocated in smaller groups around ephemeral surface water and groundwater supplies to support limited agriculture. Only as rainfall levels approached previous EIP levels in LH times was the area repopulated by Aymara kingdom societies to take advantage of its agricultural potential but now using terrace agricultural systems largely in place of raised fields. The building of vast terrace systems in the highlands under Wari and Inka occupations can be seen as a flexible drought response given higher rainfall levels at high altitude. In this same period, the Chimú society's adaptability and technical innovation (section 1.1) are able to counter somewhat the effects of drought but ultimately they exploit the water- and land-rich northern valleys through conquest to maintain their empire's sustainability— a model of survival not lost to later Inka conquerors.

The picture in the ancient Andean world is one of a library of environmentally tailored solutions with built-in flexibility to both defend and modify existing agricultural systems to overcome weather extremes and long-term climate challenges. Since Andean societies are managed by royalty and elite classes, their practicality is evident in the changes observed in the modification of agricultural systems and their political economies in the light of major climatic stress events in their history. This is not to say that environmental determinism is the overriding factor in interpreting history but rather that its catalytic role cannot be discounted in that its effect on agricultural systems decide much about the economic underpinnings of state functions.

Major New World societies sought to extend their local agricultural base by the formation of satellite communities scattered about in areas under their control exploiting different ecological zones with different product bases. This vertical archipelago system in combination with trade, import, and export provided an expanded agricultural and marine resource base for both coastal and highland cities. As ancient cities'excavation data often reveal a variety of non-native agricultural products from remote areas, a picture emerges of ancient South American societies as forward-thinking in their managed response to variations in their supply base, both through technical innovations and the diversification of supply bases abroad. Thus cities dating as far back as Caral incorporated aspects of trade centres facilitating movement between highland and coastal product streams and positioned themselves to serve as final destination points for products from satellite centres.

As exploration of ancient South America continues, it is clear that a wide variety of ecological zones existed (high-altitude altiplano zones, desert environments, coastal valleys, jungle environments, mountain valleys, and mountain slopes, among others) supporting different types of agriculture. It appears that different societies'inventiveness to originate a food-producing system served as the foundation for progress into higher levels of organization and resource security. The discovery of Mojo culture in eastern Amazonian Bolivia (Parsons and Denevan 1967) is a case in point. Vast earthworks created by native populations and based on trapping seasonal Amazonian inundation water for raised field farming and fishpond resource extraction have been discovered in a periodically flooded jungle environment that was previously thought to be uninhabitable. Current investigations of these remote areas have led to the discovery of a major civilization that was noted by early Spanish explorers but later discounted due to its improbability because of its location in jungle terrain. Perhaps archaeological discovery in South America should be rethought on the basis of determining how an ecosystem can best be exploited and then looking for traces of civilizations that have figured this out in previous centuries.

The classical Roman world seems to be on a different trajectory, although frequently compared to the Inka as yet another society maintained by conquest and predatory resource sequestering of conquered and dominated societies. Here mild and somewhat predictable Mediterranean climate translates into a stable and predictable agricultural base characterized by vast regions of fertile soils and water resources available from rainfall and rivers. Defensive measures to protect against weather and climate extremes are hardly the concern of builders; rather, the main concern appears to be ever more aqueducted water directed to cities to increase the domestic, comfort, luxury, and hygienic needs for all inhabitants, all of which is indicative of abundant water resources and the ability to control their distribution. Vast areas of fertile soil existed within their empire's boundaries so that few concerns arose about crop type limitations. Trade routes and commerce were well developed so the agricultural base of a city was essentially what was available from the known world. Importation of grain from Egypt and the Black Sea area as well as exotic goods from different regions under empire control were the rewards of this system. In this environment, technical innovations were more slanted towards providing city water resources to improve the living, comfort, and hygienic standards for all citizens as well as monumental structures defining state power. The use of water for aesthetic and decorative purposes beyond the practical is found as a statement of the benefits of civilized living under Roman occupation. A combination of military coercion and demonstration of the advantages of cooperation with authorities through increased amenities played a part in empire building and consolidation (very similar to the Inka rulers in South America). Since sites were selected according to some combination of their natural advantages (water supply, trade routes, defensibility, adjacent fertile farming zones, natural resources, livability, climate, and drainage), increasing population demands for increasing basic and luxury water supplies drove the search for more water further from near-city locations. This led to technical innovations in water transport, particularly low-angle surveying of long aqueducts, which permitted the increase of water supply to meet a city's practical and luxury needs. Rugged terrain proved no obstacle as Roman and Greek engineers included tunnels, aqueducts, siphons, bridges, and pipelines in their engineering repertoire to surmount terrain obstacles between spring supply and city. Many innovations incorporated features involving knowledge of the dynamic behaviour of water (the Aspendos Siphon, the Petra water pipeline systems, and the sluice gate system at Caesarea, for example) and indicate an engineering experience base beyond that usually attributed to the technology level of that era.

As few examples of ancient engineering texts survive to tell of engineering technology, much needs to be inferred from analysis of existing remnants of ancient water control and distribution systems. The many engineering functions of Roman army specialists contain volumes of lost knowledge only hinted at by the monumentality and scope of the archaeological remains. As an engineer observing his counterparts of past centuries, I find it striking that the leap from design to execution usually occurs in one try, indicating confidence in the design and analysis base behind monumental structures. Ancient engineers, despite their technological base being largely undiscovered, solved hydraulic and civil engineering problems of monumental scope even by today's standards and this has opened up a richly rewarding research field with many anticipated new insights to enhance our view of the technologies and management techniques of these ancient societies.

The South-East Asian Khmer civilization centred at Angkor had many characteristics of an enlightened water management system. The barays are seen as water storage reservoirs that served to provide channelled surface water while maintaining the groundwater base for agriculture and site foundation stability. The multiple baray systems, interconnected by canals to moats and pools within the city, served to maintain constant water height in moats around religious and ceremonial structures throughout the dry season by timed release of water and maintenance of a high water table throughout the seasons. The water systems at Bali are remarkable in that practical concerns related to pest control, timing of crop planting and harvesting, water delivery rates, and water resource allocation were codified in a framework with religious overtones that contained the practical experience base of many centuries of operation. The temple religious functions carried out through festivals, acknowledgement of protective and bestowing deities, sacrifices, and rituals to ensure continuity are the final expression of a perfected engineering base that is so well understood that it has, in fact, become a religion.

In many ways, commonality existed between societies in different parts of the ancient world, in that the role of water and its control through engineering methodology were understood to be vital to a successful agricultural and hygienic base that supported urban society. Seen also in the archaeological record of South America and South-East Asia are structures and strategies that acknowledge the long- and short-term variability of the water supply from weather and climate change, and provide conservation measures that exploit less susceptible groundwater resources. While some Old World societies (Petra, for example) exercise similar conservation measures due to the constraints of their desert location, generally advances in technology are directed towards improving life standards for their populations based on their perception that climate and weather effects on water supply are of secondary importance. This threat perception difference between Old World, New World, and South-East Asian societies then provides a reason for their emphasis on different types of water management and transport structures as well as conservation strategies.

While archaeological remains always pose mysteries and scant information exists from inscriptions and surviving texts to describe engineering concepts and methodologies, nonetheless different civilizations, each with their own version of the physical and natural world, managed to create successful water supply solutions to sustain their societies. Yet more fascinating is the idea that these solutions, originating from different parts of the ancient world, contain a vast array of methods to solve problems in hydraulic and hydrological science that may parallel later Western developments describing hydraulic and hydrologic phenomena. While the empirical, observational path to learning is an acceptable view of early societies' engineering development, there may be analytical capabilities yet to be discovered, as some of the results of this book indicate. It remains a fascinating exercise to see how fluid phenomena are recorded and understood by different societies with completely different worldviews of nature.

5.2 LESSONS FOR THE MODERN WORLD

As the 21st century unfolds, it is apparent that increased freshwater resources are required to meet increasing population, urbanization, industrialization, and agricultural demands in both developed and undeveloped countries. Many Third-World countries are at the point where consumption is approaching 10% of available water resources. Many aquifers in low-lying coastal cities are experiencing intrusion of seawater into freshwater lenses as groundwater is depleted for urban and farming uses; global warming and the associated sea level rise will lead to further penetration of freshwater coastal aquifers. A 3°C rise in mean world temperature (as may happen given current climate predictions in the coming centuries) will flood 30% of coastal wetlands and make many low-elevation coastal cities uninhabitable. Fossil aquifers are being depleted worldwide for agriculture and urban use with little chance of substantial recharge as groundwater levels drop below critical rainfall infiltration levels. As an example, two-thirds of India's crops are irrigated with groundwater with little chance of recharge because levels have dropped from 10 to 200 m below the land surface in some provinces. This story is being repeated in China, Pakistan, Iran, Vietnam, Indonesia, Sri Lanka, Bangladesh, and parts of the United States where groundwater pumping extracts upwards of 500 km^3/year with only half as much recharged by rain. Elsewhere in the world, groundwater resources are being depleted for export crops that have high water demands (i.e. 1 kg of coffee requires 20,000 litres of water to produce) with little confidence that production can be maintained using groundwater resources for the next 20 years. By some estimates, as much as 10% of the world's food is being grown using groundwater not likely to be replaced by infiltrating rains. Agriculture in most countries consumes more than half of all water resources; in some first-world countries with corporate agriculture, this percentage can approach 80% of freshwater resources. Land development and urban sprawl contribute yet further pressures on limited water resources as watershed surface water collection areas are diminished while groundwater resources are steadily consumed. To meet these challenges, technical, regulatory, and conservation means are now being formulated but economic development needs and ecological consequences are frequently in conflict.

As world population increases, more water is needed for agriculture, industry, and urban use, further stressing finite water resources; complicating this issue is that while the fraction of the earth's surface experiencing drought has more than doubled in the past 30 years, rainfall redistribution is uneven as water is not always returned to the same areas. For example, the United States has experienced a 7% total rainfall increase in the 20th century with the fraction classified as heavy precipitation increasing by a factor of two and localized floods and drought becoming frequent occurrences. Increasing pollution levels from all sources challenge the purity of potable water resources.

Salt contamination of northeast American freshwater sources is increasing to the point where these sources may not support marine life in the next 100 years. With a 0.5°C rise in world mean temperature, CO_2 absorption into ocean waters begins acidification processes that threaten the marine resource base and may upset the ecological balance. Currently, one-third of China is experiencing acid rain due to the extensive coal usage required to drive its export-based economy. Freshwater consumption in the 20th century is six times higher than that of the century before, which is commensurate with a doubling of the rate of population growth. Current estimates place one agricultural caloric food unit requiring 1 litre of water to produce; with the addition of two billion or more population in the next 50 years, the requirements for fresh water will increase yet further. Concerns related to global warming are equally challenging. Climate change is affecting weather patterns, precipitation, and hydrological cycles, diminishing surface water availability, soil moisture, and groundwater recharge. UNESCO estimates that climate change will account for 20% of water scarcity in future decades, in addition to the additional 80% requirements posed by population growth and economic development. Recent research indicates that 40% of the South-East Asian populations dependent on Himalayan glacial melt to supply Asian rivers, including the Yangtze and Yellow Rivers in China, the Ganges in India, the Indus in Pakistan, the Brahmaputra in Bangladesh, the Irrawady in Burma, and the Mekong shared by Cambodia, Laos, and Vietnam, are undergoing rapid shrinkage and half of the water supply could disappear by 2100 as a result of climate warming of 1°C since the 1970s. The water runoff from the 31,000 km^3 volume of Himalayan glaciers is expected to reduce by up to 67% in the coming centuries, resulting in lower runoff water amounts into the rivers and their tributaries, which in turn will have negative consequences on farming and potable water supplies to urban and rural centres. Dams along the Mekong already indicate that some countries are sequestering water resources to the detriment of downstream user communities; similar anticipatory sequestering is apparent in near-source Turkish dams controlling the Tigris and Euphrates water sources in the Middle East. Similar glacial melting in Greenland, the Arctic, and parts of Antartica is occurring as a result of shifts in world climate due to excessive global warming trends. Recent observation of rapid glacier melting in Peru and Bolivia (shrinkage by 22% since the early 1960s) may lead to catastrophic changes in water availability to coastal irrigation networks and hydroelectric power stations that will adversely affect future generations. Rainfall pattern shifts originating from Pacific Ocean warming and El Niño/La Niña cycles may be modified by global warming and therefore have an effect of undetermined magnitude on worldwide agricultural sustainability. Ocean ecosystems are likewise threatened by the possibility of the modification of oceanic current systems due to non-linear climate-ocean coupling effects resulting from fresh water incursion from melting Arctic and Antarctic ice caps. Populations in the future experiencing changes in rainfall patterns, and climate and temperature temporal and spatial excursions from previous norms will need to devote technical resources and innovations to new means of water distribution and perhaps consider population dispersal from no-recourse areas lest they encounter the fate of some societies in the historic and archaeological record.

Typically, only 40% of irrigation water reaches plant roots while the remainder is lost to evaporation and runoff. Water conservation measures are in the early stages of implementation as previous usage policies that considered water to be a low-cost, near-infinite resource, particularly in Westernized societies using corporate agriculture, are now subject to change because of competition from urban demand. It may appear that ancient societies, cognizant of the scarcity and changeability of water resources and the fragile infrastructures required to convey and control water supplies, had better control of conservation measures in the form of storage complexes that mitigated climate effects on agricultural output than their modern counterparts. Many modern societies in Peru and Bolivia live on only a fraction of the agricultural land that their ancestors cultivated in past centuries; in many cases, food is imported where in the past sufficient supplies were available locally and backed up by storage systems to overcome poor harvest years. Often in the same geographic areas occupied by their ancient ancestors, scarcity has replaced abundance. Without the modern technologies available in the developed world, many Third-World societies lack the energy availability, political foresight, economic means, and geographic blessings to provide potable and irrigation water for a sizeable part of their populations. Yet, viewing the systems of antiquity in perspective, much was achieved in these same geographical areas by simple gravity-fed water systems, integrated groundwater and surface water utilization, agricultural systems tailored to the ecological variables present, political organization to marshal labour for water supply tasks, and management expertise to coordinate activity. Certainly government oversight and competence, then as now, are important in deciding the fate of societies faced with ecological and economic challenges. In this respect, it may appear that ancient societies, given their centuries of successful coping with ecological change to maintain viable societal growth and development, were better able to cope with the challenges provided by variations in the weather and climate environment. Given present-century, non-natural climate and weather modifications superimposed on the already formidable assemblage of natural disaster challenges, societies in future times will face survival challenges not even imagined by their ancient forebears.

With changes to current practices inevitable given climate stress portents, perhaps borrowing from the library of ancient agricultural techniques adapted to climate and weather extremes may provide solutions (and perhaps salvation) for future generations. Recent trends in India and elsewhere in South-East Asia towards rain harvesting (using surface ponds to promote groundwater recharge from rains), as practised in past centuries in South-East Asian Khmer society, show that ancient water technology can play a role in answering today's problems.

In India, local reversion to using monsoon runoff to irrigate fields, collecting excess runoff into reservoirs, and using reservoir water to charge aquifers rather than using pumps to extract water from the aquifer for irrigation are now being practised. The water systems of Bali are a prime example of codified technical knowledge that works so well that it can be thought of as divinely inspired and a form of communion with higher spiritual powers. Use of ancient water temples, with their large excavated and stone-lined basins extending to the water table, are now viewed as practical ways to provide water for communities. Thus, all the accumulated knowledge of past centuries' trial-and-error modifications and methods, in light of sometimes hostile climate change, are stored in these designs and, once brought back into use, create yield improvements over current farming practices. As a further example of ancient technologies useful for present-day applications, the 20th century resurrection of a portion of the ancient Tiwanaku-raised fields in Bolivia by local inhabitants of shoreline communities around Lake Titicaca has shown productivity increases of 50–200% in the agricultural yields of key crops. For the ancient Tiwanaku, some concept of heat and its storage must have entered the minds of the agriculturalists charged with implementing these systems (although one can hardly imagine thermodynamic conceptualizations in ancient minds). Other examples related to restoring the barays of ancient Angkor to provide site foundation stability and recharge of aquifers for urban and agriculture use are presently being considered as antidotes to current water deficit problems.

With regard to climate trends, modern technologically advanced societies have, as a first step, arrived at an awareness that favourable environmental factors can no longer be taken for granted and planning to mediate future problems demands serious consideration. The scale of water problems remaining to be solved in the 21st century, given increasing population, conflicting national and regional interests, financial resource constraints, prioritization of capital allocation, bureaucratic inertia and decision-making, bureaucratic earnest incompetence and reflexive malevolence, infrastructure difficulties, and climate prediction uncertainties is formidable. Water problems were no less a concern for societies in earlier centuries with their less-developed technological solutions and fewer available options. In essence, while some ancient societies had options to disperse populations to more constant water source areas as supplies became scarce and the benefits of city dwelling became less apparent, modern societies rely mainly on moving available water to fixed population centres as technological means exist to deliver water through a complex pattern of watershed collection, reservoirs, aqueducts, pipelines, and groundwater sources. Each component of this strategy contains vulnerabilities that are only fully recognized as cost-effective as the technology's limits are approached.

While 21st century global warming trends from greenhouse gas accumulation and their dire consequences are popularly summarized (Gore 2006; Pearce 2006) and their negative consequences discussed (but not without controversy; Robinson *et al.* 2007), it is of interest to note that previous civilizations have experienced their own ecological crises, some surviving, some dying out, some modifying their agricultural technology towards greater survival levels, and all based on less challenging variations in climate patterns than those anticipated in future decades. The key to survival, if lessons from the past are to be understood, is adaptability and innovation to more productively use finite water resources, together with the will at local and world governmental levels to implement these innovations. The world of the past can offer many solutions once more is known about the breadth of ancient practices and accomplishments; examples from the past of survival and human progress can provide inspiration to present generations, demonstrating that problems can be solved by human endeavour and ingenuity and that the future is no different from the past in this regard. Failing this, the lessons of history are clear.

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