Geoinformation Technologies for Geocultural Landscapes

European Perspectives

Edited by

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GEOINFORMATION TECHNOLOGIES FOR GEOCULTURAL LANDSCAPES: EUROPEAN PERSPECTIVES

Geoinformation Technologies for Geocultural Landscapes: European Perspectives

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COST and the Action A27 LANDMARKS

COST – the acronym for European **CO**operation in the field of **S**cientific and **T**echnical Research – is the oldest and widest European intergovernmental network for cooperation in research. Established by the Ministerial Conference in November 1971, COST is presently used by the scientific communities of 35 European countries to cooperate in common research projects supported by national funds.

The funds provided by COST – less than 1% of the total value of the projects – support the COST cooperation networks (COST Actions) through which, with only around €20 million per year, more than 30,000 European scientists are involved in research having a total value which exceeds €2 billion per year. This is the financial worth of the European added value which COST achieves.

A "bottom up approach" (the initiative of launching a COST Action comes from the European scientists themselves), "à la carte participation" (only countries interested in the Action participate), "equality of access" (participation is open also to the scientific communities of countries not belonging to the European Union) and "flexible structure" (easy implementation and light management of the research initiatives) are the main characteristics of COST.

As precursor of advanced multidisciplinary research COST has a very important role for the realisation of the European Research Area (ERA) anticipating and complementing the activities of the Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries, increasing the mobility of researchers across Europe and fostering the establishment of "Networks of Excellence" in many key scientific domains such as: Biomedicine and Molecular Biosciences; Food and Agriculture; Forests, their Products and Services; Materials, Physics and Nanosciences; Chemistry and Molecular Sciences and Technologies; Earth System Science and Environmental Management; Information and Communication Technologies; Transport and Urban Development; Individuals, Societies, Cultures and Health. It covers basic and more applied research and also addresses issues of pre-normative nature or of societal importance.

Action COST A27 (2004–2008), *Understanding Pre-industrial Structures in Rural and Mining Landscapes* (LANDMARKS) belongs to the domain of Individuals, Societies, Cultures and Health. The number of signatory countries to the Action is 21: Austria, Belgium, Cyprus, Denmark, Estonia, France, Germany, Greece, Iceland, Ireland, Italy, Malta, Netherlands, Norway, Portugal, Romania, Slovakia, Slovenia, Spain, Switzerland, United Kingdom.

The point of departure of LANDMARKS is European rural and mining landscape. Pre-industrial structures mark many of those landscapes; most of them are now threatened by the abandonment of traditional practices, in particular less wealthy regions. This process implies the quick destruction of landscape differences resulting from traditional activities and ways of life. LANDMARKS aims to stimulate the European research on this topic, to produce specific databases and to structure a consistent dissemination plan by:

- Morphological analysis of relevant elements and models of integration in present landscapes;
- Research on historical techniques and technologies related to the historical use of landscapes;
- Diachronic study of specific legal and administrative practices;
- Analysis of historical landscape perception during history by the communities that inhabited and exploited them;

- Providing mechanisms for the public presentation of landscapes and optimising Cultural Heritage.

Identification and scientific evaluation are the common basis for the protection, the cultural valorisation and the social and economic vindication of these sensitive landscapes. Diversification of cultural resources and enlargement of the protected cultural heritage are keys for the improvement of the internal potential in many European regions.

The objectives of LANDMARKS are described in the *Memorandum of Understanding* of the Action and the main outcomes are mentioned in the Progress Reports of the Action (all documents can be consulted in COST and LANDMARKS web pages). The activities are centred in four working groups: mining landscapes (WG1), rural landscapes (WG2), virtual landscapes (WG3) and transversal activities (WG4).

More information
COST: http://www.cost.esf.org/
Action COST A27 LANDMARKS: http://www.soc.staffs.ac.uk/jdw1/costa27home.html
Action COST A27 “Cultural Parks, Cultural Projects and Activities”: http://www.unipg.it/COSTactionA27/parks-activities/

Preface

One of the main challenges in the field of landscape studies is to make visible and analysable the complex and sometimes sharp links that articulate landscape as a social construction. This requires a specific methodology supported by a series of techniques specifically developed for the research of landscape. In this context, the Action COST A27 "Understanding pre-industrial structures in rural and mining landscapes (LANDMARKS)" decided to approach some of the most relevant methodological and technical aspects on geoinformation technology, one of the most innovative areas in the field of landscape studies.

Greek and Austrian delegations assumed the coordination of the discussions, the organisation of a series of specialised meetings and the conceptual design of the publication. Papers collected show the growing potential of non-destructive techniques, able to record visible and invisible aspects, monumental or modest items of landscape.

Two general points can be mentioned: the increasing improvement of spatial and spectral resolution of the images and documents generated and the high capacity of geoinformation systems to articulate large data from different origins, allowing for an overall improvement in the treatment and analysis of geospatial data (recent or historical). It is not an issue of quality of illustrations, but the ability to produce innovative knowledge and facilitate its transfer from science to spatial planning. Thus, the need of an integrative management and public presentation of both cultural and natural heritage will be properly taken into account.

This publication is addressed to different readers: scholars, students, planners, policy makers involved in the protection of cultural and natural heritage. In it can be found a compendium of significant experiences and expertises, developed all over Europe and based on the research of historic landscapes. The implementation of the European Landscape Convention requires the updating and standardisation of technological approaches and the knowledge of good practices should be an excellent starting point for consolidating a common ground.

Experts from 10 countries and coming from different disciplines have collaborated: geographers, archaeologists, GIS experts, geomorphologists, computer experts, landscape ecologists, landscape planners. Such variety guarantees the significance of the publication at the European scale. The Action A27 has been a meeting point for debates and fruitful collaborations that will certainly follow in the future.

Landscape is a multifaceted net where natural and human aspects are continuously building a changing reality usually called "environment", a word that reflects an anthropocentric reading of the surrounding space. Recording landscape requires a holistic understanding and, consequently, adequate instruments for broaching research issues closely connected with social needs.

Almudena Orejas
Chair of the Action COST A27

Preface

This publication is an initiative generated within the European Project COST Action A27 titled "Understanding pre-industrial structures in rural and mining landscapes". COST, the acronym for "European Cooperation in the field of Scientific and Technical Research", is the oldest and widest intergovernmental network supporting co-operation among scientists and researchers across Europe.

This book entitled "Geoinformation Technologies for Geocultural Landscapes: European Perspectives" is one of the main outcomes of the COST A27 project. It focuses on the technologies that support analysis and research of the landscape from a geocultural perspective. The main objective of the book is to constitute a meaningful linkage among research problems, geoinformation methods and corresponding applications. The research goals, related both to theoretical and practical issues, derive from multidisciplinary fields such as archaeology, geography, geoinformation, geology, geomorphology, history, landscape research, spatial planning, and cultural resource management. All the aforementioned scientific areas have the spatial dimension in common. Their research issues can be addressed and analysed with geoinformation technology; therefore researchers should become familiar with the range of available methods and techniques dealing with geoinformation.

This volume bridges the gap between theoretically addressed research issues, methodology used for analysis and practical cases. Its main value is in addressing innovative geospatial technologies that can support different workflows needed for such analysis. It provides description of a variety of research issues and technological approaches that may be used to support processes of data capturing, mapping, and analysis. These techniques and concepts are illustrated in the selected case studies along with numerous specific examples, where these techniques have been applied.

The book consists of five main parts:

- the introductory chapter discussing the role of geoinformation technologies in geocultural landscape research;
- three methodological parts dealing with primary data capturing, data preparation for GIS analysis, and data analysis and interpretation;
- and the case studies part where practical applications of the aforementioned methodologies are presented.

References and inter-relations between all these topics are indicated by sidebar links together with a sidebar glossary enabling the reader to use the book in a more meaningful way.

This book innovates in the following respects:

- describing and discussing innovative technological methodologies and tools used in geocultural landscape research such as aerial photography and satellite images, light detection and ranging (LIDAR), digital photogrammetry, field data collection, algorithms and efficient transmission of data, spatial interpolation methods, circular statistics and visualisation techniques, testing hypotheses, geometrical methods, GIS analysis, etc. are presented and discussed;
- covering a wide range of scientific fields, research issues and target groups leading to multi- and interdisciplinarity;

- combining technical and analytical aspects, including the entire workflow ranging from data capturing and preparation to analysis and dissemination;
- and finally dealing with the European dimension, evident not only from the wide spatial distribution of the study areas; in essence, the book hosts numerous authors each of them bringing expertise from different sectors, background and disciplines.

“Geoinformation Technologies for Geocultural Landscapes: European Perspectives” is a book combining theory and practice. It aims to find its audience in researchers, lecturers and students from a variety of research fields. Also planners and public servants involved in landscape and/or spatial planning, geocultural resource management, etc. may educate themselves about the new technologies available for the support of their work processes.

The editorial board wants to express its appreciation and gratitude to the COST A27 action “LANDMARKS”:

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GEOCULTURAL PARKS

of Eastern Aegean

Introduction

The role of geoinformation technologies in geocultural landscape research

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ABSTRACT

A geographical information system (GIS) is more than a sophisticated software program; it is a powerful tool that can be used effectively in geocultural landscape research. Geocultural landscape researchers analyse the historical content of a present landscape and the landscape evolution over time; they strive to reconstruct historical states of a landscape, using different sources, methods and techniques developed in various disciplines such as archaeology, geography, history, planning sciences, etc. as well as in related auxiliary sciences. The general interest of this contribution is the application of geoinformation technology in the geocultural landscape research.

The introductory chapter overviews different functions of a GIS and demonstrates its role in a geocultural landscape analysis. The differences between GIS as methodology, science, and tool are presented, specifically dealing with research issues with a time and space component, as well as their representation in a computer-based system. The chapter concludes with a summary of research issues that may concern the interdisciplinary teams of both landscape researchers and geoinformation scientists.

1 INTRODUCTION

Landscapes evolve and alter through time. Their changes are caused by natural factors and by human activities. Natural factors that have an impact on landscape are, for example, floods, draught, erosion or even a strong wind. Erosion is a very clear example of solids displacement (soil, mud, rock, etc.) caused by sea currents, wind, ice, and fluvial processes that lead to downward or down-slope movement under the influence of gravity or biota activities. Human activities exert complex changes. On one hand, the building of new settlements and highways or expanded new districts on the suburbs of cities results in reduced space for natural landscape and agriculture. On the other hand, abandoned villages, fields or mines continuously increase the area of nature predominant landscapes. Such fluxuating landscapes need special attention and monitoring, especially to assure continuous sustainable development.

Archaeologists, geographers, geomorphologists, historians, landscape planners and other related researchers are interested in understanding landscapes and their changes through time and space. Recently, powerful computer-based tools for research and analyses have greatly aided their work. A GIS is a potent tool that not only allows the combination of data coming from different sources and in various formats, but also the capturing, storing, checking, manipulating, analysing, and displaying of data which are spatially referenced to the Earth. The related geographical information is linked to the appropriate data stored in a digital database. A GIS can serve as an important tool for decision makers, especially in nature conservation and cultural landscape management.

This chapter overviews different functions of a GIS and demonstrates its part in a geocultural landscape analysis. The differences between GIS, as a tool, methodology and science, dealing with research issues with a time and space component, as well as their representation in a computer-based system, are presented. It concludes with a summary of research issues relevant to geoinformation science, history, geography and landscape research.

2 GEOCULTURAL LANDSCAPES AND THEIR CHANGES OVER TIME

After Hartshorne (1939) ‘landscape’ is the external surface of the Earth beneath the atmosphere. According to that, landscape is nothing more or less than an arbitrarily defined section of the Earth’s surface which can be scientifically analysed as a dedicated construct under certain factors such as the elements, composition, structures and functions of the landscape.

The term ‘culture’ signifies the shared knowledge, experiences, symbols and traditions of people within the social, economic and political sphere, and, pertaining to the land these cultures inhabit, their influence upon landscape; i.e., the way cultures organise, build, destroy, abandon, leave traces, return and then rebuild. Culture as a pattern of human activity and can be recorded in the landscape either a) as built structures such as settlements, roads and immovable archaeological features, or b) as alterations of the physical environmental settings such as land use changes and over-exploitation of natural resources over time (Lambin & Geist 2006). The old dichotomy between culture and nature is nowadays overcome and the interaction and co-dependency between cultural and natural settings is widely accepted.

In the context of this book, the term ‘geoculture’ is not used in sense of a system of cultures related to space, or, more defined as by Wallerstein (e.g. 1991), of a global cultural system which is “as a tension established by three ideologies: conservatism (right), liberalism (center) and socialism (left)” (cf. Dussel 2002: 239). On the contrary, here, ‘geocultural’ attributes the specific binary characteristic of landscape, or the aggregate combination of cultural and natural environmental aspects in a given spatial scale. It identifies a dialectic relationship between these two components, specifically through the ways in which humans have utilised, exploited or been constrained by landscape/physical patterns. Natural landmarks, geomorphological features as well as environmental parameters affect human life, while human intervention and activities affect the environment. For instance, regional agricultural patterns may reflect a combination of landform shape, slope steepness, river patterns, soil type and drainage (natural features) as well as human customs, rituals, preferences, symbols and needs (cultural features).

3 GEOCULTURAL LANDSCAPE CHANGE RESEARCH

Landscape refers to a common perceivable part of the Earth’s surface (Zonneveld 1995). A geocultural landscape research includes the fourth dimension (of time) in a variety of ways and with different aims, including:

a) the explanation of the current landscape (or of particular landscape elements) by its historic development up to now (historic-genetic approach);
b) the reconstruction of former states of a landscape (or of particular landscape elements), and
c) the research of former, recent or future landscape change including (a) above as well as generating scenarios or prognoses of future landscape conditions.

Change over time is immanent in all landscapes and thus must be taken into consideration in all studies dealing with landscape development. In this chapter, a distinction is made between landscape changes caused by natural forces and changes caused by human activities. Landscape change researchers focus on different thematic areas such as historic geographical land surveys – partially acquiring historical information from historical maps or from the cadastre or registries (e.g. Bender et al. 2005, Gugl 2000); while others focus on “landscape ecology” using GIS for describing some structures and patterns (e.g. Blaschke 2006). In the analysis of a selected landscape, researchers often try to define landscapes by categorising different landscape features into classes or types which enable them to deal with the space in an effective way (e.g. Bender et al. 2005, Vermeulen & Antrop 2002).

3.1 *Natural forces influencing landscape changes*

Natural forces have the power to exert tremendous changes on the structure and functions of landscapes. Research in this area focuses upon different phases of the change process such as the identification of change influencing factors; the change itself and its consequences; the analysis of factors involved in preventing potential forthcoming altering events; and the study of possible scenarios and decision making in landscape planning in order to affect or, optimally, to control landscape change. Recently, global warming and its impact on different landscapes has gained increased attention. Researchers (e.g. Blanchon & Shaw 1995, Gude & Barsch 2005, Nakagawa et al. 2000) investigate processes which might lead to severe drought, rising sea levels, extreme weather phenomena and landslides due to permafrost melting. This scientific field is in its early phases and needs additional research. For example, it is well known that climate change affects the disintegration of glaciers, whose increased melting rate, due to the rapid temperature rise, results in the rising sea level. The consequent rise in sea level gravely affects environmental and socioeconomic factors, especially within low-lying coastal areas like in the Netherlands. This alarming development is expected to affect all estuarine areas which are commonly vital and rich areas of agriculture and development.

Erosion and its influential factors are part of a separate research area. Researchers in this field (e.g. Gournelos et al. 1999 and 2004, Kirkby & Morgan 1980, Renard et al. 1997) analyse the factors influencing erosion, for example how the amount of superficial water runoff determines the amount of the transported sediment, the vulnerability of certain areas, or the impact of the erosion and its consequences (Gournelos et al. 2004, Sabot et al. 2002). Coastal erosion due to wave action often threatens coastal areas, undermining the natural environment as well as human constructions (figure 1). Coastal erosion study depends upon several factors, such as the type of rocks in the coastal zone, their inner structure

Figure 1. Regression of the coastline in northern Corfu island (Ionian islands, Greece) is evolving rapidly, destroying human constructions, © Vassilopoulos & Evelpidou 2002.

(discontinuities, fissures, cracks, etc.), longshore currents, and wave regime, some of which are difficult to study. Another factor is the incline of the land surface which strongly influences the speed of water runoff and, if severe, results in decreasing landscape diversity which in turn makes landscapes more vulnerable to erosion and fire (Marin-Yaseli & Lasanta Martinez 2003). This is of major importance for some environments, e.g. the Mediterranean, where active processes of erosion are observed on soil and surface rocks (Poesen & Hooke 1977). Soil thinning makes it rather time consuming, and even impossible, to adequately re-establish the age-old terraces for fruitful cultivation.

Looking south of Europe, severe natural disasters are occurring in Africa. For example, Morocco, Tunisia and Libya lose about 250,000 ha of cultivable land per year due to desertification processes (Chandler 2001). In Nigeria, droughts regularly strike the whole country, contributing to famines that have endangered millions of lives. Here, the causes of the famines are numerous and bound together, one of them is the gradual disappearance of Lake Chad which at one time was the planet's 6th largest. In the course of 40 years, the lake shrunk to 1/20 of its original size because of rainfall reduction and other factors (figure 2). These changes not only led to a dramatic cutback of the fish stock, but the loss of cultivated lands, dislodging millions of people and endangering many more.

3.2 *Human factors influencing landscape changes*

The impact of human activity on landscape increased during the 20th century and is nowadays considered to be the main factor for landscape change (Goudie 2000). Humankind has influenced and changed at least 90% of the Earth's landscape (Naveh 2000). Some researchers claim that this happened mostly because of the intensified agricultural production and the

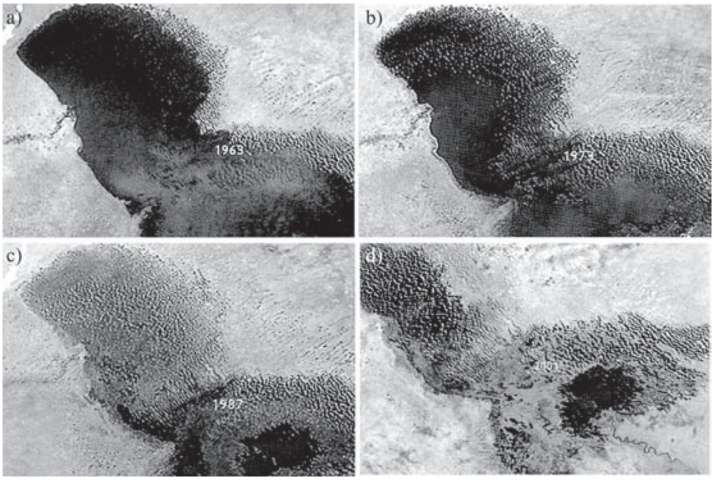

Figure 2. The evolution of Lake Chad in Africa (Chandler 2001): (a) in 1963, (b) in 1973, (c) in 1987, (d) in 2001.

abandonment of the traditional land use systems. Other factors influencing change of the landscape can be categorised into the following groups:

- intensification of agricultural production,
- abandoning agricultural production,
- building new infrastructure,
- extending existing cities and their suburban areas,
- abandoning villages and rural areas,
- population growth.

All mentioned factors are categories of land use change which is one of the most dynamic reasons of landscape change (Lambin & Geist 2006). A characteristic example from the Mediterranean is the island complex of Cyclades (Greece) which experienced tremendous landscape changes during the last 50 years. Many residents abandoned the cultivated land in high slope areas. These slopes required the construction and maintenance of terraces in order to keep the soil from eroding, which required a significant cost in time and money. The size and shape of terraces prohibited machinery on the crops which further reduced viability and productivity. The result of the abandonment of terraces is the progressive loss of soil's resources leading to soil thinning and shrub growth. Figure 3 shows the changes in landscape in the island of Syros in Greece. Well preserved agricultural terraces are presented on the picture on the left. The picture on the right shows abandoned terraces, lost soil and denudated relief.

The second example shows change in the land use in the Franconian Alb in Southern Germany (figure 4). The study areas are located in mountain regions in which recent landscape changes led to the reduction of landscape diversity. The picture on the left was taken approximately in 1930 and the one on the right in 1990. The analysis of the landscape change showed that the increased forest coverage largely took place on former rough pastures. This doubled the proportion of the wooded surface to about 40%. Former rough pastures and wastelands were either planted or abandoned. Today, these categories account for only 1% of the studied area. The correlation

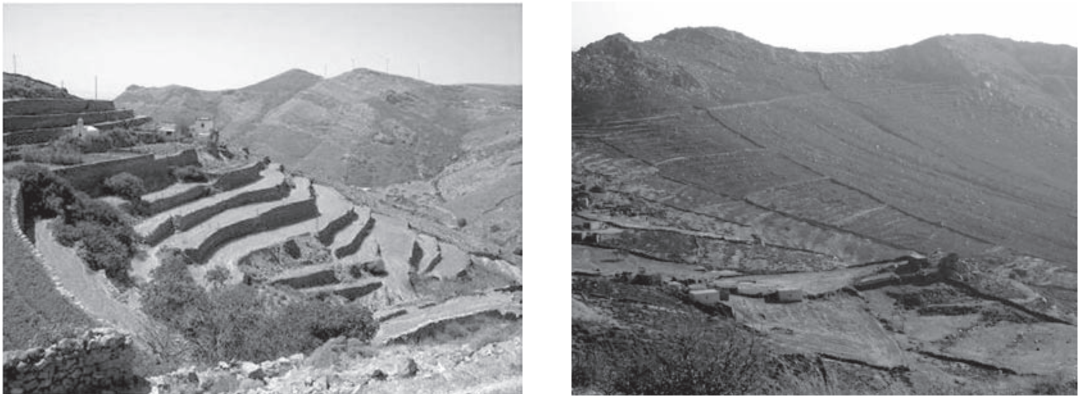

Figure 3. (a) Well preserved terraces in Syros island, Cyclades, Greece, © Vassilopoulos and Evelpidou 2003; (b) Abandoned terraces in Serifos island, Cyclades, Greece, © Vassilopoulos and Evelpidou 2002.

Figure 4. Landscape change in the Ailsbach valley in Southern Germany between 1930 and 1990 (Bender et al. 2005).

between slope and land use shows also that the steep slopes were frequently changed into woodland (Bender et al. 2005).

Another characteristic example of human factors influencing landscape change is the case of Acheloos River in western central Greece (figure 5). The Acheloos delta is a very dynamic system influenced primarily by fluvial and marine processes. Some of the delta plain features have been changed several times during the past decades (Sabot et al. 2003). The oxbow lakes which existed in 1960, were drained for cultivation in 1986 (figures 5a and 5b). Thus, we can observe the expansion of agricultural land and a decrease of wetlands (Vassilopoulos et al. 2005).

The major anthropogenic intervention in Acheloos is the construction of four hydroelectric dams. Most of the deltaic field area appears to be subjected to human intervention, focusing on the practical use of the area and the growth of organised cultivations along with the road network. The construction of dams for hydroelectric power and for land use within the delta area have slowed down fluvial processes (figure 5c and 5d), diminishing the transportation and deposition of material on the delta front. Thus, nowadays in the region, marine processes predominate, eroding the coastline. The area which in 1960 was covered by the river's prodelta is now submerged (figures 5e and 5f).

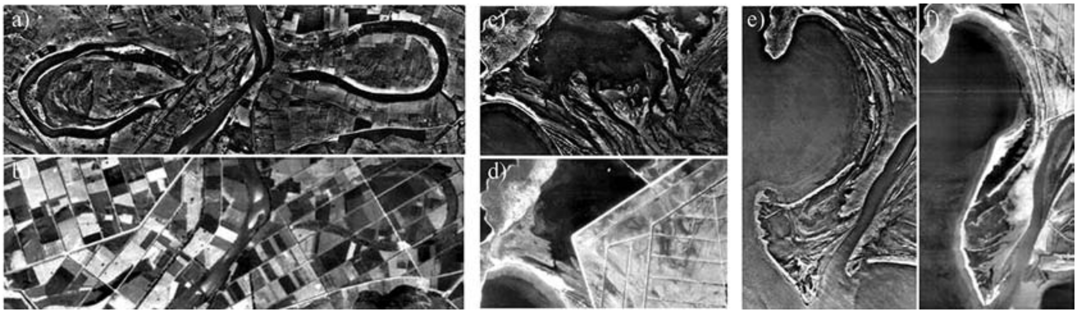

Figure 5. Landscape changes in Acheloos Delta: (a), (c), (e) images of the year 1960; (b), (d), (f) images of the year 1986, © Hellenic Military Geographical Service 1960 and 1986.

The changes to the landscape caused by human use disrupt the natural equilibrium. In nature, many destructive forces are counter-balanced by another natural process, thus maintaining a balance in the landscape. Such dynamics are minimised or altered by the human component, not always for the better. This field is complex and requires the analyses of much data.

4 DIGITAL DATA FORMATS AND SOURCES FOR GEOCULTURAL LANDSCAPE RESEARCH

A GIS enables the integration of data needed for the geocultural landscape research, its storage in a database management system, the manipulation and analysis of the data, and finally the visualisation of the results. The data needed for geocultural landscape analysis in a GIS, especially in the case of change monitoring, are provided in many different formats and come from various sources. For instance, these include cadastral data, aerial and satellite images, field survey data, land registers, and various statistical and expert data. The study of remotely observed data gives the scientist a first view of the area's state. More contemporaneous data though, can only be acquired by scientist's in situ research through fieldwork. This data is then combined with data and information from other sources and integrated into the GIS.

4.1 *Data formats*

There are two data formats which can be integrated in the GIS: raster and vector. Raster data consist of a matrix with an implicit specification of the spatial location attributable to the system of rows and columns. The single elements of the matrix are called pixels which include the image information. Such raster data could be scanned analogous maps, image interpretations, orthophotos, or satellite images. A special group of raster data are grids which can represent a digital elevation model. A georeferenced raster (see section 5.2) might be used for digitisation of different characteristics and therewith the productions of a vector layer.

In general, vector data are used for the representation of discrete features defined by coordinates which can be linked to related geographical information stored in an attribute table. The features can be points (locations), lines, or polygons. One common way of generating vector data can be the digitisation of scanned cartographic material in the GIS (see section 5.1).

Aerial photos and satellite images:
cf. chapters "The application of digital vertical aerial photogrammetry in the recording and analysis of archaeological landscape" of Corns & Shaw and "The use of satellite remote sensing for detecting and analysing cultural heritages" of Heinrich et al.

4.2 *Aerial photos and satellite images*

Aerial photographs and satellite images provide information in different levels of detail and accuracy, depending on their scale and origin. The new generation of satellites provide very high resolution imagery that is comparable to aerial photography.

The study of aerial photos or satellite images is very important, especially when observing and analysing images of different dates in order to trace changes in landscape through time. In that case, alterations of the environment are immediately seen, especially when dealing with sensitive environments (e.g. river deltas), and can be tracked down and depicted on maps of environmental change. Depending on the nature of the study, the available shots and their characteristics, the researcher decides whether the use of aerial photos or satellite images is appropriate. Specifically, for the study of the evolution of the environment for a period of several decades before the present, the use of aerial photos is essential.

The analysis of both aerial photos and satellite images includes their interpretation by direct observation or by specialised software. The aerial photos' and satellite images' interpretation can either be stereoscopic or not. In the case of stereoscopic observation, two adjacent images with a common area are required. The process can take place either by using analogue images and a stereoscope (figure 6), or digital images and the appropriate software (figure 7).

The stereoscopic observation provides the scientist with the ability to view the studied areas as if he were above them. This way, it is possible for the researcher to recognise many structures that cannot otherwise be detected from the photos. In the case of importing a photo interpretation's result in a GIS, the traditional way through stereoscope, requires an extra stage, namely import and georeferencing of the developed map and then vectorising it. Image interpretation through special software and hardware leads to the direct digitisation of the observed forms in a GIS. For the stereo-observation of aerial photos through computers, the use of special equipment is required, including software and hardware. But, before this stage, the preparation of aerial and satellite images needs adjustments. This stage concerns the processing of the digital images with various techniques in order to improve the imagery due to errors of photography and distortion. This stage contains the application of geometric corrections (e.g. removal of the deformation

Figure 6. Stereoscope with two analogue images, © Vassilopoulos & Evelpidou 2008.

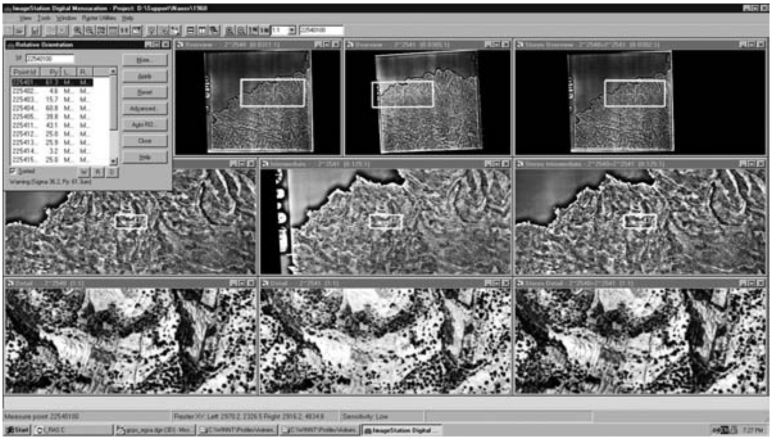

Figure 7. Photo interpretation procedure done within Image Station software (Evelpidou 2003a): The upper part of the figure shows three sequential aerial photos which are then photointerpreted and displayed in the middle of the figure. A box from the middle part is enlarged in the lower third of the figure.

imposed by the photographic lens attributes) and radiometric corrections (removal of the distortion caused by the atmosphere, e.g. due to refraction or diffraction).

Image Station photogrammetric software:
www.intergraph.com/learnmore/sgi/photogrammetry/digital-photogrammetry.xml

Through the use of special liquid crystal glasses, the photointerpreter may view the area stereoscopically and, following a procedure similar to digitisation, may import and finally depict the interpreted forms into a GIS. The user defines the information layers in which each interpreted and simultaneously digitised characteristic will be stored. Figure 7 shows a photo interpretation procedure done through the Image Station photogrammetric software.

4.3 *Global Positioning System (GPS)*

Global Positioning System (GPS):
cf. chapter "Using mobile GIS for Field Digital Data Acquisition (FDA) in archaeological field survey" of García-Dils de la Vega & Ordóñez Agulla.

Global positioning system (GPS), growing in use and popularity, provides specially coded satellite signals that can be processed in a GPS receiver, enabling the receiver to compute position, velocity and time. At least three GPS satellite signals are used in order to compute the location of the GPS receiver. This technological advance has provided researchers with excellent geographical precision during fieldwork. Precision is achieved through use of different types of GPS technologies. The use of simple, portable GPS devices (figure 8a) can provide precision with an error 0.2–1 m depending on the receiver. For certain cases this error is not significant, while the procedure is quite fast.

In the case of drillings or pinpointing of archaeological findings, the accuracy of a portable GPS is often not sufficient. Here, a differential GPS can be employed, which requires a more time consuming procedure. Furthermore, a differential GPS constantly provides geometrical corrections according to the nearest constant trigonometrical points, thus achieving precision up to 0.05 m (figures 8b and 8c).

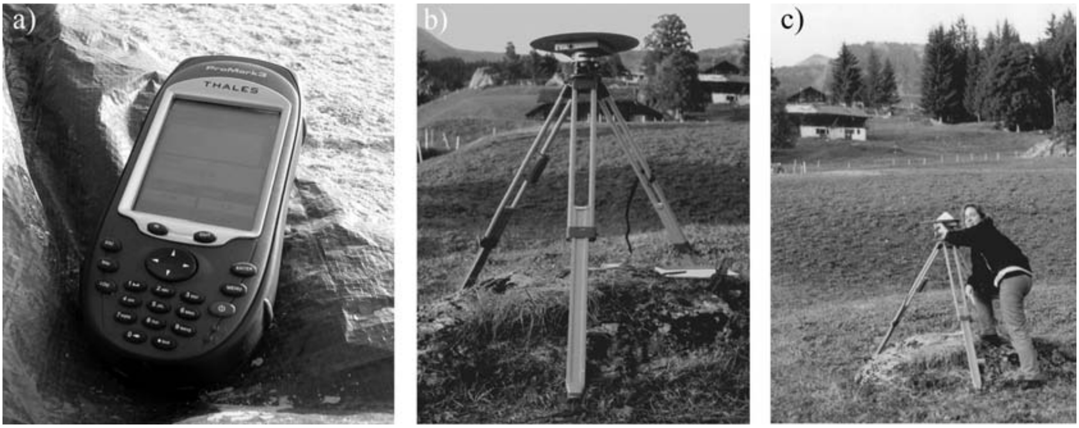

Figure 8. (a) Portable GPS, © Vassilopoulos & Evelpidou 2007; (b), (c) Differential GPS, © Krek 1991.

4.4 *Data acquired by the field work*

In the field, data related to formations' micro-structures such as composition, foliation measurement, striation directions, dating of formations, etc. may be acquired. In order to achieve the measurements needed, many techniques can be used, among which, most common, are those of core sampling, drilling (figure 9a) or setting of measuring devices. Once the samples or cores are collected, proper laboratory research will provide the desired results. In order to analyse an area stratigraphically, research is held under the expertise provided by palaeontology and advanced stratigraphy (figure 9b). Concerning the composition and texture of the studied formations, the techniques used are grain size analysis, micro-observation of thin sections of the formation, use of chemical reagents, etc. As far as dating is concerned, many different methods exist using different elements such as the C^{14} dating, the pollen analysis, or the

Figure 9. (a) Drillings for the collection of core samples of sediment, (b) Stratigraphic study of the core samples, © Vassilopoulos & Evelpidou 2007.

Figure 10. Collection of sand samples from dune formations, © Vassilopoulos & Evelpidou 2007.

luminescence technique. The latter is based on the fact that the emission of radiation towards the material causes the release of electrons from the valence band and their diffusion towards the conduction band. The population of the trapped electrons is relative to the specimen's age and the radiation intensity of its neighbouring material.

Figure 10 shows the application of luminescence techniques in coastal dune formations in the Aegean, Ionian and Cretan Sea, aiding the accurate dating of the formations' age, the research of their creation eras, and the drawing of conclusions concerning possible changes in the aeolian status, the sea level, or the possible existence of periods of intense sand accumulation.

5 GIS AS A SOFTWARE TOOL

GIS are often associated with the software used for the implementation of their concepts and technical structure. The GIS software has been produced by several companies. Their products enable the geocultural landscape researchers to use the functionalities provided by these software packages and to use the data integrated in the system. In this chapter, only the most commonly used functionalities and capabilities for geocultural landscape researchers are explained. The research of landscape alterations includes many separate stages which depend on the nature of the studied changes and the time during which they took place. The use of particular functionalities depends on the analysis that can be best supported by GIS software. The description within this section follows the usual order of the whole analysis process starting with acquisition and georeferencing of data, their integration from different data sources, execution of simple or complex queries, visualisation, 3D analysis, and simulation.

5.1 *Vector data acquisition*

Vector data acquisition may be accomplished by using different methods. Most common is the digitisation of information included in raster files. Onscreen digitisation is the most common way of vectorising information. This way, one has to follow, using the computer mouse, objects shown on a raster layer. Digitisation is a time consuming process and that is why many attempts have been made to automate this procedure. Consequently, many different software programmes for automatic digitisation exist, as well as for semi-automatic digitisation. The latter is an activity in which the researcher supervises the process and gives directions to the software each time the path is not one-track, especially in the case of an intersection with two or several lines available for continuing the vectorisation.

Onscreen digitisation:
cf. chapters "The concept of a historic landscape analysis using GIS", section 2.4, of Bender and "Use of historical cadastral maps in modern landscape research and management" of Domaas & Grau Møller.

Semi-automatic digitisation:
cf. chapter "Mapping and analysis of linear landscape features" of Gugl.

Digitisation includes points, lines/polylines, or polygons, set on different information levels according to the object's geographic nature or to the information they depict (e.g. contour lines, hydrographical network, etc.). Each geographic element is accompanied by a database which holds all descriptive information.

As mentioned, digitisation is the most common method of data acquisition; however, it is not the only one. Other common methods are:

a) Automatic point creation from a database that must include geographic coordinates of the points to be created. This method's most common example is a database of points taken through the fieldwork and registered in a GPS memory.
b) Geocoding, through which a GIS automatically creates points, based on their descriptive information stored within the database, and associates them to another information level. A typical example is the placement of points to addresses (descriptive information from the information layer of the database that will be geocoded) based on an urban design net (e.g. linear information layer which also includes addresses).
c) Segmentation as a process of partitioning a raster image into regions.

5.2 *Georeferencing of data*

Georeferencing:
cf. chapter "Use of historical cadastral maps in modern landscape research and management", section 3, of Domaas & Grau Møller.

All data imported into a GIS has to be georeferenced, which means the assignment of spatial reference information to a raster image through the definition of at least three control points. The word was originally used to describe the process of referencing the image of a map in a geographic location. Nowadays, it is commonly used as well for establishing a relation between raster or vector images to map projections or coordinate systems. When data from different sources need to be combined and then used in a GIS application, it becomes essential to have one common referencing system. The researchers can georeference a set of points, line segments, polygons, images or even 3D graphic elements.

In the process of georeferencing, the operator has to define the control points for which the geographic coordinates are accurately known, select a coordinate system and its parameters, and minimise residuals. By inserting the real coordinates of the controlling points, the translation and rotation of the image or map occurs by moving it into the position of the selected coordinate system. Residuals are the difference between the actual coordinates of the control points and the coordinates predicted by the geographic model created using control points. They provide a method of determining the accuracy level of the georeferencing process.

5.3 *Map overlay*

Map overlay involves the analytical capabilities of a GIS between map objects and the descriptive information related to the presented objects. The geometrical characteristics of the objects are directly shown within the map window. A combination of layers may be done by calculating the logical intersection of map objects on two or more information layers. Descriptive information is stored within the database of each information layer and geographical information may be calculated by the GIS and added to new fields of the database. Different information layers

Combination of layers:
cf. chapter "The workflow of a historic landscape analysis using GIS", section 2.1, of Bender.

presenting a variety of content may be displayed as separate information layers or in a combination with topics of interest.

5.4 *Simple queries*

Simple queries are the basic functions included in a GIS which among others include functions ‘find’, ‘select’, ‘info’ and ‘distance measure’. The function ‘find’ enables the user to find particular features or patterns. Finding leads to the identification of items of interest either to the map or to the database. ‘Select’ enables the selection of map objects with specific characteristics which may be depicted both in the map window and in the database. For single maps, or relatively small areas, the human brain is very efficient at finding and selecting map objects. However, as data volumes increase, automated methods are required to effectively extract and use information from the map. ‘Info’ returns the information stored in the database for the selected map object. The ‘distance measure’ function enables measuring the distance simply by pointing the locations that needs to be measured on the map, and then displayed on the computer screen.

A range of quantitative queries enable the determination of objects which are defined by their coordinates, the determination of areas where the object is found, etc. These queries also involve the assignment of surface or linear objects’ size, the distance between specific objects or from a specific point, etc. The desktop GIS programmes try to include these functions in the most probable intuitive way.

5.5 *Complex queries*

Complex queries may include the assessment of issues controlled by user defined variables. A GIS platform which contains appropriate data can evaluate different parameters and respond with an estimation for difficult questions/issues as, for instance, environmental changes which may occur after a specific time span, or ‘what happens if’ type of questions. For example, in some areas it is very important to know what will happen during, and what might be the result of a possible water level rise in a river catchment or in the sea. This capability was used for the recreation of the palaeolandscape of Cyclades Islands (figure 11), according to a sea level rise of 120 m over the last 18,000 years (Gaki-Papanastassiou et al. 2005). Such analyses are very useful in environmental problems that modern society faces, like for example ‘what if sea level rises x m?’, ‘what if water level rises x m in a riverbed during a flood’, ‘what if a dam breaks and how much time is available for settlement evacuation?’ The ability to respond to a variety of simple and complex questions is one of the most useful features of a GIS.

Visualisation by cartograhy: *cf. chapter “The workflow of a historic landscape analysis using GIS”, section 2.1, of Bender.*

5.6 *Visualisation by cartography*

Visualisation can be used in all phases of a research. Very often it represents an intensive phase during the last stages of research, including the

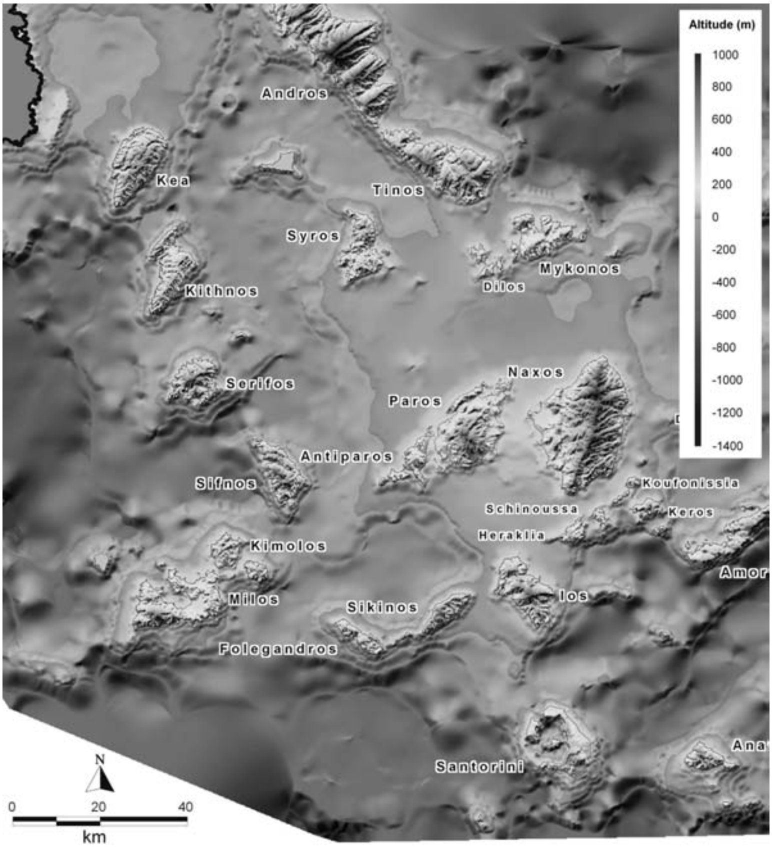

Figure 11. The relief of Cyclades Islands, Greece (Gaki-Papanastassiou et al. 2005).

selection of the map sections that need to be printed, using an appropriate symbology, creating a legend, and generally following all necessary steps in order to develop a map (e.g. orientation, scale, etc.). Basically it is used as the substantiation framework of the study's results and conclusions, but it usually starts at the beginning of the research, since every detail that comes from the observation of aerial photographs, satellite images, fieldwork, etc. is simultaneously gathered within different information layers.

The correlation between information layers is established through GIS, and it is the first step to develop a map. Maps and visual representations are also created in order to reach conclusions for research purposes or for a particular geocultural landscape analysis. The creation of a map is not an easy process, since it requires knowledge of all the proper symbology of the depicted characteristics, as well as scientific know-how that will filter out the inclusion of unnecessary data and will ensure the optimal depiction of the necessary characteristics.

The representation of the database information within the map is achieved through thematic cartography procedure. Thematic cartography can also be used for the representation of the results from specific queries set by the user. There are many types of thematic maps and each type is used in a different way and has specific attributes (Dent 1999, Slocum et al. 2008). Some thematic types can represent differently the variety of information stored into the database. One simple example is the application of specific colours on the different types of land use. Other types of thematic maps represent specified ranges of a value (e.g. the geographical distribution of morphological slopes of an area). A thematic map also can represent town populations with dot clouds which are denser when the population is higher. It also can represent more than one type of information in the form of histograms or pie charts.

5.7 *3D GIS analysis*

A 3D GIS analysis is complex and requires appropriate models enabling and supporting such analysis. First of all, the transition into 3D means a higher diversity of object types and spatial relationships which need to be considered. A simple example is the visibility study in a purely environmental or geoarchaeological application (figures 12a and 12b).

For environmental applications, the visibility study delivers one of the most significant parameters for the selection of a waste/recycling center. However, the development of maps showing the locations from which such an under construction area will be visible, is not a simple procedure without the assistance of GIS. For geoarchaeological applications, e.g. for a visibility study of several places from a principal site, the analysis of multi-variable parameters constitutes a powerful tool. In such an application, figures 12a and 12b show the visible parts between the observer and point A, and the observer and point B (Evelpidou 2003b). There are many different 3D analysis applications for different research needs, such as slope and aspect analysis, viewshed analysis, cross section, and others.

Environmental applications, aspect analysis:
cf. chapter "Spatial interpolation and terrain analysis", section 3, of Hofierka.

Visibility study, viewshed analysis:
cf. chapter "GIS landscape models for the study of pre-industrial settlement patterns in Mediterranean areas", section 4.2, of Chapa et al.

Slope:
cf. chapter "GIS landscape models for the study of pre-industrial settlement patterns in Mediterranean areas", section 4.1, of Chapa et al.

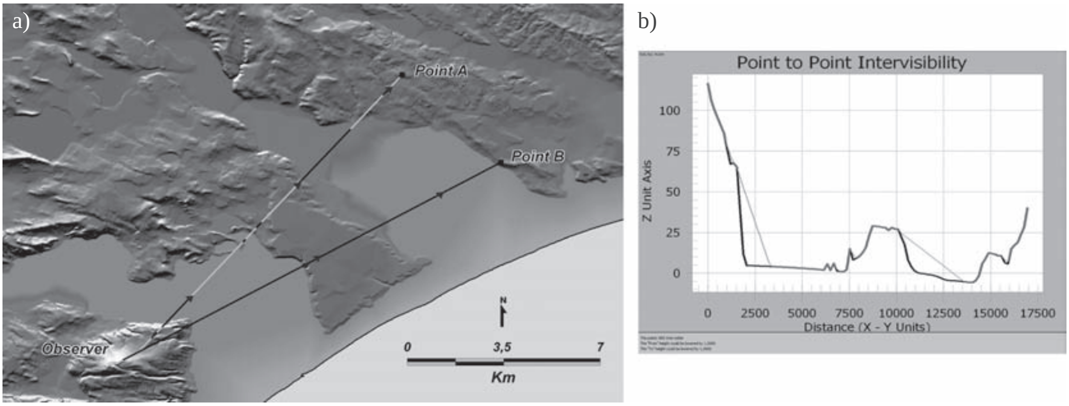

Figure 12. (a) The visibility between the observer, point A and point B. The light grey parts of the line depict the parts that observer may observe, while the opposite happens for the dark grey parts (Evelpidou 2003b). (b) The algorithm may develop a cross section which depicts the parts between the observer and point A which are visible (light grey line) and invisible (dark grey line). Moreover, the algorithm may give the height which could be lowered or raised with the 'to' or 'from' point in order to be intervisible (Evelpidou 2003b).

5.8 *Spatial modelling*

A spatial model can depict the expected result from a decision or set of decisions. A GIS includes spatial models or numerical analysis methods to enable more complex analysis. Spatial modelling used for predictions and for developing a decision making system is one of the most demanding analytical uses of a GIS. Engineers and planners can evaluate alternate solutions to problems by 'what if' type of questions. Spatial simulations are such examples. They involve complex procedures and models. Spatial modelling often represents a study's final stage, during which the researcher depicts, through simulation, the upcoming state, and has a number of applications in environmental study and analysis.

Decision making:
cf. chapter "The workflow of a historic landscape analysis using GIS", section 3.2, of Bender.

The most common data set used in spatial modelling is the digital terrain model, useful for the creation of digitised contour lines, hypsometric and trigonometric points. Through simulation, the altimeter value for every point of the map based on the existent elements can be calculated. On the following picture (figure 13), the results of a spatial modelling analysis in order to develop a decision making system are shown, representing the Psarianos watershed in Crete island (Greece) in case the dam breaks (Evelpidou et al. 2007). These kinds of applications are dynamic and time dependant.

Digital Terrain Model (DTM):
cf. chapter "Spatial interpolation and terrain analysis" of Hofierka.

The quality of the result is only as good as the model, but the ability to test solutions before decisions have to be made usually provides very useful information to the decision makers. This type of use of a GIS will evolve over time, as the GIS is implemented and used.

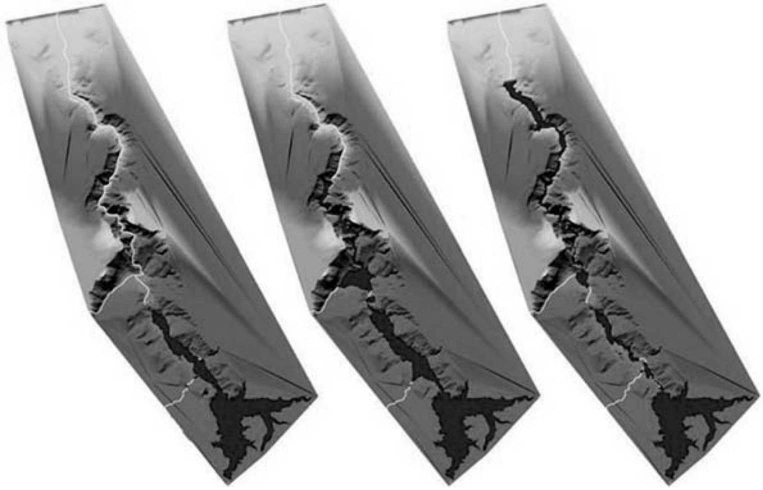

Figure 13. The spatial modelling analysis of Prasianos watershed showed that in case of the dam breakage the reservoir of the dam looses all of its water in 55 minutes, the flood wave reaches the "OUTFALL" in 92 minutes and delivers a discharge of approximately 10,000 m^3/sec and the maximum velocity of the flood wave is 15.3 m/sec (Evelpidou et al. 2007).

6 GIS AS A METHODOLOGY

A GIS can be used as a software tool, but also as a methodological approach following a series of procedures defined by the user. In this section, the methodology is considered as a set of procedures defined and applied by the geocultural landscape researcher using a GIS. These procedures can be either completely supported by a GIS or they can be partially accomplished by manually executed procedures where only some segments of research are done with the help of a GIS. A GIS can be possibly combined with other software packages that allow for an exchange with the GIS data formats. The development of a methodology enables the researchers to formalise the procedures used within their analysis. If properly designed, it can be exchanged by researchers and repeated in various research studies. The advantage lies in a methodology which is developed, formalised and efficient and can be shared by the researchers within the same or similar area of research.

6.1 *The methodology design loop*

The design of the methodology depends on the research questions and the needs of the landscape research. The authors of this chapter suggest using a methodology loop according to which the researcher begins with a priority question (figure 14). The research question, or a set of questions and their characteristics, define further steps in the process of research and the methodology design. The methodology design includes a description of the steps and phases necessary to undertake the geocultural landscape research, resulting in the scientific analysis of the results. It defines several elements of the methodology (figure 15) such as data sources, input information and knowledge, data needed for research, steps and procedures that need to be undertaken in the process of research, GIS and other IT tools needed to support the analytical functions, and expected scientific results.

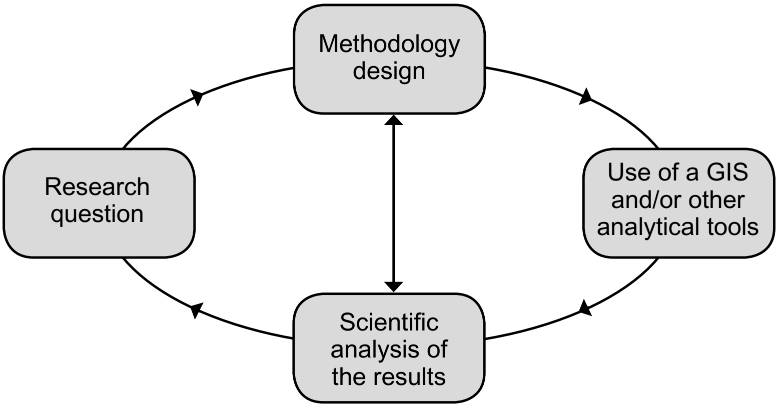

Figure 14. The methodology design loop.

Several factors influence the selection of the methodological procedures and software which can support the researcher. When dealing for example with erosion processes, the researcher has to clarify the interactive factors in order to attain erosion’s final result (figure 16). In this case, the first step is to analyse and to understand the role of each factor in an erosion process, and then to define the way these factors interact in order to simulate them and generate a “forecast” which contains the requested result.

The design of the methodology is followed by the actual use and implementation of the software in the phases defined within the methodology (figure 14). In the analysis of the erosion processes, for example, the researcher conducts a simulation with the help of GIS tools. If the simulation is perceived as a function and the rest of the factors as variables, then the first case is to import the influencing factors into the GIS. In the final stage, the landscape researcher performs a scientific analysis of the results gained from the use of GIS and other analytical tools.

The methodology loop is suggested by the authors of this chapter, and aims at stressing the need of revisions and feedback as the result of the new insights gained in the process of research. For example, in the phase of the use of a GIS tool, the researchers might recognise the need for using other analytical tools. This new knowledge will reflect the changes

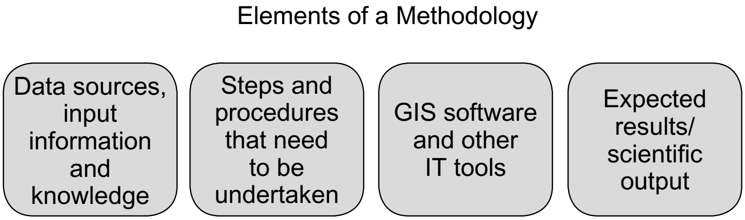

Figure 15. Elements of a methodology.

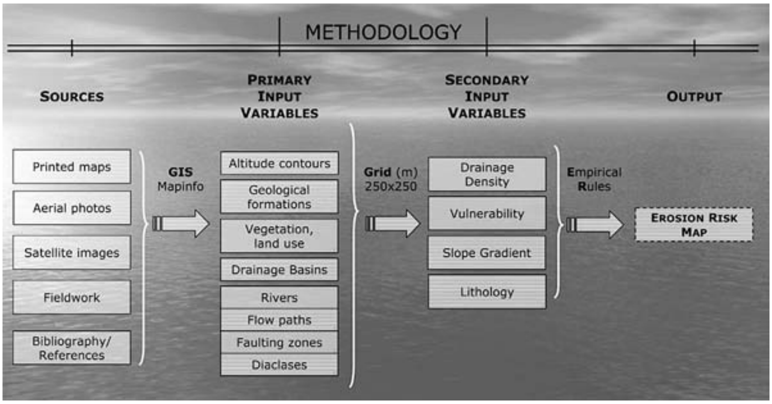

Figure 16. A methodology for the estimation of erosion risk (Gournelos et al. 2004, Sabot et al. 2002).

of the methodology design – including new software tools into the methodology design. Something similar can happen in the stage of the scientific analysis of the results where each of the former steps in the loop, for example the methodology design, or even the research question, can be revised and improved according to the new knowledge gained within the process of research.

6.2 *Example of a methodology and its elements*

Figure 16 shows an example of the elements used within the methodology designed for the analysis of erosion risk's spatial distribution (Gournelos et al. 2004, Sabot et al. 2002). This analysis is determinative for the prevention of forthcoming erosion events and focuses on the investigation of erosion risk in the selected area. The methodology based on a GIS used for analysis and predictions, enables to depict results on thematic maps (figure 17).

The designed methodology used the methodology elements presented on figure 16. The data sources included printed maps, aerial photos, satellite images, fieldwork and the literature relevant for the analysis of erosion risk. The primary input factors influencing the erosion risk were identified and include (Sabot et al. 2002) variables of altitude, geology, land use, vegetation, drainage networks, drainage basins and faulting zones. Analysis of the correlations between the primary factors enables to define the secondary factors. For example, rocks' vulnerability is the correlation result of land use, vegetation, faults' existence in the area, etc. In the case of erosion risk analysis, the secondary variables include the drainage density, the slope gradient and the vulnerability of the rocks (Gournelos et al. 2004, Sabot et al. 2002).

The secondary variables are used as an input for the simulation of the erosion risk. The simulation which is achieved by using the proper empirical rules, applied with the help of a short algorithm developed in a GIS programming language. The results of the scientific analysis are the thematic maps showing the geographical distribution of the erosion risk classified in several risk classes. Figure 17 depicts the parameters estimated with the use of a GIS and the final erosion risk map which was developed based on the interaction of the described parameters.

6.3 *Development of specific GIS modules*

A very important tool provided by GIS software is the ability to develop new modules which are actually algorithms applied as add-on software on the GIS platform. Database management can often prove to be very time-consuming, even though in some cases the chosen actions are specific and prearranged. The development and execution of an algorithm which contains a script of the actions can apply them automatically, saving time and effort for the user. Besides database management, the development of modules can be used for the implementation of actions which refer to geographical queries.

A relevant example is the problem that occurred while dealing with the need to trace predominant directions of linear characteristics in the Beziers

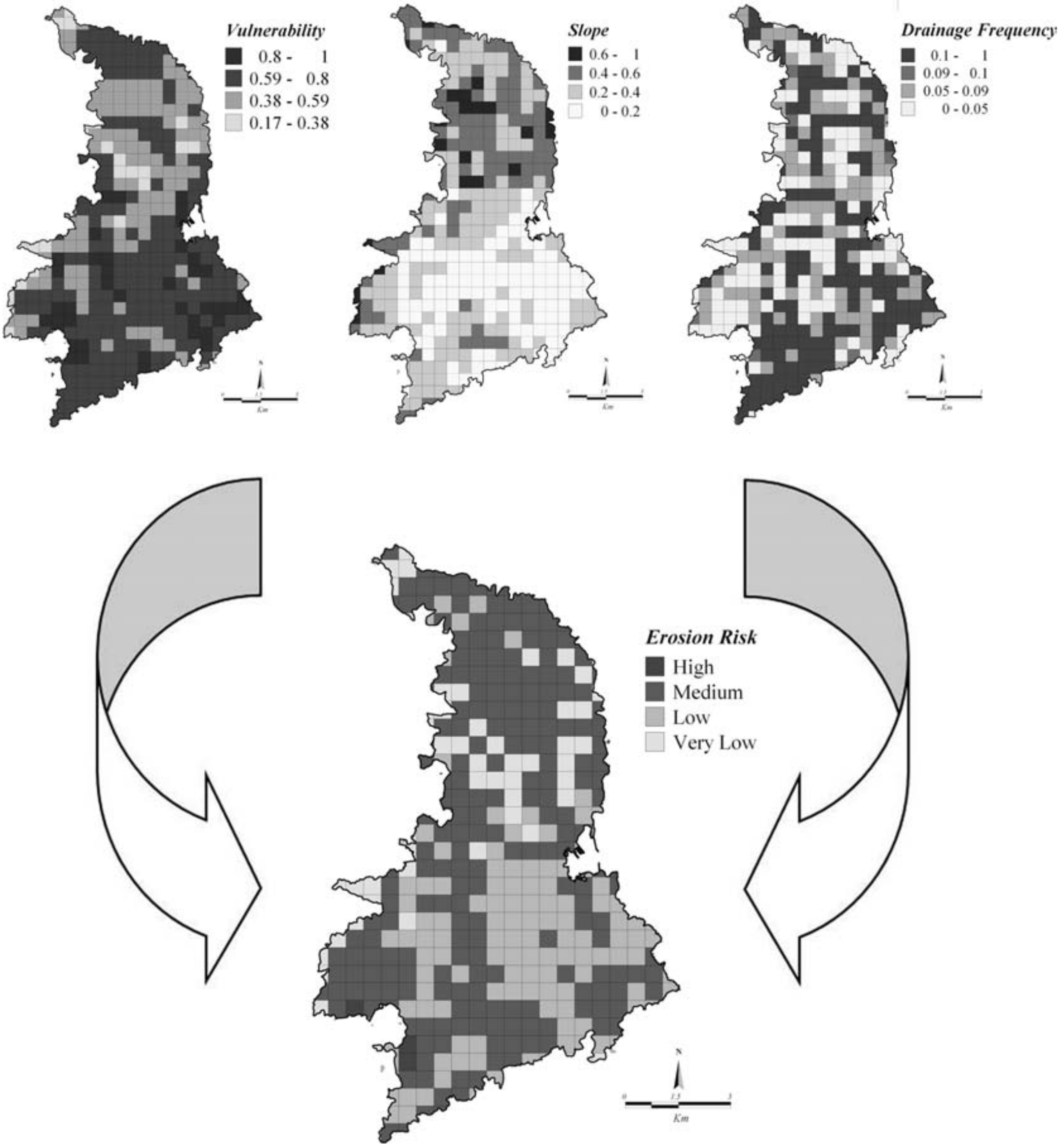

Figure 17. The principal parameters for the erosion risk model were calculated and geographically distributed, and then used to extrapolate an erosion risk index and to develop the final erosion risk map (Gournelos et al. 2004).

area in France for research on Roman cadastres (Clavel-Lévêque 1992). The typical method that was followed for this research included four steps:

a) depiction of possible cadastre lineaments on transparent paper, from maps and aerial photographs,
b) creation of grids of various line width and cell size in transparencies which are set on top of the lineament transparencies in order to locate the lines which have orientation similar to the grid,
c) calculation of the amount of lineaments contained within each grid,
d) conclusion on the prevailing cadastre orientation.

Roman cadastre:
cf. chapter "Mapping and analysis of linear landscape features" of Gugl.

To solve this problem, the cadastre grid software was created (Clavel-Lévêque et al. 1998, Vassilopoulos 2001). These newly created software tools provided the user with the ability to create a grid of specified size, orientation and line thickness which is then automatically updated with the amount of lineaments whose direction matches that of the grid. In figure 18 such an example is shown. Lines fitting to the grid have been tracked, selected and bolded by the system. This way, the user only deals with the import of size and orientation numbers, and automatically receives the wanted result in the form of a statistic graph. The numerous statistic graphs are finally compared in order to derive the desired result.

7 GISCIENCE AND ITS RELEVANCE FOR GEOCULTURAL LANDSCAPE RESEARCH

GIScience is the science behind the GIS technology. It considers fundamental questions raised by the use of systems and technologies. It is the science needed to keep the GIS technology at the cutting edge. As a multidisciplinary research field, it includes many disciplines such as cartography, geomorphology, geography, photogrammetry, geodesy, planning, cognitive psychology, artificial intelligence, and more.

MapInfo Professional:
GIS software for mapping and geographic analysis.
www.mapinfo.com

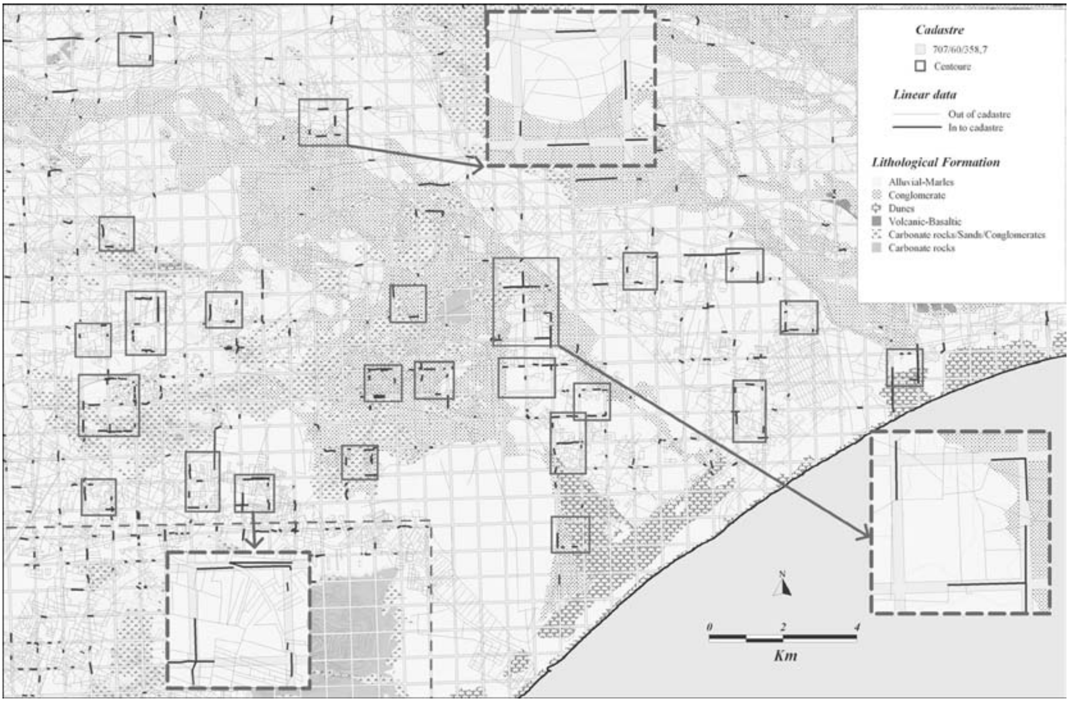

Figure 18. The cadastre grid software, an algorithm created to function through the GIS MapInfo, automatically creates different grids, tracks the lines coinciding to the grid and makes all needed geographical and statistical analyses (Evelpidou 2003b).

The terms ‘geomatics’ and ‘geoinformatics’ have similar meanings, and are popular in Europe and Canada (Goodchild 1992, Wright et al. 1997). The research questions related to GIScience and geocultural research range from those related to ontologies, categorisation and structuring of the landscape elements, their visualisation and representation on the map, to the issues concentrated on data modelling, integration and representation of time and space. In this chapter, we address research issues relevant for GIScience and geocultural landscape research. They are discussed below and present an open-ended list which can be extended with new topics as they appear to be relevant in the moment of investigation.

7.1 *Questions of representation*

Questions of representation deal with the elements of the geocultural landscape, their structure and representation in a GIS involve issues such as: which elements are necessary for the geocultural landscape analysis; how should the selected elements or objects be presented and stored in a computer-based environment; which are the most appropriate inputs the researcher should use for the selected methodology; which criteria are to use in order to select the most appropriate representation of the geocultural landscape elements and their correlations? The criteria for the selection of representation can be the data quality, the quality of the model, the accuracy of representation, data volume or compatibility with other researchers in this research field. A visualisation of the selected elements is related to the representation and is itself a very interesting research area.

7.2 *Ontologies*

Ontologies study conceptions and the nature of being. GIScience deals with a set of concepts and their relationships, and focuses especially on the possible ways of structuring, identifying and describing these elements which in GIScience are often called objects. Ontologies are used to reason about spatial objects and their representations. The research in this area, carried out by several geoinformation scientists (e.g. Fonseca 2001, Fonseca et al. 2002, Frank 2001), can be of interest to geocultural landscape researchers. Further research should investigate the possible implications of GIScience in this area and its applicability for the research issues relevant for geocultural landscape analysis.

7.3 *Questions of quality*

Data quality is a well established research field in GIScience and has been discussed before, for example by Chrisman (1983 and 1991), Frank (1998), Fisher (1999), Goodchild & Jeansoulin (1998), Guptill (1991 and 1993), and Tayi & Ballou (1998). Additionally, the International Standardisation Organisation (ISO), the European Committee for Standardisation (CEN) and the Spatial Data Transfer Standard (SDTS) provide classifications for spatial data quality dimensions. Data quality represents only one field of research. Questions of quality address different levels of quality: quality of the data sources, data quality itself, quality of the model, quality of representation, and quality of information that can be extracted from an information model. They are all relevant for geocultural landscape research, because they influence the quality of the scientific results gained by the help of the acquired data sources. Understanding the quality of data sources and information helps researchers to understand the quality of their results and consequently the quality of the decisions taken by the information gained from the information model. Related issues deal with the way the quality can be expressed, described and measured.

7.4 *Questions of display*

Research related to the methods of display focuses on the interpretation of the meaning of the data (semantics) and how different forms of display affect the interpretation of geographic data, and the ability to retrieve information from the data. The research deals with the questions how the data should be displayed in order to provide the necessary information and prevent manipulation, and what basic properties of display determine its success? These research questions are of special importance for researchers that use geographic data and combine them with other information sources, which is often the case in geocultural landscape analysis. The way in which the data is presented and displayed influences the interpretation of this data and with this also the results of the analysis. An example of this would be a very aesthetic and well designed representation of a planned landscape in 3D which could lead to a higher acceptance of this particular planning alternative as opposed to a 2D map representation of the alternative solution. The scale chosen for the display influences the ability to extract the information from the map; too small scale does not allow the extraction of a detail sometimes needed for the interpretation of the gained scientific results.

7.5 *Questions of data integration*

Such questions deal with the integration of data stored in a variety of formats and the inter-operability among different information systems. Some standards and specifications that support interoperability among different systems have been developed by the Open Geospatial Consortium (OGC) which is a non-profit, international, voluntary consensus standards organisation that is leading the development of standards for geospatial and location based services. Standardisation organisations ISO and CEN work on these issues and develop standards for geographic data and metadata. The research issues are significant for the geocultural landscape researchers who use different software packages and different de-facto-standards, but would like to exchange their results, data and analysis with other researchers in their field.

7.6 *Questions of methodology design*

New software tools and computer-based methods change the procedures and processes used in geocultural landscape research and analysis. Relevant research issues concern changes and reengineering of these processes (Hammer & Champy 2003). Questions about the design of methodology focus on possible standardisations of methodologies needed for specific geocultural analysis and their applicability for other research areas. The possibility of standardisations within a selected methodology has to be investigated in addition. The research questions related to the design and selection of an appropriate methodology deal with issues such as: what is the optimal workflow for a specific analysis; how many steps should be taken; which software tools are the most appropriate for the selected phase; how can they be combined with other software packages used in other steps within the analysed methodology?

7.7 *Questions of analytical tools*

Analytical software tools are very important for geocultural landscape research. The success of the researcher's work and the interpretation of the results depend on the proper selection of these tools. Relevant questions include the following: which analytical software tools are needed for geocultural landscape researchers and how should they be designed in order to support researchers in their work; which computer-based methods and tools are needed to support specific types of decisions made using GIS; how should these tools be designed for the specific needs of geocultural landscape researchers?

7.8 *Design of a GIS user interface*

The design of a GIS user interface is a recognised research topic in GIScience. The research in this area goes back to the early 1990s (Kuhn 1989 and 1995, Richards & Egenhofer 1995). A GIS is often, in spite of these efforts, considered to be difficult to use, designed for experts and considered to be a rather complex software package. Additional research is needed in order to understand human interaction with a GIS and different representations of space offered by a GIS. Special groups of users such as geocultural landscape researchers might have special requirements for the design of the user interface. The research issues are related to the design of intuitive and intelligent user interfaces which will include representations made more like the ways people perceive the space.

7.9 *Time and space*

How to represent time and space in a GIS, is a very important issue. The currently used concepts represent time-space relation in the form of a series – which can be time, feature, and attribute or raster series. Time series are a collection of time and corresponding values. They can be indirectly georeferenced through a many-to-many relationship which means that many time series records can be related to many spatial features. An attribute series is a collection of time-value pairs that are related to one spatial feature. A feature series is a collection of features indexed by time. Each feature in a feature series exists for only a period of time. Raster series are a collection of rasters indexed by time. Each raster is a "snapshot" of the environment at some instant in time (Goodall et al. 2004). The research in this field deals with an innovative representation of time and space, spatio-temporal query language, and spatio-temporal inferential statistics beyond point objects.

8 CONCLUSIONS

This chapter presents different attributes of geoinformation technologies that may be applicable in geocultural landscape research. A GIS is often seen only as a software package which can help to accomplish certain analytical tasks. Even as such, many researchers considered it very complex and difficult to be taught. Thus, it is still basically used by educated and trained personnel, most of whom are researchers in this field or help researchers with the execution of selected computer-based analytical tasks. During the last few years new developments in geoinformation technologies have taken place, supporting non-experienced users in their experiments. As a result, GIS software became more and more friendly and useful to non-experienced users. A well known example of geoinformation technology supporting non-experienced users is the application provided by Google, named Google Earth. This application can be simply accessed via Internet and is available to anyone interested in an online geographical representation of the landscape.

GoogleEarth:
http://earth.google.com

The implementation of geoinformation technologies in geocultural landscape research is not limited to the use of a software package. More attention should be paid to GIS as a methodology and to the possible changes it could provide in workflow and analytical tasks. These technologies may change the researcher's tasks, processes, or even workflows. Additionally, the value of modelling and its consequent impact on the results' quality is crucial for the interpretation and the analysis of a GIS output. Data and information quality is only one of the many issues GIScientists have to deal with. Additional research related to the quality of the models used within the geocultural landscape research community and consequently the quality of the information and analytical results extracted from these models is needed. A cooperation of both research communities, GIScience and geocultural landscape research, can bring insightful results to both research communities.

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Part I

Primary data capturing

Using mobile GIS for Field Digital Data Acquisition (FDA) in archaeological field survey

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ABSTRACT

This chapter discusses an implementation of a low-cost solution in archaeological research concerning the on-site data input of geographical information in a GIS by means of a handheld computer equipped with GPS, i.e., using mobile GIS and FDA (Field Digital Data Acquisition) methodology. The main advantage of this methodology is to avoid the degradation of the information from the moment of its acquisition on-site to the time of its processing and input in a GIS. Using FDA methodology is possible to capture data directly on-site using a handheld computer equipped with GPS, GIS and database software, and digital cartography. Another advantage of FDA is the economy of time, without having to waste it collecting data in conventional format on-site, to have to postprocess all this data in a computer with the risk of loosing vital information. FDA methodology guarantees the correct location, delimitation and documentation of settlements or landmarks, making the work on-site and realtime.

1 DATA COLLECTION/CAPTURE AND ITS IMPORTANCE IN ARCHAEOLOGY

Field Digital Data Acquisition (FDA) or Field Data Collection Automation (FDCA) is a methodology nowadays in full expansion in very different fields of study of various realities with spatial or geographic base, going from administrative management – for instance, the 2010 Decennial census of the United States is going to be carried out using an automated system for field data collection (N.N. 2006) – down to scientific research or nature conservancy (TNC Global Invasive Species Team 2005/07).

In archaeology, the study of the territory on a large scale has traditionally encountered the difficulty of having to record suitably the delimitation of archaeological sites, emergent structures or historical landmarks, either with a pure scientific purpose, or with the aim of establishing protection areas in urban planning documents. The principal difficulties that the on-site researcher has to face are (cf. Campana & Francovich 2006, Coloso et al. 2006):

– The exact positioning of the limits of sites, structures and landmarks in the map; even using the potentiality offered by Global Positioning

Systems (GPS), it is not always easy to be located in the cartography, and errors are frequent (Topouzi et al. 2002);
- The possibility of transcription errors with the on-site data, particularly if the transcription was made by a different researcher;
- The prohibitive prices of GPS and FDCA technologies.

This chapter is focused on data collection in the on-site delimitation of archaeological sites, with the double purpose of documenting the diachronic evolution of the landscape and protecting efficiently these sites, combining the requirements both of heritage protection and urban planning.

The methodology presented in this chapter is only one of the possible approaches. As has been repeatedly pointed out (Forte 2002, Lock 2003, Ziebart et al. 2002), the use of computers and digital data in archaeology are centred mostly on the post-excavation data analysis, rather than in on-site digital data capture on-site. While digital systems of archaeological record in excavation are also well known (Wheatley & Gillings 2002), this chapter will deal specifically delimitation in large scale projects focused on the territory. This methodology is based in the use of a Personal Digital Assistant (PDA) – particularly, HP iPaq hX2790 – linked via Bluetooth to a GPS external device, using the Microsoft Windows Mobile 5.0 operating system and the software ESRI ArcPad 7.0.1.

Initially, digital cartography along with aerial and satellite photographs of the study area are downloaded to a memory card, for use in the PDA. Once, the researcher is located in the working area, he has to establish a link (via Bluetooth) between the PDA and the external GPS device. Then, the system is ready to surf in real time over this area, capturing data directly on the spot, in the same format that it will be used later on the desktop computer in the GIS programs.

Global Positioning System (GPS):
a satellite based navigation system that allows the determination of the exact geographical location on Earth with accuracies up to one metre.

Personal Digital Assistant (PDA):
a compact, handheld computer which can be used as organiser, navigator, mobile phone, web browser, media player or GIS platform.

Bluetooth:
a standardised interface which is used for communication between mobile handhelds, such as mobile phones or PDAs, and computers or other peripheral devices for data transfer. It replaces the cable connection between devices.

2 GLOBAL POSITIONING SYSTEM (GPS)

The Global Positioning System (GPS), officially named NAVSTAR GPS, developed by the United States Department of Defense (U.S. Coast Guard Navigation Center, n.d.), is nowadays the only fully functional and fully available Global Navigation Satellite System (GNSS) in the world. By means of a constellation of at least 24 medium Earth orbit satellites that transmit precise microwave signals, the system enables a GPS receiver to determine its location, speed and direction. As of September 2007, there are 31 actively broadcasting satellites in the GPS constellation; the additional satellites improve the precision of GPS receiver calculations by providing redundant measurements. The GPS receiver, basically, calculates its position by measuring the distance between itself and three or more GPS satellites, using trilateration method.

The current GPS consists of three major segments. These are the space segment (SS), a control segment (CS), and a user segment (US). The first one is composed of the orbiting GPS satellites, equally distributed among six circular orbital planes, which have approximately 55° inclination – relative to Earth's equator – and are centred on the Earth. Orbiting at an altitude of approximately 20,200 km, each satellite makes two complete orbits each sidereal day, so it passes over the same location on Earth once each day. The orbits are arranged in such a way that at least six satellites are always within line of sight from almost everywhere on Earth's surface.

The control segment (CS) is dedicated to track the flight paths of the satellites. This task is carried out by monitoring stations operated by the National Geospatial-Intelligence Agency (NGA) and the US Air Force. The third segment of the GPS System is the user one, the GPS receiver. In the case proposed in the present chapter, is used an external GPS device, connected via Bluetooth with the PDA.

Each GPS satellite continuously broadcasts a navigation message, giving the time, an almanac and an ephemeris. The almanac consists of coarse orbit and status information for each satellite in the constellation. The ephemeris gives the satellite's own precise orbit and is transmitted every 30 seconds. The almanac assists in the acquisition of other satellites, while an ephemeris from each satellite is needed to compute position fixes using that satellite. It is very important to keep in mind that the coordinates are calculated according to the World Geodetic System of 1984 (WGS84), and the importance of adjusting the local datum. Atmospheric conditions affect the speed of the GPS signals as they pass through the atmosphere and ionosphere, causing error in the determination of the position. These effects are smallest when the satellite is directly over the GPS device, and become greater for satellites nearer the horizon since the signal is affected by the longer time needed to arrive at the device.

WGS84 (World Geodetic System 1984):
is a uniform three-dimensional coordinate system for the whole world and geodetic basis for GPS devices.

The GPS includes a feature called Selective Availability (SA) (Milbert 2006) that introduces intentional random errors of up to a hundred metres into the publicly available navigation signals to confound, e.g. guiding long range missiles to precise targets. This SA was set to zero on 1st of May 2000 following the instructions given by the U.S. President Bill Clinton (The White House 2000). In September 2007, the U.S. Government announced its decision to procure the future generation of GPS satellites, known as GPS III, without the SA feature. Doing this will make the policy decision of 2000 permanent and eliminate a source of uncertainty in GPS performance that has been of concern to civil GPS users worldwide for some time (National Executive Committee 2008).

After SA has been turned off, the largest error in GPS is usually the unpredictable delay of the signal through the ionosphere. There are some techniques to improve accuracy:

- Augmentation. Augmentation methods of improving accuracy rely on external information being integrated into the calculation process. Examples of augmentation systems include the Wide Area Augmentation System (WAAS) and Differential GPS.

Differential global positioning system (DGPS):
Enhanced Global Positioning System (GPS) that uses broadcast corrections from ground based reference stations to refine the positional accuracy.

- Precise monitoring. The accuracy of a calculation can also be improved through precise monitoring and measuring of the existing GPS signals in additional or alternate ways.

Other Global Navigation Satellite Systems (GNSS) are GLONASS – GLObal NAvigation Satellite System – now in the process of being restored to full operation, and the Galileo Positioning System, being built by the European Satellite Navigation Industries for the European Union (EU) and European Space Agency (ESA). But, as already stated, the GPS is nowadays the only fully operational GNSS.

3 HARDWARE AND SOFTWARE

As quoted, the hardware used by the authors consists basically of (cf. figure 1):

- A Personal Digital Assistant (PDA): HP iPaq hX2790, with Intel PXA270 processor 624 MHz, 3.5" transflective TFT display, 384 MB total memory (320 MB ROM and 64 MB SDRAM) and Bluetooth wireless technology, that it is used to connect to the GPS external device. It has also Compact Flash and Secure Digital Expansion Slots, which allow reading high capacity memory cards, nowadays up to 8 GB and 4 GB. These specifications permit processing cartography and aerial photography.
- A GPS external device: Holux GPSlim236 Wireless Bluetooth GPS Receiver, which use SiRF Star III chipset. This device has 20 channels, which provide fast acquisition and reacquisition. The spatial accuracy,

Figure 1. Personal Digital Assistant (PDA) and GPS external device linked via Bluetooth protocol.

with EGNOS/WAAS/Beacon, is <2.2 m, horizontal (95% of time) and <5 m vertical (95% of time). Of course, it is possible to employ any other GPS device, provide that use any of the following protocols: National Marine Electronics Association (NMEA) 0183, version 2.0, Trimble Standard Interface Protocol (TSIP), Rockwell PLGR, Delorme Earthmate.

The software is:

- PDA Operating System: Microsoft Windows Mobile 5.0.
- GIS software: ESRI ArcPad 7.0.1. The main goal in this case is to use standard GIS format files for PDA and PC, avoiding conversions between them. The chosen standard is ESRI shapefile.

ArcPad:
a software provided by ESRI for mobile GIS and field mapping applications which can be used for capturing, analysing, and displaying geographic information.
www.geographymatters.com/software/arcgis/arcpad/index.html

This is a low cost solution. In the international European market, it is possible to buy the hardware for about 520 € plus taxes. About the software, the PDA operating system is included with the device, and for ESRI ArcPad a regional distributor should be approached.

4 PREPARING THE FIELDWORK

Before going to the field, it is necessary to prepare the files for their use in ESRI ArcPad. Concerning the vector data, there are two possibilities. The first and easier possibility is to use just shapefiles to record and display digital data both in PC and PDA. The second option, used by the authors of this chapter, who use in the PC ESRI ArcGIS ArcInfo and personal geodatabase, is, by means of the ArcPad Tools for ArcGIS included with ArcInfo, checking data out from the personal geodatabase into a shapefile for use on ArcPad and, using these same tools, data and any changes can be checked back into the geodatabase.

It is very important to stress the importance of knowing the local datum. The GPS use the WGS84 as the native reference system. But local maps use different datum in every European country. For example, in Spain is used the European Datum of 1950 (ED50). In Spain and Portugal, for instance, the difference between these two systems, for the same reference point, is about 100 m.

ArcGIS ArcInfo:
a GIS and mapping software of ESRI which includes all functionality of the ArcGIS products and adds advanced spatial analysis, extensive data manipulation, and high-end cartography tools.
www.esri.com/software/arcgis/arcinfo/about/features.html

Datum:
is the fundamental point where the reference ellipsoid, which estimates the globe, is fixed.

It is needed the following basic information:

- Cartographic data. Obviously, every European country has its own standards, and every study case has its own necessities. The authors use raster and vector maps at 1:10,000 and 1:50,000 scales in the field, and 1:2,000 and 1:500 in the city. For the purposes of the diachronic study of the landscape, it is used cartography from the end of 19th century, in which the toponymic information is richer than nowadays.
- Remotely sensed data. Aerial photography used from 1944 onwards and satellite imagery gathered from 1986 (figure 2).
- Various thematic shapefiles, for instance, administrative limits in different historical moments, hydrology, digital elevation models (DEM) of different resolutions or any landscape features.

Vector data:
data which are represented by the coordinate geometry of points, lines, or polygons.

Figure 2. Integration of 2002 cartography (scale 1:10,000) with 1944 aerial photography and archaeological sites delimited with ArcPad (marked with light grey polygons). Note the variation of the watercourse of more than 600 m. In this case, the archaeological settlements are industrial roman olive-oil facilities.

Prior to beginning fieldwork, it is necessary to design carefully the digital data forms which are going to be filled in the survey process, making them general enough to accommodate wide variability in phenomena, yet narrow enough to attribute quickly and to generate relevant and comparable data categories (Tripcevich 2004b). Mobile GIS forms are limited by small screen size (in this case, 240 × 320 pixels), so are widely used pull-down menus. In ArcPad, digital forms are based on XML and VBScript.

About the hardware, in fieldwork is essential to foresee battery consumption of the PDA and GPS, having different alternative ways to charge the batteries, like car lighter chargers; also, data backup strategies, like synch to a laptop. The authors of this chapter always store information in non-volatile Flash card.

XML (Extensible Markup Language):
is a general-purpose specification for creating custom markup languages which are tailored to a particular type of data by defining own elements. The Web3D consortium recommends XML to be used for representation of richly structured documents on the World Wide Web.

5 THE ARCHAEOLOGICAL SURVEY

Once the preliminary data are ready and stored in the PDA, it is time to go to the field. The traditional way for recording archaeological distributions and landmarks with GPS was using a GPS device along with maps and paper forms. It is easy to imagine the difficulty of doing the archaeological survey in a broad, featureless plain without a GPS, but even using a GPS device, is obviously time-consuming.

Using mobile GIS, it is possible to know in realtime, at every moment, where you are, seeing in the display not only the coordinates of the current position of the surveyor, but also this position inside the map or aerial photograph. If the purposes of the survey are diachronic, for instance, it is possible to know instantly if a ruin corresponds to a 18th century agricultural exploitation, because you have in the PDA device the maps made in the end of 19th century (García-Dils et al. 2008) (figure 3).

Prior to beginning fieldwork, it is advisable to check the satellite availability for the day of surveying in a given place. There are some applications which manage the almanacs, like the one provided by Leica Geosystems (2008). You have to input into the program the latitude, longitude and height of the place where is going to be carried out the fieldwork, and to download the last almanac available. The program displays the satellite availability, along with Geometrical Dilution of Precision (GDOP) which provides information about the expected accuracy of the 3D position solution, and Position Dilution of Precision (PDOP) which provides information about the expected accuracy of the 2D position solution with fixed height. GDOP values should be below five for surveying applications, while PDOP information is mainly used for navigation applications. Also, it is interesting to evaluate the accuracy of the position given by the GPS device going to a landmark recorded in the cartography that we have stored in the PDA, like a geodesic vertex.

Leica Geosystems:
a company with expertise in products and services related to capturing, analysing, and presenting spatial information. ERDAS IMAGINE is one of the provided softwares for digital image processing.
www.leica-geosystems.com

As Tripcevich has noted (2004b), the potential contribution of mobile GIS to survey fieldwork should be considered in three categories: data acquisition, management and analysis. The researcher has the possibility to query and explore large digital datasets while in the field, analysing realtime potential relation among settlements.

With ESRI ArcPad, it is possible to use different types of shapefiles to record archaeological information:

- Point shapefiles: useful to record archaeological distributions of artifacts, for instance, constructive remains of a roman ‘uilla’, like walls, pavements, but also bricks and tiles, including ceramic fragment location;
- Line/polyline shapefiles: to record paths, roads, land divisions, walls, cadastral lines, etc.;
- Polygon shapefiles: to store delimitation of different density concentration areas of artifacts, big structures or of the entire archaeological site.

The mobile GIS equipment permits to record archaeological distributions below the scale of the archaeological site by documenting concentrations of artifacts using polygon geometry. It is needed to evaluate artifact distribution over the surface of an entire region. This is just surface survey. The spatial accuracy offered by the hardware described in this chapter proved to be sufficient to map archaeological distributions at a much

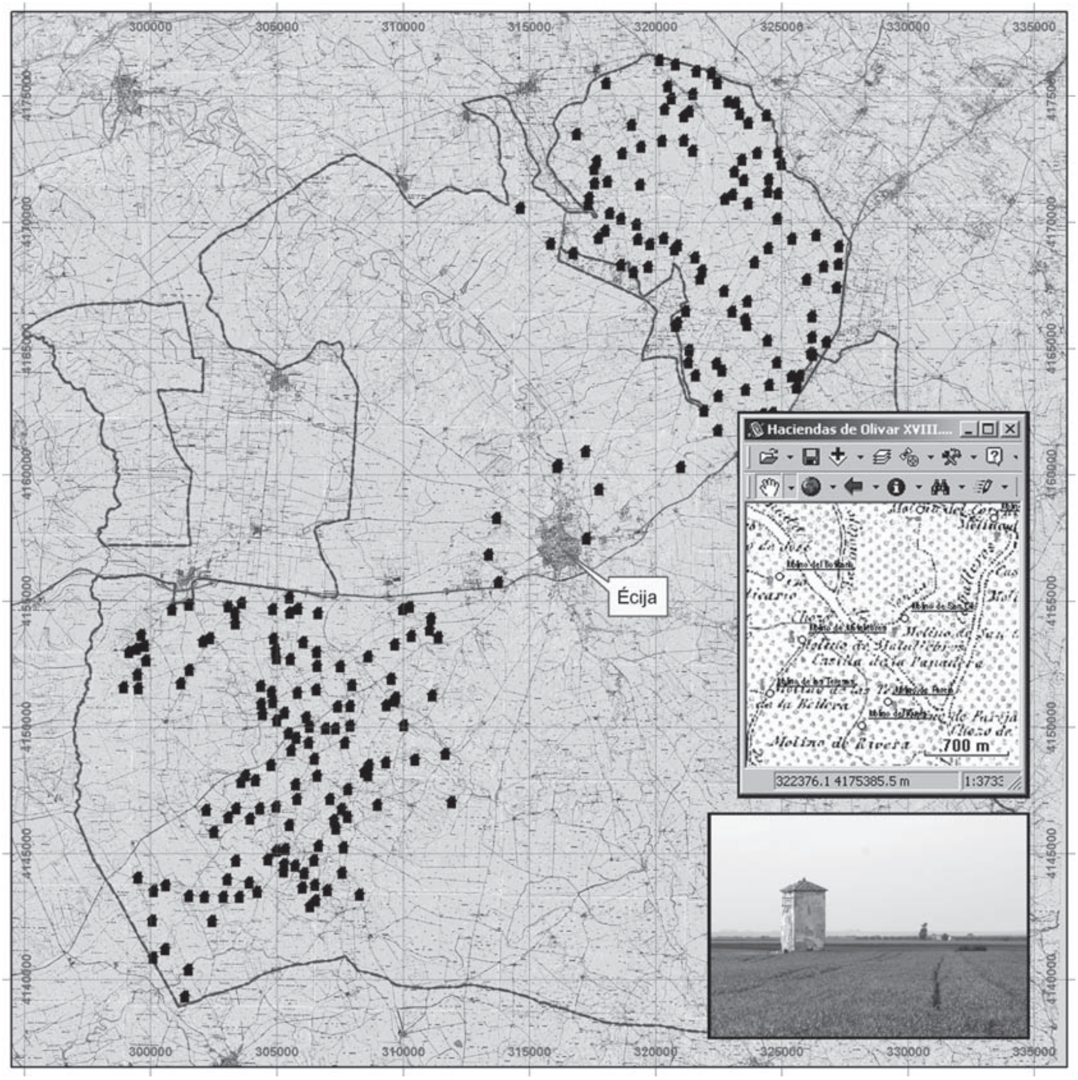

Figure 3. Inventory of 18th century agricultural exploitations in the countryside of Écija (Seville, Spain), using for the fieldwork 19th century cartography georeferenced in ArcPad.

finer resolution and level of detail than was feasible without the use of a mobile GIS (Campana 2005, Mundigler 2002, Tripcevich 2004a).

6 CASE STUDIES

The methodology proposed in this chapter has been repeatedly tested as a case study during the on-site development of the research tasks associated with the study of the birth and evolution of a colonisation landscape in the countryside of the south of Spain, in Écija (Seville). The purpose of this project – named AstiGIS – is to analyse through the application of GIS technology the different steps shaping the various processes of territorial arrangement developed in the territory of this city over time (Sáez Fernández et al. 2006).

The city of Écija is located at a strategic point of the Sevillian countryside. A colony of Roman citizens, Colonia Augusta Firma, was established here, over the native settlement of Astigi, at the end of the first century BC. This was carried out within the framework of the political and military reorganisation of the Hispanic provinces by the first roman emperor, Augustus. Astigi became the political centre of the Genil valley and the surrounding countryside. The erection of the first monumental buildings in the centre of the colony, devoted specially to the cult of the imperial house, and the design of a Hippodamic city planning, are two examples of elements creating a new urban image, a Roman style city in an indigenous context.

The formalisation of the colony entailed significant changes in the organisation of the adjacent countryside. Previously it had been structured by a group of turdetanian oppida (fortified places). The colonial foundation involved the introduction of a different scheme, with a predominance of dispersed rural property (uillae). The cadastre was the essential instrument for bringing about the transformation of the country after the conquest. A centurial grid – a typical Roman system of land distribution – has been detected to the east of Écija, in a softly undulating landscape, over lands with excellent agricultural potentialities. The orientation of the grid conforms with almost total accuracy to geographic north; it is 22.12° different to that of the town plan. The module used is 20 × 20 actus (710 m), and the currently known extent is about 170 km^2 (Sáez Fernández et al. 2002a).

The centuriation and allocation of plots was accompanied by the arrangement of communication networks, essential for the exploitation of the resources. The Singilis riverbed was regulated, thus providing a quick and inexpensive route for the export of agricultural surpluses. From the time of Augustus onwards, this territory was especially dedicated to olive oil production; this left characteristic signs in the landscape, such as the dense occupation of the river banks by pottery workshops (figlinae) producing olive oil amphorae. The state’s supply needs were a factor of major importance in the development of the countryside, particularly from the age of Claudius onwards, when the wealth generated by oil exports was reflected in the blooming of the rural population and the intensification of economic activity.

One of the main documents generated in the study of this area is the “Archaeological Chart”, a digital map of archaeological sites distribution currently in progress but in its final stage. This has greatly benefited from the application of the FDA methodology, which was specifically implemented for the solution of some of the aforementioned problems.

FDA methodology has been used in the study of some other territorial processes developed in this area. The creation of a new Christian frontier in the middle of 13th Century involved the fixing of township boundaries and the establishment of 32 village settlements following the expulsion of ancient Islamic inhabitants of the territory and its inclusion in the royal jurisdiction. In the second half of the 18th century, a new colonisation took place in the territory of Écija with settlers coming from the Netherlands, Germany and Switzerland. New communities were created, configuring a fossilised landscape in which the boundaries of the colonies as well as the allotments network were defined with notable precision, so that nowadays they can be recognised and analysed on the spot (Sáez Fernández et al. 2002b). A final example of the benefits in the on-site application of FDA methodology deals with the inventory and georeferencing of still surviving olive oil facilities that were in operation during the 19th Century and the first half of the 20th, and the study of their role as territorial markers in the landscape (García-Dils et al. 2008).

Georeferencing:
defining the existence of an object in physical space by means of coordinate systems and map projections (e.g. the positioning of an aerial image to its location on the globe).

cf. chapter "Technologies for integration and use of historical maps into GIS – Nordic examples" of Do-maas and Grau Møller.

7 CONCLUSIONS

The possibilities offered by mobile GIS are not new; GIS and GPS have been widely used in archaeological survey in the last 15 years, and a considerable body of literature has been produced about the progress that this

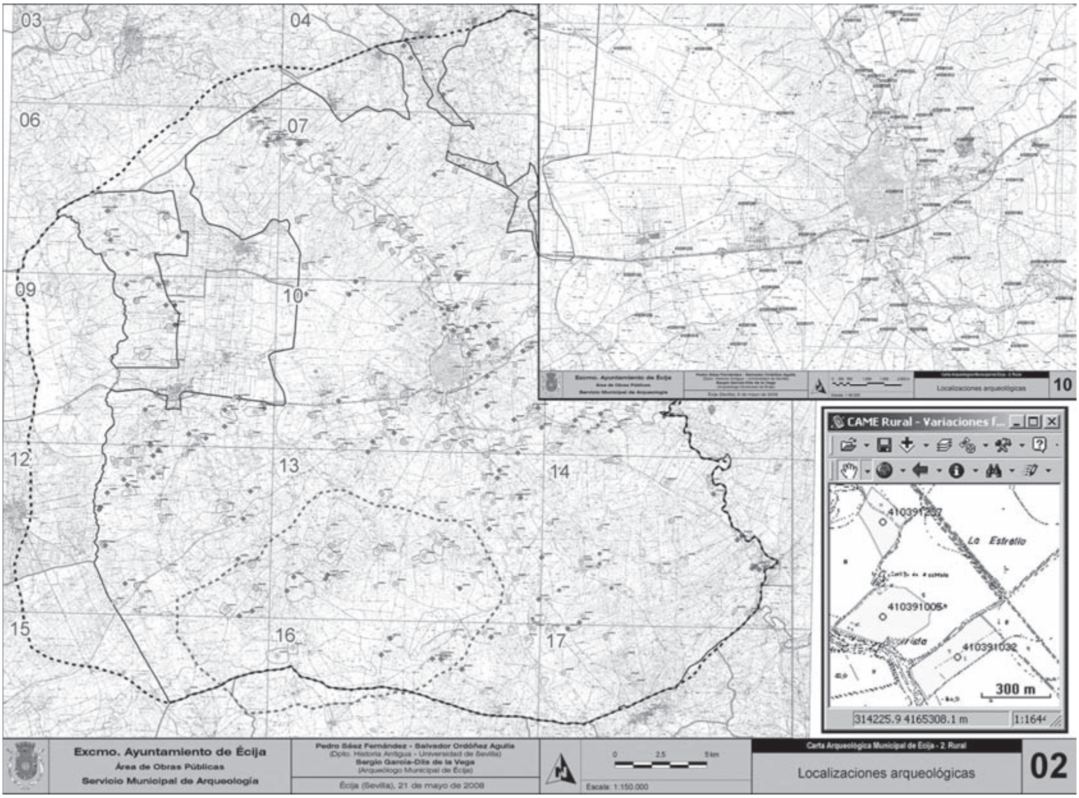

Figure 4. Delimitation of archaeological sites for planning purposes. In the territory of Écija (Seville) are protected more than 200 archaeological sites from nearly 500 inventoried places.

new technology has involved in archaeological investigation. But with mobile GIS the fieldwork is easier and faster than was previously possible with a GPS and a paper map, and is possible to have while in the field a wide range of different maps and photographs from different times. With the rapid evolution of technology experienced in recent years, it is easy to expect a similar fast development in the implementation of mobile GIS as an efficient and cheap tool in the hands of archaeological teams.

Cost effectiveness is a main variable, if not the principal if we are dealing with commercial field archaeology and not with university projects. For instance, in Spain, the delimitation of archaeological sites is linked to the planning permission process (figure 4), and is made usually by individuals or little archaeological enterprises. Time is money, and fast and accurate site delimitation is cost saving. In this way, the workflow proposed in this chapter is a far more efficient one than the time-consuming procedures used in traditional approaches of data collection and mapping developed in the past.

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The application of digital vertical aerial photogrammetry in the recording and analysis of archaeological landscapes

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ABSTRACT

Aerial photography has played a significant role in allowing landscape experts to understand archaeological features, and their relationship to the surrounding terrain. This approach often utilises single aerial images whose archaeological features are subsequently identified and transcribed. The use of digital photogrammetry has been widely applied to all aspects of modern mapping and collection of geospatial data, however there has been little transfer of these techniques to understanding archaeological landscapes.

This chapter outlines the basic theory as well as technologies and techniques used within digital photogrammetry. Sections include:

- Explanation in the development of photogrammetry and the fundamental principles of stereo photogrammetry;
- Description of photogrammetric project design selection of image sensor, management of image capture, appropriate image scale and scanning methodology;
- Explanation of the probable computer software and hardware needs;
- Explanation of the digital photogrammetry process to highlight preferred workflow systems, including:
  a) Setting up a digital photogrammetry project and the simple definition of inner and exterior orientation, aerotriangulation and geometric control;
  b) Automatic extraction of Digital Elevation Model (DEM), explaining Digital Terrain Model (DTM) editing and suitable resolutions;
  c) Explanation of orthoimages, including image resolution, image-merging and appropriate data management;
- Finally a review of the practical products of digital photogrammetry and their application and integration within a GIS to assist the understanding of cultural landscapes.

1 INTRODUCTION

Aerial photography provides an exceptionally rich resource to a range of earth scientists, including archaeologists. Whereas maps depict selected features presented in the form of lines and symbols, photographs provide the user with a complete view of the landscape, through variations in colour, contrast and texture across the image. With experience, even the most subtle elements of relict landscapes can be discerned from aerial images. Single images, taken at oblique angles in low early morning or late afternoon sunlight use the strong shadows to enhance features. Such photographic images have been used for many years to identify and interpret archaeology, but to gain geometric or spatial information a more scientific approach is required.

Photogrammetry is the science and technology of extracting quantitative information about physical objects and the environment through the processes of recording and measuring from photographic images. In the study of landscapes, photogrammetry is an exceptionally powerful resource. It enables not only the accurate mapping of landscape features and morphology, but given the high quality of photographic detail it enables the user to interpret, identify and analyse the significance of visible features within a geometrically correct framework.

We often use the results and products of aerial photogrammetry without necessarily being aware. Nearly all national mapping is, in fact, created in this way. However, it is often the case that the vector-based mapping products takes precedence over the other data created by the photogrammetry, that have the potential to provide ‘landscape scientists’ with a most valuable resource. In order to derive topographic mapping from vertical aerial photography, the modern photogrammetric process creates detailed Digital Elevation Models (DEMs) and geometrically-corrected photographic images (orthophotos), both assets in their own right.

Vector-based mapping products:
abstractions of the real world where positional data is represented by the coordinate geometry of points, lines and polygons.

Digital elevation model (DEM):
the digital representation of the Earth’s surface and providing information about its elevation.

Geometrically-corrected [photographic image]:
the removal of topographic relief, lens distortion and camera tilt from a photograph to produce an image that has a uniform scale, equivalent to a map.

The development of photogrammetric applications for PCs has replaced the previously complex optical-mechanical (analogue) instruments and has brought aerial photogrammetry into the realm of the non-specialist. It is now a realistic proposition for landscape scientists to plan and process a photogrammetric project designed to generate orthophotos and detailed DEMs specifically for landscape analysis.

2 BRIEF HISTORY OF VERTICAL AERIAL PHOTOGRAMMETRY

The principles of projecting images optically and the understanding that geometric measurements from such images could be used in the preparation of maps happened well before the invention of photography. References to such ideas are found in the works of both Aristotle and Leonardo da Vinci (The Center for Photogrammetric Training 2005, Wolf & Dewitt 2000). The invention of a practical photographic process in 1839 was the first real step in the development of science of photogrammetry. The French military was at the forefront of experiments in using photogrammetry for topographic mapping, and in 1849, Colonel Aimé Laussedat, of the French Army Corps of Engineers undertook experiments using balloons and kites to obtain aerial photography (Mikhail et al. 2001). The difficulties involved in obtaining aerial photographs curtailed this research and it was not until the invention of the aeroplane in 1902 that the potential of aerial photogrammetry could be fulfilled. Eleven years later the aeroplane was used first to take photographs for mapping purposes.

Early photogrammetry was based on the measurement and interpretation from single images, but in 1909 a German scientist, Dr. Carl Pulfrich experimented with two overlapping images, a technique known as stereo photogrammetry (Wolf & Dewitt 2000). This became the basis for most of the instruments for photogrammetric mapping, techniques which developed rapidly during both World Wars as their application to reconnaissance and mapping was proven.

3 THE FUNDAMENTALS OF STEREO PHOTOGRAMMETRY

Stereo photogrammetry is a complex mathematical science, the study and understanding of which requires examining geometric concepts beyond the scope of this chapter. Their detailed description and analysis is the subjects of many publications (e.g. Burnside 1985, Mikhail et al. 2001, Wolf & Dewitt 2000) while the aim of this chapter is simply to introduce some of the fundamental principles which are still integral to modern digital systems.

Accurate mapping cannot be undertaken directly from a single vertical aerial photograph as the image will contain distortions due to a) slight tilt angles inevitable when the image is taken, and b) relief displacement due to changes in the terrain over the image (figure 1). Given that these distortions cannot be quantified by measuring from a single photograph

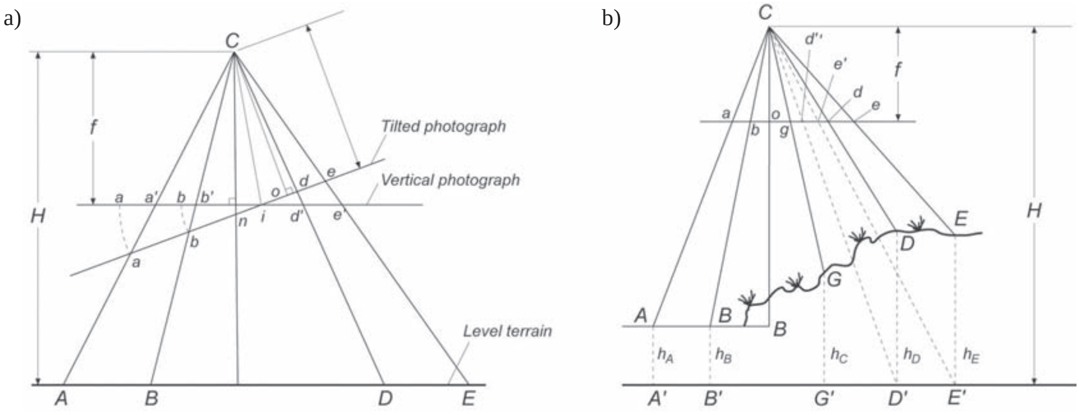

Figure 1. Schematic diagrams showing the distortions due to the effect of a) tilts and b) relief present in aerial photography. In a) ground point A will appear at position a on the photograph, displaced from the true position a' due to tilts. In b) the position of ground point E is e on the photograph, displaced from its correct plan position e' due to the relief (after Davis et al. 1981).

alone, an alternative approach utilising overlapping photographic images was developed, known as stereo photogrammetry. The schematic diagram in figure 2 shows how the image representation of the building is different on the two photographs due to the change in the position of exposure. Taking these two images, and the principle of stereoscopy – our ability to perceive objects in three dimensions, it is possible to view the area of overlap with a 3D perspective (Davis et al. 1981). In practice, this can be achieved using a simple viewing device such as a stereoscope, which allows each of our eyes to view only one of a pair of photographs, from which our brain can then perceive the 3D perspective. In this process, the brain is resolving the parallactic angle from the differences on the images due to the change in position of exposure. Geometrically, the parallactic angle corresponds to linear distortions on the photographs, known as parallax, which can be measured and height information then calculated (Burnside 1985). This is an important concept that will be returned to later in the chapter.

Parallactic angle:
the angle of inclination between two lines of sight upon a single object.

Parallax:
the apparent displacement of an object observed along two different sight lines.

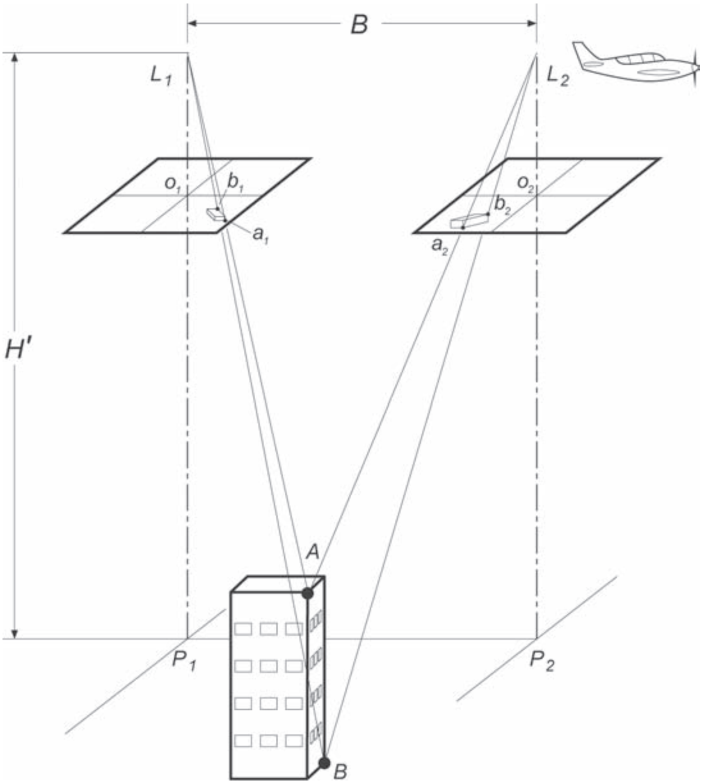

Figure 2. The basic premise of stereo photogrammetry. The building appears in two images, taken at L_1 and L_2 respectively. The top of the building is represented by the points a_1 and a_2 and the base by b_1 and b_2. If we view one image in each eye our brain will recreate a 3D impression of the building. In reality, with changing heights in landscapes our brains process the two images and instantaneously perceive the 3D model across the whole overlap area (after Wolf & Dewitt 2000).

In photogrammetry, these basic concepts are taken forward to enable measurement and mapping using methods and instruments which allow for the stereo-restitution of overlapping photography. How this has been achieved has evolved as technology, in particular computing systems has developed over the years.

4 EVOLUTION OF TECHNOLOGY

4.1 *Analogue instruments*

Before the development of modern computing systems in the 1970s, stereo-plotting instruments comprised optical projection or optical-mechanical systems. The geometric basis of these technologies was to replicate the precise position of the camera at the two positions of exposure, using lamps to project images of both photographs. The operator views the projected images through a binocular optical system and through stereo restitution he is able to perceive a 3D model of the overlap area (figure 3).

Resolving the inner orientation (the camera's internal geometry, generally known from the camera calibration), the exterior orientation (the space position – X, Y, Z and the angular tilts of the camera – ω, φ, κ), and

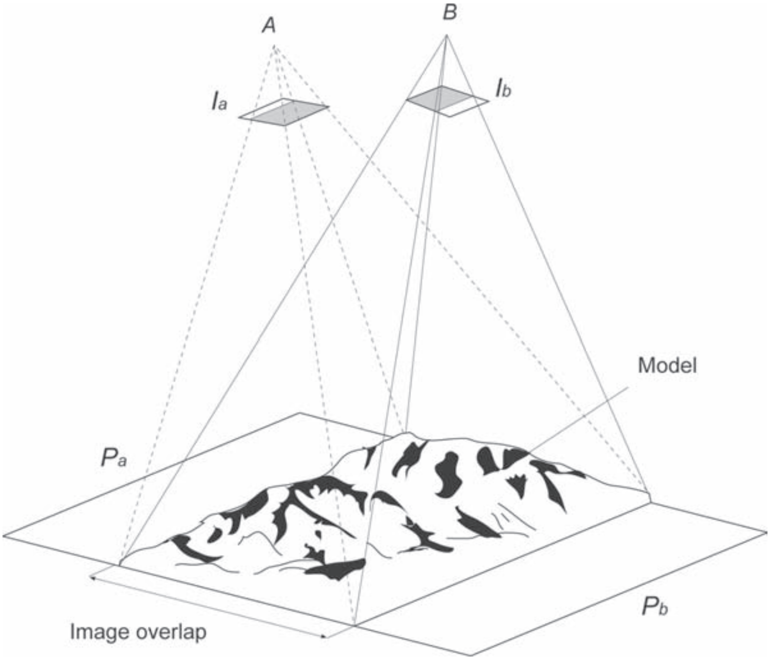

Figure 3. Lamps at A and B project the photographic images Ia and Ib which are viewed by the left and right eyes respectively, allowing the operator perceiving the 3D model of the overlap area. The geometry and orientation of the projection system is the key to precise and accurate measurement from the model.

the absolute orientation (levelling and scaling of the model) are the fundamental stages in setting up these instruments. These orientations are achieved by precisely adjusting the rotation and shift screws of each projection lamps following a set orientation routine when observing known ground control points through the instrument optics.

Mapping information is extracted by the operator moving the tracing table to follow features, adjusting its height to keep on the model surface, thus measuring elevation.

4.2 *Analytical instruments*

These analogue systems were expensive to build and complex to operate. Thus, with the development of more powerful computing systems, the optical and mechanical elements of instruments were replaced by servo-motors and encoding devices. Known as analytical plotters, these instruments use mathematical models to resolve the inner, relative and absolute orientation of the images (Linder 2006). No optical or mechanical model is actually created, instead it is formed digitally. This is translated to the operator by servo motors applying shifts and rotations to the images as the viewing system moves across the images.

This not only increases the versatility of the instrument, allowing a greater range of photography types and focal lengths, but also increases the accuracy compared with analogue instruments. Importantly, analytical instruments also provided faster and more accurate solutions to the issue of aerotriangulation. This technique – which will be discussed further in this chapter – allows control information to be passed from model to model, fundamental to all but the smallest mapping projects.

Aerotriangulation: *the simultaneous geometric resection and intersection of image rays from an aerial camera that allows the extension of the horizontal and vertical control from relatively few ground control points.*

Even so analytical photogrammetry still required the use of expensive, cumbersome precision instruments and as such remained the realm of the specialist operator.

4.3 *Digital photogrammetry (softcopy systems)*

A fully digital system was the inevitable conclusion of these developments; the final technological breakthrough was affordable high quality scanners to obtain digital images from the aerial photography. Softcopy systems have been available since the early 1990s (Leberl & Thurgood 2004, Usery 1996). They were initially dependent on powerful workstations, but the rapid advances in PC processing power and storage capacity has seen a recent growth in desktop based software (Maalouli 2007, Ruzgiene & Alekniene 2007). In these systems, the physical photographs have been replaced by digital images, and as this chapter will explain, complex processes of pixel matching and some powerful mathematical algorithms allow the extraction of detailed height models and subsequently the creation of geometrically corrected images, called orthoimages. It is these elements which make this such a powerful tool in landscape recording and analysis.

5 SENSORS AND PLATFORMS

The ‘standard’ vertical aerial camera was, during the analogue and analytical period of photogrammetry, the only practical ‘sensor’ available. For primary image capture such cameras are still in common use – characteristics include the large film format, 23 cm × 23 cm, fixed focal length, 153 mm with central shutter, and high quality calibrated optics. The ‘platform’ for the camera is a small dedicated airplane, with the camera built into the floor, looking vertically downwards. These aircraft can fly a range of heights between 300 m and 7,500 m.

Developments in digital camera technology have added to the range of sensor options (Schenk 1999). They operate in a similar way to the film cameras – with a CCD (charged coupled device) replacing the film magazine, and mass storage devices on board to store the image data. The economic advantages of these digital cameras are clear as the costs of film, photographic processing and image scanning are removed. However, it is only the recent developments of multiple array CCD sensors that have enabled the image size and quality to match that of the large format cameras (Gruber et al. 2004, Neumann 2004). The specification of these sensors is continuously improving, the table 1 listing a selection of parameters from the Vexcel™ Ultracam Digital Aerial Camera:

CCD (charge coupled device):
electronic image sensor which convert both optical luminance and colour into a digital electric signal.

Table 1. Selection of parameters from the Vexcel™ Ultracam Digital Aerial Camera.

Colour (multispectral)	4 channels, RGB & near Infrared
Colour image size	4008 × 2672 pixels
Colour physical pixel size	9 µm
Ground size of pixel (500 m flying height)	5 cm

Multispectral:
the ability to capture light from frequencies beyond the visible range that the human eye can sense (e.g. infra-red).

As well as a range of potential uses for the data gathered by the near infrared channel, the sensitivity of the sensors can be adjusted to suit lighting conditions, opening up the potential for enhanced imaging in shadow areas.

Near infrared channel:
electromagnetic radiation whose wavelength is longer than visible light but shorter than microwaves (0.75–1.3 µm) used to detect archaeological evidence in soils, vegetation and water.

Softcopy photogrammetric systems, however, with the improved processing options open up the potential of imagery from a wider range of sensors mounted on different platforms to be exploited. The only constraint is the images have to respect the basic photogrammetric principles – the required stereo overlap and known sensor geometry. Spaceborne satellites are increasingly providing new sources of imagery. Satellite sensors such as Quick Bird, IKONOS, Spot 5 and Orbview 3 provide data which most softcopy photogrammetric systems can process.

Sensor geometry:
the geometric characteristics of an airborne digital optical sensor used in the interior orientation setup within photogrammetry.

At the other end of the scale and technology spectrum images can be captured using standard digital cameras, calibrated by the user. A range of low cost ‘platforms’ exist in the form of kites or helium balloons, which can operate at very low heights, 10–50 m, ideal for limited area investigations.

Satellite sensors:
cf. chapter “The use of satellite remote sensing for detecting and analysing cultural heritages” of Heinrich et al.

6 SOURCING IMAGERY

Existing vertical aerial photography can seem an attractive resource. This is particularly the case with historical aerial collections which can provide a snapshot of the landscape in past times. However, caution should be applied as to successfully process these images will require the camera calibration details which may not be obtainable.

Commercially available photographs – for example those supplied from national mapping agencies – tend to be captured at a too small scale to be of great value in studying cultural landscapes. As will be discussed later in this chapter, the scale affects both the level of detail and the accuracy.

For landscape studies often the most effective solution is to commission new photography for a project. This has the distinct advantage that the photo scale can be selected specifically for the survey requirement (and budget), but careful pre-flight planning is necessary. An additional benefit of acquiring new photography is that the copyright of the images and derived products will be owned. With existing imagery licence fees may be applicable whenever the material is used or published.

7 PLANNING A DIGITAL AERIAL PHOTOGRAMMETRIC PROJECT

In advance of undertaking an aerial photogrammetric project a number of issues need to be addressed to ensure the project returns appropriate results for the landscape being surveyed, and within a given budget:

7.1 *Scale of photography*

Focal length:
the distance in mm from the optical centre of the lens to the focal point located on the sensor or film. Focal length adjusts both the field of view and the level of magnification within the image (24 mm: wide angle, 300 mm: tele).

The photo scale is determined by the relationship between the focal length of the sensor and the flying height of the aeroplane (Burnside 1985),

$$S = f/H \tag{1}$$

e.g. standard aerial camera f = 152.4 mm; therefore for a photo scale of 1:5,000, H = 762 m.

The significance in choosing the scale is that it will have a direct influence on the size of smallest features which can be discerned, and on the number of photographs required – affecting both acquisition and processing cost. The larger the photo scale the lower the aeroplane has to fly, and the more images are required to cover the ground. A final scale must be selected that balances several factors; the number of exposures, extent of survey, and feature size when commissioning aerial photography.

Table 2. Photography scales and potential applications in landscape analysis.

Photoscale	Potential Use
1:20,000	Historic land-use characterisation
1:7,500	Identification of deserted settlements, relict field systems and boundaries
1:1,500	Structural details of monuments and inter-relationships

As a simple rule to calculate the suitable mapping scale that can be derived from photogrammetric products, the photoscale can be divided by 5 (Wolf & Dewitt 2000), e.g. a photo scale of 1:10,000 is appropriate for the creation of 1:2,000 mapping data.

7.2 *Scanning resolution*

Digital sensors can be used in aerial photography, but it is still common to capture images onto film and subsequently scan these images in preparation for softcopy processing. This raises the issue of scanning resolution which needs to be considered in conjunction with the photo scale, and a pixel size resolved. An example would be to take 1:7,500 scale photography, scanned at 21 μm resulting in a pixel size of 16 cm on the ground. As it is generally accepted that 2–4 pixels are required to perceive a feature within an image (Welch & Jordan 1996), in this example the smallest feature visible would be ca. 50 cm. If this is not acceptable, and important features may be missed then the option is to increase the photo scale, or increase the scanning resolution. Standard scanning resolutions are 7 μm, 14 μm and 21 μm.

7.3 *Data volume and storage*

Any increase in scanning resolution will affect the image-file size and the impact on processing time and data storage has to be considered. It is worth considering that it is an exponential relationship between resolution and file size.

Table 3. Scanning resolution and affecting file size.

Resolution	Colour	B&W
7 μm	n/a	1300 MB
14 μm	787 MB	262 MB
21 μm	350 MB	117 MB

These file sizes are for individual images, but a project could easily involve over 100 images, so an adequate storage facility is essential. With these issues in mind the selection of scanning resolution should be made using the principle, ‘as high as necessary, as low as possible’. However, this is further complicated by the fact that, as this chapter will later explain, the level of detail of the DEMs generated from photogrammetric processing will be affected by the image scan resolution.

7.4 *Flight lines*

The standard approach to an aerial image-gathering flight is to fly lines in strips parallel to the longest dimension of the project area, thus keeping the number of strips to a minimum. The images are required to have at least 60% overlap along the line of the strip to ensure the stereo coverage needed for mapping is complete. There must also be a lateral overlap of at least 20% between neighbouring strips to ensure that no gaps occur and that sufficient common ground exists to define tie-points to join the strips which make up the block of photography (Linder 2006).

Tie-points:
a feature that can be identified in two or more images that can be selected as a reference point. Used in the process of aerotriangulation.

Low raking sun angles:
the increased ability to visualise micro topographic relief variation due to the shadows cast by the sun early or late in the day when it is low in the sky.

7.5 *Time of day*

Although low raking sun angles can be excellent at emphasising subtle landscape features, the shadows they create present serious problems in the digital photogrammetric processing stage. Generally about 30° is the minimum sun angle acceptable and as such flights should be planned across the middle of the day.

7.6 *Season (time of year)*

The season is also a limiting factor, again because it will affect the sun angle, and hence the shadow on images. It may also have a profound effect on vegetation foliage cover. Photogrammetric mapping systems have no way of penetrating vegetation, so in dense deciduous woodlands it is important to plan accordingly.

8 SOFTWARE AND HARDWARE

An increasing range of software options – supplied by the leading geospatial companies – are available to undertake the photogrammetric processing of aerial photography. Amongst those available are:

Table 4. Software for photogrammetric processing.

Company	Software
Leica Geosystems	ERDAS Imagine/Photogrammetry Suite 9.1
Supresoft	Virtuozo
R-Wel Inc	Desktop Mapping Systems
PCI	Geomatica 10

The minimum hardware specification to operate these photogrammetric systems on a Windows 2000/XP/Server 2003/Server 2000 platform is:

Table 5. Minimum hardware specifications for photogrammetric systems.

Hardware	Properties
Processor	2 GHz or greater
Memory (RAM)	1 GB or greater
Graphics card	24-bit or accelerator running at 1280 × 1024 pixels

These are the minimum requirements, but given the potentially large file sizes increased processor speed and RAM will significantly improve performance.

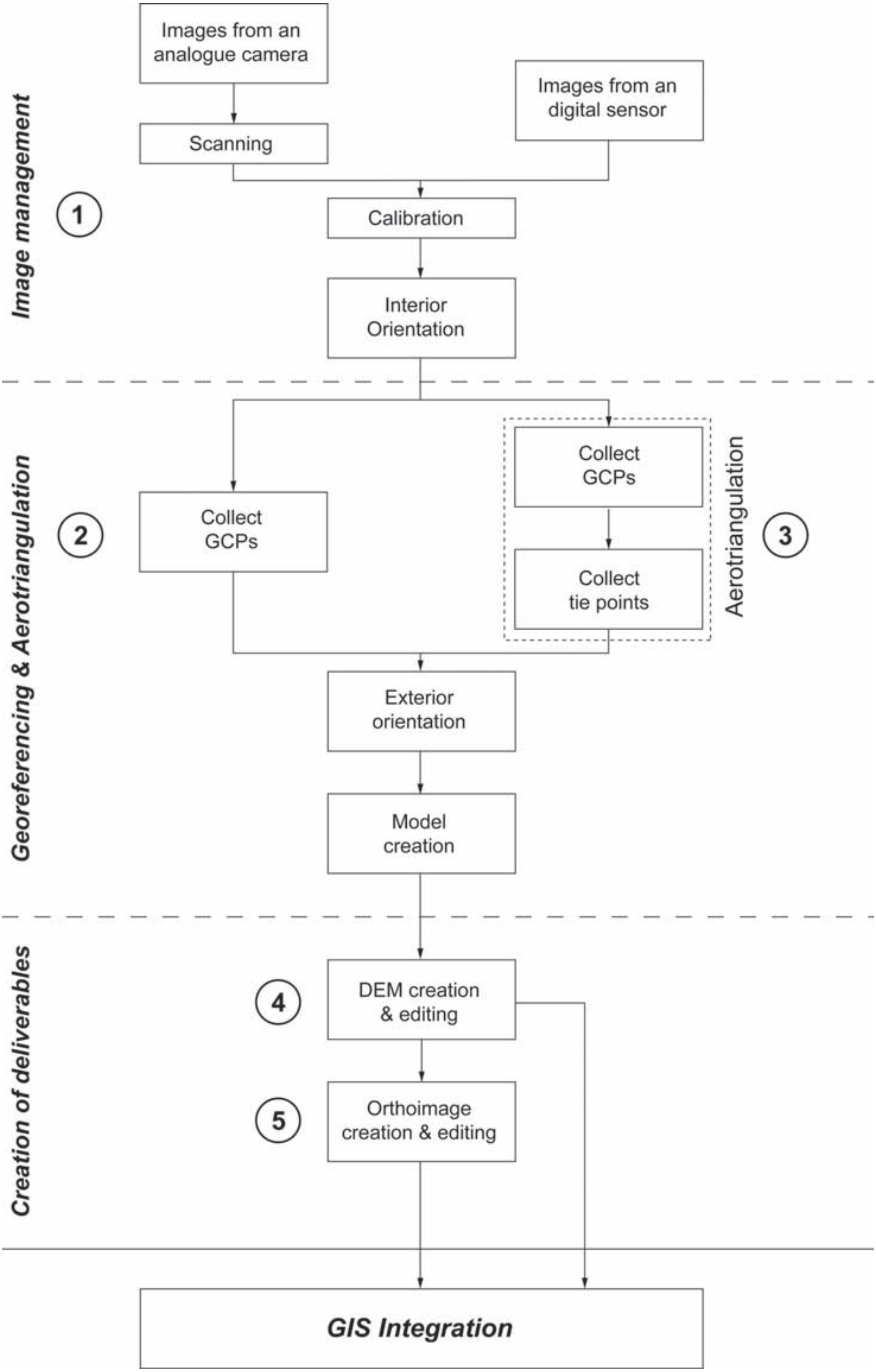

Figure 4. A simplified digital photogrammmetric workflow (PCI Geomatics 2003).

Modular structure:
a system that is made from self-contained components with well defined interfaces to neighbouring components.

Georeferencing:
defining the existence of an object in physical space by means of coordinate systems and map projections (e.g. the positioning of an aerial image to its location on the globe).

Digital photogrammetric software packages are often designed with a modular structure that mirrors the physical work-flow of the photogrammetric process (figure 4). This workflow guides users through the procedures that at first look seem daunting. Although there are differences between software systems, five interlinked core modules are usually present. The first three modules: Image Management, Georeferencing and Aerotriangulation essentially enable the user to construct a digital photogrammetric project by importing and calculating the orientation parameters of the aerial images. The final two modules use this data to allow the measurement of coordinates, which are then used to create the deliverables, DEMs and orthoimages.

9 IMAGE MANAGEMENT

Typically, in the first step of the photogrammetric workflow the user adds the raw data into the photogrammetric project. The main component of data imported is the primary scanned aerial photographs or digital satellite images. The format of these files is usually TIFF, as compressed imagery will reduce the quality of any photogrammetric output. Associated with the series of images are accompanying camera or satellite information files that contain the specification and calibration details of the sensor used to capture the images.

Specification and calibration details of the sensor:
data used to correct the distortions introduced into an image due to curvature of the lens, focal length and the effects of perspective.

Fiducial marks:
Small crosses or v-shaped indents located at the corners and midway along the four sides of an analogue aerial photograph used to establish an image coordinate frame.

For each of the imported images the software must establish the relationship between the coordinate space of the camera and the scanned image, a process known as interior orientation. Within the camera, accurately positioned symbols known as fiducial marks are distributed around the edge and at the centre of the focal plane, and they appear on every image. These marks are digitised and the inner orientation of each image is established. The digitisation of the fiducial marks can be done manually by the operator or semi-automatically by the software. For images captured using a digital sensor, such as satellite images, the size of the CCD chip and the Y scale factor are used to calculate the photo coordinate system.

10 GEOREFERENCING

Exterior orientation, as explained earlier, is the ability to replicate the precise location of the sensor at the moment of image capture with respect to the Earth’s surface. Exterior orientation of each image is recorded by six parameters that describes the tilt (three angles ω, φ, κ) and location (coordinates X, Y, Z) of the sensor at the time of exposure. These values can be generated by two methods.

1. Ideally they are captured accurately during the actual aerial survey by airborne GPSs (X, Y, Z) and onboard inertial measurement unit (IMU). This data may be provided as an additional service, and cost, when specifying the detail of an aerial survey (Goad & Yang 1997).

2. If this data is not available, exterior orientation can be calculated retrospectively using ground control points (GCPs). GCPs are captured by accurately measuring distinct features that can be identified both in the landscape and on the photographs. Ideally they should be features which can be identified at the resolution of the raw image to avoid misidentification. They should be close to ground level to avoid displacement of the ground coordinate due to effect of lean on the image, and from a wide range of elevations across the image. Experience suggests that wall corners, manhole covers and distinctive road markings provide good quality control.

In areas devoid of such distinguishable features targets need to be placed on the ground prior to the aerial survey. These pre-marked targets need to be of a suitable size to be visible on the photographs, with a central point which can be precisely positioned. The scale of photography will determine the form of the pre-mark, ranging from a square metre board with central marker 5 cm in size for large scales, to 10 m long plastic sheeting laid in the form of crosses for small scales.

The coordinates of ground control points are required to survey quality (sub centimetre) in the mapping system chosen for the project. Differential global positioning system (DGPS) technology is the most appropriate method for undertaking this task. A minimum of three GCPs distributed evenly and at angles to each other across the image must be used, although ideally the actual number of GCP per image is at least double this.

Differential global positioning system (DGPS):
Enhanced Global Positioning System (GPS) that uses broadcast corrections from ground based reference stations to refine the positional accuracy.

11 AEROTRIANGULATION

As mentioned previously, aerial survey projects will often contain many images, with large blocks of photography comprised of a multiple parallel strips. Collecting the exterior orientation data for all these images individually would be a major expense, at least three GCPs would have to be surveyed and processed per image (Mikhail et al. 2001). However, to resolve this problem a technique known as aerotriangulation was developed. This process enables GCP established in one image to be passed along the strip to neighbouring images. Although it can be considered a ‘black box’ process due to its complexity, the principles of the method should be considered. Aerotriangulation is completed by designating tie or pass points that mark the location of features that can be clearly identified in two or more images. These features are selected and points digitised at their location. Each image shares six tie-points with its neighbour and as with GPC they are distributed evenly in a gridded formation across the overlapping areas, in a pattern similar to the six on a gaming dice. Preferably these are not too close to the image edge where displacement due to terrain relief is at its greatest. It is often easier to carry out this process within the software with printed copies of the aerial images at hand. The procedure of tie-point collection can be carried out automatically by some

Gridded formation:
the laying out of a two dimensional structure by equally sized square cells arranged in rows and columns which are referenced by its x, y location.

software; however, this stage of the process is critical to the quality of the project as a whole, and should be carried with great care. Once all tie-points have been created, the software can apply a rigorous mathematical model (bundle adjustment) and calculate the exterior orientation values for all images within the photogrammetric project (the ω, φ, κ and X, Y, Z parameters).

Bundle adjustment:
the minimisation of the reprojection error between the image location and the predicted image.

The process of aerial triangulation is often the most difficult and lengthy procedure in creating a successful aerial survey project. For a relatively small additional cost many aerial survey companies can undertake this stage of processing and supply the client with all the exterior orientation values to accompany the scanned aerial images. This is well worth considering as this is one of the more skilled elements of the processing where operator-experience is advantageous, and will lead to significant time savings.

12 DEM CREATION

As explained earlier, the parallax difference between two overlapping stereo images can be used to determine the height of the feature. Resolving a stereopair (X-parallax) can be achieved by the user viewing the pair of overlapping images with a floating point, or stereo cursor superimposed. Initially the floating points are at different locations on each image. Adjusting the difference in the X value between the two points until they coincide resolves the parallax at that point of the image. This is usually done by rotating the mouse wheel on the PC. Once a pair of floating points positions have been resolved, elevation (Z) and location (X, Y) can be calculated for that location. To carry out this procedure manually over the complete model would be impractical, so a process known as Automated Terrain Matching (ATM) rapidly replicates this action (Karabork et al. 2004). The software is able to automatically find matching pixels between a pair of overlapping images. The location of the matched pixels is resolved, and a height value for that pixel is generated.

Kernel:
a unit array of pixels used in digital imaging analysis, usually made up of an odd number of pixels (e.g. 3 × 3).

The ATM process is carried out by a matching matrix or kernel that compares and correlates groupings of pixels in each image. The kernel progressively moves along the whole image until all attempts are made to match all the pixels in a model. Unsuccessful matches result in holes in the DEM. The dimensions of the kernel can be varied within the software with its size determining the probability of a successful match and the final resolution of the DEM. A large kernel size (32 × 32 pixels) will produce a DEM which has few if any holes and needs little editing. However, the resulting DEM is of a low resolution and generalises detailed landscape features such as relict field structures. In comparison a small kernel size (2 × 2 pixels) will generate a high resolution DEM but with a larger number of holes. Some software packages employ a pyramidal structured kernel that initially use the coarse kernel and reduce the kernel size to refine the DEM.

Pyramidal structured kernel:
a kernel that has representations at several pixel levels (e.g. 1 × 1, 3 × 3, 5 × 5, etc.).

Coarse kernel:
a kernel of a large size (e.g. 9 × 9).

When choosing an appropriate kernel one must take into account both data processing and storage overheads. Smaller kernels take long periods to process and construct DEMs that are, due to their fine resolution, large digital files (100 MB). The specifications of the DEM creation should balance overall file size and processing against the level of detail required. Modelling a large area of landscape for a simple background elevation map a coarse kernel size will suffice. In comparison, if an individual monument or relict field structures are to be modelled, then a fine kernel is more appropriate.

Once a DEM has been created by the ATM process, editing of the height data will need to be carried out. The visual characteristics of land surface cover control success of the height generation procedure. For areas of the landscape that display little textural difference, e.g. extensive grass, it can often be difficult to generate height values automatically due to little variation in neighbouring pixels. Consequently DEM models often contain large holes which can be filled during the editing process using interpolation methods. Surfaces of water bodies such as lakes and ponds have poor or no height data assigned to them as they often display reflected light. Users must designate a single height value for the water level surface and apply this value to the cells DEM situated at a water body.

Interpolation:
a mathematical method of estimating new data points within the range of a discrete set of known points.

cf. chapter "Spatial interpolation and terrain analysis" of Hofierka.

It is not usual for DEMs to contain elements of noise where DEM values appear to be distorted or have failed. Processing techniques within most software systems can be used to apply Median and Gaussian filters to smooth the terrain. As in all aspect of automated data production, care must be taken to avoid smoothing features of potential interest that maybe confused as noise.

The final DEM produced is a record of the elevation of all features within the original imagery including, vegetation cover, buildings and other features. Once a DEM has reached its final stage of creation it can be exported into most GIS packages to enable the production of elevation and relief shaded models for further analysis and visualisation. Most software has the ability to export created surfaces as .DEM and ASCII .xyz files.

13 ORTHORECTIFICATION

Orthorectified images, more commonly known as orthoimages, are digital images that have been geometrically corrected for mapping. As shown earlier in this chapter, a standard aerial photograph contains displacements across the image which is caused by both the sensor and topographic factors. These displacements prevent reliable scaled measurements being made from the image, and also from integrating the aerial image successfully with a GIS. Distortion caused by a camera position, tilt and lens can be removed systematically by the calibration file and the derived exterior orientation information. Removal of the distortion caused by topography is achieved by using the DEM to calculate and correct

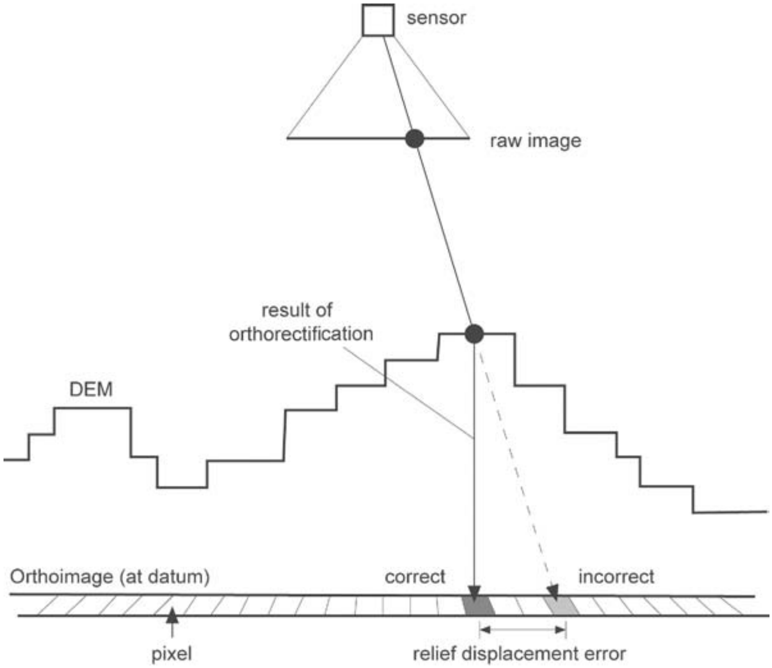

Figure 5. Illustration of the correction process when using sensor geometry and a DEM to orthorectify aerial imagery (PCI Geomatics 2003).

relief displacement error for each image pixel (figure 5). As orthoimages are derived products, one must therefore note that the condition of the underlying DEM will affect the quality of the final orthoimage. A DEM which includes poor positioning and imperfect models will inherently produce imperfect orthoimages.

Within an aerial survey project orthoimages are created for each aerial image that intersects with the created DEM (figure 6). In reality orthoimages, such as those bought commercially are constructed from several orthorectified images merged together into a single seamless image. This process can be carried out within most photogrammetric software packages where orthoimages can be colour balanced and pieced together in a similar to a jigsaw or mosaic. A similar product can be derived by using standard image processing software, e.g. Adobe Photoshop, where more advanced image manipulation tools are often available. Once editing of an orthoimage is carried out within a non photogrammetric product, care must be taken to reapply any georeferencing to the image. Freely available software such as GeoTIFF Examine allows the user to convert standard TIFF images to georeferenced (GeoTIFF) format by applying simple geospatial parameters.

Data management issues must be addressed when considering the creation of orthoimages that cover a large area. To create a single orthoimage for the complete survey area is impractical as the resulting file size for a high resolution image would be greater than most computer

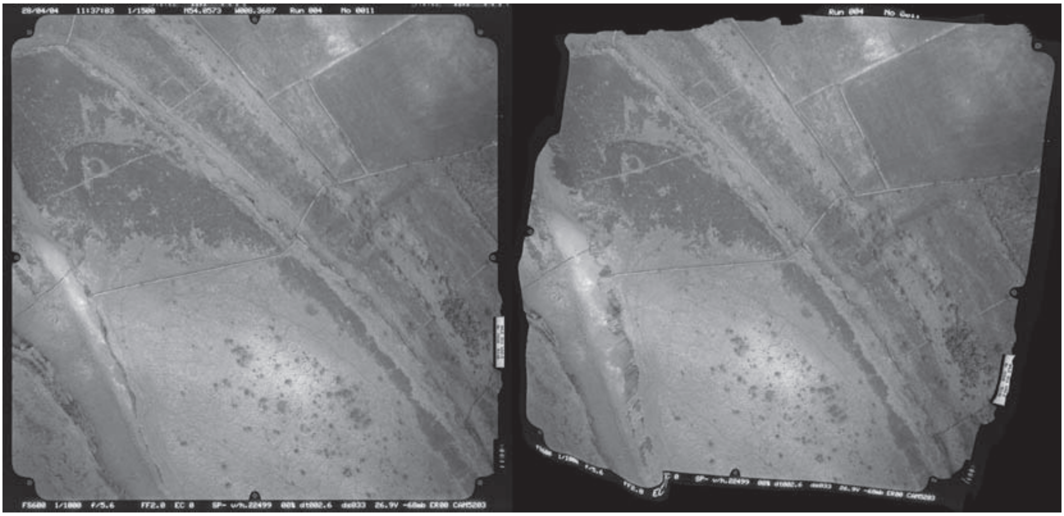

Figure 6. Example of vertical aerial image before (left) and after (right) the process of orthorectification.

systems could display, e.g. a 1:7,500 aerial survey covering 70 km^2 will contain approximately 11 GB of orthoimagery. At the outset of orthoimage creation, an effective data management framework must be established that enables orthoimages to be tiled into smaller units in a systematic way. Creation of the final orthoimages must take into account the requirement that users need to display the image using a standard computer system. In practice, orthoimagery with a 16 cm pixel resolution can be separated into 1 km^2 TIFF image tiles of approximately 60 MB each.

14 INTEGRATION WITHIN GIS

As both DEMs and orthoimages are created by digital photogrammetry, they are intrinsically geocoded by their creation process, the inclusion of these data sets within the GIS environment is simple. Both data sets can be imported as raster layers and utilised with landscape analysis and visualisation.

Geocoding:
the process of assigning geographic coordinates to map features or data records.

Orthoimages can be used as a background image when constructing cartographic products. The introduction of orthoimages enables people who are unfamiliar with vector based cartographic conventions to orientate and locate themselves within the landscape. Orthoimages can be interpreted for many uses including historic landscape characterisation (HLC) and analysis (HLA), land use monitoring and planning. Important features within orthoimages can be digitised and subsequently vector datasets can be incorporated into a GIS forming the basis for further analysis (Buckinghamshire County Archaeological Service 2006).

Historic landscape analysis (HLA):
cf. chapters "The concept of a historic landscape analysis using GIS" and "Workflow of a historic landscape analysis using GIS" both of Bender.

Oblique aerial images often show higher levels of landscape feature detail due to their ability to exploit lower sun elevations that are unsuitable within vertical aerial images. However, the lack of geometric control

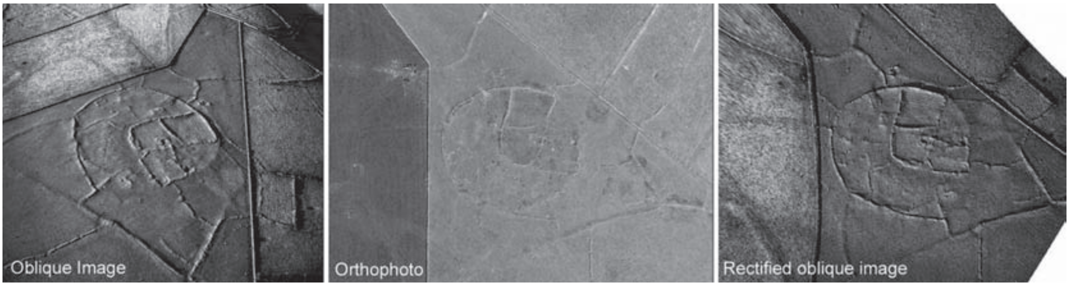

Figure 7. Example of the rectification process of detailed oblique aerial imagery to orthoimagery of the same local.

within oblique images inhibits there accurate rectification and hence use in precise analysis. Features within orthophotos can act as a framework to aid the georeferencing of oblique aerial images: Identical features than appear clearly in both an oblique and an orthoimage can be used to georeference and rectify the oblique image (figure 7).

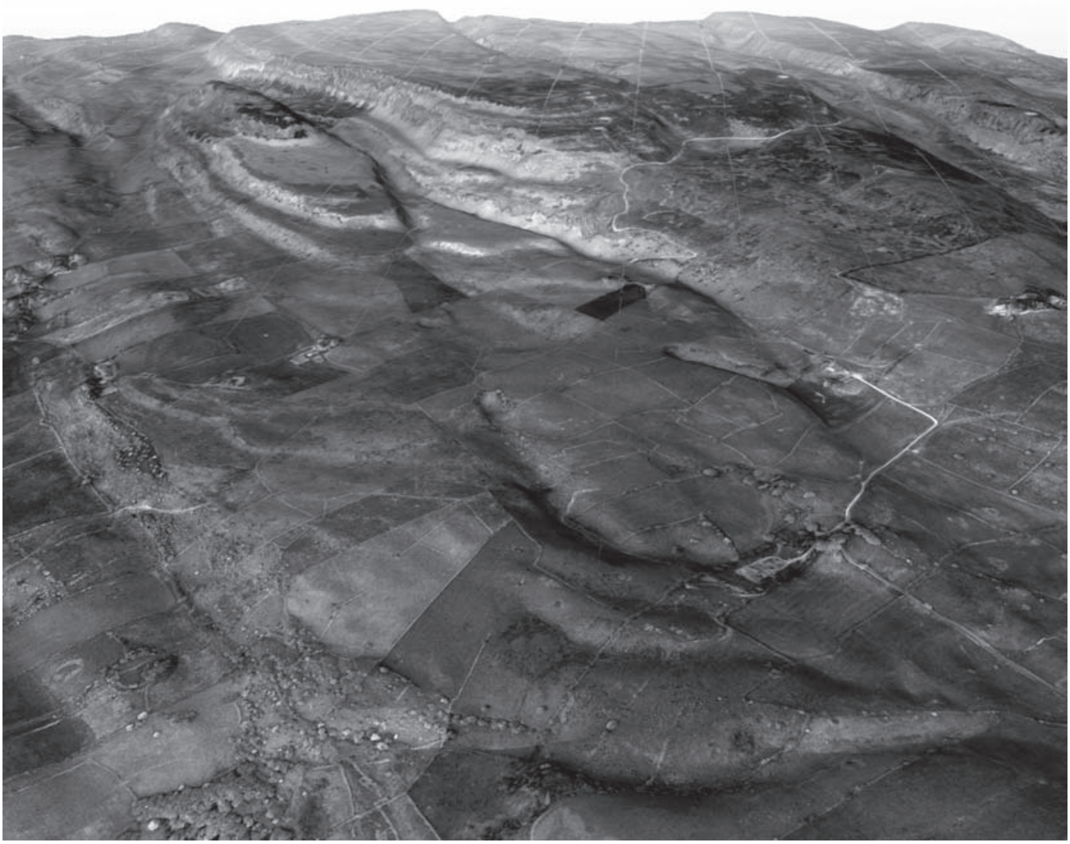

Figure 8. A 3D perspective view archaeological landscape of Mullaghfarna, County Sligo. The generated orthophoto is draped over an underlying DEM both created by digital photogrammetric software.

DEMs have great uses within GIS, especially due to their ability to be analysed. New raster data products including relief shade, aspect and viewshed analysis can be derived from DEMs and integrated within landscape models. DEM data products have a powerful role as a background to many vector-based landscape maps, where the combination of semi-transparent DEM and relief shade raster layers can effectively illustrate topographic relief. The ability to alter sun angles within the GIS enables the viewer to emphasise topographic features that are normally hidden to the naked eye and in turn further understand their morphology and interrelationships (Parmegiani & Poscolieri 2003).

The development of 3D technology within GIS has enabled users to visualise geographic data sets in a realistic and effective environment that is more innate to our perception of landscapes (figure 8). In combination, orthoimages and DEMs can be used effectively within 3D GIS to visually reproduce the recorded landscape (Wijayawardana 2003). Users can explore, navigate and observe the landscape from physically unattainable locations and perspectives.

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The use of satellite remote sensing for the detection and analysis of geocultural heritages

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ABSTRACT

Earth observation from space has opened new perspectives for many applications, particularly since a new generation of satellites provides very high resolution images comparable to aerial photography. This new data allows for classical visual interpretation as well as for automated classification methods and information extraction techniques that can be applied for the modelling of geocultural landscapes. For this purpose image processing procedures may be used but need to be occasionally adapted because of the unprecedented high level of detail. The objective of this chapter is to introduce imagery from recent satellites like Ikonos-2, QuickBird or OrbView-3 and to outline their benefit for the investigation of geocultural phenomena. Explained methods and techniques comprise the pre-processing of the satellite data, the image enhancement for image quality improvement, the classification process and the information extraction as well as advanced methods such as artificial intelligence. As far as research in (geo-)archaeology has already been done using these introduced methods, practical examples are linked to the theoretical aspects. The aim is to help to overcome constraints to the application of this relatively new high resolution satellite data in the field of geocultural landscape research.

1 INTRODUCTION

1.1 *Remote sensing and geoarchaeology*

The observation of geocultural heritage is a relatively new application area of remote sensing. It is part of interdisciplinary research in geoarchaeology which combines the contents and methods of physical geography, human geography, and geosciences with archaeological sciences as well as historical sciences and ancient oriental studies (Brückner 2006). The modern techniques of remote sensing may assist in two

Remote sensing:
science of acquiring, processing and interpreting images that record the interaction between electromagnetic energy and matter (Sabins 1996).

ways: Firstly, remotely sensed images and their processing methods help to detect and interpret discernible historical geocultural structures such as archaeological sites and ancient agricultural systems. Secondly, the imagery may be combined with additional data such as sedimentary profiles, pollen analyses, or historic maps to generate and visualise palaeo-environmental information. The second approach does not allow for the direct identification of geocultural structures. Hence, this article addresses primarily the detection and interpretation of archaeological features and ancient field structures. For that purpose especially ultra-high resolution satellite imagery is needed. In the past, the medium resolution of the satellites like Landsat or SPOT was insufficient to capture archaeological sites at a detailed scale for an adequate interpretation. Presently there exists a series of new imaging devices including, among others, high-resolution satellites, satellites with hyperspectral sensors and radar devices, airborne laser scanners, and large-format digital aerial cameras, which allow for the detection of archaeological features such as ancient settlements, roads, or other indicators of human activities. The present chapter will, however, mainly focus on high-resolution satellite imagery.

Hyperspectral:
the use of many narrow sections of the electromagnetic spectrum in remote sensing.

Looking at ancient remains from the ground, their existence, their spatial significance or potential relationships to adjacent archaeological features may often not be identified. Observations from the bird’s eye view, however, help to overcome these problems (figure 1). Theoretically, narrow line-features with 1–2 metres in width and medium-sized areal features within a range of 200–1000 square metres may easily be identified in Ikonos-2 and QuickBird imagery (cf. Campana 2002). The author states, that the Etruscan-Hellenistic oppida and Roman villas as well as churches, monasteries, medieval castles and villages in Tuscany are potentially visible. Figure 1 shows as an example

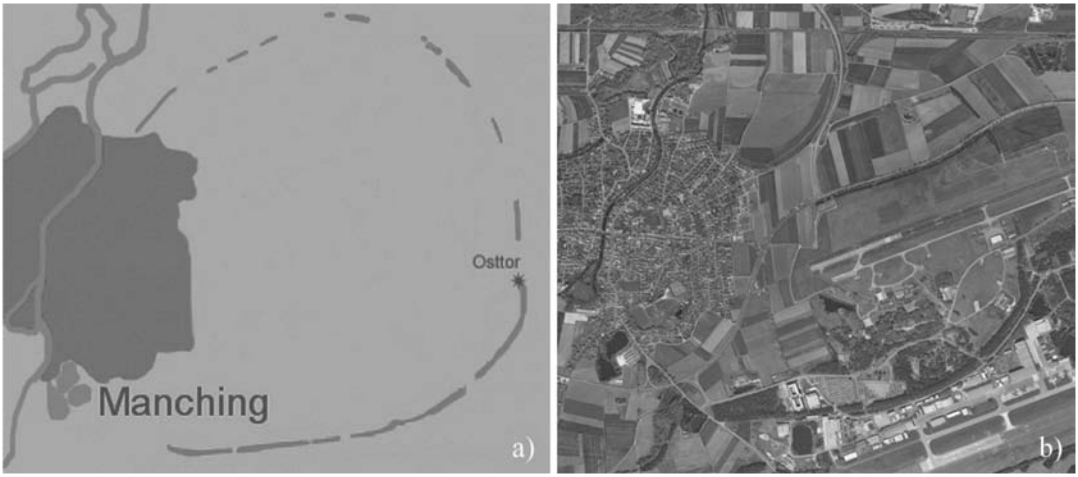

Figure 1. Oppidum in Manching, Germany: (a) Site plan (for further reading see Krämer n.d.); (b) Orthophoto © Luftbildarchiv des Landesamtes für Vermessung und Geoinformation München.

the Celtic oppidum of Manching in Germany, demonstrating the level of detail in satellite imagery. Until present, aerial photography has been employed more often than satellite imagery due to the higher spatial resolution and the well established methodology. However, with the new generation of ultra-high resolution satellites, data with comparable ground resolution and additional beneficial properties are available (cf. section 1.2). In the case of historical land-use patterns, successful studies using low- to medium-resolution satellite imagery have also been conducted to extract ancient field-division systems from Landsat data (Montufo 1997).

Moreover, traditional fieldwork missions imply comparatively high financial expenditures. So in this respect, satellite remote sensing represents a useful alternative, a fact which has already been demonstrated in several studies (Beckel & Harl 1983, Campana 2002, Grøn & Loska 2002, Gruen et al. 2004, Jahjah et al. 2007, Masini & Lasaponara 2007, Saturno et al. 2007, Sever & Irwin 2003, Shennan & Donoghue 1992). But it is also clear that the new space-based technology will probably never represent a full replacement of terrestrial archaeological research (Aurdal et al. 2005). Although the costs of acquiring and analysing satellite data are not negligible, remote sensing technology is a valuable addition to the traditional methods in the detection and analysis of geocultural heritages.

1.2 *Advantages of high resolution satellite imagery*

In the recent years, satellite imagery with ultra-high spatial resolutions of one metre and better in the panchromatic and 2.5 to 4 metres in the multispectral range became available and allow an appropriate visual interpretation which has been only viable with aerial photographs so far.

Beside this, satellite images have a higher spectral resolution, which means that the data is recorded in various wavelengths – visible and non-visible – that provide more information about the ground conditions than normally visible to the human eye. For instance, the use of near infrared (NIR) may enhance the detection of surface anomalies caused by buried remains, due to the sensitivity of the NIR band to different phenological states of vegetation (Masini & Lasaponara 2007).

Furthermore, images from CCD sensors, which are commonly aboard the new generation satellites, have a much larger dynamic range than film-based images, resulting in a more detailed radiometric information. Generally speaking, the radiometric resolution describes the ability to discriminate slight differences in the electromagnetic energy which can be seen in the images as different grey values.

CCD (Charge-Coupled Device): *an analog shift register mostly consisting of a matrix with light-sensitive photodiodes.*

For obvious reasons, the temporal resolution is another plus for the use of satellite data: The high revisit rates allow the image collection of the same area at different periods of time, thus permitting the selection of the most appropriate seasonal data (cf. also phenology).

Table 1. Ikonos-2 visual interpretation (modified after de Laet et al. 2007).

Attribute	Archaeological description
Tone	Tonal differences in soil may indicate buried structures (crop marks)
Texture	Different vegetation textures may indicate buried features (crop marks)
Shape	Knowledge of shapes of archaeological features may assist with determining whether a feature can be considered as archaeological or not
Size	The dimensions of the feature are also important in order to regard the feature as archaeological or not
Spatial patterns	Spatial patterns among different features may represent an ancient settlement
Orientation	Some archaeological features are consistently orientated in a certain direction
Shadows	Appearance of positive archaeological features
Spatial relationships	Ruins that have been abandoned for a very long time are sometimes located in isolated areas. Depending on their state, the ruins may still be associated with other nearby ancient features.

Orbit:
path of a satellite around the planet Earth.

Another interesting point is the coverage of an area. In comparison to aerial photography, a satellite image covers a larger area due to its imaging geometry. Earth-observing satellites fly in orbits at altitudes of about 450 km (QuickBird) to almost 700 km (Ikonos-2) with swath widths of about 7 km (EROS-B) to 17.6 km (WorldView-1; cf. table 1).

1.3 *Characteristics referring to geocultural features*

1.3.1 Archaeological structures and ancient field systems

Constructions and formation processes related to cultural heritage sites have left long-lasting traces which are sometimes not visible for the human eye but are detectable by satellite sensors from the bird's-eye perspective. Already at the end of the 1980s Gierloff-Emden (1988), in part based on photographic work performed and later described by Mette (1990), reports about the detection of the Roman “centuratio” landuse system in the Po Plains west of Venice in specially processed NASA Large Format Camera Space Shuttle photographs. Grøn & Loska (2002) describe this advantage in their report about the different characters of anomalies that may refer to cultural heritages and the reasons for their recognition in satellite images. As the authors point out, the material of mounds may often differ from the underlying subsoil (e.g. turf, larger stones, etc.) and may be an indicator for the existence of underground features. Remnants of ancient structures currently still rising above the ground such as ramparts, mounds, or transport infrastructure may locally influence the drainage and thus result in variations of vegetation cover (cf. figure 2) and soil moisture, thereby causing differences in the electromagnetic radiance. If they are not used anymore, in the course of time, pits or ditches and heavily used tracks will be filled with material. There, the soil differs from the adjacent ground and becomes visible in images. Thus, Menze et al. (2006) studied “tells”, which are settlement-mounds found in the Near and Middle East representing prehistoric and early historic villages and towns. The aim of the research was to develop and assess a (semi-)automatic tell detection strategy based on SRTM data combined with Landsat ETM+ imagery. Also ancient settlements stemming from the

NASA (National Aeronautics and Space Administration):
an agency of the United States government, responsible for the nation's public space program.

SRTM (Shuttle Radar Topography Mission):
the acquisition of remotely sensed data of the Earth‘s surface from space in February 2000 for the generation of a homogeneous digital elevation model.
www2.jpl.nasa.gov/srtm

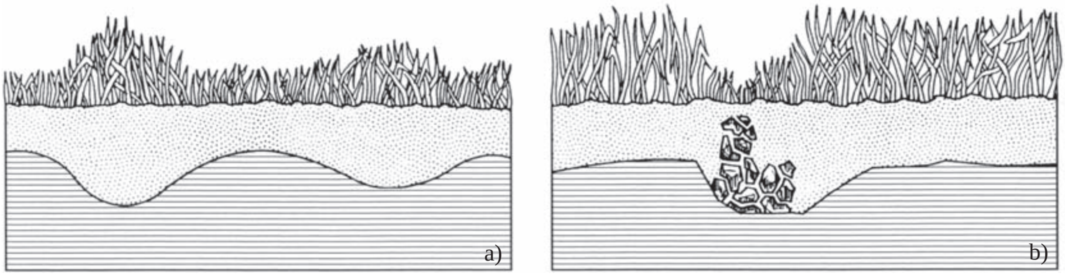

Figure 2. Positive and negative vegetation properties: (a) ancient tombs (better growth conditions); (b) subsurface wall remnant (aggravated site conditions) (Albertz 2007: 210).

agriculture- and hunting-dominated times can often be detected because these places show an unusually high concentration of traces. Settlements were the centres of the exploitation of their surroundings. Animals were brought in and, together with their dung and urine, changed and compressed the ground in a special manner.

Since very high resolution satellite images have spatial resolutions close to aerial photographs, a visual interpretation is quite common for the detection of geoarchaeological features. De Laet et al. (2007) developed a list of archaeological attributes for the visual identification of ancient features in high-resolution imagery (table 1).

1.3.2 Other geocultural structures

Beside the aforementioned clearly identifiable archaeological structures and ancient field systems exists another group of geocultural features where typical anomalies per se are not recognisable without additional data. Those comprise landscape- and soil profiles, pollen analyses, as well as historical maps and records. One major objective of (geo-)archaeology is the palaeo-geographical reconstruction of regional landscape evolution, comprehending aspects like erosion- and accumulation periods as well as changes of vegetation or climate. In these cases, satellite imagery may only be used for the mapping of the current conditions with regard to specific landscape features which might indicate a certain development. In combination with other data and findings, geocultural heritages can thus be identified.

2 EARTH OBSERVATION SATELLITES

2.1 *Satellite imagery in the past*

Most research projects dealing with the detection of archaeological features and making use of satellite remote sensing were based on imagery captured by the Landsat and SPOT satellites. The following paragraph should give a little insight into the early days of space-borne remote sensing and its data usability for the detection and analysis of cultural heritage.

In 1972 ERTS-1 (Earth Resources Technology Satellite 1, later renamed Landsat-1), specifically designed for monitoring the Earth's surface, was launched by NASA. The aim of this mission was to test the feasibility of collecting multispectral Earth observation data from an unmanned satellite. Since that time, another six Landsat satellites were launched and they have collected a vast amount of data from all around the world. The tremendous success of this Earth observation program is due to several factors such as: a combination of sensors with spectral bands tailored to Earth observation, functional spatial resolution, and good areal coverage. In 1985, the program became commercialised, thereby providing data to a wide range of civilian users. In the beginning, the most popular instrument on board Landsat was the so-called Multispectral Scanner (MSS) which was followed by the Thematic Mapper (TM), an instrument with a spatial resolution of 30 m in all bands except for the thermal band, having 120 m. Landsat-7 even has a panchromatic channel with 15 m spatial resolution (figure 3) and its thermal is 60 m. Fowler (2002), Montufo (1997), and Shennan & Donoghue (1992) used Landsat TM imagery to detect and map archaeological features, but they figured that their use is limited by the low resolution. They considered the data to be (better) suited for the prospection for areas with a high archaeological potential.

Spatial resolution:
refers to the area on the ground that an imaging system, such as a satellite sensor, can distinguish.

Panchromatic channel:
a band collected in a broad visual wavelength range but rendered in black and white. The term is historically referred to a black and white photograph of a colour scene.

14 years after the launch of Landsat-1, France, in cooperation with Sweden and Belgium, started the SPOT series of Earth observation satellites, which were designed to serve as a commercial provider of image data. The images of the first SPOT generation have been effectively used in mapping the regional landscape character, but in many cases the spatial

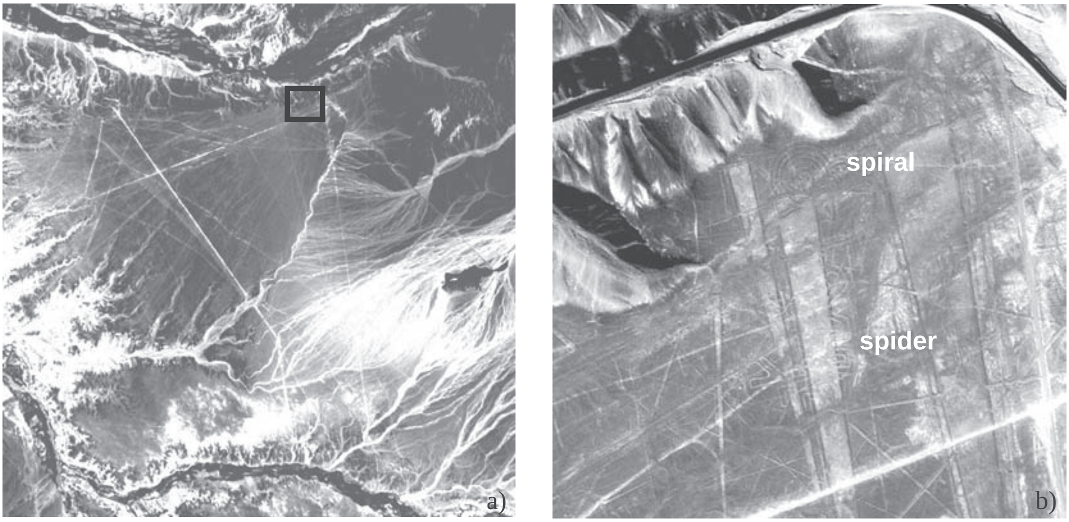

Figure 3. Nazca lines in Peru, comparison between Landsat and Ikonos images: (a) Landsat 7, 15 m, pan-sharpened, 2002, © U.S. Geological Survey; (b) Ikonos-2, 4 m, 2001, Courtesy of GeoEye. © 2008. All rights reserved.

resolution (in the order of tens of metres) turned out to be too coarse to directly reflect cultural heritage. Research projects in this area have been conducted by Shennan & Donoghue (1992) and Fowler (1995 and 2002). Although the latest SPOT-5 satellite has a panchromatic band with 2.5 m spatial resolution, it does not meet the requirements for the identification of small archaeological features. Only very high resolution satellite imagery allows for the detection of geocultural heritages on a detailed level.

2.2 *Specification of high resolution sensors*

The increased availability of high-resolution imagery proved to be crucial for an efficient exploration of large sites. Table 2 outlines satellite sensors with very high resolution which are useful for geoarchaeological applications. Examples of these satellite images are represented in figures 4 and 5. Radar devices are not listed as this chapter concentrates on the introduction of optical satellite data, but the authors refer to the latest TerraSAR-X satellite with up to one metre resolution (TerraSAR-X 2007). The new generation of radar sensors have high potential for the identification of archaeological features, but this has to be treated as a separate paper due to the complex technology.

Radar (Radio Detection and Ranging):
an active sensor system which operates in the microwave region of the electromagnetic spectrum and generates its own illumination as an outgoing signal that interacts with the target.

Depending on the task, the data has to be chosen carefully concerning panchromatic and/or multispectral wavelengths, ground resolution, swath width and costs. For many requests suitable satellite images can be found in archives, and if no adequate imagery is available, new satellite

Table 2. Main characteristics of very high resolution sensors (pan = panchromatic, RGB = red green blue, NIR = near infrared).

Sensor	Launch	Bands	Ground resolution [m]	Swath width [km]	Price [per km²]	Image provider
WorldView-1	2007	pan	0.5	17.6	n/a	DigitalGlobe www.digitalglobe.com
QuickBird	2001	pan, RGB, NIR	0.61 2.44	16.5	≥16 US$	DigitalGlobe www.digitalglobe.com
Ikonos-2	1999	pan RGB, NIR	1 4	13.8	≥16 US$	European Space Imaging www.euspaceimanging.com
OrbView-3	2003	pan RGB, NIR	1 4	8	≥10 US$	OrbImage www.orbimage.com
EROS-B	2006	pan	0.8	7	≥17 €	ImageSat International www.imagesatint.com
ALOS-PRISM	2006	pan	2.5	70	≥25,000 ¥ (per scene)	RESTEC www.alos-restec.jp
CARTOSAT-2	2007	pan	0.8	9.6		Antrix Corporation Limited www.antrix.gov.in
KOMPSAT	2006	pan RGB, NIR	1 4	15	≥14 €	SPOTIMAGE www.spotimage.fr

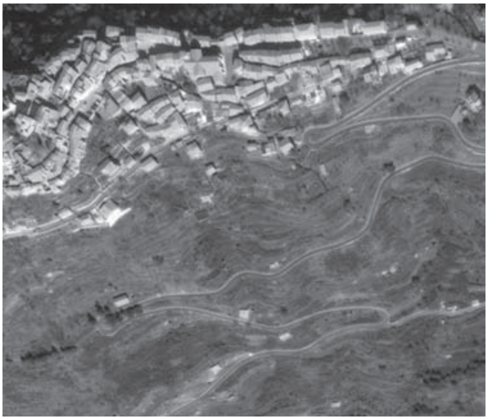

Figure 4. Terrace landscape near Baiardo, Liguria, Italy, QuickBird image, Google Earth, © 2008 DigitalGlobe.

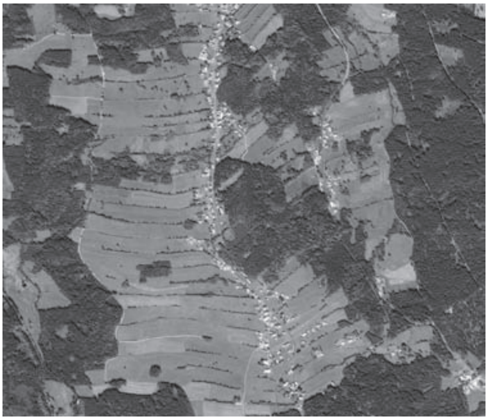

Figure 5. Medieval field strips (“Waldhufen”) near Mauth, Bavaria, Germany, Ikonos-2 image, Courtesy of Space Imaging © European Space Imaging GmbH.

data can be ordered through a satellite tasking process. In the latter case, a satellite is programmed to record data within a specific time frame.

3 DIGITAL IMAGE PROCESSING

3.1 *Some fundamentals*

Digital image processing: *computer-aided methods of manipulation, enhancement, and analysis of digital image data.*

IDRISI: *www.idrisi.com*

ERDAS IMAGINE: *www.erdas.com*

PCI Geomatics: *www.erdas.com*

ER Mapper Pro: *www.ermapper.com*

ENVI: *www.ittvis.com/envi*

Digital image processing comprises all computer-aided methods of manipulation, enhancement, and analysis of digital image data. Today, high-performance computer technology and user-friendly software packages allow the processing of huge data volumes. A variety of commercial software products is available at relatively affordable prices including the following: IDRISI, ERDAS IMAGINE, PCI Geomatics, ER Mapper Pro, or ENVI.

The aim of image processing is the transformation of image pixel values by applying mathematical operations to obtain images for both a better visualisation and interpretation, and easier handling during further processing steps. The numerical functions comprise geometric and radiometric corrections, image enhancement, data fusion and classification. The following subsections give a short account of procedures that have to be considered while working with satellite images. For further reading, the readers are kindly referred to the textbooks by Albertz (2007), Campbell (2002), CCRS (2007), or Lillesand et al. (2004).

3.2 *Pre-processing methods*

Normally, satellite images have sensor- and platform-specific geometric and radiometric distortions which have to be corrected first unless the image provider supplies already geocoded data, but this will be more expensive. Geometric distortions may be caused by the imaging system itself or by the relief and small shifts in the satellite position, whereas radiometric distortions result from variations in scene illumination, and atmospheric effects such as vapour, haze, fume, or dust. Each of these varies due to sensor and platform peculiarities as well as due to environmental conditions during the imaging process (CCRS 2007). Common software packages include tools for geometric correction. The distortions can be corrected by applying interpolation algorithms or parametrical operations, the latter ones take the geometric modelling of the imaging geometry into account. Differences in terrain heights can be considered, whereas the interpolation operation assumes continuity in the image. In both cases, the transformation is based on ground control points (GCPs). These are clearly discernible points with known ground coordinates in the reference system (Albertz 2007).

Geocoded data:
data with assigned geographic identifiers such as coordinates to map features and other data features (e.g. street addresses).

GCPs (Ground Control Points):
points on the Earth's surface of known location (within an established coordinate system) which is used to georeference image data sources.

Radiometric corrections aim at the removal of atmospheric effects to retrieve the actual surface reflectance. For that purpose, complex calculations for modelling the illumination conditions are frequently applied. The German Aerospace Centre (DLR) developed a commonly used method called ATCOR (Richter 2004), which works with software packages including ERDAS IMAGINE, PCI Geomatics, and ENVI (cf. figure 6).

Furthermore, the quality of both analysis and interpretation may be significantly improved by a fusion of different images with varying spatial resolution covering the same area. This process is called pan-sharpening (in the case of using fine-resolution panchromatic data) and also resolution merge. Usually, the geometric detail of a high-resolution panchromatic image is fused with the colour information of a low-resolution multispectral image which is particularly important for large-scale

Image fusion:
the process of combining relevant information from two or more images into a single image resulting in a more informative layer.

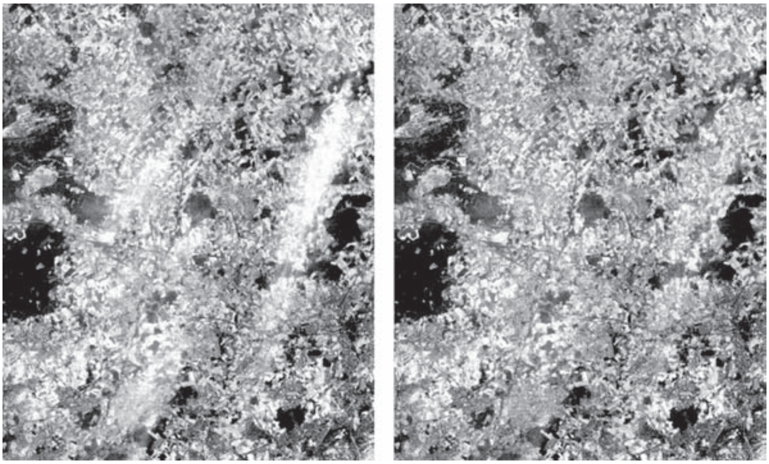

Figure 6. Atmospheric correction applied on a satellite scene: (a) without ATCOR; (b) with ATCOR, © R. Richter, DLR German Aerospace Center (Richter 2004).

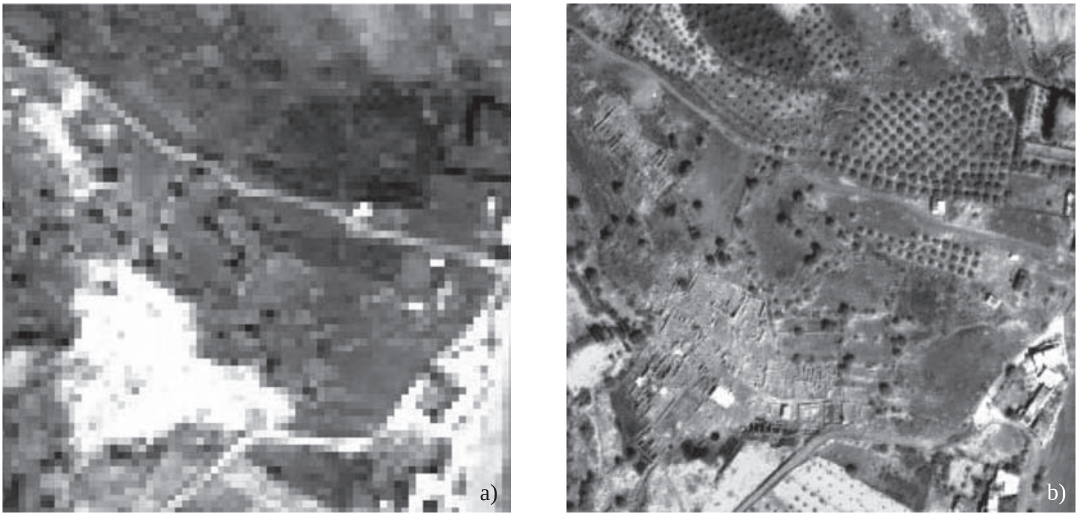

Figure 7. Ikonos-2 images of an archaeological site in Crete, Greece: (a) multispectral image with 4 m spatial resolution; (b) pan-sharpened multispectral image with 1 m resolution (Pavlidis n.d.).

applications. Zhang (2004) impressively demonstrates one possible procedure using the example of QuickBird data of Sydney. In terms of cultural heritages, pan-sharpening represents a very useful and promising method how Pavlidis (n.d.) demonstrates in figure 7. Georeferenced and radiometrically corrected satellite images permit an improvement of the image quality and accurate measurements of positions, lengths and area extents.

3.3 *Image enhancement*

Texture:
the distinctive physical composition or structure of an object's surface, especially with respect to the size, shape, and arrangement of its parts.

Image enhancement comprises techniques for the emphasis of tonal and textural differences in satellite images (CCRS 2007). Numerous methods can be applied for the improvement of image quality and contrast in order to realise an easier, quicker, and more reliable image analysis. For each application and each image, a customised adjustment of the grey value range and distribution is usually necessary depending on the spectral response of the targets (e.g. forest, snow, water, etc.). It is possible to distinguish three groups: radiometric, spatial, and spectral enhancement techniques.

Histogram:
a graph of the number of times a value occurs across a range of possible values.

Radiometric methods are used for an improvement in image contrast. As a matter of fact, a scene never occupies the whole range of digital values (e.g. for 8 bit data: 256 grey levels) which is reflected in a low contrast image. A histogram is the best method to visualise the distribution of grey values in an image. By applying linear or non-linear, e.g. logarithmic transfer functions, the grey values can be converted, resulting in an improvement of the contrast (cf. figure 8).

The second group represents spatial filtering techniques which aim at the improvement of geometric and spatial details as well as the elimination

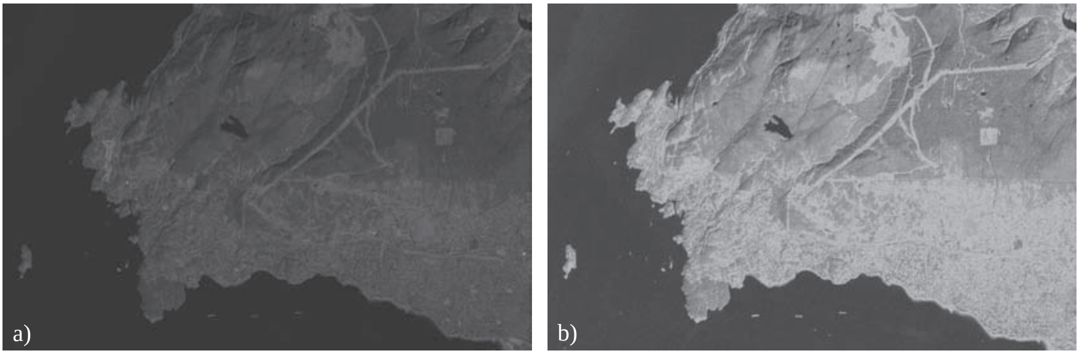

Figure 8. Effect of image enhancement on band 8 of a Landsat scene: (a) original band without enhancement; (b) with contrast stretch enhanced image, © Department of Natural Resources Canada.

of noise. This set of processing functions is designed to highlight or suppress specific features such as edges, thereby changing the image structure in such a way that a central pixel is recalculated and replaced by the values in the overlaid coefficient matrix which is moved over the whole image. The effect of filtering depends on the size of the moving window and on the chosen filter kernel coefficients. Masini & Lasaponara (2006 and 2007) applied spatial filtering when they investigated the feasibility of using satellite QuickBird data for the identification of geocultural features and obtained very promising results. In their studies they integrated an edge detection algorithm (Gaussian smoothing kernel) for reconstructing urban shapes of buried remains and for identifying land divisions of ancient Greek colonisation.

Last but not least, the spectral enhancement methods improve the multispectral data by calculating new “synthetic” bands (frequently called “indices”) with a higher level of information or with partly enhanced data. These procedures include arithmetic operations between bands of the same multispectral image or multitemporal images expressed by the addition, subtraction, multiplication, and/or division and their combination of pixel values. Spectral ratioing is a typical operation for pointing out specific phenomena based on their spectral differences in the image. Accordingly, the Normalised Difference Vegetation Index (NDVI) is a useful and widely applied index for monitoring vegetation conditions. It is the ratio of the near-infrared radiation that is influenced by the vitality of the vegetation, and the red portion of the electromagnetic spectrum (Albertz 2007). The formula reads:

NDVI (Normalised Difference Vegetation Index):
a measure for photosynthetic activity that highly correlates with the density and vitality of the vegetation cover.

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$

where NIR = near-infrared band, RED = red band.

Campana (2002) and Masini & Lasaponara (2006) applied the NDVI in studies related to archaeological landscape features in Tuscany and in the Basilicata Region (Italy). There are other promising indices, too, which are able to emphasise specific image contents including e.g. the Leaf Area Index, the Enhanced Vegetation Index, the Weighted Difference Vegetation Index, or the Soil Zone Index.

PCA (Principal Component Analysis):
a multivariate statistical method to identify and extract principal components in correlated datasets.

Another common operation for image enhancement is the principle component analysis (PCA) which is based on statistical methods and aims at a reduction of the data redundancy and the correlation between the bands of a satellite image. In this case, the most relevant information is compressed into fewer bands, while the information content is statistically maximised (Campbell 2002, Lillesand et al. 2004). Hence, both interpretation and analysis of the generated components are simpler and more efficient for a visual interpretation or for further procedures, such as image classification.

These enhancement methods are quite common and simple to apply and allow for feature extraction in geocultural landscapes. To this end, further methods, which include the Tasselled Cap Transformation (TCT, Kauth & Thomas 1976), operations for texture analyses (Haralick et al. 1973), and colour space transformation (Haydn et al. 1982), are only be mentioned here, and not described in detail.

3.4 *Classification and information extraction*

Before conducting an image classification, the satellite data should be prepared by applying pre-processing methods and image enhancement procedures for the improvement of the image quality. If additional data like digital terrain models or geological or soil-related maps are used, they have to be harmonised with the satellite image.

The overall aim of image classification is the automatic categorisation of all pixels in an image into specific classes which identify areas of land cover and land use. The traditional way is the pixel-based classification that only refers to the spectral information in a satellite image. Every element in a landscape is characterised by a certain spectral signature representing a specific combination of grey values. The differences between the elements may vary significantly and differ in relation to the wavelength, too. For instance, vegetation is hardly distinguishable in the visible wavelength range between 0.5 and 0.6 µm because of the strong absorption of the radiance, whereas the near-infrared shows a strong reflection and allows for differentiation. In this case, the image classification aims at gathering spectral fingerprints and categorising the data (Albertz 2007) based on a supervised or unsupervised approach. The latter uses statistical operations, whereas the supervised classification integrates training sites of known objects. Classification algorithms are usually integrated in remote sensing software packages, for example: the maximum-likelihood approach, the minimum-distance approach, the box classifier and the hierarchical classification. In practice, pixel-based classification algorithms are better applied on medium- to low-resolution images. De Laet et al. (2007) stated that pixel-based classification leads to reasonable results, but it cannot realise the extraction of unique classes of archaeological features. The reason is primarily due to spectral

Pixel-based classification:
automatic categorisation of all pixels in an image into land cover classes or themes.

similarities between archaeological and surrounding landscape elements. For further reading about the theory of pixel-based classification, the readers are kindly referred to the afore-mentioned books by Lillesand et al. (2004) or Albertz (2007).

A second and today quite common method for categorisation is an object-based approach taking into account the spectral information, the shape, and textures. The most popular software for conducting object based classification is Definiens developer (former eCognition). As Baatz et al. (2004) state in their user guide, ultra-high resolution satellite data is characterised by high information contents, sharpness, accuracy, high image-clarity and integrity – all factors diminishing the problem of allocating individual pixels to their most likely class. For that reason, a segmentation algorithm was developed to extract homogeneous image regions. These so-called primitives are the basis for the actual classification step which comprises the assignment to defined thematic classes. As Jahjah et al. (2007) and de Laet et al. (2007) showed in their studies, an object-based classification on archaeological sites using QuickBird and Ikonos-2 imagery is a promising and suitable technique for the automated extraction of geocultural objects.

Object-based classification:
beside the spectral signature the categorisation can be based on shape, size as well as relations of neighbourhood and hierarchy.

Definiens Developer:
www.definiens.com/definiens-developer_7_7_8.html

3.5 *Advanced methods*

At this point, advanced methods are only briefly mentioned due to their complexity but show that there exist further more advanced techniques for the analysis and the interpretation of spatial patterns in satellite images. The methods may be summarised by the category “artificial intelligence” and comprise among others the following: expert systems, Bayesian networks, neural networks, fuzzy logic systems, wavelets, and the chaos theory. For further reading, literature of Campbell (2002), Zilouchian & Jamshidi (2000), or Stolz (1998) is recommended.

One example of a structural and statistical image analysis approach in archaeology using satellite data is explained in the following subsections to give an insight in the advanced technology of image processing.

Artificial intelligence:
the capability of a device to operate in such ways that are normally associated with human intelligence, such as reasoning, learning and optimising through experience.

3.5.1 Modelling

The detection of debris- or soil-covered archaeological remnants is a challenging task for the application of remote sensing. Difficulties arise here especially when thick sedimentary layers on top of ancient structures hide their presence in almost all spectral bands of the respective satellite sensors. Frequently, the only band which reveals this presence at least partially is the thermal infrared band (TIR). The comparatively coarse resolution of the TIR bands (for ASTER e.g. 90 m), however, hampers its otherwise efficient use.

On the other hand, recent research results have shown that geocultural structures may in many cases be detected from digital elevation models by using derived local features like slope and curvature, provided they show up as either noticeably raised or lowered features (cf. morphometry-based approaches set forth by Bishop et al. 2001, Bolch & Kamp 2006, Flach et al. 2009). However, these methods still include several

ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer):
an instrument aboard the earth-viewing satellite TERRA launched by the NASA.

problems, mainly due to the resolution of the DEM (which today can be generated from spaceborne stereo-images) and the frequently smooth or fuzzy boundaries of raised or lowered remnants. It seems therefore reasonable to use both modalities – multispectral satellite imagery (and especially the TIR band) as well as DEM data. Promising results in this direction were shown by Buchroithner & Bolch (2007), in the detection of particular supraglacial features. Using these results as a starting point, a statistical model which incorporates certain apriori knowledge about morphologically pronounced geocultural structures and relates it to the observable modalities may be considered (Flach et al. 2009).

Let R denote the (pixel-) domain of the co-registered modalities – multispectral satellite imagery and topographic features like (relative) elevation, slope and curvatures. Combining all these modalities in a vector we get a vector field, i.e., a feature vector per pixel. The sought-after segmentation is described by a field which assigns a segment label to each pixel. In order to cope with the slope- and exposition-dependent variation of the aforementioned multispectral values, another hidden quantity may be introduced into the model, a slowly varying shading field. All these quantities are denoted as follows:

Segmentation:
a process of partitioning a digital image into multiple regions. Each of the pixels in a region are similar with respect to some characteristic property, such as colour, intensity or texture.

$$\vec{x}: R \to \mathbb{R}^m \quad \text{vector field of features (observable)} \tag{2}$$

$$\vec{\alpha}: R \to \mathbb{R}^m \quad \text{shading field (unknown)} \tag{3}$$

$$s: R \to K \quad \text{segmentation field (unknown)} \tag{4}$$

where K denotes the set of labels used for segmentation. In the simplest case, there are only two possible labels – one for the sought-after archaeological feature (“foreground”) and another one for the rest (“background”). This is, however, not sufficient (for good results), since one cannot hope to describe the different appearances of e.g. soil-covered channel systems or fortresses and the remaining regions with vegetation, rocks and gravel by only one conditional p.d. for feature vectors (see below). That is why e.g. three different segment labels for the “background”, two labels for the “object of desire” and one special label for the boundary between might be advisable.

The statistical model relates all three quantities by a p.d.

$$p(\vec{x} \,|\, \vec{\alpha}, s) = p(\vec{x} \,|\, \vec{\alpha}, s)\, p(\vec{\alpha})\, p(s) \tag{5}$$

where it is assumed that the shading and the segmentation are a-priori independent.

In more detail, the model constituents function the following way: The prior p.d. for segmentations $p(s)$ models two aspects: The first one is that we expect the segments to be more or less compact – a segmentation s is a-priori the more probable the shorter the overall boundary length of all segments. Second, it forbids the situation of two neighbouring pixels labelled by one of the background labels and one of the foreground labels respectively – transitions from background to foreground should be separated by boundary labelled pixels. This is based on the assumption that this special boundary label will be correlated to features characteristic for boundary features.

Finally it can be assumed that the conditional p.d. for the field of observable features x is pixelwise independent, given the segmentation and the shading:

$$p(\vec{x}\,|\,\vec{\alpha},s)=\prod_{r\in R} q(\vec{x}_r-\vec{\alpha}_r\,|\,s_r;\theta_{sr}) \tag{6}$$

where the q-functions are conditional p.d.-s for the feature vectors given the segment label and q_k, $\forall\, k \in K$ denote certain parameters. We chose multivariate normal distributions here – which have the following parameters: a $m \times m$ symmetric covariance matrix A_k and a m-dimensional mean vector m_k for each of the segments.

3.5.2 *Estimating the segmentation and the shading*

Suppose for that we already know the parameters of the normal distributions, i.e., the model is completely determined. The recognition task then consists of the following: given the observation field x we have to estimate the best shading field α and then to estimate the best segmentation field s. Since we do not know the optimal segmentation, we have to sum up over all of them in order to estimate the shading field:

Normal distribution:
also called Gaussian distribution, representing an important type of continuous probability distributions. The probability function is a symmetric graph (Gaussian bell curve).

$$\overset{\rightarrow *}{\alpha}=\arg\max_{\alpha} p(\vec{\alpha}\,|\,\vec{x})=\arg\max_{\vec{\alpha}} \sum_{s} p(\vec{\alpha},s\,|\,\vec{x}) \tag{7}$$

Once we know the shading field, we estimate the segmentation based on the a-posteriori marginals:

$$s_r^{*}=\arg\max_{k} p_r(s_r=k\,|\,\vec{\alpha},\vec{x}) \tag{8}$$

Both tasks are very difficult, because it is necessary to sum over a huge number of segmentations – in the first task over all segmentations and in the second one over all those segmentations with a fixed label k in the pixel r. Actually there exist no good algorithms to calculate these quantities efficiently, and we use a Gibbs Sampler (Geman et al. 1990) to estimate the marginal a-posteriori probabilities for the segmentation task and apply the Expectation-Maximisation Algorithm (Dempster et al. 1977, Flach et al. 2002, Schlesinger & Hlavac 2002) in order to solve the first one.

Gibbs Sampler:
an algorithm to generate a sequence of samples from the joint probability distribution of two or more random variables with the aim to approximate the unknown distribution.

3.5.3 *Learning the covariance matrices and means*

All the statements made above only apply if we know the parameters of the multivariate normal distributions. The latter can be estimated by maximum likelihood learning, given an expert's segmentation of the scene. It is indeed possible to ask an expert to segment a scene into "foreground" (sediment-covered raised or lowered landforms indicating archaeological structures) and "background" (everything else). But this is not enough – remember that above more than one segment label for foreground as well as more than one segment label for background has been introduced. There is no “expert” who can tell how to choose optimal sub-segments in the foreground and background respectively. Hence, one has to apply the Expectation-Maximisation Algorithm again in order to learn the required parameters partially unsupervised. Since even an expert cannot be completely sure where to draw the correct boundary of sediment-covered archaeological structures, it is advisable to relax his/her segmentation by defining three regions – background, foreground and some corridor in between, leaving the system to learn the optimal boundary.

The resulting iterative learning scheme may then consist of the iterative repetition of the following subtasks:

- Given the actual parameters of the normal distributions and the actual estimation of the shading field, sample segmentations, and estimate the marginal probabilities $p_r(s_r = k \mid \vec{\alpha}, \vec{x})$ for each pixel r.
- Use these marginals to improve the parameters of the normal distributions, i.e., the covariance matrices A_k and mean vectors m_k for all segments $k \in K$.
- Re-estimate the shading field $\vec{\alpha}$ based on the current marginals and parameters of the normal distributions.

4 OUTLOOK

With the launch of further satellites with ultra-high resolution sensors, the inventory of optical satellite imagery will expand. GeoEye-1, developed by GeoEye Corporation and planned for launch in 2008, will acquire data with 0.41 m panchromatic (resampled to 0.5 m as the current operating license with NOAA does not permit the commercial sale of imagery below 0.5 m resolution) and 1.65 m multispectral resolution (Geoeye n.d.). The Korean KompSat-3 satellite is under development and designed for sub-metre panchromatic and 3.2 m multispectral resolution. France plans to launch the Pleiades satellite in 2009, providing data with 0.7 m panchromatic and 2.8 m multispectral resolution. The Indian Earth Observation Program also intends to launch new satellites (Cartosat-3, Resoucesat-3) with advanced devices acquiring data in the sub-metre range. These satellites are only a small selection of upcoming missions, there are further developments including also radar devices which achieve data with similar high resolution.

The book chapter wants to demonstrate that satellite data has a high potential for the extraction of geoarchaeological features. The further technical improvement of the upcoming satellite sensors will allow for a better identification of hidden and hardly discernible phenomena. In combination with other remotely sensed data, e.g. radar or laser scanning, the chance for automated detection and analysis of geoarchaeological landscapes will increase. The methods have to be adopted and improved. There is still a gap in research due to the relatively new application of remote sensing in geoarchaeology. However, by realising interdisciplinary efforts between archaeologists, land planners, and remote sensing experts, this gap could be closed.

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Shedding light on the past: Using airborne LIDAR to understand ancient landscapes

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ABSTRACT

This chapter looks at the use of airborne LIDAR (light detection and ranging), which is also known as airborne laser scanning (ALS) for recording ancient landscapes. It examines the basic concepts of how LIDAR operates and what it can and cannot do. Working through the process from data collection to production of interpreted maps and plans, it looks at the various stages of the process, the decisions that need to be made at each stage and the questions that need to be asked to ensure that the data is used most effectively. It considers the different forms in which the LIDAR data can be provided as well as the best ways to use the data to create images from which to map and interpret archaeological remains. It also touches on the specific use of LIDAR for the recording of features in woodland. However, this chapter is written from the point of view of an end user and concentrates for the most part on using the data once it has been acquired. It is not designed to be a comprehensive technical description of all aspects of LIDAR. Furthermore, whilst there is some discussion of the different formats in which LIDAR data can be provided (e.g. point cloud and digital model) it deals primarily with the processed digital models derived from point cloud data sets.

1 LIDAR – WHAT IS IT AND WHAT DOES IT DO?

LIDAR is the name used in a number of heritage related bodies to describe airborne laser scanning. In basic terms it consists of an active laser beam being transmitted from an airborne platform (fixed wing or rotary) and the return pulse being measured. The precise location of the transmitter is known due to a combination of Global Positioning System (GPS) of the aircraft and the Inertial Measurement Unit (IMU). Using the principle, long familiar in terrestrial survey with a total station instrument, of measuring distance through the time taken for a pulse of light to reach the target and return it is possible to record the location of points on the ground. Whilst a single pulse is transmitted from the platform, there will be multiple returns or echoes recorded depending on the nature of the sensor and the land surface being surveyed (see below

Global Positioning System (GPS):
a satellite based navigation system that allows the determination of the exact geographical location on Earth with accuracies up to one metre.

cf. chapter "Using digital field data acquisition (FDA) in archaeological prospection" of Garcia-Dils de la Vega & Ordóñez Agulla.

for further detail). Airborne LIDAR, therefore, provides the ability to collect very large quantities of high precision 3D measurements in a short time. It doesn't necessarily provide any information about the point being recorded in the way that multispectral data can, nor does it give any inherent information about the nature of the feature being recorded. What it records is the three-dimensional location of a point in space and sometimes information on the intensity of the reflection. For further details of the principles behind LIDAR see Holden et al. (2002), Pfeifer & Briese (2007) or Wehr & Lohr (1999) and for further information on the use of intensity data see Challis et al. (2006) and Höfle & Pfeifer (2007). For specific examples of how it can be applied in an archaeological context see the English Heritage Aerial Survey and Investigation web page.

English Heritage Aerial Survey and Investigation:
www.english-heritage.org.uk/server/show/nav.8730

LIDAR is seen by some as a magic bullet that solves all the problems of a surveyor by providing all the data required. This is especially true when it is mentioned that it can "see through trees". This is a slightly misleading statement that can lead to disappointment if the properties of LIDAR are not properly understood. The key element of LIDAR is light and as such it cannot see through trees or anything else. However, in some circumstances it can usefully be used to record the ground surface under a canopy of trees, something that is discussed in further detail below (see section 5).

It should also be noted that unlike some remote sensing tools LIDAR is an active sensor in that it sends out a beam and as such it is possible to use it at night or in circumstances when passive sensors would not work.

2 PREREQUISITES

Before beginning to think about commissioning a LIDAR survey it is necessary to be very clear about what is required from it. LIDAR is a relatively new technique for archaeologists and whilst it is particularly useful in certain situations and can produce spectacular results (Bewley et al. 2005, Devereux et al. 2005) it is less useful in others and always needs careful interpretation (Crutchley 2006). It is therefore important to be very clear about why LIDAR is being used and what is to be gained from the survey. Since LIDAR primarily records height information, the features being surveyed must have a 3D surface aspect. LIDAR does not penetrate the ground, so if the archaeological features of interest are not represented on the ground surface then LIDAR will not be able to record anything except the general topography of the survey area. This is a useful resource in itself, but if this is all that is required then LIDAR may not be an appropriate source, as basic topographic height data at scales suitable for general topographic relief are available from alternative sources. Depending on the resolution required, there are commercial datasets available in some countries such as from the Ordnance Survey or NextMap® in the UK or even freely available from the web (e.g. by the U.S. Geological Survey).

Ordnance Survey:
Great Britain's national mapping agency.
www.ordnancesurvey.co.uk

NextMap® Britain:
the company Intermap Technologies provides a national coverage of 3D digital elevation data and orthorectified radar imagery; also available for other European countries.
www.intermap.com/right.php/pid/4/sid/328

U.S. Geological Survey (USGS) – National Map:
provides together with the EROS Data Center (EDC) access to free geospatial data.
http://seamless.usgs.gov

Once it is clear that there are features that can be recorded by LIDAR, the next stage is to be clear about the end use of the data. Is the LIDAR data required as the primary source, an interrogable data set that can be analysed by different staff to provide an interpretation of archaeological features, or is it seen as a background layer for other datasets available elsewhere? This decision will determine the form in which the data will be provided, which will in turn dictate the requirements for software and hardware; the precise nature of these options are discussed in more detail below. If data is required for interpretation, you need to decide whether there is the capability in-house or whether this should be an additional element of the project. The analysis of LIDAR data for the identification and characterisation of archaeological sites requires the same skills as air photo interpretation, e.g. the ability to recognise slight earthwork banks or ditches based on their appearance with reference to shadows and highlights. If this is the requirement, then you should also consider the possibility of commissioning a mapping survey using sources other than just LIDAR, e.g. a full aerial photographic survey using both historic and modern photographs.

If the aim is just to use the surface model derived from the LIDAR data as a background layer, the hardware and software requirements are probably quite low, but the processing of the data to an appropriate format for GIS etc. will need to be budgeted for. If, however, the intention is to analyse the data in-house and carry out any type of interpretation, then the appropriate hardware and software must be available to deal with the large datasets. Whilst it is possible to view the processed data that is provided by most suppliers in standard GIS packages such as MapInfo or ESRI ArcGIS, without specialist extension modules this is not a very user friendly option (see below). If there is the further requirement to map archaeological data (or indeed any other type of feature) from the LIDAR data, then this presents a different set of problems. Until recently there were no simple tools for mapping from processed LIDAR data, i.e., derived surface models that can be manipulated to control height exaggeration and lighting position (see section 4.2), and English Heritage (EH) have had to develop their own flowlines and working practices. However, given that software and hardware capabilities are changing all the time, it is wise to consult with someone already actively working with such processed data as described above.

MapInfo Professional:
GIS software for mapping and geographic analysis.
www.mapinfo.com

ESRI:
a provider of GIS and Mapping Software. ArcGIS is a complete system and integrated collection of GIS software products.
www.esri.com

The other issue that has been raised in passing is that of expertise. If the intention is to carry out processing of the data in-house, then someone familiar with the process of generating and manipulating digital models is required; if the plan is to interpret features of archaeological or other geocultural interest from these models, then again someone with the appropriate skills is required, especially if the intention is to look at other sources at the same time, something that is recommended for reasons given below.

3 COMMISSIONING THE SURVEY

The Heritage3D project on the use of laser scanning in heritage contexts, has produced a guidance document “Developing professional guidance: laser scanning in archaeology and architecture” (Barber 2007). This includes a section on the commissioning of an airborne LIDAR survey, finding a contractor and ensuring the survey is carried out to the correct standards. What are not currently specified in the guidance, are details of what those standards and specifications should be for looking at archaeological sites and landscapes. The key factor is the final resolution of the data. This is initially defined by the resolution of the point cloud, but is also affected by the processing into a grid pattern for the generation of digital models (see below), and this is defined by a combination of the different variables related to the survey. The initial figure quoted is likely to be point density. This is defined by Heritage3D as the average distance between x, y, z coordinates in a point cloud, and for LIDAR refers to the number of hits on the surface within a one metre square for the raw data. It must also be remembered that these are not necessarily regular hits and a point density of four hits per metre may mean that one square has two and another has six. When the data are then processed into a grid that can be interpolated to form a raster surface, the process of interpolation can reduce the final resolution such that an original point spacing of four points per metre may be reduced to a ground resolution of 0.5 m in the grid. This is particularly relevant when using filtering into terrain and off-terrain classifications.

Heritage3D:
a project that aims at the development and the support of best practice in laser scan-ning for archaeology and architecture. www.ceg.ncl.ac.at/heritage3d

Interpolation:
a mathematical method for estimating new data points within the range of a discrete set of known values.

Whilst it is obvious that a greater ground resolution is likely to be able to record more features, the cost of obtaining and using these larger datasets needs to be borne in mind. However, the continuing improvement in the speed of new sensors is likely to reduce this issue in future. Some of the variables leading to the final resolution of the data are defined by the aircraft, such as altitude and ground speed, others by the LIDAR system including laser frequency, scan frequency and scan angle. The actual laser frequency of the system is generally fixed; early LIDAR systems had a frequency of 10–15 KHz, whereas today there are systems capable of up to 250 KHz, and the likelihood is that rates will increase in the future. In order to increase point spacing it is necessary either to reduce the altitude of the aircraft, which is often impossible due the regulations imposed by national aviation authorities such as the Civil Aviation Authority (CAA) in the UK, or reduce the scan angle. The relationship between the scan angle and frequency needs to be maintained so that the resolution along track and cross track remains proportional; reducing the scan angle reduces the swath and increases the number of passes that need to be flown. At an altitude of 1000 m and ground speed of 120 knots, a 15˚ scan angle produces a swath of 536 m; a scan angle of 7˚ produces a swath of only 246 m. Using the same degree of overlap to ensure accurate registration, what would take 3 passes and just over 10 mins flying time, turns into 6 passes and 26 mins. The Unit for Landscape Modelling (ULM) at Cambridge

Unit for Landscape Modelling (ULM):
is part of the Cambridge University and specialises in the application of GIS and remote sensing techniques in landscape ecology. www.uflm.cam.ac.uk

University provide a very useful calculator on their web site to assist in planning surveys, but the critical cost factor is that, at a given altitude, reducing the scan angle reduces the swath and increases the number of passes that need to be flown to cover a given area.

Therefore taking all this into account and balancing cost against product, English Heritage experience suggests that whilst 0.5 m resolution is ideal for small areas, anything greater than about 20 km^2 becomes too expensive, though this is likely to change in future with improvements in sensors. Furthermore, several surveys have been carried out using 1 m resolution, which has proved perfectly adequate at recording the majority of features (e.g. barrows, enclosures and mining pits only 1 m across) that we would expect to be able to see on aerial photographs in open areas, and even data at 2 m resolution can provide some archaeological information. Further work is required on the optimum resolution for looking at woodland (see below) and there will of course always be variations based on the density of vegetation, but it is none the less useful to provide some outline guidance.

The other key element to be defined when commissioning a survey is the actual form that the data will be provided in. During the process of a LIDAR survey, there are a number of stages at which data is generated and can be provided to a client:

- The data is collected by the scanner as a series of points in space, flown over a number of passes to ensure a sufficient overlap to allow quality control checks. This is carried out by the data provider.
- Data is registered and placed in a common coordinate system, typically the global coordinate system WGS84. If a transformation into a local coordinate system is required this will be carried out in cooperation with the purchaser – the necessary coordinate system has to be defined.
- After the data has been registered it is then possible to compute the differences between the strips to ensure that the discrepancies between scans that could lead to interference patterns are within the predefined tolerances. This can either be carried out by the customer if individual scan data is provided or by the data provider.
- Data provided as gridded file that can be imported into various software packages to create digital models (see below).
- Models manipulated within specialist software to emphasise the features of interest to aid interpretation. In open landscape this is best done with the data derived from the first return of the laser pulse; in areas of woodland or other dense vegetation the filtered data is more appropriate.

WGS84 (World Geodetic System 1984):
is a uniform three-dimensional coordinate system for the whole world and geodetic basis for GPS devices.

Grid:
is an array of equally sized square cells arranged in rows and columns which are referenced by its x, y location.

In order for the client to be able to reprocess and manipulate it for their own purposes, it is important to ensure that the most appropriate form of data is chosen. At the various stages a variety of different products can be provided, including point clouds, gridded data, flat image files derived from the data and interactive digital models (see below for further detail). Given the relative newness of LIDAR as a technique for archaeological survey, it is very much in the technical phase of operation and is consequently quite jargon heavy. Many of the terms used will be familiar to those used to working within GIS, but may be confusing to others who are planning to commission a survey. Whilst it is not essential to understand all the technicalities of how LIDAR operates, it is useful to understand the difference between the different products and the meaning of some of the key terms. What follows is not a comprehensive list of all the phases of a survey or all the potential products, but, together with the list above, it should provide a basic introduction and help explain some of the main differences between them.

The most important difference to understand is that between “raw” and “gridded” data. In the simplest of terms raw data are simply a series of tables that record the x, y, z and intensity data for large numbers of points on the ground (N.B. “the ground” refers to the surface struck by the laser pulse and does not necessarily equate to a point at ground level). Gridded data have been interpolated from the original recorded data into a regular spaced two-dimensional grid of 3D points, represented as an array of equally sized square cells arranged in rows and columns; each cell is referenced by its x, y location. If point data is viewed in a GIS what is produced is a point cloud, which is exactly what it sounds like; a cloud of points. A point cloud is defined by Heritage3D as a collection of x, y, z coordinates in a common coordinate system that portrays to the viewer an understanding of the spatial distribution of a subject. It may also include additional information such as an intensity or RGB value. However, one of the key things to remember is that these are individual points in space that have no physical relationship between them. Generally, a point cloud contains a relatively large number of coordinates in comparison with the volume the cloud occupies, rather than a few widely distributed points. For most archaeological purposes the data is better viewed as a surface.

A surface is a continuous field of values based on interpolation from the recorded discrete points. Using a surface allows the data to be visualised more easily, allowing lighting effects and slope analysis to be used. Surfaces come in different forms, the most common being raster and TIN (Triangulated Irregular Network), so it is important to know what is required. A raster surface is generally stored in grid format – consisting of a rectangular array of regularly spaced cells with z values; the smaller the cells, the greater the resolution of the grid. Because values are interpolated into the grid it is impossible to locate individual features more precisely than the size of the grid cells.

TIN (Triangulated irregular network):
a method of irregular tesselation of triangles based on a set of points. A special case is the Delaunay triangulation.

A TIN consists of nodes that store the z values connected by edges to form continuous, non-overlapping triangular facets. Because the input features used to create a TIN remain in the same position as the nodes or edges, a TIN maintains all the accuracy of the input data, whilst at the same time allowing modelling of values between the known points.

Digital Surface Model (DSM):
a model of the Earth’s surface (or a section of thereof) that includes all features on it such as vegetation, buildings etc.

As a rule, the surfaces produced by suppliers will tend to be raster as these are much simpler to create and fulfil the main requirements of surfaces derived from LIDAR data so the question of TINs will not be addressed here. A much more vital and relevant issue is that of the distinction between the types of raster surface available, most specifically between DEMs, DSMs and DTMs. Put simply a DSM (Digital Surface Model) is a model of the surface of the earth (or a section thereof) that includes all the features on it such as vegetation, buildings, etc. By contrast a DTM (Digital Terrain Model) is a “bare-earth” model that uses algorithms to remove all those features that it estimates to be above the natural ground surface by comparing the relative heights of recorded points. As this chapter is aimed at end users, it is not the place to discuss the various filter methods but these are discussed in detail in Sithole & Vosselman (2004). The term DEM (Digital Elevation Model) can unfortunately be used in different communities for both which can complicate matters. One key factor that should be considered, however, is that in general terms these processes work on the basis of comparing points and removing those where there is a significant difference between those around them and the point in question based on the supposition that the anomalous point is not on the ground. Whilst this is very useful in terms of removing modern features and can be particularly successful in wooded areas (see below), it is possible for them to “filter out” features that are actually of interest or even create artefacts.

Digital Terrain Model (DTM): *a “bare-earth” model that represents the elevation of the natural ground surface (topography).*

These surface models can be provided in a number of formats depending on the software that is being used to analyse the data, so it is important to be clear on how the data will be used from the outset. It is possible to supply the data simply as a flat TIFF image (e.g. hill shaded to produce shadows and highlights or contour shaded), which is usable to a point, but this is very limited.

One other factor to bear in mind when deciding the format of data is the way it needs to be broken down. It is quite possible for a large area covering several tens of kilometres to be provided as a single dataset, but the size of the files may make it impractical to actually work with. It may be preferable to specify data to be supplied as discrete blocks or tiles (e.g. the 2 km by 2 km squares supplied by the Geomatics Group of the UK Environment Agency).

Geomatics Group: *is a unit of the UK Environment Agency providing aerial survey and airborne LIDAR data. www.geomatics-group.co.uk*

In summary, the key choice between data sets comes down to that between data provided as a point cloud and data provided as a raster image. There are pros and cons to both sets of data that are detailed below:

Point cloud

Pro

- All the subtleties are present in point cloud form; whilst there may be some additional interference patterns no data has been filtered out;
- If provided as x, y, z data it can be read by most standard GIS software;
- With additional 3D components to GIS or standalone software it is possible to manipulate the data extensively;
- No additional processing costs.

Con

- Limited usefulness in wooded areas;
- Risk of artefacts that have to be processed out e.g. strip misalignments;
- elevation changes due to GPS errors and spikes.

Raster surface
Pro
- Easily readable in standard GIS software;
- Major artefacts processed out;
- Algorithms for woodland remove trees revealing hidden archaeology (N.B. conifers – see below).

Con
- Possible creation of other artefacts and/or smoothing away of features;
- Limited options for manipulation depending on the format of the processed data;
- Additional processing costs.

There are clearly positive and negative points for each and the decision on which to use must be based on the proposed use.

One final major factor to bear in mind, when commissioning a LIDAR survey, as with many other types of survey, is the issue of copyright. This is an issue not just with regard to how you wish to deal with the data, but also with regard to how it can be made available to third parties, e.g. local groups, etc. without the equipment available to local authorities, etc. This is both a technical and legal issue. Unless specified in the contract it is likely that copyright in the initial data will be retained by the supplier. Many aspects related to copyright with regard to LIDAR data are currently unclear, but there are definitely issues related to change of copyright following “added value”. If an image is created based on the data supplied is this still under copyright? It is likely that there will be less concern with regard to any imagery generated from the data, rather than the raw data itself, but all these issues need to be agreed and laid out very clearly in the contract. This is especially important with reference to third party users.

4 USING THE DATA

There are three key elements relate to the using of the data once it has been provided; the nature of the imagery; the requirement for interpretation and the requirement for mapping from the data.

4.1 *Imagery*

Whether the processing is carried out in-house or processed data is being provided, what are generally required for interpretation are hillshaded images, either greyscale or colour. This is because they mimic the appearance of aerial photographs and as such are easier for those used to dealing with photographs to deal with. As noted above, these will preferably be available in a form that can be manipulated to allow the maximum potential for data extraction. 3D packages that allow the control of lighting are most beneficial, preferably with the ability to exaggerate the

Hillshade:
a surface model with a hypothetical illumination aiming at a better visualisation of the surface for analysis or graphical display.

z factor. However, it is important to be aware that the exaggeration of the z factor will also emphasise any background noise and could also enhance artefacts. In terms of the imagery on which the mapping and interpretation will be based, what are required are either multiple images or some form of composite. The simplest images to produce are single hillshaded images. A single graded colour tends to be more useful than mixed colours when using a hillshaded image as the latter can be too distracting. In order to minimise the chances of features being missed due to excessive shadow, or alignment parallel to the light source, you should have a minimum of four images lit at a different angles (45˚, 135˚, 225˚ and 315˚). It is better to have eight and ideally you should have the ability to view all available angles and azimuths (see below), but unless you have the software to view the data interactively the number of images that need to be viewed soon becomes unwieldy. As well as hillshaded images it is also possible to create height-coded ones. These can be colour coded according to preference such as from blue (low) to red (high) and can aid in the interpretation of features where the hillshaded LIDAR image is unclear or to help understand topographic locations. Whilst both types of image are based on height data, the hill shaded image is the representation of a hypothetical illumination of a surface based on the light source being placed in a given location; it uses shadows and highlights to help interpret features. The height-coded image by contrast relies less on the shadows than on the height difference between features being revealed in their colour.

An alternative way to view the information from multiple angles is in a single composite image, and the simplest way to generate one of these is to overlay a series of single hillshaded images on top of one another. This process was first attempted by staff from the Cambridge University Unit for Landscape Modelling (ULM) and then enhanced by P. Crow from the UK Forestry Commission (Devereux et al. 2005). It involves creating four separate hillshaded images lit from 90˚ intervals (45˚, 135˚, 225˚ and 315˚) and each given a separate colour scale (black, red, blue and green). The various images are then combined using the transparency/opacity features available either in the GIS package such as ESRI ArcMap, or in a standard photo processing package such as Adobe PhotoShop. By placing the different layers in a specific order with different degrees of transparency, it is possible to create a single image with the effects of lighting from four different angles (figure 1).

Unfortunately whilst this does create a single image with shadows from four different angles, it is not ideal. Firstly, by using four different images superimposed on one another it risks masking subtler features such as very slight banks or ditches that would be visible on a single image lit from the correct direction. Secondly, whilst four angles do highlight a broader range of features than any single image, they may still miss some that might be highlighted using a different angle and elevation (figures 2 and 3). Figures 2 and 3 show the same area of mining covering 1 km by 700 m near Chancellors Farm on Mendip. The ditched features running in the main from the top to the bottom of the image are the remains of lead mining rakes dating from the medieval period to the early 18th century

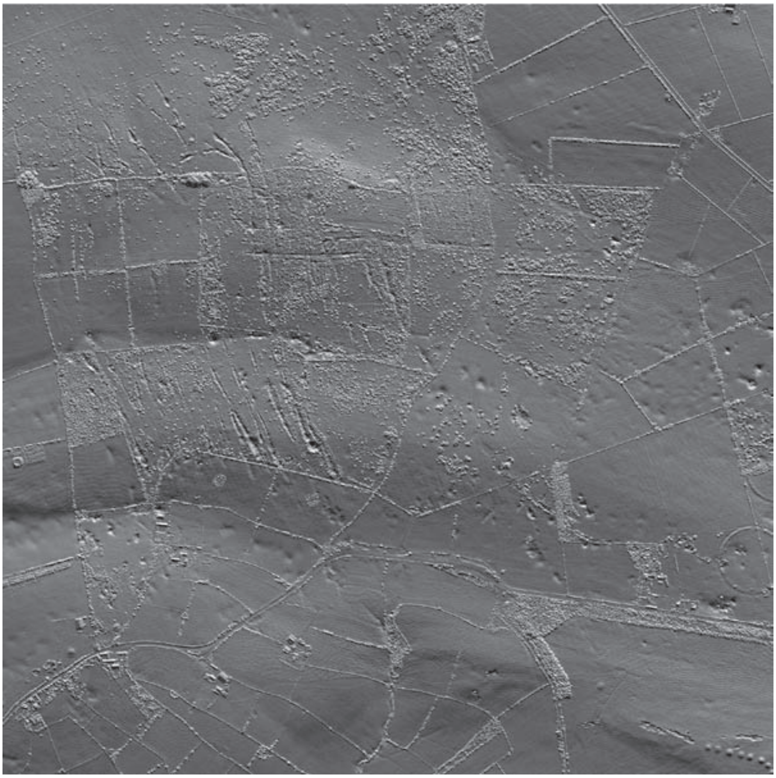


Figure 1. Composite image combining four individual colour images with different degrees of transparency. LIDAR courtesy of Mendip Hills AONB, © Cambridge University Unit for Landscape Modelling, April 2006.

Somerset Historic Environment Record:
is an online database of all known archaeological sites, events undertaken on them, scheduled monuments, listed buildings, registered landscapes and historic landscape character within the current county of Somerset.
http://webapp1.somerset.gov.uk/her/map.asp?flash=true

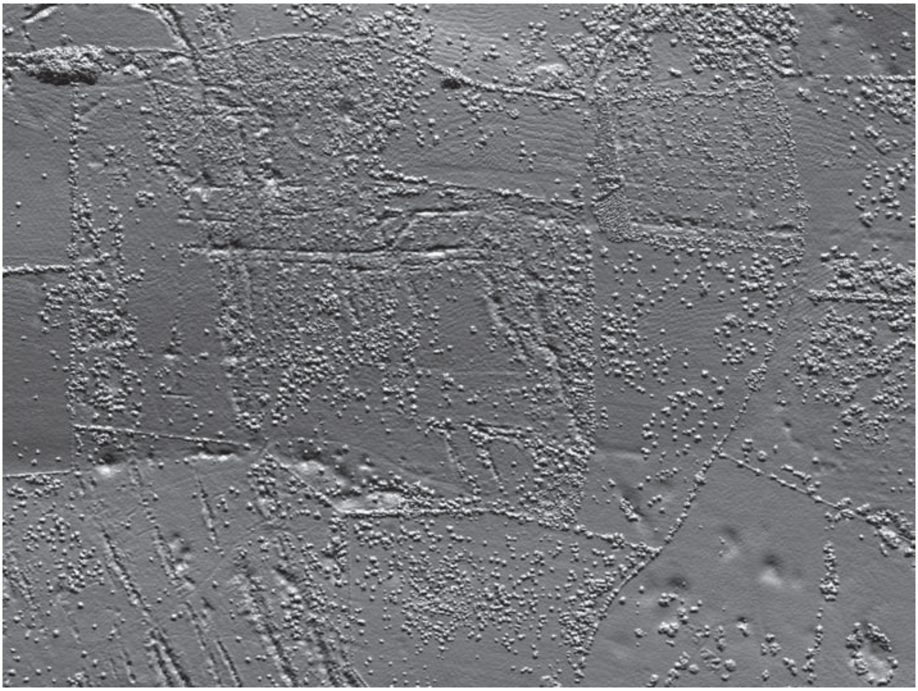
PCA (Principal Component Analysis):
a multivariate statistical method to identify and extract principal components in corre-lated datasets.

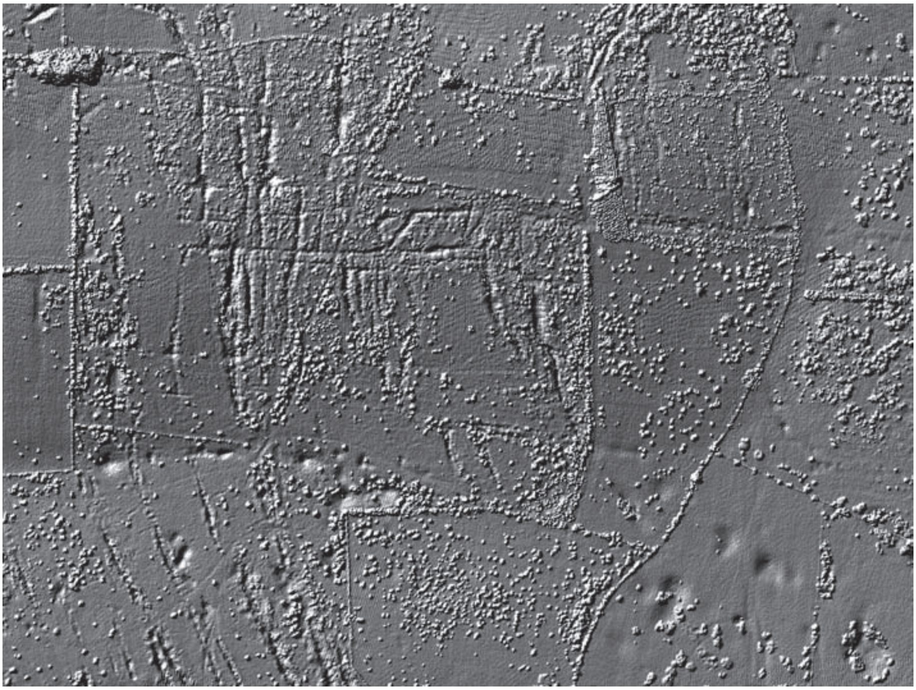
(Somerset Historic Environment Record). It is noticeable that the rakes in the bottom left corner of the images are much less well defined on figure 2 than figure 3 with the shading from a single direction.

An alternative method for the creation of a single image is to use advanced techniques of statistical analysis of the variations within the data. The advantage of this technique is that where overlaying multiple images creates issues with regard to the visibility of subtle features, principle components analysis (PCA) produces a single, composite image possessing the property of ‘equal illumination’ from all directions. So far these have again only been looked at in a trial by ULM and UK Forestry Commission. Whilst the results look very promising, this is currently a complex procedure and not available to most users without specialist software. However, this is likely to change as such software becomes more readily available (Devereux et al. 2008).

4.2 *Interpretation*

The key product of LIDAR is height data; by using the processing facilities to place the light source in an advantageous position, in combination with





Figures 2 & 3. Close-up of the composite image showing the effects of multiple images (figure 2) in masking subtle features when compared to the single lit image (figure 3). Each image is derived from the unfiltered last return data gridded to 1 m ground resolution. LIDAR courtesy of Mendip Hills AONB, © Cambridge University Unit for Landscape Modelling (April 2006).

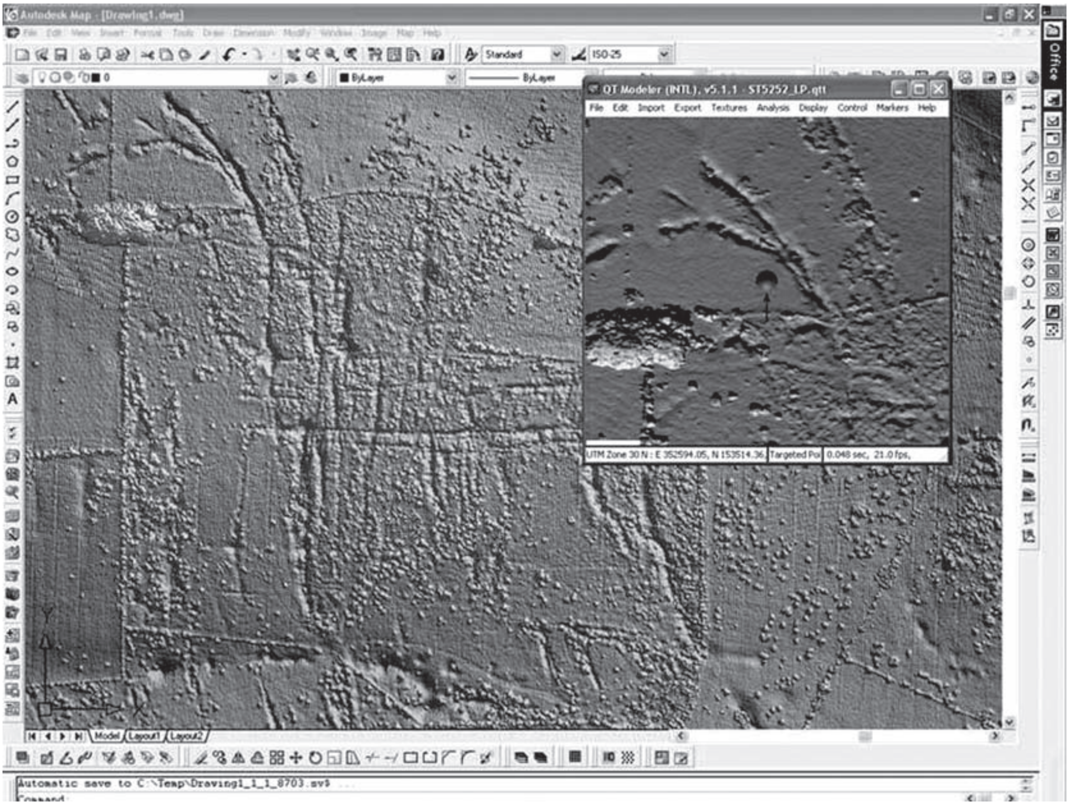
the exaggeration of the height of features, the hillshaded image produced is equivalent to an aerial photograph taken with low winter sunlight on earthworks. As such it is best interpreted by someone skilled in aerial photograph interpretation, because although LIDAR data can reveal features of archaeological interest, these may not be obvious to the untrained eye and can easily be misinterpreted. This is particularly true with regard to features of a recent origin. Whereas it is generally relatively easy to spot modern features such as field boundaries, etc. on an aerial photograph, it is easier for the unskilled to be misled when looking at imagery derived from LIDAR because there are none of the clues of colour, etc. in the image. Given that a LIDAR survey will generally be carried out with other sensors such as digital cameras or scanners, there should be additional data that should be looked at simultaneously to minimise this risk. Ideally, if a survey is carried out with the aim of extracting archaeological information, other aerial photographic sources should be examined at the same time. Inspection of historic aerial photographs will be particularly beneficial as this may help with the interpretation of features not visible on the current photographs taken at the same time as the LIDAR survey, but which may have their origin in agricultural activity from the last few decades. A good example of the potential pitfalls of not using all readily available sources is given in Crutchley (2006), where a feature that could be interpreted as a Roman fort was shown to have somewhat later origins.

4.3 *Mapping*

To interpret and map the archaeological features from the LIDAR data, it is necessary to make it available in a suitable mapping package. Software may make it possible to work directly with the 3D data and create interpretative layers, but most packages that are suitable for interpretative mapping become unwieldy with the massive datasets created by LIDAR, and therefore it is often necessary to use simplified 2D raster versions of the data created as described above. Ideally, this should be used alongside the software that allows the viewing of the 3D data to aid the interpretation. This solution was investigated in the most recent English Heritage project (Mendip Hills). Using a suite of programs that allow the creation of files in a proprietary format that can then be viewed via a free downloadable viewer, e.g. the Quick Terrain Reader. This meant that for each tile of data a flat image file with shaded relief was provided to the interpreter for importing into AutoDesk or an appropriate GIS, together with a file that could be interrogated interactively through the viewer. This enabled the interpreter to examine the data themselves, changing the elevation and azimuth so as to emphasise features of interest by highlighting them with the use of shadows. Whilst it is was not initially possible to plot features against the 3D image, it was possible to view the 3D and flat images simultaneously and map features onto the flat image based on what was visible in 3D (figure 4). If it is not possible to see the features on the flat image even with the assistance of the 3D image, a revised flat image can be created using the parameters determined by the interpreter

Mendip Hills:
is a project where LIDAR data is being examined simultaneously with standard aerial photographs.
www.english-heritage.org.uk/server/show/nav.10591

Quick Terrain Reader:
is a free viewer for visualising 3D models provided by Applied Imagery.
www.appliedimagery.com



```
Automatic save to C:\Temp\Drawing1_1_1_8703.sv$ ...
Command:
```

Figure 4. Screenshot showing the simultaneous use of 2D and 3D data for mapping and interpretation. The LIDAR image in the background covers the same area as that in figures 2 & 3; the small window is looking at the features in the top left of the main image, covering an area of 250 m by 250 m.

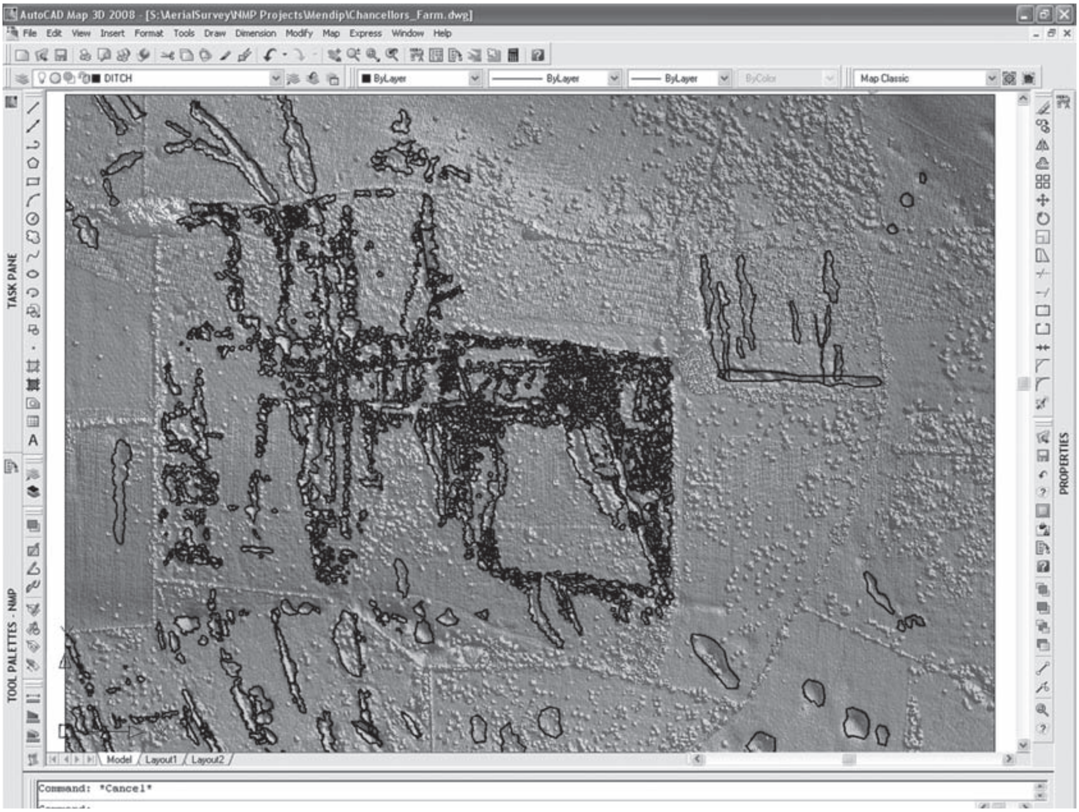
in 3D. The added advantage of this system is that it is possible to provide data to third parties (e.g. partner organisations or independent researchers) as both 3D and 2D data with the interpreted vector data overlaid on the DTM if necessary.

The more recent versions of Autodesk AutoCAD Map (2007 onwards) include the facility to view raster surfaces with interactive hillshading defined by a user-controlled light source together with height exaggeration. Placing these facilities within the CAD environment means that it is now possible to combine the mapping elements of CAD with the 3D facilities that allow the enhancement of LIDAR data, which are so crucial in its interpretation.

AutoCAD Map 3D:
a GIS platform for creating and managing spatial data which bridges CAD and GIS provided by Autodesk, Inc.
www.autodesk.co.uk/adsk/servlet/index?siteID=452932&id=10547878

5 CANOPY PENETRATION

One of the key benefits of LIDAR is seen as its ability to penetrate woodland and reveal features on the forest floor, but this is true only to a point. As noted above LIDAR is basically light and will only record features



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Command: *Cancel*
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Figure 5. Screenshot of interpretative mapping over LIDAR derived imagery.

where light can penetrate. However, contrary to the common perception of a laser beam as an extremely narrow band of light, the light pulse emitted by the airborne laser is dispersed during flight so when it hits the target surface it can have a footprint of anywhere between 0.1–1.5 m. With such a large surface area, there is a greater likelihood that at least some of the beam will penetrate through gaps in the canopy, depending of course on its density and strike the ground surface below; the less leaves on the trees to begin with, the better the chance of some of the beam reaching the ground. This is the reason why woodland surveys are best flown in autumn or winter in leaf-off condition and when the undergrowth is also low. It is also the reason why LIDAR is more successful in broad leaved deciduous woodland than in close packed conifer plantations (Devereux et al. 2005).

There are a number of parameters with regard to any LIDAR survey, and whilst these have been defined for standard surveying in open land, there are some differences when surveying in woodland. There has been some discussion between those using LIDAR in woodland as to whether scan angle makes a difference with the suggestion by some that a narrow scan angle is preferable. In fact, there is ample evidence that wide angles are equally effective; Doneus in Austria used a scan angle of 22.5° (Doneus & Briese 2006) and Sittler in Germany used a 20° angle (Sittler 2004).

A more important factor may be point density as it would appear that the more points there are within a square metre, the more chance that one or more of them will hit the ground. More detailed work on the utility of LIDAR within woodland has been carried out by P. Crow of Forest Research, the Research Agency of the Forestry Commission in association with ULM (Devereux et al. 2005 and 2008). It is notable that the most effective surveys carried out by ULM for the Forest of Dean were carried out with 0.5 m gridded data, with the extreme detail of Welshbury being captured at 0.25 m, whilst Doneus (below) used eight hits per metre.

An alternative approach to working in woodland has been taken by M. Doneus of the Institute for Prehistory of the University of Vienna, Department for Airborne Remote Sensing in Archaeology. He has been looking at the most recent form of airborne LIDAR, full-waveform laser scanning. With this equipment, instead of the usual measurement of the first and last returns (with the possibility of additional returns between), full waveform digitisation records the whole received echo signal, a process that produces a complete 3D model from each pulse. By combining the added detail from the whole pulse of the beam such as the echo width and amplitude, it is possible to produce much more accurate models of the ground surface by eliminating ground cover that can give a false reading that appears to be the ground surface (Doneus & Briese 2006). At present this is very much in the research stages, but could become a practical product in the near future. Although using full waveform digitisation produces even greater amounts of data, it is unlikely that those commissioning a survey would want to carry out any of this processing themselves; rather they would be presented with a set of images, or a DTM and the size of the original data files would be irrelevant.

Digitisation:
the representation of an object, image or document using a digital form. An example is the scanning of hard copy photographs to produce a digital jpeg image.

6 CONCLUSION

In summary, LIDAR can be seen to be a very useful tool for archaeological survey when used in the right environment and where the aims of the survey are clearly defined. It should not, however, be seen as a universal survey tool and one that should necessarily be used on every occasion. It is also vitally important that the use to which the data will be put is made clear at the beginning of the planning phase to ensure that it can be utilised most efficiently. Finally, there is still an issue with regard to the day to day use of the data by large numbers of staff without specialised equipment, but this is something that has improved and will no doubt improve further over the coming years and allow the full exploitation of the obvious benefits that LIDAR data can provide.

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Part II

Data preparation for GIS analysis

Geometric data preparation for GIS applications

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ABSTRACT

The chapter surveys geometric modelling techniques in geographic information systems (GIS), and geometric data processing oriented towards efficient visualisations of 3D geometric models. Two main categories of 3D data, accor-ding to the representation method, exist. One is surface representation, based on polygonal meshes, and the other is volumetric representation (volume graphics) using volume elements or voxels. The authors are particularly interested in approaches supporting and improving transmission and visualisation of archaeological and geoscientific 3D data over the internet. The stress is on 3D model simplification and compression techniques, also including solutions developed by the author's group.

1 INTRODUCTION

In the last years, the 3D geometric modelling of real objects, of whatever size and complexity, is increasingly used by, and becoming more important to archaeologists and historians. The resulting models are displayed in virtual environments in museums, on the internet, or in video kiosks at excavation sites. Archaeologists have used virtual reality (VR) primarily for virtual surface reconstruction and visualisation (El-Hakim et al. 2003, Schindler et al. 2003), but interest is also increasing in the use of VR to perform analysis (Rowe et al. 2003). The availability of interactive navigation and manipulation in virtual worlds has supported powerful applications, such as virtual recovery, assembling and restoration of lost, broken or damaged archaeological finds (Addison & Gaiani 2000, Zheng et al. 1998). 3D visualisation has also proved to be a particularly valuable tool for better understanding and analysis of data handled by geoarchaeologists, geologists, surveyors and other geoscientists and GIS users (Adderley et al. 2001, Clevis et al. 2006, Grunwald & Barak 2003). The increased power of modern CPUs, graphic hardware devices, and a wide range of data acquisition techniques, including laser scanners, a microwave-imaging-based synthetic aperture radar (SAR), accurate GPS coordinates and aerial photography, allow good quality 3D models to be obtained on reduced timescales.

Virtual recovery:
a specific approach to recreate and connect broken pieces of relics and visualise various possible alternative results in virtual space before performing the actual restoration.

Microwave imaging:
a process for obtaining a visual representation of real objects by using a data acquisition device that utilises microwaves. Typical microwave imaging device is the synthetic aperture radar (SAR).

Synthetic aperture radar (SAR):
a microwave imaging device aboard satellites or aeroplanes which works by collecting the echo returns from radar pulses and processing them into a single radar image.

The remote use of 3D models represents another interesting topic which is discussed in section 2. There are numerous advantages of 3D visualisation over the internet, including an increased accessibility of the software, use of distributed data resources, and multiple user access. *Virtual Reality Modelling Language (VRML)* is a standard format for describing and transmitting 3D objects, and worlds, composed of geometry and multimedia in a network environment. It offers a well structured description of geometric scenes and therefore many producers of 3D modelling software now support VRML exporting. The scene files store the coordinates of the points as an indexed point set and the topological connections of the points to build polygons. *Extensible 3D (X3D)* is another standard that has been widely accepted as a successor to VRML. It introduces many new features, but still provides backward compatibility with VRML files. Shape modelling in X3D is made extensible by providing a unified programming interface and by exploiting XML transformation.

Two main categories of 3D data, according to the representation method, exist. One is *surface representation*, based on *polygonal meshes*, and the other is *volumetric representation (volume graphics)* using the volume elements or voxels.

In section 3, the main features of surface models and the main operations on polygonal meshes are discussed. Firstly, triangular mesh decimation techniques are presented, intended to simplify models and increase visualisation speed. Mesh decimation inevitably decreases the quality of the model and so cannot be employed when all the details are required. Various data compression methods must be used instead. The authors present an efficient triangular mesh compression algorithm developed by their group. The mesh decimation and compression methods can also be combined to achieve progressive transmission and visualisation of surface models.

In section 4, volumetric models and their processing are described. Such a model does not explicitly determine an object's boundary, as a surface model does, but it can represent the object's internal structure. In order to optimise visualisation, in the volumetric representation, a model simplification can be simply achieved by decreasing the sampling rate. The data compression and progressive transmission are typically realised by a utilisation of digital video compression algorithms. Amongst other efficient solutions, this chapter also briefly summarises the original quadtree-based algorithm for lossless compression of volumetric models developed by the authors.

In the concluding section 5, the main findings and practical results of the presented work are briefly summarised.

Polygonal meshes:
a set of vertices, edges and faces that describes the shape of a polyhedral object in 3D computer graphics. The faces usually consist of triangles, quadrilaterals or other simple convex polygons, since this simplifies rendering, but may also be composed of more general concave polygons, or polygons with holes.

Triangular mesh decimation techniques:
used for simplifying triangular meshes representing a 3D model to increase the speed of visualisation and transfer. It is done by removal of vertices and triangles according to the criteria that the visual outlook of the model must not be significantly degraded.

Triangular mesh compression algorithm:
is specially designed for compression of triangular mesh data and therefore achieves better compression ratios than general-purpose data compression algorithms.

2 THE REMOTE USE OF 3D MODELS

The basic component of almost all systems that support remote use of 3D models is the visualisation component. Visualisation is based on representation of data in graphical form. The goal of visualisation is to create an additional level of insight into the data, in order to improve our understanding. Various types of visualisation occur in GIS systems, but in general two major fields are recognised: 2D visualisation, which is mainly concerned with maps, and 3D visualisation, which is used for representation of various 3D entities. These, for example, include representation of terrain described with a digital elevation model, representation of buildings described with a boundary (polygonal) model or some kind of geological phenomena, which is often represented in form of a volumetric model. Since real time visualisation in 2D is now almost standard in existing remote GIS systems, the rest of the chapter will place its emphasis on 3D visualisation.

Boundary (polygonal) model:
a polygonal mesh that represents the skin (boundary) of a polyhedral model in 3D computer graphics.

Various approaches have been developed and presented for visualisation of 3D models over the internet, such as VRML, X3D, Microsoft Chrome, Adobe Atmosphere, etc., but only two of them have been accepted as a standard for representation of 3D graphics on the worldwide web by the Web 3D Consortium. These two standards are VRML and X3D.

Web 3D Consortium:
www.web3d.org

Virtual reality modelling language (VRML) was created in 1994. The general idea behind the standard was set in paper presented by Dave Ragget at *The First International Conference on the World-Wide Web*, but his original name for the standard was Virtual Reality Markup Language. The idea caught up and ignited a productive discussion between Ragget, Mark Pesce, Tony Parisi and Tim Berners-Lee during which the core of the standard was set. The authors decided to base the structure on the format used by Silicon Graphics modeller named Open Inventor, with the approval of SGI. Although VRML did set the first milestone in the development of 3D contents for the WWW, it did not gain extensive popularity due to its limitations. The most significant limitation was that only static virtual worlds could be represented in VRML 1.0. The founders of the VRML were aware of the issues and in 1997 a new, revised version, called VRML 2 or VRML97, was approved. This version quickly gained popularity and was widely used even on personal pages. Using VRML a virtual 3D world can be represented in a simple text file. The text file is split into parts called nodes. With various types of nodes it is possible to describe the geometry (vertices, edges, polygons) and surface (surface colour, texture) of a specific 3D objects, create animations, insert sounds, lighting, connections to external URL pages or other virtual worlds, etc. The user who wants to experience this virtual world only needs a simple plug-in for his or her internet browser. This browser loads the text file and transforms it into a three dimensional virtual representation.

Open Inventor:
a C++ object-oriented 3D toolkit offering a comprehensive solution to interactive graphics programming problems to provide a higher layer of programming for OpenGL.
http://oss.sgi.com/projects/inventor/

Static virtual world:
a virtual world that consists only of static models and does not include any animations or other dynamic changes.

With a quick development of special purpose graphics hardware, VRML quickly started losing its popularity. With its strictly software-oriented design, it could not keep up. Today, VRML is only widely used in educational and scientific circles, where an open specification is valued. VRML is also well supported by many graphical modelling and animation applications which often offer a possibility to save/export a 3D model into a VRML format. Very good examples of VRML in

Virtual Heart of Central Europe:
www.vhce.info

action can be seen on the web page of the international European project entitled Virtual Heart of Central Europe. Universities from four different countries and four different Central-European towns (Prague – Czech Republic, Bratislava – Slovakia, Graz – Austria and Maribor – Slovenia) have created multimedia representations of several historical buildings and monuments in their home towns, including VRML representations. A stage in the preparation of the Maribor cathedral VRML model is shown in figure 1a, and figure 1b shows the VRML representation of Maribor town hall viewed from its courtyard.

Extensible Markup Language (XML):
is a general-purpose specification for creating custom markup languages which are tailored to a particular type of data by defining own elements. The Web3D consortium recommends XML to be used for representation of richly structured documents on the World Wide Web.

The Web 3D Consortium was well aware of the drawbacks of VRML and quickly started developing a new modern standard for presentations of 3D contents on the web. This standard was named Extensible 3D (or shortly X3D) and is a successor to VRML. The standard X3D is still in development, although many key specifications have already been set. The X3D is still built around the same 'node based' paradigm, but the structure of the X3D file can now be represented in a number of different file formats, including the popular Extensible Markup Language (XML) format. XML encoding of data files makes the integration of X3D contents into other web-based applications much smoother and also makes the management, control, validation and exchange of data much easier. Besides the possibility of XML encoding, the X3D introduces many new features and some other significant advantages over VRML, such as more mature design, componentisation, which allows the specifications of profiles tailored to a particular market segment (CAD, medical visualisation, GIS), integrated support for fully exploiting the capabilities of hardware graphics accelerators and much better extensibility, while keeping the full functionality of VRML. From the user's point of view, use of the X3D encoded contents is much the same as use of VRML encoded contents. In order to enter the X3D encoded virtual world, the user only needs a

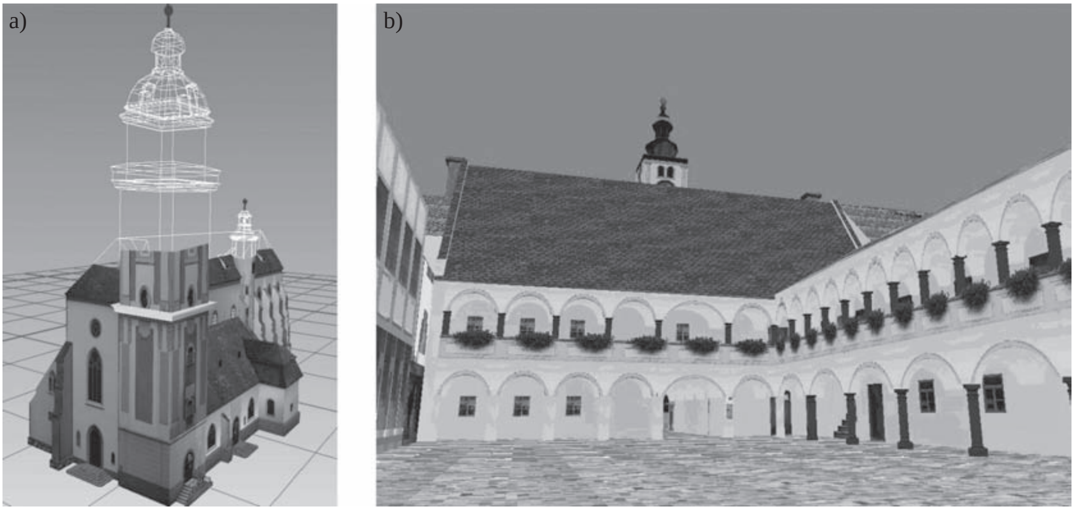

Figure 1. Representing the sights of Maribor in VRML: (a) the cathedral, and (b) the town hall.

special X3D browser which usually comes in a form of a plug-in for existing internet browser that can be downloaded from the internet. Although the standard X3D is still in development, some X3D browsers already exist and many authors have already started creating or transforming their contents into the X3D format.

Despite the advantages of X3D, VRML is often still a preferred choice. Because the VRML structure has been established for a long time, many 3D modelling applications support direct export of models into VRML 2, or at least the VRML 1, format. We will probably have to wait until the X3D standard is fully defined for direct export to it to be widely available. Software tools that can transform VRML files into X3D format already exist so, at the moment, using VRML format might seem a better, or at least simpler, solution for displaying 3D contents on the internet, but the advantages of the X3D will make it a very attractive choice. Despite the fact that full specifications have not yet been drawn up, authors should look to the future and consider using X3D format, since that will certainly be the way to go.

VRML and X3D are good tools for visualisation of 3D objects on the internet, but may not suitable because the existing GIS data cannot be straightforwardly transformed in VRML or X3D representation. Often, the reason for this is the sheer size of the data. Some types of GIS data can occupy 100, 200 or even more MB of storage space even in their original form (archaeological readings performed with laser scanning technology being a typical representative) and transformation of these data into a VRML or X3D format increases the size as additional information is added. To overcome or at least limit the problems that arise, compression algorithms are often introduced. Compression algorithms determine some specific properties of the data and exploit these properties to reduce the size of the data. Compression may cause loss of information, or it may be lossless. The former can reduce the size of the input data more significantly and, if the primary goal is just visualisation or graphical representation of the data, it may often be satisfactory. Special-purpose algorithms tailored to specific types of data can perform very effective compression without the loss of ‘visual information’. Lossless compression is used in cases where analytical treatment of the data is required.

One additional important approach to compression of data must be mentioned here. This is so-called progressive compression. With progressive compression a multiresolution representation of a 3D model is created. At the starting resolution, the representation of the model is very coarse and at each next level additional data is added and the representation becomes more detailed. At the final level the fully detailed representation is obtained. This approach is very useful for representation of large data on the internet, especially for data that occupy several 100 MB of storage space in its raw format and require significant amount of time for transfer from the server to the client’s computer. When the user navigates to a specific page on the internet, a small amount of data is transferred to his computer, from which the first coarse representation of the model is created and visualised on his computer. As additional data is transferred, the model gets more detailed and the visual information shown to the user becomes clearer. In this way the user can already perform some rough analysis of the data during the transfer or quickly stop the transfer of the data.

3 SURFACE MODELS

Surface models and, amongst these, polygonal meshes are by far the most popular representation of 3D data. Other methods incorporate constructive solid geometry (CSG), free-form patches, subdivision surfaces and dense point clouds for direct point-based visualisation, but they are not utilised in GIS and archaeological applications.

Constructive solid geometry (CSG):
is a procedural technique for creating solid models often used in 3D computer graphics and CAD systems. Complex objects can be created using sets of few basic primitive objects and boolean operators for combining them.

Free-form patches:
is a specific part of a surface which is described by a set of mathematical equations and is used to describe the skins or boundaries of 3D objects.

Subdivision surface:
is a smooth mesh obtained at the end of the iterative process of subdividing a base coarse polygonal mesh.

Typically, topological (or connectivity), geometric, and property data are used to represent a 3D polygonal mesh. The basic element of such a model is a vertex in 3D space. Two vertices are connected by an edge, and a surface surrounded by a loop of vertices and edges represents a polygon. A shell constructed from topologically adjacent polygons represents a surface. The superiority of polygonal meshes over other 3D representation techniques arises from several factors. There is excellent support in hardware and software visualisation standards. High-resolution 3D scanners and related software for topology construction from scattered points now have improved performance. Above all, there is the simplicity of the basic idea itself. Usually, the polygons are triangles, forming the triangular meshes. The triangles are produced either directly or by triangulating general polygons. They are typically accepted directly by hardware rendering systems and can be often manipulated and visualised in real-time even on low-cost machines.

CAD (Computer Aided Design):
allows to design and especially to draft a part or a whole product on a high standard of graphic data processing.

Polygonal models, representing complex 3D geometric shapes, are produced by various CAD systems, fractal terrain generators, 3D scanners, and other tools. The CAD systems and fractal terrain generators produce vertices (geometrical data) and polygons (the topology) that construct the surface, while the 3D scanners generate only vertices. Special algorithms for surface reconstruction from a cloud of points are applied to generate polygons from the vertex set. After we obtain the polygons (in most cases triangles), we can process polygonal/triangular meshes by specialised algorithms, aimed to facilitate storage requirements, accelerate visualisation and data transmission.

Free the models website:
provision of free content for 3D applications and 3D/game engines.
http://telias.free.fr

Cyberware:
company that manufactures a variety of instruments for 3D scanning.
www.cyberware.com

Three examples of triangular meshes are shown in figure 2. Free models of a Greek trieme boat and an ancient helmet have been obtained at Free the models website, and the Venus statue model has been, by the courtesy of Cyberware, downloaded from the company's website. The author's own software was used for visualisation.

Due to high performance of today's computers and 3D capturing devices, models can be described with meshes containing ever more triangles. Models with several millions of polygons are very common today (Michelangelo's David statue has 56 millions triangles,

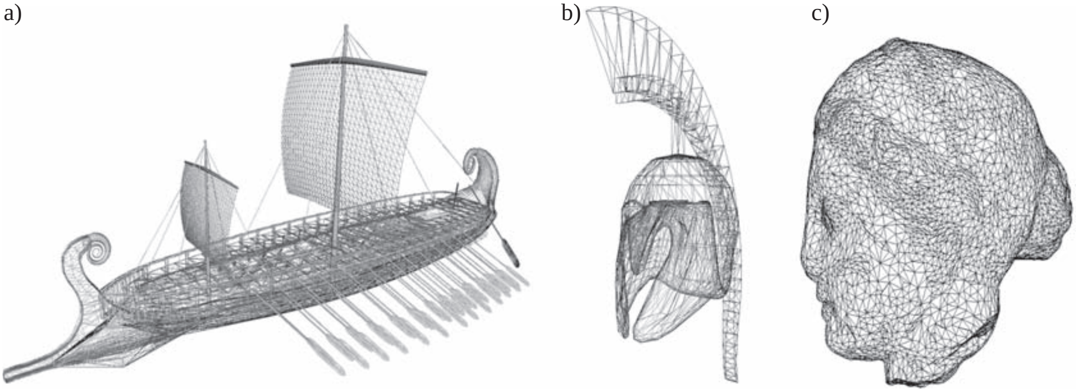

Figure 2. Triangular meshes of (a) a Greek trireme boat, (b) an ancient helmet, and (c) the head of the Venus de Milo statue.

and St. Matthew has 372 millions triangles). The complex meshes are expensive to store, transmit, and render, leading to the need for solutions several practical problems. *Mesh simplification* or *mesh decimation* optimises the rendering efficiency by significantly reducing the number of polygons without great loss of visual information. *Level-of-detail (LOD) approximation* further improves rendering performance by defining several versions of a model at various levels of detail and by varying this level based on the distance to the viewer. A technique of mesh decimation can also be used to minimise the memory space occupied by the mesh, but such compression rarely preserves the model precision required for later analysis and manipulation. Special lossless *mesh compression methods* have therefore been developed. Although they mostly address the geometry and connectivity data only, and rather few approaches address the property data as well, they achieve impressive compression ratios. The compressed topology data often does not exceed 1.5 bits per triangle. Three-dimensional mesh compression is so important that it has been incorporated into several international standards. VRML, X3D, MPEG-4 and MPEG-7 all utilise this possibility. With the popularity of the internet, *progressive compression and transmission* has been required. This approach utilises the advantages of all previously mentioned methods: mesh simplification, LOD approximation and mesh compression. When a mesh is transmitted, better and better approximations to the model are progressively shown as data is incrementally received. Moreover, a user can stop the transmission whenever he/she finds out that the mesh being downloaded is not what he/she wants or the resolution is already good enough for his/her purposes.

LOD (Level-of-detail) approximation:
is the defining of several versions of a model at various levels of detail based on the distance to the viewer.

Lossless mesh compression method:
an algorithm for compressing triangle or polygonal mesh data without losing information resulting in identical in- and outputs.

3.1 *Triangular mesh decimation*

Triangular meshes can be huge and, consequently, cannot be manipulated quickly. If they are too large, they cannot be manipulated at all. This problem can be annulled or at least mitigated by simplification of a mesh to the size, which enables faster or even real-time manipulation. The simplification decreases the number of vertices and triangles but it purposely retains all the details necessary for some quick analyses and acceptable visualisation quality. Figures 3a and 3b show the mesh and the corresponding rendered surface of Anubis with 28,384 vertices and 55,500 triangles. The free model has been downloaded from 3D Nuts website. The simplified mesh in figure 3c consists of only 3,926 vertices and 6,623 triangles (around 14% of the original model size), but the resulting surface (figure 3d) is still visually agreeable.

3D Nuts:
provision of free models and detailed 3D Studio MAX tutorials.
www.3dnuts.com

The main idea is to simplify the triangular mesh in regions where triangles are similarly oriented. The simplification can be done manually, relying on the user's experience and intuition, but this approach is of no use with larger models. To remove this obstacle, so-called mesh decimation algorithms were developed, which simplify triangular meshes automatically. The first triangular mesh decimation algorithm was introduced by Schröder et al. (1992). All mesh decimation algorithms can be classified according to the elements they are directly eliminating from the mesh (i.e., vertices, edges, or triangles) (Garland & Heckbert 1995, Franc & Skala 2000, Krivograd et al. 2002):

- *Vertex decimation methods* are the most frequently used. They are based on the original approach of Schröder et al. (1992). The vertices are evaluated, and incrementally removed from the mesh according to their importance. Methods differ in evaluation criteria and in the required triangulation type (see Garland & Heckbert 1995 for an overview).
- *Edge decimation methods* eliminate previously evaluated edges. A removed edge is replaced by a vertex. Triangles, which degenerate to edges, are removed (Hoppe et al. 1993, Garland & Heckbert 1997). Some algorithms, that combine vertex and edge decimation method, also exist (Franc & Skala 2001).
- *Triangle decimation methods* are supposed to evaluate and directly eliminate triangles but, up to now, approaches using this possibility have not been reported.

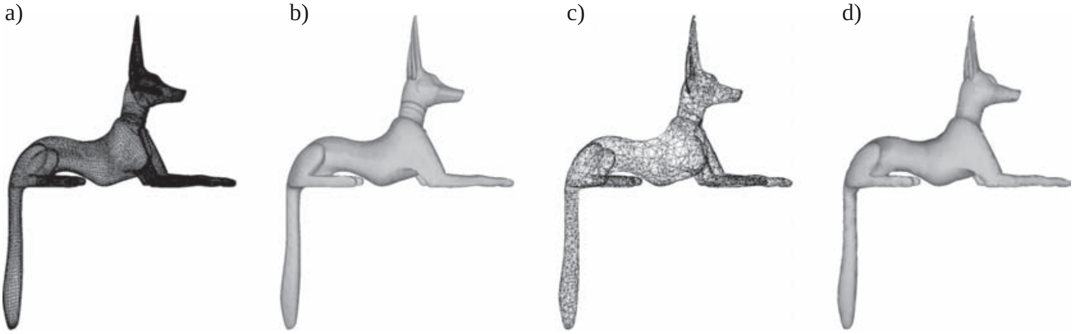

Figure 3. Triangular mesh and the corresponding rendered surface of Anubis (a, b), the mesh decimated to 14% of the original size (c), and the corresponding, still visually agreeable surface (d).

The basic idea is the same for all mesh decimation methods. The elements (vertices, edges, or triangles) are firstly evaluated according to an evaluation criterion. The most suitable element for removal is chosen then. For example, the vertex decimation method in figure 4a selects vertex v_i. The chosen element and all the adjacent triangles are then removed. Triangles t_0 to t_4 are removed in figure 4b. The area released by the removed triangles is anew triangulated (figure 4c). Finally, all the elements that have participated to the described actions are re-evaluated (the vertices v_j, v_k, v_l, v_m, v_n in figure 4c), and the next element is chosen for elimination. The process is repeated until the termination criterion is met. Huge triangular models can be usually simplified to 1% or even more, without significant loss of visualisation quality.

3.2 *Triangular mesh compression*

Before triangular mesh compression methods are applied, each triangle is described by the coordinates of all three vertices. In a typical mesh, each vertex is shared by around six triangles, thus resulting in high redun-dancy in uncompressed data. If each vertex coordinate is represented with 32 bits, we get 480 redundant *bits per vertex* (*b*/*v*). Such wasteful representation of triangular meshes is used in the STL format introduced in 1987 (Wohlers 1992). The first improvement came with introduction of vertex indexing. The vertices are stored as an indexed list, and each triangle is presented by three vertex indices. In this way, redundancy in geometrical data is removed, but additional data (vertex indices), describing the topology of a triangular mesh, are necessary. The topology data describes how the triangles fit together. For each triangle we need $3[\log_2 n]$ bits where n is the number of vertices. As there are approximately twice as many triangles as vertices, we need $6[\log_2 n]$ b/v. Such a representation is used in the VRML standard, but its advantages are mainly lost by encoding real coordinates and integer vertex indices in a pure textual form (Ames et al. 1997). A VRML file with the .wrl extension may be

STL format:
is a file format used to represent 3D CAD models in stereolithography and other solid free-form fabrication technologies created by 3D Systems. STL files describe only the surface geometry of a 3D object without any representation of colour, texture or other common attributes. The STL format specifies both textual (ASCII) and binary representations.

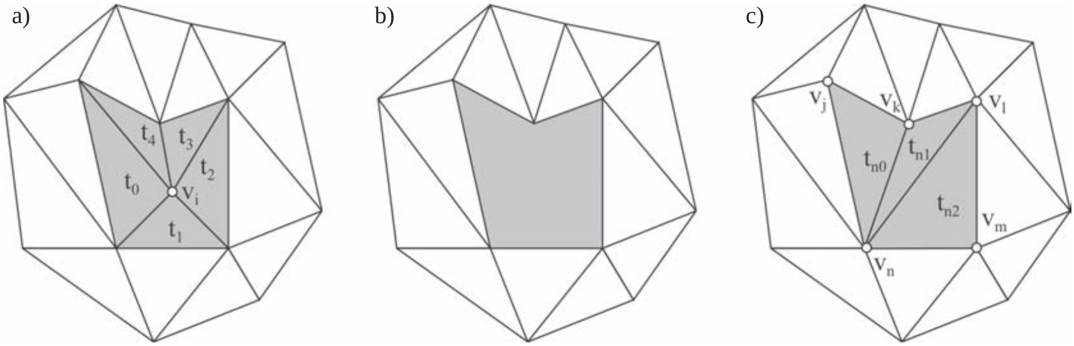

Figure 4. Vertex decimation process.

compressed using gzip. The resulting compressed file (with the .wrz extension) can be transferred over the internet more quickly, but the data compression method traditionally employed (intended to minimise redundancies in alphanumeric streams) appears inadequate for triangular mesh compression. The main reason is that the triangular meshes differ significantly from pure alphanumeric data – besides geometric information expressed by real numbers representing vertices coordinates, they also contain topological information. None of the classical compression methods can efficiently compress the topology. More advanced data-specific compression techniques have to be applied.

The compression of triangular meshes was a hot topic even before VRML was invented. Turan (1984) showed in his pioneering work that any planar graph could be encoded by at most 12 *b*/*v*. The first widely used approach for reduction of the topological information of triangular meshes was based on triangle strips, which have been widely accepted by computer graphics community through OpenGL (Woo et al. 1999). A new triangle in a strip is defined by two previous vertices and a new vertex (figure 5). This approach gives acceptable results, if long triangle strips can be built. In this case, each vertex is sent to the output stream twice on average. Deering (1995) was the first who broke the limit of sending each vertex at least twice. By employing a vertex buffer of sixteen vertices, he reduced the average amount of vertices to be transmitted twice to only six percent. Such topology description requires (1/8 log *n* + 8) *b*/*v* (Hoppe 1996). Experiments with vertex buffers of different size have been performed by Bar-Yehuda & Gotsman (1996). They proved that a topology of triangle meshes can be compressed by sending each vertex only once if a buffer of $12.75\sqrt{n}$ vertices is provided. Taubin & Rossignac (1998) suggested a method which converts a triangular mesh into spanning trees of vertices and triangles, and they needed 4 *b*/*v* for topology description. Gumhold & Strasser (1998) presented a local compression algorithm which is fast enough for real-time applications. They used a cut-border data structure for compression and decompression. The connectivity is encoded with about 1.7 bits per triangle (around 3.4 *b*/*v*). In the same year, Touma & Gotsman (1998) presented the algorithm that even nowadays repesents, with some later improvements, the best single-rate compression algorithm for triangle meshes. Their algorithm

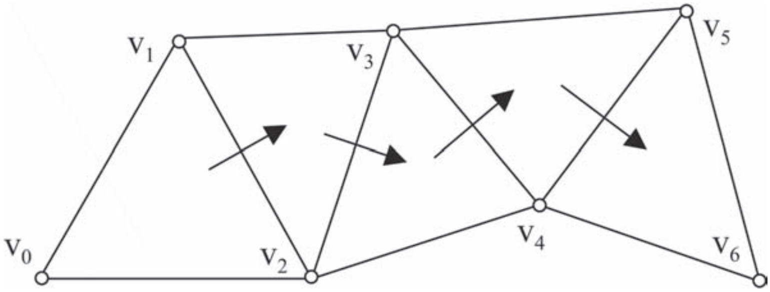

Figure 5. A triangular strip.

compresses the mesh topology as a sequence of commands ADD, SPLIT, MERGE, and the so-called automatic closures (figure 6). On average, this algorithm needs 1.78 *b*/*v* (it was tested with approximately 150 examples). The method of Touma & Gotsman (1998) has been improved by Isenburg (2002) with a help of simple heuristic for the next edge selection. The improved method has been tested on the same set of examples as the basic one. On average it needed 1.66 *b*/*v*, i.e., 6.7% less than required by the Touma & Gotsman (1998) approach.

In 2005 the authors introduced their original algorithm for compression of triangular meshes (Krivograd et al. 2005). In contrast to other methods, their approach does not compress a single triangle at a time, but takes as many triangles as possible. It uses four commands ADD, ADD_ONE, SPLIT_MERGE, SKIP, and an automatic closure. On average, it needs 1.70 *b*/*v*, thus 4.5% less as Touma & Gotsman (1998) approach, and 2.5% more than Isenburg (2002) approach. On the other hand, the author's method typically requires 20% less commands as that of Isenburg (2002). It is also used a heuristics to adaptively choose a method for further compression of coded states. RLE, VLC, Huffmann, and arithmetic coding are all possible.

The latest triangular mesh compression methods achieve excellent compression ratios but, frequently, even the compressed models are too large for reasonably quick transfer over the internet. The development of new data acquisition devices continually leads to increases in the size of geometric datasets. Consequently, a limited bandwidth of communication channels requires more and more efficient compression algorithms. It is unrealistic to expect a compression algorithm to assure the required speed in all circumstances. However, the situation can be improved by enabling users to usefully spend the time while waiting to receive a transferred mesh. From this comes the idea of *progressive compression and reconstruction of triangular meshes*. A user does not now have to wait to receive an entire model in a single indivisible portion. Instead, he/she

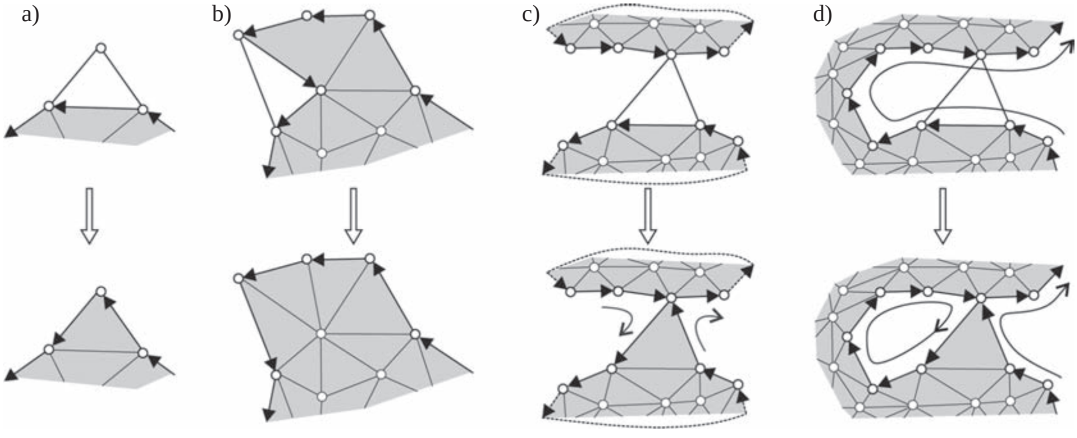

Figure 6. Commands in Touma & Gotsman (1998) algorithm for triangular mesh compression: (a) ADD, (b) automatic closure, (c) MERGE, and (d) SPLIT.

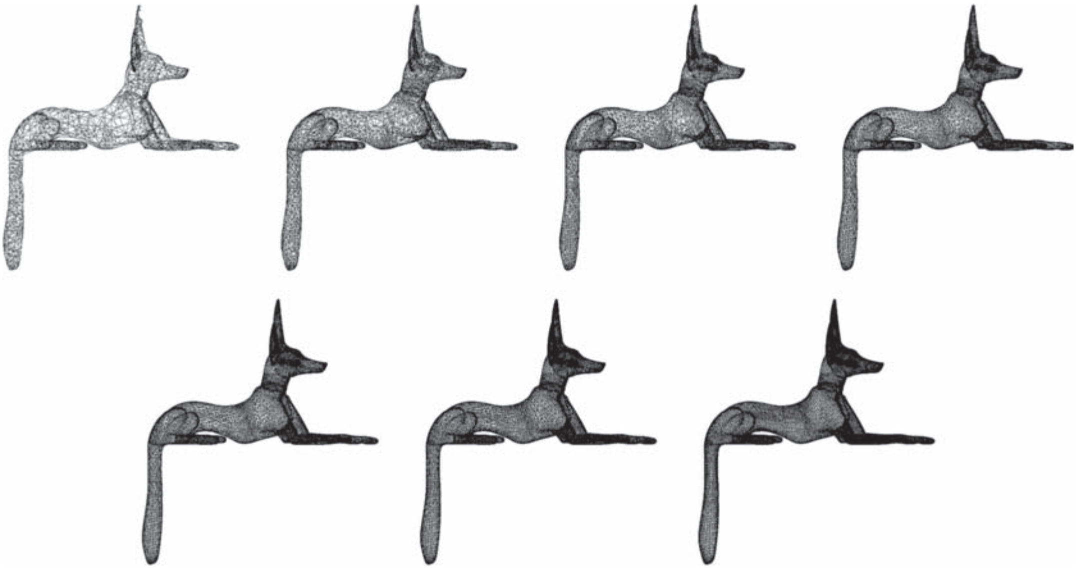

Figure 7. Progressive reconstruction of a triangular mesh.

can already perform some simple calculations or other analyses while the model is being progressively transmitted and visualised in separate portions, from rough outlines of the main surface features to high resolution details. This well-known concept has been adapted to the problem of triangular mesh compression by Hoppe (1996). A combination of three complementary algorithms is utilised in its implementation: mesh decimation, mesh compression, and multiresolution mesh decompression. A triangular mesh is first simplified to some lower resolution. In contrast with a simple mesh decimation process, the progressive algorithm does not reject details, but stores them to enable restoration of the original mesh on the receiver's side. This process may be repeated several times to prepare the model for gradual and progressive reconstruction. Figure 7 shows an example of the progressive reconstruction, incorporating seven resolutions. The freely available model of Anubis has been used (3DNuts). Note that this progressive scheme, as a whole, does not currently introduce any compression. However, a lossless compression algorithm is typically employed at each simplification level to reduce the memory requirements and to accelerate the transmission as a whole. Several progressive algorithms for triangular meshes have been developed (Alliez & Desbrun 2001, Bajaj et al. 1999, Grabner 2002).

3D Nuts:
www.3dnuts.com

4 VOLUMETRIC MODELS

Voxel or volumetric data are used for representation of entities in 3D space, which either carry important information about the objects' interior or are unsuitable for the common boundary representation (B-Rep). Voxel data may be seen as an image in 3D space or a 3D array of pixels. Hence comes the term voxel, which is short for a volume element or a volume pixel. It logically follows that a voxel is a single element inside this 3D array. Each voxel carries the information about its position in space and some additional value representing some property of the data at this specific point. This value can be a single numerical value, representing, for example, density, or a vector combined from various components, representing, for example, velocity. The values are obtained by scanning real data at some points in space. Although these points can be set at purely random positions in 3D space, they are usually aligned according to a regular grid. In practice, the volumetric data is most commonly acquired as a set of 2D cross-sections taken at regularly spaced intervals. The images representing these cross-sections are called slices, and a set of slices stacked in the appropriate order forms a volumetric model of data. The most typical examples of such data acquisition are MRI (magnetic resonance imaging) and CT (computational tomography) scanners used in medicine.

Volume graphics are superior to polygonal models in many respects. While the boundary representation carries only information about the surface of the model, the voxel representation also carries information about the internal structure of the model. The voxel representation is defined on a uniform grid, enabling the use of the existing and well developed image processing techniques by extending the data to the 3rd dimension. Model simplification, when required to optimise rendering, can be simply achieved by decreasing the sampling rate. Animation effects as, for example, 3D morphing or particle emission, are also more easily computed on volume graphics than for surface models.

Despite all these advantages, voxels also have drawbacks. They have a predetermined accuracy linked to the resolution. The memory requirement, however, represents the most significant disadvantage. This creates problems with both visualisation and transfer of voxel data. A while ago, the size of the random access memory was often smaller than the size of the voxel dataset and the processors were too slow to perform volume visualisation in real-time. These dificulties spawned two different, but closely linked branches of research. The first branch was more oriented towards visualisation and has produced many different algorithms, such as voxel splatting, ray casting, and shear-warp factorisation. Lately, the research focus has shifted towards exploitation of the abilities of graphics hardware. Although the existing graphics accelerators are oriented toward acceleration of B-Rep models, very efficient visualisation of voxel data can also be implemented with smart approach. Thus, algorithms for real-time visualisation of large volumetric datasets, combining the intelligence of the early approaches and the pure force of modern hardware, already exist.

4.1 *Voxel data compression*

The second branch of voxel data related research was more oriented towards compression of the data. As already mentioned, in the beginning, the main problem was how to load the whole volumetric dataset into memory. As this could not be achieved by using a lossless compression approach, initial research was more oriented towards compression with data loss. A number of different algorithms for compression of volumetric data have been introduced. Now some of the more important and popular algorithms are surveyed:

- The first voxel compression method was introduced in 1992 by Hesselink and Ning, and was called vector quantisation (Hesselink & Ning 1992, Ning & Hesselink 1993). The idea behind it is very simple, as the value of each voxel is represented with a codeword. The bit-length of the codewords is usually shorter than the bit-length used for storing voxel values and hence the compression is achieved. If, for example, original voxel values are stored as 16 bit values and we use 8 bit codewords, the compression ratio is around 2:1. It is clear that such approach causes data loss.
- The next compression method was presented by Muraki (1993). His method is based on subdivision of the voxel space into sub-spaces and encoding of these sub-spaces with wavelet transformations. A lot of existing advanced compression methods today are based on this approach. Wavelet transformations also present the base of compression algorithm used in the popular image compression standard JPEG 2000. Although lossless compression can be achieved with wavelet based approach, the method presented by Muraki and most other existing wavelet based compression methods are not lossless.
- Fowler & Yagel (1994) presented the first algorithm for lossless compression of volumetric data. This algorithm uses a combination of differential pulse code modulation (DPCM) and Huffman coding. DPCM technique belongs into a set of compression methods called predictive techniques. The value of the next voxel in the dataset is always predicted from the previous samples and the difference between the predicted and actual value is stored.
- Yeo & Liu (1995) presented a method for compression of voxel data based on discrete cosine transform (DCT). In their approach, the voxel space is at first divided into blocks sized 8 × 8 × 8 voxels. DCT is performed on each of these blocks with which the DCT coefficients are obtained. The algorithm then performs scalar quantisation on these coefficients and uses zigzag encoding to remove the correlation between the coefficients. In the last step, additional compression is performed by using a combination of run-length encoding and Huffman coding. Clearly, due to the use of scalar quantisation, this approach is not lossless.
- Chiueh et al. (1997) presented an algorithm for compression of voxel data based on discrete Fourier transform (DFT). Their idea was to expand a well known approach for image compression, used in the well

Huffmann coding:
an entropy encoding algorithm used for lossless data compression. The basic idea is to use a variable-length code table in which the source symbols with higher frequency of occurrence are represented by shorter codes.

Zigzag coding:
a special encoding used in image processing and image compression algorithms. The original signal representing the image is transformed into a new signal with a diagonal zigzag traversal over the image.

known JPEG algorithm, into 3D space. The authors at first perform DFT to obtain so called Fourier coefficients. These coefficients are later quantised and at the end the entropy encoding is performed. Again, because quantisation is used, this algorithm is not lossless.
- Zhu et al. (1997) presented a new wavelet based algorithm for compression of voxel data. Their approach applies the wavelet transformation twice. At first, the wavelet transformation is performed over the whole voxel space. After initial transformation, the algorithm determines interesting structures and homogeneous areas in the data and encodes these areas with an octree. The second wavelet transformation is then applied on the non-empty and non-homogeneous blocks of data. This method is also not lossless.
- A further algorithm for compression of voxel data was presented by Rodler (1999). His approach significantly differs from all previously mentioned methods. Instead of looking at the voxel space as a whole, Rodler based his algorithm on encoding slices of the dataset. This does not cause any problems, as the input data are usually represented as the set of slices. By approaching the task looking on the voxel data as a set of arranged slices, the problem becomes very similar to compression of digital video, and Rodler used many ideas from this field. At first, the correlation between neighbouring slices is calculated using ‘temporal’ prediction. 2D wavelet transformation is then performed over the ‘predicted’ slices and later, the obtained wavelet coefficients are quantised. In this step the algorithm also performs thresholding, during which all the coefficients under the set threshold are removed. At the end, the remaining wavelet coefficients are encoded into a special data structure that supports fast random access. Due to usage of quantisation and thresholding this approach is also not lossless.

Discrete Fourier transform (DFT):
a specific form of Fourier analysis that requires a discrete function as input. The DFT transforms the input function which is given in time domain into another function given in frequency domain.

Octree:
a tree data structure in which each internal node has up to eight children. It is commonly used for representation of spatial subdivisions in 3D computer graphics.

Although the described algorithms perform efficient compression, each and every one of them has some drawbacks. Most of them are strictly oriented towards compression with some information loss. While such approach might be appropriate for visualisation, it is insufficient in some fields where the analysis of the data is as important as the view of the data (i.e., medical analysis). The authors decided to develop and introduce a new algorithm which would perform lossless compression of volumetric data while supporting progressive compression and reconstruction (Klajnšek & Žalik 2005). This algorithm is appropriate for efficient storage of data as well as web-based visualisation of volumetric data.

The basic idea behind this algorithm is similar to Rodler’s approach (Rodler 1999), as the authors also consider the voxel space as a set of slices. At first, each slice is encoded with a quadtree. To achieve this, each slice is split into small equally sized blocks (usually the size of these blocks is 4 × 4 or 8 × 8 voxels) called macro-blocks. In the next step, neighbouring homogeneous macro-blocks are joined together thus creating larger blocks. With this bottom-up approach the quadtree representation of the slice is obtained as shown in figure 8. In the next

Quadtree:
a tree data structure in which each internal node has up to four children. It is commonly used for representation of spatial subdivisions in 2D computer graphics.

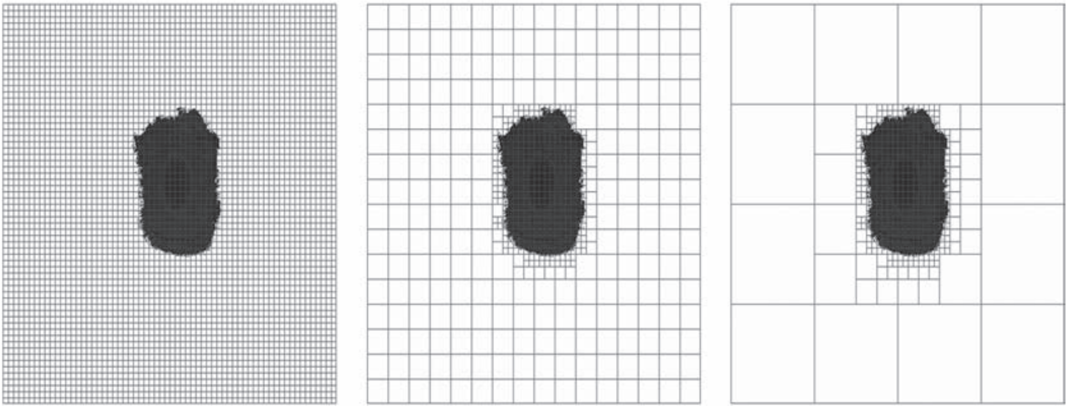

Figure 8. Obtaining the quadtree representation of a slice using the bottom-up approach.

step, the quadtrees related to adjacent slices are compared and equal nodes in the quadtrees are determined and marked. Clearly, only such nodes have to be stored, only for the first quadtree, as the data can be copied to the consecutive slices during the decompression process. In the final step all the remaining nodes are stored using the entropy encoding algorithm. This entropy encoding algorithm takes into consideration both the properties of the node and the macro-block encoded by this node, as well as the correlation of this macro-block to the macro-block of the same position on the previous slice, to maximise the efficiency of the compression algorithm.

The described algorithm performs lossless compression of volumetric data. It keeps all the advantages of the octree-based algorithms, but the comparative analysis has shown that data coherence is better exploited by the new algorithm. It has been tested on numerous voxel datasets and on average the achieved compression ratio was between 2.5 and 4.5. Due to its quadtree-based nature the algorithm also supports progressive data reconstruction. Example of progressive reconstruction of a voxel dataset representing the human head is shown in figure 9. The quadtree compression can also be easily adapted to work on systems with low-memory (this is not the case with the octree compression). This feature makes the algorithm very interesting for a possible hardware implementation.

Volumetric data have already found their way into practical applications, despite their nature and some limitations. However, with the rapid development of computer hardware, visualisation of large and even very large volumetric datasets in real-time is already possible, at least for locally stored data. On the other hand, visualisation of volumetric data over the internet is still in development and no standard has been yet accepted. This might soon change as a special working group inside the Web3D consortium is working on specifications for volume rendering inside the X3D. Today, the common approach is to download the complete voxel dataset at first and then visualise it with a locally run special-purpose application.

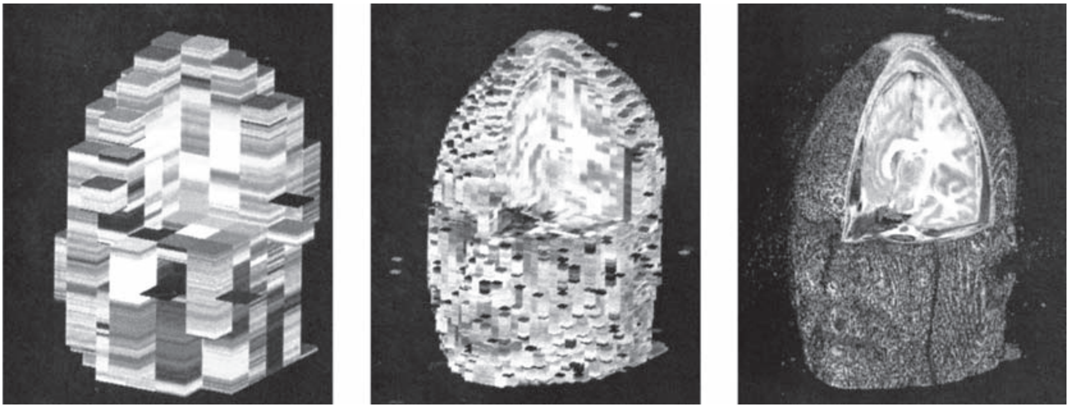

Figure 9. Example of a progressive reconstruction of volumetric data.

5 CONCLUSION

Geometric data processing oriented towards efficient visualisations of 3D geometric models are being surveyed. The stress is on 3D geometric modelling techniques applicable in the archaeological or geographic context. No matter whether a polygonal mesh is employed to represent spatial object's shape, or a volumetric model is used to additionally show the object's internal structure, the problems associated with the storage, transmission and visualisation of large amounts of geometric and topological data are faced. Due to high performance of today's computers and 3D capturing devices, polygonal meshes can be created with many millions of triangles, while the nature of voxels implies that they will occupy much storage space. Such large quantities of data, in the order of hundreds of megabytes are in both cases expensive to store, transmit, and render (visualise), thus creating a number of practical problems. In virtual environments enabling interactive navigation and object manipulation, there is a particular interest in quick response, without decreasing significantly the visualisation quality. To efficiently exploit distributed data resources and other advantages of the internet, additional requirements have been set for the data transmission speed. As the authors point out, techniques of geometry and topology data simplification, compression, progressive transmission, reconstruction and visualisation are herewith introduced to cope with these problems.

In addition to other approaches, the authors describe their two original lossless data compression algorithms, one for the triangular meshes and the other for the voxel models. Both algorithms achieve satisfactory processing speed and impressive compression ratios. The key element of this methodology is to detect the properties of various types of 3D models and to develop specially suited algorithms that transform the model into the appropriate form by keeping the visual quality at the highest possible level. The polygonal models are supported by several standards, as VRML, X3D, and MPEG-4, but an external application is still needed to import a voxel model into a VRML browser. Besides the ability to incorporate/plug the presented algorithms in VRML and X3D viewers, various goal applications are also studied that enable 3D data manipulation, including those from archaeological context and GIS, so that the routines can efficiently cooperate with the core code of the application.

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The concept of a historic landscape analysis using GIS with focus on Central Europe

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ABSTRACT

Against the background of accelerated changes of landscapes and the threatening danger of losses in the quality of landscapes, a number of scientific disciplines dealing with applied and diachronic landscape analysis have emerged in the last 20 years. This chapter aims to further them by developing an interdisciplinary concept of a Historic Landscape Analysis (HLA) based on a landscape information system (LIS), which can be applied in most parts of Europe. The information system is adapted, on the one hand, from a physiological modelling of landscapes that derives from the patch-matrix-concept developed by the North American landscape ecology. On the other hand, it has roots in the cadastres and topographic maps that were generated in many European countries since the 18th century. In addition, this chapter discusses how to model, set up and apply the landscape information system and, in particular, how to integrate historical data. Methods for analysing and evaluating the structures of, and changes in landscapes as well as for simulating and managing the future development of "traditional" or "historic" landscapes are discussed in another chapter within this book.

1 INTRODUCTION

1.1 *Cultural landscape*

After Hartshorne (1939: 216f.) 'landscape' is "the external surface of the Earth beneath the atmosphere". According to that, landscape is nothing more or less than an arbitrarily defined section of the Earth's surface which can be scientifically analysed as a dedicated construct under certain aspects (elements, structures, and functions of the landscape). The term landscape serves above all for the identification of research concepts at the interface between natural and cultural sciences (Schenk 2002a).

However, the frequently used term 'cultural landscape' points to the unsolved problem of how to integrate biotic and abiotic, natural and anthropogenic landscape units, respectively. This problem of a not yet achieved integrated analysis can also be seen in the distinction between nature conservation and preservation of historic monuments (cf. Gunzelmann & Schenk 1999).

A historic (or historic-genetic) landscape analysis – understood as the defining and the representing of phases and processes of landscape development – provides knowledge about the landscape and helps to form a synthesis and interpretation of its characteristic traits. Additional help comes from tracing historic conditions of landscape (cf. Schwineköper 2000) either in a more socio-economic or in an ecological sense.

Two principal subjects of current historic-geographic landscape research can be recognised, described in two programmatic publications by Gunzelmann (1987) and Bender (1994a): isolated, static landscape elements (usually relics of former landscape-forming processes) and the landscape's functional structure. All relevant studies inventory, describe, and possibly evaluate landscape, but the element-based approach (e.g. BayLfU 2004, Gunzelmann 1987, von den Driesch 1988) follows the tradition of "historical geographic survey"[1] (Denecke 1972) while the diachronic process-based approach is more sophisticated in the contextual observation of the landscape's functional structure (e.g. Bender 1994b, 2007).

The fundamental question for a cultural landscape information system is how landscape can be categorised to assign a value to the diachronic approach for direct applications within the planning process. Landscapes are shaped by the variation of land cover, and it is possible to determine these landscape units based on the diverse forms of anthropogenic use (Palang et al. 1998). When assessing such units, for instance, as a contribution to nature conservation management and landscape planning, one should not focus on individual objects but if possible consider a four-dimensional perspective that is oriented in both spatial and temporal interrelationships (Bender 1994a).

1.2 *The purpose of historic landscape analysis (HLA)*

Many of Europe's cultural landscapes have undergone a remarkable change since the early 19th century, and over the course of the 20th century many traditional land use units and forms of use have been abandoned (Cousins et al. 2002, Houghton 1994, Lamarche & Romane 1982, Olsson et al. 2000, Pärtel et al. 1999, Petit & Lambin 2002, Verheyen et al. 1999, Vuorela et al. 2002). As a consequence of the agricultural production intensification on the one hand, and the retreat of agriculture from unfavourable sites on the other, many of the extensively managed traditional land use systems have started to disappear, which finally resulted in the fragmentation and isolation of anthropogenic ecosystems.

Today, both afforestation and the natural process of secondary succession of fallow fields, meadows and pastures lead to new and unusual sights in many places, occasionally with negative effects on the attraction of certain tourist landscapes (Hunziker & Kienast 1999). By small-scale

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[1] all literal quotations translated by the author.

diverse landscape structures, many single landscape elements get lost that have as “witnesses of the past” a “source value” and an “education value” (Schenk 2002b). Also aesthetically “depleted” scenery communicates regional identity (“home”) only to a limited degree (Schenk 2002b).

Exact knowledge of historical landscape conditions and of landscape change over time are important in relation to documentation and conservation of the heritage. This knowledge is particularly valuable for more effective landscape planning at the local level, and also could facilitate and improve predictions of the current and future state of the landscape as well as enable scenarios for future conditions (Marcucci 2000). However, appropriate linking of social and ecological data and scales for an effective natural resource management is still a challenge (Oldfield et al. 2000, Vogt et al. 2002, von Haaren 2002).

Ecological and socio-economic aspects of cultural landscape change have been the object of numerous studies in the past few years, especially land use changes and abandonment since the middle of the 19th century (e.g. Bender 1994b, Lamarche & Romane 1982). Another working group deals specifically with landscape elements having a “cultural-historic value” (e.g. Gunzelmann 1987, von den Driesch 1988). These studies use different methods for assessment and visualisation of landscape change and its results. Therefore, the aim of future research is the development of minimum standards for a high-resolution method appropriate for an exact assessment and analysis of land use changes in the Central European cultural landscape.

1.3 *Concepts of history in landscape analysis*

Time-depth in cultural landscapes and landscape change has been a scientific objective for a long time. In Germany, for instance, the concept of landscape change analysis has been generated through different geographical research approaches. These include the “historical geographic survey” (Denecke 1972) with its deduction of cultural landscape cadastres (Fehn & Schenk 1993), the genetic cultural landscape research with studies related to the development of individual landscapes (Bender 1994b, Bund 1998), and the applied historical geography with contributions to landscape protection and landscape planning (Gunzelmann 1987, Schenk et al. 1997).

For an applied historical geography, which is interested in the present situation, it might be enough to only observe the historic development of the landscape elements that survived until today (Jäger 1987). However, to enable future evaluation, it could be useful to reconstruct past landscape conditions as exactly as possible (Bender 1994a). Thus, genetic cultural landscape studies add the fourth dimension of time. Here the problem arises of finding temporal as well as spatial information without gaps. The time continuum can be achieved by longitudinal sections and cross-sections. In spatial sciences, the cross-section method is used more often (Jäger 1987). Pure longitudinal sections are used only in exceptions, for example in histories of farmsteads, which can reveal – depending on available data – an actual gapless tracing of former ownership conditions, the agricultural area in use, etc. (cf. PUG 2000).

Cross-sectional surveys, especially land use mapping of time-slices, form the main part of cultural landscape development studies. A state of the landscape, which represents the traditional land use system, should be the starting point for the diachronic analysis of landscapes. Due to the fact that European landscapes achieved their highest diversity in pre-industrial times, it is important to obtain data that originate at least from the 19th century (Antrop 1997).

2 METHODS OF DATA PREPARATION

2.1 *Data sources*

In identifying historic landscape elements a number of different methods are applied, often in combination: survey and mapping, remote sensing (e.g. aerial archaeology, identification of historic field systems, Seger & Kofler 1998), archival research. The diachronic approach to landscape is principally retrospective, i.e., an attempt to reconstruct the creation and development of the persistent landscape elements. Topographic and historic maps, aerial and satellite images, land registers which include geodetic survey maps and land plot records, even survey maps of landscape elements, as well as various statistics and archived material are taken into consideration for the research (Bender 1994a, Bender et al. 2005b).

Historic maps:
cf. chapter "Use of historical cadastral maps in modern landscape research and management" of Domaas & Grau Møller.

Aerial and satellite images:
cf. chapters "The application of digital vertical photogrammetry in the recording and analysis of archaeological landscape" of Corns & Shaw and "The use of satellite remote sensing for detecting and analysing cultural heritages" of Heinrich et al.

Likewise, the continuity of the sources is of great importance. This means, several time periods and corresponding landscape conditions must be represented by common attributes that are collected and recorded using a standard procedure. However, these data sources have to be verified on an individual basis in order to assure consistent data. Up to now, many studies have accessed and attempted to compare various data sources (cf. table 1) or have refrained from going back to temporal data from the 19th century (e.g. Olsson et al. 2000).

Table 1. Examples of landscape change studies.

Authors	Country	Extent	Time period	Nb. of time slices	Nb. of land use types	Source	Scale of source
Petit & Lambin (2002)	Belgium	91 km^2	1775–2000	7	6	HM, TM, Landsat	1:11,520–1:25,000; Landsat
Bender et al. (2005b)	Germany	20 km^2	1850–2000	4	9 (34)	CM (LR, FS)	1:5,000
Vuorela et al. (2002)	Finland	9 km^2	1690–1998	9	15	HM, CM, TM et al.	1:4,000–1:42,000
McClure & Griffiths (2001)	UK	n/a	1812–1990	2	n/a	HM, LR	1 inch : 1 mile, 1:10,000
Cousins (2001)	Sweden	6 km^2	1690–1998	5	7	CM, LR, FS	1:4,000–1:30,000

Legend: HM = historic maps, CM = cadastral maps, TM = topographic maps, LR = land register, FS = field survey.

For diachronic landscape analysis using GIS, documentation of (historic) landscape conditions should cover all (at least two) chosen time slices showing a largely similar quality with regard to scale, spatial resolution and information density (Bender 1994a, Bender et al. 2005b). Factors such as map scale, map precision, raster resolution, the classification used, and the significance of 'borders' between classes (i.e., ecotones instead of exact borders) influence the results more or less strongly (Lang & Blaschke 2007).

Spatial resolution:
refers to the area on the ground that an imaging system, such as a satellite sensor, can distinguish.

Land registers and topographic maps are generally best suited sources for such a landscape information system (LIS), as long as they are so-called serial sources, created more or less regularly under the same conditions over long periods of about 200 years. The mapping criteria of the historic maps need to be verified and the lowest common denominator regarding the information density has to be found, especially since one and the same landscape element type in different sources could be defined differently. The use of additional sources can be considered to upgrade the level of quality of the "poorest" time slices.

The integration of a variety of data types into a GIS ("Multi Input") often fails due to the incompatibility of data. Nevertheless, the approach can be useful when using cadastral data along with remotely sensed data. The evaluation of land-register maps along with aerial photographs, for example, achieves a higher degree of resolution. That permits a discrimination of forested areas into deciduous, coniferous and mixed woodlands; while other areas of relevance to nature conservation, such as orchards and small structures including field verges and hedges, can also be identified (Blaschke 2001).

The difference in quality, especially of cadastral and topographic maps are significant factors (cf. the example of Bavaria, though a similar case can be made for Austria, with their temporal as well as geometric resolution and information density; figure 1 and table 2). The higher number of land cover and land use types and the better positional accuracy in the cadastral maps help to document areas which are relevant for nature protection and important for the integration in communal landscape planning (e.g. in Germany it is standardised to a scale of 1:5,000). Another advantage is the provision of information by the cadastre that concerns economic, social and cultural factors and can be used to develop explanations of changes in landscape patterns – beyond the more physical data (DTM) of topographic maps. On that basis it is possible to develop prognoses and scenarios (Hawkins & Selman 2002).

Digital Terrain Model (DTM):
is a "bare-earth" model that represents the elevation of the natural ground surface (topography).

cf. chapters "Spatial interpolation and terrain analysis" of Hofierka and "Shedding light on the past: using LIDAR to understand ancient landscapes" of Crutchley.

The cadastral maps document the boundaries of the land plots and also divide each plot of real estate into different sub-plots by the type of use. Related data have been collected comprehensively in large parts of Central Europe since the 19th century (cf. Heider 1954, Messner 1967). The types of land use, ownership status and other attributes are listed (mostly for tax purposes) in the land register's land plot records.

Moreover, supplementary attribute data (e.g. stemming from landholding and agricultural administration) can be added. To help explain the causes of landscape change, information from DTMs can be integrated

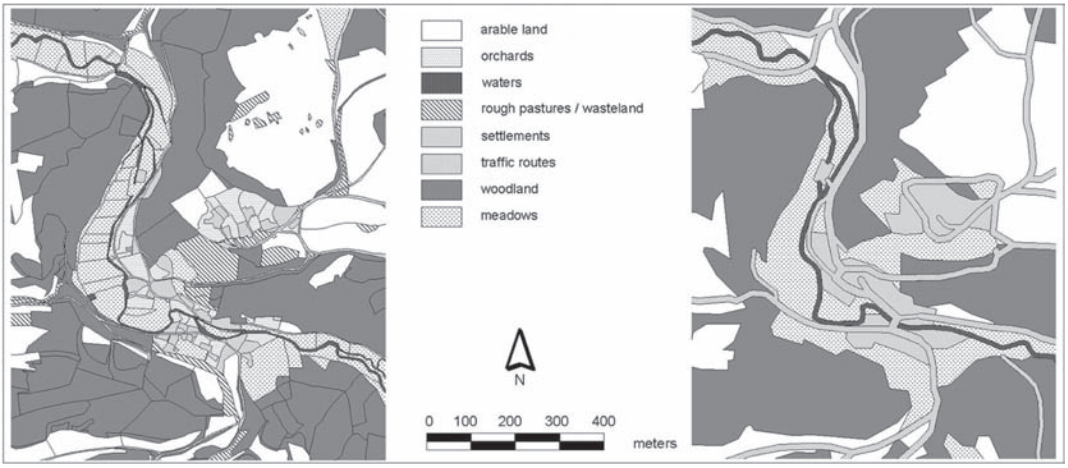

Figure 1. Comparison of two temporal layer maps after evaluation of cadastral maps (left) and topographical maps (right) in a section of Wuestenstein district, Franconian Alb (Bender 2005a).

Table 2. Topographic and cadastral maps as a source for landscape change analyses in Bavaria.

Parameters	Cadastral maps	Topographic maps
Projection	Soldner Polyeder	Gauß-Krüger (Soldner Polyeder)
Scale	1:5,000	1:25,000
Positional accuracy	±0.5–1.5 m	±3–15 m
Observation origin	1807–1853	(1801–1841) 1920–1960
Observation interval	~10–40 years	~5 years, in former times much longer intervals
Nb. of land use units	~10+	~5+
Minimum mapping unit	“real state of land use”	area > 1 ha (*ATKIS)
Additional attribute data	DTM, soil taxation, land register, IACS	Digital terrain model (DTM)
Digital continuation	DFK	ATKIS-DLM

Legend: ATKIS = Amtliches Topographisch-Kartographisches Informationssystem (Official topographic-cartographic information system), DTM = Digital Terrain Model, IACS = Instituted Subsidies and Control System, DFK = Digitale Flurkarte (Digital Cadastral Map), DLM = Digitales Landschaftsmodell (Digital Landscape Model).

into a land register-based GIS and merged with the land plot data. This equally applies to socio-economic data obtained from land surveys and agricultural administrations (e.g. property, farm types), and it provides a means to correlate categories of change with explanatory variables such as soil quality, relief, etc. (Bender et al. 2005b, Bender 2007).

The availability and ease of using maps (depending on the size of the investigation area and mapping scale) normally determines the choice of source, but most research studies are based on topographic maps of a middle scale, i.e., 1:25,000 up to 1:50,000 (e.g. Schumacher 2006, Walz et al. 2003).

Another advantage of the cadastral map as source is a methodological reason, as the cadastre of the 19th century corresponds very closely (in its contents and function) with the aerial photographs which are used to create or update modern topographic maps. Thus, topographic maps are only secondary sources and on the basis of the cadastre, generalised maps can be reduced to a medium scale, although historic-geographic rules for cartographic generalisation (e.g. hierarchies of landscape element types) have not yet been worked out.

Cartographic generalisation: *is the process of abstracting/simplifying cartographic information as a result of changing scales accompanied by increasing complexity.*

2.2 *Mapping*

The requisite starting point for all phases of landscape analysis is a detailed and scientific acquisition of the landscape. This process is aligned to models in terms of down-scaled and generalised images of the reality. Therefore, a physiological approach is most suitable in the temporal dimension. Landscape can be operationalised most easily as a synthesis of different physical (persistent) elements (e.g. Hartshorne 1939). In this context, it may be expected that corresponding documentation could also be established for bygone times. Information about functional aspects can then be connected to the elements, which are gathered in an objectively-quantitative manner.

The concept of historical geography to describe objects in the real world as discrete point, line or area elements of the cultivated landscape offers a widely-used option for landscape mapping. This concept has roots in cartography and was, for instance, transferred via the Netherlands (e.g. ‘Cultuurhistorische relictenkaart van de Veluwe’ 1977) to German-speaking cultural landscape research (von den Driesch 1988). This kind of segregation of elements is as pragmatic as it is arbitrary, depending not on the research objective but on the scale of observation; it leads to a separation of landscape’s individual parts from their spatial-temporal connections (cf. Gunzelmann 1987).

The patch-matrix-concept from the Anglo-American landscape ecology (Forman & Godron 1986) is more appropriate for the analysis of scenic connection, as it understands the landscape as a mosaic or pattern of self-homogeneous landscape elements (patch, ecotope, land unit, landscape element). These patches can be merged to types or classes, which correspond to a land cover type or a land use type in cultural landscapes. The patch-matrix-concept was among others deduced from the theory of island biogeography (MacArthur & Wilson 1967) and first developed for natural landscapes. In this case, for instance, disturbance patches represent singular, chronic (ongoing), or repetitive disturbance events (by bushfire, hurricanes, avalanches, etc.), or introduced patches outline anthropogenic clearing areas within a forest-matrix. The patches representing the smallest homogeneous units are defined according to the relative problem (thematic resolution) and to the scale (spatial resolution). Utilising the dimensions of patch, class, and landscape, it is also possible to develop hierarchies relative to land use types and scale.

Patch dynamics have established as a crucial approach, determining the relations of patches among themselves and the spatio-temporal change by means of landscape metrics (Pickett & White 1985, Turner 1990). That is the basis for the North-American quantitative landscape ecology, which attempts to conceive the landscape structure by indices

Landscape metrics: *cf. chapter “Landscape metrics – a toolbox for assessing past, present and future landscape structures” of Lang et al.*

describing the area, the shape, the diversity and the topology, to document for monitoring purposes, and to serve as a parameter for ecological simulation models (Botequilha Leitão et al. 2006, Lang & Blaschke 2007). However, the defining of distinct borders in natural landscapes with its fuzzy transitions (ecotones) was criticised quite early in this modelling approach. An exact spatial separation of land uses arises in the cultural landscape only in the 20th century. Apart from that, this discretisation corresponds with the request to adopt the research results in planning (Blaschke 2001).

2.3 *Inventory*

The simplest form of inventory is a so-called site register, as for instance, a bio-geographic species registers (cf. Plachter 1991). A similar, but more complex method is the monument topography or the historical geographic survey (Denecke 1972, cf. also the “register of cultural goods” in Upper Austria, Jeschke 2000). Because of its spatial representation (two-dimensional discrete areas instead of dimensionless points and their coordinates), the habitat register includes more information than the site register.

Both methods of documentation require value definitions whether any specific example or object meets the criteria for the particular inventory. However, these types of register cannot guarantee that a documented “non-occurrence” in a certain place or area is as definite as a documented occurrence. This concerns objects that were not seen during documentation, or the importance of that has not (yet) been recognised. The objective is a complete documentation, which can only be approximately attained: only more or less approximate diffusion patterns can be completed from the site registers (Plachter 1991).

There are many examples of registers covering areas or aspects of a landscape. For monument protection the inventories of architectural and archaeological monuments, e.g. the Bavarian Viewer ‘Monument’, GIS-based since 2006; for nature protection the reserve and biotope registers or maps, e.g. the Bavarian biotope mapping (FIS-Natur or FIN-Web as Internet version); and for agricultural administration the EU instituted subsidies and control system IACS which monitors agriculture with GIS and remote sensing since 2005.

__Bavarian Viewer ‘Monument’:__
an information system which includes all known monuments of Bavaria.
www.geodaten.bayern.de/tomcat_files/denkmal_start.html

__FIN-Web:__
an information system which includes all data about nature conservation and landscape preservation in Bavaria, Germany.
http://gisportal-umwelt2.bayern.de/finweb

__IACS (Integrated Administration and Controll System):__
aims to adequately manage the applications for agricultural subsidies for a series of crops and for livestock.
http://agrifish.jrc.it/marspac/PECO/regulations.htm

Systematic documentation of historic cultural landscape elements in a “cultural landscape cadastre” was prompted by applied historical geography (Fehn & Schenk 1993) with its long tradition of researching these elements (cf. Jäger 1987). It offers an interdisciplinary context for cultural landscape conservation (Schenk et al. 1997). The selection of the cadastre’s contents (elements and their attributes) and its ways of functioning (information, analyses, valuations, etc.) have, however, not been clarified yet (cf. table 3).

Schenk (2002c) suggests that a cultural landscape cadastre serves to list, describe, and explain cultural landscape structures and elements in an inventory. However, it remains unclear whether the term “cadastre”

Table 3. Examples of a cultural landscape inventory from Austria, Switzerland and Germany.

Institution	Cultural landscape Inventory	Contents	Web address
University of Berne, ViaStoria – Center of Transport History	IVS Inventory of historical traffic routes in Switzerland	discrete landscape elements (of certain type: traffic routes)	http://www.viastoria.ch http://ivs-gis.admin.ch (accessed 25.07.2008)
Landschaftsverband Rheinland e.V.	KULADIG digital cultural landscape cadastre	area-wide representation intended (several time slices) + discrete landscape elements	http://www.kuladignw.de (accessed 25.07.2008)
University of Applied Sciences Neubrandenburg	KLEKS cultural landscape element cadastre	discrete landscape elements	http://www.kleks-online.de accessed 25.07.2008)
Leibniz Institute of Ecological and Regional Development (IOER)	Landscape change in Saxony	information about research projects on landscape change	http://www.ioer.de/nathist/sax_proj.htm (accessed 25.07.2008)
Federal State of Tyrol, Tiroler Raumordnungs-informations system (TIRIS)	Cultural landscape inventory Tyrol	discrete landscape elements (of certain type: agricultural area) + analyses	http://tiris.tirol.gv.at (accessed 25.07.2008)

covers an area-wide survey of a landscape with its qualities (as in the original concept of the digital cultural landscape cadastre KULADIG provided by the Landschaftsverband Rheinland), or an appropriate listing of suitable objects (BayLfU 2004) within a “matrix” of, for instance, forests, agricultural land, and settlements.

It has to be worked out in detail, which structures and elements of an object are worthy for listing in the cadastre. For that purpose, applied historical geography produced numerous lists of types which cover a regional and/or functional spectrum of important cultural historic landscape elements (e.g. Gunzelmann 1987, von den Driesch 1988, Bender 1994b), and are extensively harmonised within the discipline.

As long as a cadastre is limited to particularly valuable cultural historic elements, the weakness of biotope mapping will be repeated (cf. Plachter 1991). This method forces the registrar to evaluate the historic quality at the same time as registering each element. But the cultural landscape cadastre with the help of an analysis of development of the cultural landscape (e.g. via historic maps, Schenk 2002c) should firstly record the spatio-temporal basis of the valuation (cf. Bender 1994a). Thus, the methodical sequence of distinguishing between an object and its value (cf. Renes 2002) should be that the expert first takes a systematic gapless or area-wide survey, then evaluates the findings and finally selects the objects in order to create an inventory of the cultural landscape. Appropriate methodical (preparatory) work was done some time ago, especially in Austria (Fink et al. 1989, Peterseil & Wrbka 2001).

2.4 *LIS modelling*

We assume that analyses of cultural landscapes ultimately require implementation of a GIS in order to successfully manage the abundant information about land units, attribute data, and temporal layers. The GIS serves predominantly to calculate the proportion of each (changing) land use type and to visualise, analyse and assess the landscape changes as well as to manage future landscape development and preservation. These purposes lead to the establishment of a large-scale diachronic cultural landscape information system.

Vector data model:
a representation consisting of either points, lines, or polygons which are useful for storing data with discrete boundaries (e.g. land plots).

Entity relationship model:
an abstract representation viewing the real world as a set of objects (entities) and relationships among these objects.

Object-oriented model:
is a representation which stores data as objects instead of as rows and tables as in a relational database.

An implementation of such a LIS by the use of a vector model (usually simple and complex polygons for subplots by type of land use) is consistent with the concept of historical geography, describing objects in the real world as discrete point, line, or area elements of the cultivated landscape (Plöger 2003). In addition to it, the principal programme architecture needs to discuss whether an entity relationship (ER) model in combination with a layer model, or an object-oriented model should be deployed. Only a system which maintains the spatial data completely on the physical level is able to fulfil all requirements because it is scale-independent, temporally and thematically flexible and allows additional extensions (Ott & Swiaczny 2001). Object-relational models offer the management of the relations between subobjects (i.e., sections of transport routes or systems) or classes of thematically connected objects in a hierarchically layer structure (i.e., grassland and its different subtypes such as pasture, meadow, etc.). It may be close to reality (Burnett & Blaschke 2003), but there exist insufficient experiences on the use of the object-oriented modelling for data storage also containing multiple time-slices. Thus, a widespread application is not to be expected at the moment (cf. Plöger 2003).

Relational database:
a data structure in which collections of tables are logically associated with each other by shared fields (ESRI GIS dictionary, http://support.esri.com/knowledgebase/).

Hybrid data storage is essential in all common desktop GIS applications. Spatial and thematic data are stored separately in different data formats and geo-relationally interlinked by a joint key. The construct represents a combination of a layer-oriented GIS and a relational database system (Ott & Swiaczny 2001, cf. figure 2). Using the concept of time slices, attribute data can be maintained easily in a temporal database, which consists of several tables representing the time-slices (Litschko 1999). According to the type of topographic maps, ER modelling is in principal simple. It includes discrete areal units with the (unique) attribute “land cover” as well as discrete point and line entities with the type notation. In contrast,

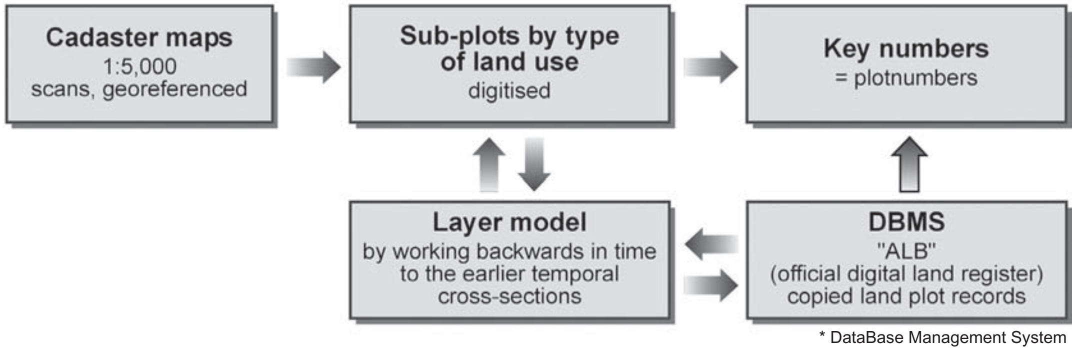

Figure 2. Physical Modelling in a land-register based diachronic LIS (Bender et al. 2005b, changed).

the landscape model of the cadastre (cadastral map and land register) contains plots of real estate as well as plots by type of use and additional attributes, such as land use type, ownerships, or soil quality, that can be completed with additional data of the public authorities.

A raster-vector-conversion of relevant landscape elements can be performed by semi-automatic software solutions. However, due to the complexity of the map content (especially of the historical maps), time saving is not (yet) possible (cf. Böhler et al. 1999). Instead landscape elements (plots) have to be digitised manually, whereas the production of the latest time slice is facilitated by the already existing digital cadastral maps. Bygone time slices are produced by successive mapping of the changes only. Distortions and projection errors of the historical maps can be minimised by pre-processing of the historical base maps in order to enable a visual correction (Bender et al. 2005b).

Raster-vector-conversion: *cf. chapters "Use of historical cadastral maps in modern landscape research and management" of Domaas & Grau Møller and "Mapping and analysis of linear landscape features" of Gugl.*

2.5 *3D visualisation and modelling*

The presentation of results in three dimensions has become a standard procedure in several disciplines (3D and 4D landscape models, e.g. Appleton 2002, Bishop & Lange 2005, Ervin & Hasbrouck 2001, Muhar 2001), in general allowing for better illustration and trans-disciplinary integration in the planning process (Schmid 2001). It should be stated here that the procedure means not only the placing of a map on a DTM, but also consideration of the temporally changing vertical extents of land use classes (e.g. forest crowns 20 metres above ground level) in an digital surface model (DSM). From the point of view of physical geography, for instance, effects on insolation conditions are derivable, whereas in cultural (historic) geography variations of visibility can be investigated. In this issue a feedback to the landscape analysis seems to be possible and useful.

Digital surface model (DSM): *the digital representation of the Earth's surface "beneath the atmosphere" including vegetation, buildings, etc. and providing information about its elevation.*

3 CONCLUSION

A land plot or patch based multitemporal LIS provides an accurate basis for the analysis of historic cultural landscape conditions as well as long-term cultural landscape change. However, the GIS-based model for research on cultural landscape change should provide a standardised procedure for the description and analysis of change which is applicable to any location. A bottom-up approach is adequate that initially entails the detailed study of a small region, which later can be generalised to larger area units. It should be a basis for a spatial model suitable for more or less traditionally used European landscapes (cf. Ott & Swiaczny 2001) wherever topographical maps and/or continual land-register data have been compiled since the early 19th century. The standardised acquisition during a span of 150 years cannot always attain the optimal level of detail, however, "cadastral system has an important role to play in sustainable development" (Williamson 2001). Possible applications of this approach, for instance, on detailed reconstruction of ancient landscapes, on quantification and description of landscape change, on identification and explanation of human induced processes, and on landscape conservation or planning purposes, will be presented in another chapter within this book.

Application of the concept of historic landscape analysis: *cf. chapter "Workflow of a Historic Landscape Analysis using GIS" of Bender.*

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Technologies for integration and use of historical maps into GIS – Nordic examples

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ABSTRACT

The use of analogue historical maps is discussed using the example of cadastral maps from Denmark and Norway. It is demonstrated that digitalisation is a worthwhile undertaking, because the content of the maps is unique in relation to detail (a scale of 1:4,000) and historical situation around 1800 at a time when enclosure was changing the entire landscape. The transformation from raster maps to digital vector data is described and the problems involved in this are examined. Likewise, different methods of evaluating the process in relation to accuracy are discussed. Examples are given of how the digital data can be used in historical landscape research. Land use around 1800 is a topic that it is possible to illustrate and to calculate by means of vector data. In the same way, information on the soil quality integrated in the maps can be used to make thematic maps showing the status around 1800 and indicating where retrospective studies can be used to give further information on changes in settlement structure in the Middle Ages and Iron Age.

1 INTRODUCTION

When dealing with historical landscapes, it is essential to have good informative maps from the period in question. When the historical period is within the last 50 years, it is usually no problem to have either good topographical maps or air photos. Recent papers show that this is well known, especially in analysis of development of vegetation (Duncan et al. 1999, Duran et al. 2006, Isager & Broge 2007, Kadmon & Harari-Kremer 1999, Mark et al. 1995, Mottet et al. 2006, Simonston & Johnson 2005). But further back in time problems may arise. Detailed reliable maps have only been produced since the end of the 18th century, so basic cartographic information can only be provided for the last 200 years in most countries. An important exception is Sweden which has cadastral maps preserved from the beginning of the 17th century. Maps can be used for contemporary studies, but they can also be the basis for retrospective studies of older landscapes. A good example of a detailed study of one settlement around 1820 is an Austrian research project based on the Land register of 1822 with the same type of maps used in this Nordic chapter. Essentially the Geoinformation System (GIS) was used to study contemporary social strata (Gruber 2000).

This chapter deals with solutions for using such old analogue maps in GIS for two Nordic countries showing different types of maps and different landscapes. The problems involved in digitalisation of these maps are methodically described by way of a presentation of the contents of the maps. Furthermore, examples are offered showing the additional analyses that can be made when the maps are digitised.

2 PRESENTATION OF HISTORICAL MAPS

Historical cadastral maps provide information on land use and different types of management (Kain & Baigent 1992). They also contain large amounts of information on structures, areas and elements in the agricultural landscape. They usually describe not only the distribution of agricultural fields, meadows and pastures, wetlands, heath lands and bare land, but also point elements such as buildings, hamlets, stone heaps, and linear elements such as roads, fences, streams and rivers. In most cases, a historical land consolidation map is supplemented by a written document that describes every parcel of farmland in detail (land use, soil quality, production capacity, owner, etc.).

2.1 *Denmark*

In Denmark, the maps in question are the so-called Original 1 maps (an example is shown in figure 1). They are the oldest cadastral maps of the country and are in essence economic maps with topographical contents added. They are insular maps covering an appropriate settlement and cultivation area (a village, an estate or a single farm). The background of the maps is twofold and the maps usually carry several layers made at different times (Grau Møller 1992, Korsgaard 2006).

The initial layer was made at the enclosure. In Denmark, this process took place in the period 1770–1810 and meant dissolving the open field system and the common rights involved and layout of a new system of individual fields. Almost every village was enclosed and had a map drawn which on one hand was the cartographic basis for the land surveyor to make his proposal for a new land distribution, and on the other hand was the future documentation for the new distribution. The specification for the maps are not precisely known, but from the preliminary education of land surveyors it is known that the scale had to be 1:4,000 and that a certain set of signatures had to be used – at least a number of standard signature boards are known (Balslev & Jensen 1975, Grau Møller 1992, Korsgaard 2006). But in this process of mapmaking the old landscape also had to be

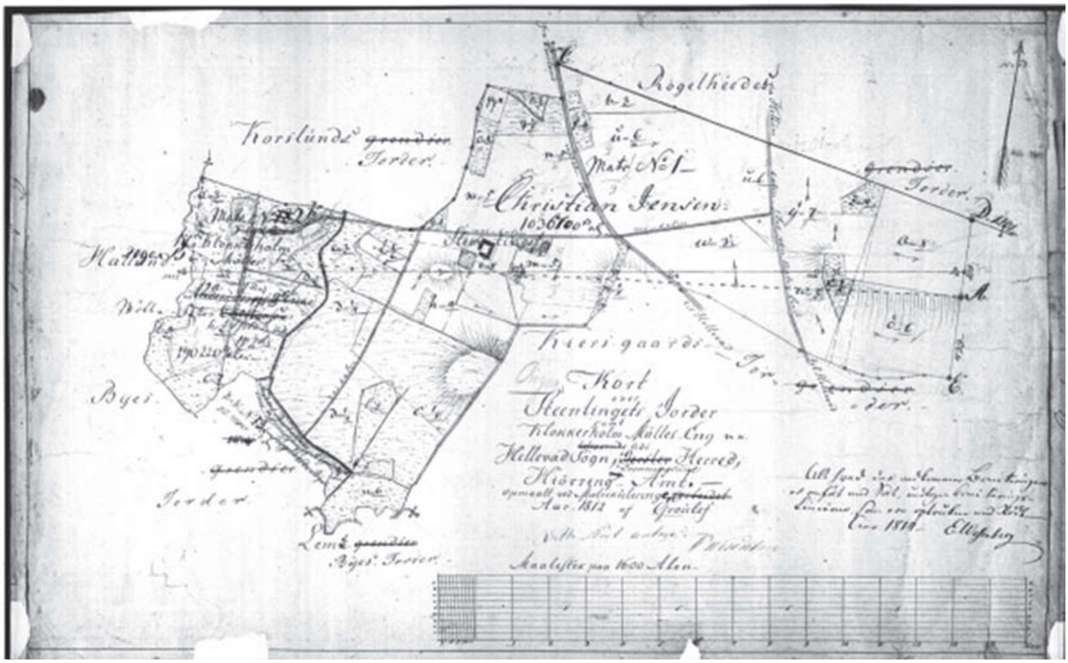


Figure 1. Example of an Original 1 map from Denmark – the single farm Stentinget in the parish of Hellevad, North Jutland (source: National Survey and Cadastre, Copenhagen). The original scale is 1:4,000 – a scale bar is shown for 1,600 alen (1 alen = 62.81 cm), which corresponds to 1 km.

drawn as a reference or fixed-point for the peasants and their landlords involved in the process of enclosure. Therefore, many features might be found on the maps, which are reaching backwards to former structures, but with an actual expression at the point of drawing. These are:

- land use (of different kind),
- settlement,
- old roads and pathways,
- old fences (usually wattles, eventually stone walls),
- fields and field names from the open field system,
- burial mounds (as a characteristic hindrance of cultivation at present and for the future).

The new features of the landscape were a plan which the farmers had to implement in the following years and consisted of:

- new divisions of fields (usually rectangular without much consideration for the topography of the landscape, but following the slide bar of the land surveyor) and corresponding numbers and names of the farmers;
- roads following the new fields, that is straight lines in contrast to the old roads;
- settlement – farms moving out from the village might be indicated (by a sketch or a statement in words) being part of the enclosure plan, but usually no settlement is drawn.

The next phase of the maps was making a new cadastre as basis for a new taxation of the rural areas. This was initiated in 1806, when not all villages were enclosed. The first phase was to ensure that precise maps were available forming the basis of measuring the area each farmer disposed of. Not all parts of the countryside had been cartographically represented at the enclosure: single farms and estates were not enclosed, but many estates had their landholding mapped in the same process as the villages, as the landlord had to pay for the maps anyhow. The missing areas were mapped, but also the existing maps were tested: lines were drawn across the map and measured in the landscape. If the deviation between the lines internally was more than 0.5%, the map was redrawn in order to secure an accuracy acceptable for further land measurement. As a cadastral map several features were added to the map:

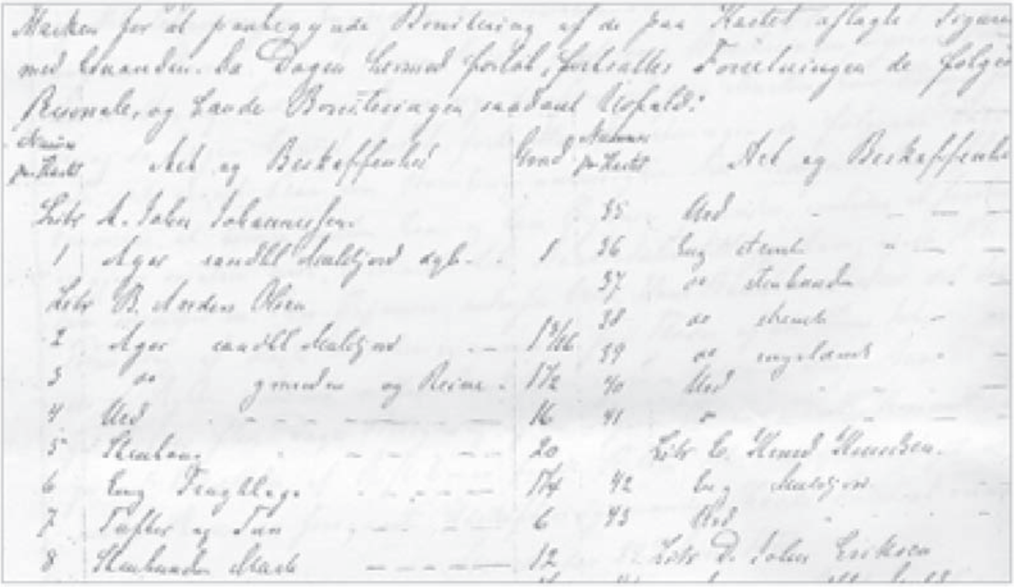
- eventual changes of land division after the enclosure;
- new numbers of each cultivation unit (farm, smallholding or houses) – the numbers are unique to each map unit (village) – and are actually the basis of the cadastre system still used;
- calculation of the area of each cultivation unit (written on the map and in the corresponding books);
- estimation of the quality of the soil at a national scale 0–24 (in the books the final taxation value was calculated on the basis of the area and this figure of quality). The final level of taxation was finished nationally in 1844, from which year the cadastre is named;
- again new settlement was not added because a topographic element as living houses and barns/stables was of no importance for the taxation.

Other phases might be added as the map was used as a cadastral map, meaning that new land divisions or other changes might be added. At a certain moment, the number of changes was so confusing that a new map was drawn and called Original 2 map and Original 3 map for another phase.

2.2 *Norway*

In 1857, a new Land Consolidation Act was passed in Norway, further developing the system introduced in the 1822 Act. Before this, strip-farming had been practised on many farms, especially in Western Norway, where it was a result of long-standing agricultural practices. Strip-farming began at quite an early date to ensure that land, particularly areas suitable for grain production, was fairly partitioned between all those entitled to a share of the farmland (both tenants and owners; Frimanslund Holmsen 1976, Sevatdal 1991). Rules for allocating strips of land may be found in the old Norwegian regional laws that were later collected in King Magnus the Lawmender's national code of 1274, and later in the 1687 Norwegian Law Code (Norsk Lov). The 1857 Land Consolidation Act made radical changes to the earlier system. It brought about extensive reorganisation of agricultural areas, partly because land

Figure 2. The 1874 cadastral map of the farm Grinde in Leikanger municipality including the holding investigated in detail, Eineberg.



[illegible] for at paabegynde Boniteringen af de paa Kartet aflagte Figurer med Haanden. Da Dagen [illegible], fortsattes Forretningen de følgende [illegible], og [illegible] Boniteringen saadant Udfald:

Numer paa Kartet	Art og Beskaffenhed	Grund	Numer paa Kartet	Art og Beskaffenhed
Lote	A. Johan Johannesen.		35	Ured
1	Ager [illegible]	1	36	Eng [illegible]
			37	do [illegible]
Lote	B. Anders Olsen		38	do [illegible]
2	Ager [illegible]	[illegible]	39	do [illegible]
3	do [illegible] og [illegible]	1½	40	Ured
4	Ured	16	41	do
5	[illegible]	20		Lote C. [illegible]
6	Eng [illegible]	1¼	42	Eng [illegible]
7	Tufter og Tun	6	43	Ured
8	[illegible]	12		Lote D. Johan Eriksen

Figure 3. The written protocol gives information about 1440 separate infield areas at the farm, including ownership, land use, soil description and production capacity.

consolidation procedures were now required even if only one of the farmers involved requested this (Frimanslund Holmsen 1976). Before this all the farmers involved had to agree before land consolidation procedures could be started. These changes were introduced because the central government considered the old system of strip farming to be an obstacle to more efficient, modern farming techniques.

The 1857 Land Consolidation Act was the first law to require land surveys and the production of maps and written protocols (figures 2 and 3).

Therefore, the most important and extensive material in Norway is provided by the cadastral land consolidation maps from the nineteenth century at a scale of 1:2,000. Older military maps from the eighteenth century cover only certain areas. The availability of detailed historical maps is more limited in Norway than in the other Nordic countries. Sweden, Finland and the Baltic States all have large numbers of cadastral maps dating back to the 17th century, and several thousands are available from the 18th and 19th centuries (Tollin 1991).

Using the farm Grinde as an example of a land consolidation process; the farm is located on the slopes of the northern side of the Sognefjord in Leikanger municipality, Western Norway:

- 10 December 1872: Three of the farmers request land consolidation;
- 3 April 1873: First session of the land consolidation court at Grinde;
- 29 September 1874: Land consolidation map and written protocol recording parcels of land, production capacity and ownership are completed;
- 12 June 1875: Preliminary land consolidation plan put forward for consideration;
- 19 September 1875: Agreement on changes in land ownership and boundaries;
- 30 September 1875: Agreement on buildings and roads to be moved;
- Autumn 1875: Appeal lodged;
- 20 June 1876: Reassessment of land consolidation;
- 19 September 1876: Final agreement on land consolidation and boundaries.

3 PROBLEMS AND SOLUTIONS OF DIGITALISATION

In order to make these informative maps digital it is necessary to proceed through several processes which are routine within GIS, but not so commonplace when dealing with historical maps. Hu (2001) has tested the accuracy of a 1261 Chinese city map and found that when compared with modern maps the relative accuracy was high (even if not the precise positions had the right coordinates). The challenge is to make these cadastral maps digital and make an evaluation of their precision in terms of modern coordinate systems. The analogue maps have to go through a process of scanning – joining digital files – warping – georeferencing (Grau Møller 2004). The maps in Norway and Denmark are different, as indeed is the landscape and the purpose of the projects was different. In Norway, a project on a very small scale was undertaken, while the strategy of the Danish project was to produce digital maps on landscape scale to make comparative analysis. The steps of the two strategies will be explained in sections 3.1 and 3.2.

3.1 *Norway*

The historical cadastral maps were digitised manually. The software ArcInfo (ESRI 1994a and 1994b) was used for digitising and processing, and ArcView (ESRI 1996a and 1996b) was used for displaying and analysing map files. In order to retain the detailed information on point, line and area features, the map objects were digitised in vector format and coded.

ArcGIS ArcInfo: *the current GIS and mapping software of ESRI which includes all functionality of the ArcGIS products and adds advanced spatial analysis, extensive data manipulation, and high-end cartography tools. www.esri.com/software/arcgis/arcinfo/about/features.html*

In step 1 of coding, the features from the cadastral map, the digitised points and lines were coded continuously, but during interpretation of the map various problems were encountered. Some map symbols were only included as a background or a visual effect, but nevertheless looked like real map symbols. This was particularly true of the symbol used for single boulders. Fieldwork was needed to better distinguish between visual cartographic effects and real geographical elements. In the case of lines, it was discovered that a single line on the map could represent several different elements or functions on the ground at the same time. Since it was not clear either how many different types of linear elements there were on the map or in how many ways they were combined, each new type or combination was simply assigned a numerical code, increasing the value of the code by ten each time, during the digitising process. A separate table was made corresponding to the description in plain text. Increasing the numerical code by ten each time made it possible to give new, closely related elements neighbouring numbers (e.g. road: 40, planned road: 41). The table was later structured so that the main linear function was in one column with a unique heading, and new columns with unique headings were added whenever a line representing new combinations of elements or functions was found. In all, 18 unique codes were used for this process. In the GIS, the table could then be linked to the linear coverage in a "one-to-many" relationship.

Next, the historical land consolidation maps, with their local, individual coordinate systems were transformed or warped to the coordinate system NGO1948, which is used for the standard Norwegian 1:5,000 economic maps. Geometric transformation from one coordinate system to another requires a minimum of four common fixed points, tics, which must be identified on both maps or on the historical land consolidation maps and in the terrain using land survey techniques. If there are non-systematic errors, a larger number of fixed points have to be used, and they must be evenly distributed over the mapped area. Several of the common points that were identified initially were found to be misplaced and could not be used in the final transformation.

Affine transformation: *the conversion of one orthogonal plane coordinate system into another one applying translations, rotations and/or different changes in scale.*

The transformation was carried out in ArcInfo using an affine transformation (first order polynomial warping). Affine transformation scales, rotates and translates all coordinates in the coverage using the same equation. If the geometrical irregularities in the cadastral map are too great, the transformation accuracy will be low, and another method must be used, generally polynomial warping of a higher order as described in the Danish example.

In step 2 of coding, each polygon in the digitised land consolidation map was automatically given a unique identification number and listed in a table. Elements such as stones, stone walls and buildings, which are not described in the written protocol, were coded at this stage and included in the table. The owner after land consolidation was also listed in this table. A further column was added for the numbers used for parcels of land in the written protocol, which corresponded with many of the polygons.

In step 3, the information from the protocol had to be structured in a table before it could be used in the GIS. A spreadsheet, and not a database, was chosen for storage of the information since it was impossible to foresee all the combinations of information in the protocol. Using a spreadsheet made it possible to add new columns when new types of information turned up without disturbing the data already present. Next, the information from the protocol was linked to the polygon coverage by first using the unique polygon value in the first table (a “one-to-one” relationship) and secondly using the protocol value as identification when linking the protocol table to the first table in a “one-to-many” relationship.

3.2 *Denmark*

For scanning, an image scanner with the capacity to handle originals up to 1 m in width is used to scan the photographic black and white copies of the maps. Scans are normally initiated using the line-art (black and white) setting, although sometimes greyscale setting is used. Important in this process is the need to carefully balance the image resolution setting, making appropriately detailed and precise scans but avoiding generating an image file which is too big to handle in the further processing stages.

The process of joining digital files may be necessary because in practice the maps might be so big that in the archive they were cut into pieces along straight cutting lines in order to fold the maps and keep them on shelves (Denmark). Copies were made of the pieces of the maps and it was then necessary to use graphical software to join or append the maps and to cut away the part of the map outside the depicted landscape. In other instances it might be necessary to put small maps together with bigger maps in order to find sufficient control points for georeferencing in the following processing stages.

Warping and georeferencing are performed together in one step using the software programme Airphoto. It is essential to use some sort of warping to warp the map around some georeferenced control points, but on the other hand it must not overly distort the image of the map. A process of georeferencing without warping which can be undertaken in some GIS software is usually not sufficient, as the image map may contain

Georeferencing:
defining the existence of an object in physical space by means of coordinate systems and map projections (e.g. the positioning of an aerial image to its location on the globe).

Airphoto:
part of the Bonn Archaeological Software Package (BASP) which is a non-profit software project. http://uni-koeln.de/~al001/basp.html

Ground Control Points (GCPs):
points on the Earth‘s surface of known location (within an established coordinate system) which is used to georeference image data sources.

internal incorrectness, which the warping process may compensate for. In practice, the procedure of warping used the polynomial transformation. Essential are the georeferenced control points, of which at least four have to be selected from around all the corners and the internal of the map. The coordinates of the selected control points were taken from modern, topographical maps (at a scale of 1:25,000), which in itself carry a slight imprecision (control points were given in UTM coordinates, datum WGS84). This method gives an average internal inaccuracy generally between 10–20 m for the control points (see figure 4). As a rule, points with higher values should not be accepted (new control points have to be found), but in reality it is difficult to get values below 10 m. The software displays the inaccuracy of the individual points so they can be moved or deleted if the value is too high. In certain landscapes, it may be a problem to find control points in all corners of the map, because it requires that points are still recognisable after 200 years. Property lines have a good reliable stability, certain buildings are preferable (churches for instance) and roads may also be acceptable, but generally water courses and coastlines are too unstable to be reliable.

Another modern type of map was used to find control points in a smaller map scale for different reasons. Digital cadastral maps exist (vector format), but their dependence on the old analogue cadastral maps is very big – only a random number of points have been checked by land surveying in the recent years. In practice, this means that a distortion of the old map may occur in the digital map. Preferably another dataset must be used, the topographical maps, which are only made at the scale of 1:25,000 in present time.

Vector data:
data which are represented by the coordinate geometry of points, lines, or polygons.

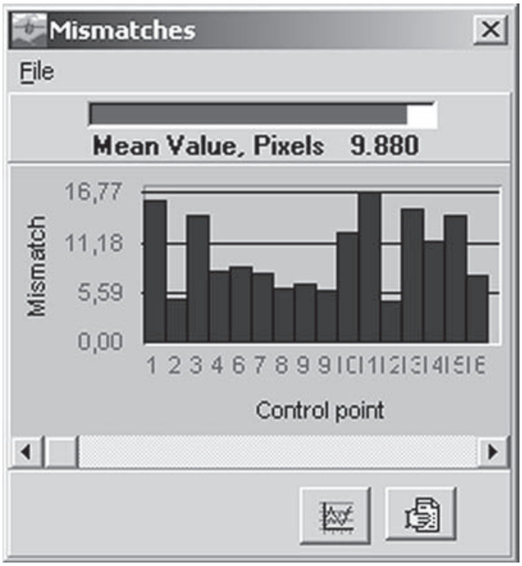


Figure 4. Box showing the errors of control points (software Airphoto) from one transformation process with 17 control points and a mean value of errors of 9.8 pixels.

It is worthwhile undertaking these processes to georeference the maps because they were so rigorously tested for accuracy when they were created 200 years ago. A deviation of only 0.5% on internal lines indicates a high level of internal accuracy and reliability, and the modern process of georeferencing can adequately compensate for any general scale inaccuracy.

Vectorisation:
a process of converting analogue maps into a digital vector representation (points, lines, and/or polygones).

Rasterisation:
a process of converting analogue maps into a digital raster representation (pixels with discrete values).

Vectorisation is the next step in making the maps digital. Generally, one way of digitalising the maps is rasterisation, i.e., keeping the maps in the scanned, but georeferenced version, however because of the diverse level of information it was decided to create vectorised data. The vector format opens the possibility of linking graphic elements to a database and performing spatial analysis, however the option is retained to convert the vector data back into raster data and perform special raster analysis.

Legend:
the reference area on a map that lists and explains the colours, symbols, line patterns, shadings, and annotation used on the map.

It was decided to digitise using a standard legend for all the maps. The actual legend of each insular map might vary a little; in practice, some maps might have a more detailed legend. Following the legend of each map could be seen as considering the map as a piece of art with its own individual understanding. Instead, the aim is to reconstruct a landscape based on the old maps, and for this reason it is not appropriate to allow such individual and more detailed signatures. However, a GIS makes it possible to add specific information and comments to an attribute table associated with the data. When analysing at a landscape level, it is important to have a comparable and compatible set of data, therefore, a fundamental step is to interpret the maps using a standard

Table 1. List of themes in the vectorising process.

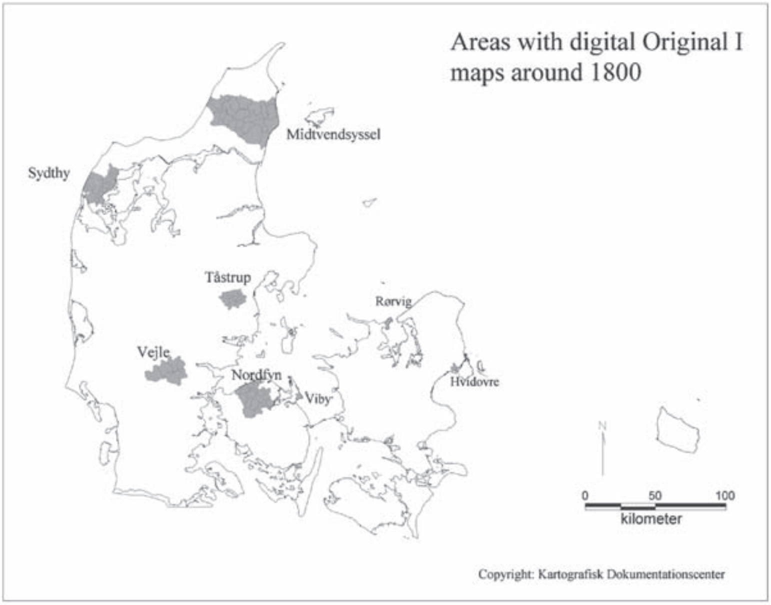
Land use (all polygons):	• Cultivated field • Meadow • Forest • Scrub and brush • Grassland (common) • Bog (for peat cutting) • Heathland • Sand dune • Raw material pit • Lake • Common village area • Settlement site • Garden • Church yard
Administrative boundaries:	• Parish (polygon) • Settlement and cultivation area (polygon) • Cadastre unit (polygon) • Soil quality (polygon) • Forest reserve (according to 1805-law) (polygon) • Field name (text placed on the map) • Wattle (polyline) • Stone fence (polyline)
Natural boundaries:	• Coast line (polyline) • Water course (polyline) • Canal (human made) (polyline)
Settlement:	• Building (polygon) • Water mill (polygon) • Wind mill (polygon) • Church (polygon)
Infrastructure:	• Road 20 (roads more than 12 ‘alen’ wide (1 alen = 2 feet) (polyline) • Road 12 (roads between 6 and 12 ‘alen’ wide) (polyline) • Road 6 (roads 6 ‘alen’ wide or less) (polyline) • Pathway (polyline) • Old road (polyline) • Old pathway (polyline)
Prehistory:	• Burial mound (polygon)

legend. This is a human task which can not be given to machines reading the analogue maps. It even requires a certain amount of detailed knowledge of the landscape and its history meaning that such a job can not be done in another country or region (with low salaries) – or at least it is necessary to obtain this experience before being able to perform a reliable job.

Another problem is that as a consequence of the warping and georeferencing process, gaps or overlaps may be created between the maps. Landscape does not have this kind of irregularity, so in the vectorisation process this somehow has to be compensated, especially at the fringes of the maps. For this reason the result cannot be claimed to represent an all together precise landscape around 1800, but an interpreted, constructed image showing the essential features, which were also interpreted by the map surveyor around 1800. In the digital version, the internal relations are probably more reliable than the exact positions. But there is not much possibility of controlling with landscape around 1800.

The standard legend can be seen in table 1. It is basically divided into six main groups, which have then been subdivided. One strategy might be to digitise all land use in one table and then subdivide in the attribute table; another strategy might be to make each sub-category into one table – this makes digitising much easier when you do not have to write into the attribute table. It is possible to subsequently integrate the tables for one category into another table.

This method has been used for several years in Denmark in order to produce historical, digital maps of landscapes (see figure 5). The areas


Areas with digital Original I maps around 1800

Copyright: Kartografisk Dokumentationscenter

Figure 5. Map showing the areas of Denmark where the method described in section 3.2 has been used.

chosen have been research areas in projects dealing with landscape history, for instance the big interdisciplinary project Changing Landscapes, consisting of four big investigation areas. Also, working in cooperation, authorities dealing with landscape management have made use of the digital maps. Over the years, the method has been refined, the GIS changed, but basically the same principles have been applied and the conclusion is that the method is applicable to all parts of the Danish countryside.

Project Changing Landscapes: *coordinated at the University of Southern Denmark since 2000, aims at creating a scientific basis for understanding the historical background to the appearance of the present landscape.*
www1.sdu.dk/Hum/ForandLand/english

4 METHODS FOR ANALYSING TRANSFORMATION ACCURACY

The method described here is a simple method for a first quick evaluation of the accuracy of the transformation (Domaas & Ihse 2005). It is based on the standard used by the Norwegian Mapping Authority, SOSI v. 3.1 (Statens Kartverk 1999). The measurement of accuracy is based on tests of point accuracy. The SOSI standard gives a description of the accuracy that may be regarded as acceptable for maps at different scales, using point mean error (PME) or standard deviation (SD). In this standard, the level of accuracy is regarded as acceptable when:

– more than 68% of the mapped point elements have a displacement error of less than the PME;
– fewer than 27% of the mapped point elements have a displacement error of between 1 and 2 times the PME; and
– fewer than 5% of the mapped point elements have a displacement error greater than the PME; multiplied by a factor of 2.

This standard, which was designed for testing of point accuracy, was here applied to linear features. In this study, the level of accuracy was tested in combined historical and modern economic maps, using the SOSI standard for point mean errors. The tests were intended to show whether the discrepancies between the two types of maps used in the study, measured as displacement calculated along lines, exceeded the levels listed above. The method can thus be described as a buffer-overlay analysis.

SOSI (Systematic Organisation of Spatial Information): *the national Norwegian standard for geographical information which includes definitions of geometry and topology, data quality, coordinate systems, and metadata.*

Buffer: *a GIS technique to construct a corridor arround an outline or line with a specific distance.*

Overlay techniques: *a process of superimposing two or more layers in a GIS with the aim to do visual or analytical operations.*

4.1 *A method of geometric transformation in seven steps*

The historical land consolidation maps, with their local, individual coordinate systems were transformed to the coordinate system NGO1948, which is used for the economic maps in Norway. But any maps and coordinate systems can be used. The transformation was carried out in several steps:

− In the first step, the fixed points from the historical map that could also be identified on the modern economic map were digitised. The geometric positions of the tics, read from the economic map, were used to transform the historical dataset. Affine transformation or first order polynomial warping was used here. All tics were used in this first step.

- In the second step, all tics that had received high error values in the transformation process were checked. Any that were obviously misplaced were removed, but the ones that were not obviously misplaced were retained even if they had high error values. In some cases, high error values may be due to the fact that non-systematic errors are not sufficiently corrected. Then it can be considered to use a higher order polynomial warping. After this, a new transformation was carried out.
- In the third step, the common elements were digitised from the economic map.
- In the fourth step, the data set from the historical map and the economic map were superimposed on a combined map and could be viewed together, as they had the same coordinate system. A visual check was made of how well they coincided.
- In the fifth step, surveyed datasets were translated into a common format. In this case the survey was also based on NGO1948, and all the maps could now be viewed together in a GIS. If surveyed datasets are in another coordinate system, they have to be transformed onto the chosen coordinate system. This step was performed only where there were surveyed datasets.
- The sixth and seventh steps involved creating buffer zones of different widths using the SOSI standard described in table 2 and then calculating the length of lines inside the various zones. The purpose of this was to analyse the accuracy of the transformation.
  - In the sixth step, buffer zones (B) of different widths were created, using the SOSI standard described above. Buffers B1 and B2 were drawn around common elements in the economic map and the survey, where zone B1 is ±1 PME and zone B2 is ±2 PME. Taking the economic map and the survey separately, the buffers were then combined to create areas representing a discrepancy (D) smaller than ±1 PME, D1 ($B1 \cap B2$), a discrepancy between PME ±1 and ±2, D2 ($B2 \cap \bar{B}1$), and a discrepancy larger than ±2 PME, D3 ($\bar{B}1 \cap \bar{B}2$).
  - In the seventh and last step, calculations were made of how much of the corresponding linear elements, L, from the historic maps were to be found inside each discrepancy area. These calculations were done as an overlay analysis, using the "select by theme" analysis in ArcView.

Table 2. Point mean error for maps at different scales (Statens Kartverk 1999).

Scale	Point mean errors
1:250	0.13 m
1:500	0.21 m
1:1,000	0.36 m
1:2,000	0.58 m
1:5,000	2.0 m
1:10,000	4.0 m
1:20,000	8.0 m
1:50,000	15.0 m

When using affine transformation and having identified many (>20) common points, it is possible to calculate the Standard Deviation for the offset of the transformed points instead. Especially when the transformation is based on a land survey of the common points, giving a very high accuracy of the true position, this is an easier procedure (Hamre et al. 2007).

4.2 *Discussion of map quality*

Map quality is measured by assessing the discrepancy between two data sets, the test data and the reference source. Positional accuracy has been almost the only focus of attention as regards paper maps. In the case of digital maps, other aspects must also be considered, such as the accuracy of the original based on the scale and method of digitisation, when the map was made and when it was last updated, its completeness, and the correctness of the coding.

Several methods are used to digitise historical cadastral maps (manual transfer, manual digitisation, automatic tracing etc.). To make the maps available in "modern" coordinate systems, they have to be transformed. Several methods are used (manual, warping, and affine transformation; Domaas 2004). So far, no standards have been developed to evaluate the quality of this type of work. Metadata such as positional accuracy have therefore been given in many different ways (root mean square, RMS; standard deviation, SD; point mean error, PME; or intervals) or just neglected, and there is generally no evaluation of other quality aspects, such as completeness, correctness in coding and resolution.

Root mean squared error (RMSE):
is the error of the predicted values to the actual value (e.g. reference image) expressed as the square root of the mean sum of the square errors.

When cadastral maps are transformed by warping, common points are needed for use during the warping process, and also for testing the accuracy of the final transformation. It is often difficult to find enough common points to obtain a valid statistical result (Vuorela et al. 2002). Affine transformation gives RMS accuracy directly, and also gives X and Y errors for all points used for the transformation, so that a PME or SD can be calculated. Even so, it is difficult to find enough common points to satisfy statistical requirements. Other, supplementary methods are therefore needed to evaluate the results of transformation of cadastral maps so that the information contained in cadastral maps and their written protocols can be utilised in various types of landscape studies.

The different approaches taken for describing positional accuracy make it difficult to compare the results of studies based on cadastral maps. It would therefore be useful to agree on a standard way of describing positional accuracy. Drummond (1995) discusses several ways of describing positional accuracy in a GIS and concludes that standard deviation is most appropriate.

Resolution, or rather a failure to specify it, also makes it difficult to compare the results of different studies (table 3). The resolution of a data set defines the smallest feature that can be resolved or separated into its constituent parts (Clarke & Clark 1995) and it can also be described as a geometric threshold such as minimum area or minimum width (Morrison 1995).

If the data sets used are rasters, the resolution will be the size of the raster cell, but it is nevertheless possible to use a resolution that is finer than is justified by the quality of the original material (Statens Kartverk 1999). If the data sets are vectors, there is no way of determining the appropriate resolution, or the minimum area or width that can sensibly be used in calculations, without thorough testing.

A possible operational solution to these issues is to use the accuracy term SD. The minimum width of an object that can be distinguished and the minimum distance between two objects that can be separated can then be defined as the SD, while the minimum area (A_{min}) can be defined as:

$$A_{min} = SD^2 \tag{1}$$

for square areas or

$$A_{min} = \Pi * (SD/2)^2 \tag{2}$$

for circular areas.

This should give a probability of more than 68% that a part of a feature will be inside its digital representation. In cases where there is only one object of a kind for quite a distance, and the digital representation of it on the cadastral map is 2*SD or even more distant from its representation

Table 3. Information on the accuracy reached when transforming cadastral maps on to modern map systems. (PME: point mean error, RMS: root mean square error, SD: standard deviation). See table 2 for PME of modern maps.

Authors	Cadastral map	Modern map	Transformation method	Resolution	Transformation accuracy
Skånes 1996	1:4,000 and 1:8,000	1:10,000	Tollin/manual	5 m and vector	expected PME <4 m
Lundberg & Handegård 1996	1:2,000	1:5,000	?	?	?
Pärtel et al. 1999	1:5,000 (1705)	1:10,000	warping – vector	10 m	23 m (RMS)
Cousins 2001	1:4,000 (1688/90 and 1784/99)	1:10,000	warping	5 m	<5 m
Austad et al. 2001 and Domaas et al. 2001	1:2,000 (1874)	1:5,000	affine – vector	vector	<2.0 m (PME-line), 4.0 (RMS)
Lundberg 2002	1:2,000	1:5,000	?	?	?
Vuorela et al. 2002	1:4,000 (1690)	1:20,000	warping	?	28.1–26.2 m (RMS)
Vuorela et al. 2002	1:4,000 (1846)	1:20,000	warping	?	6.9–6.5 m (RMS)
Vuorela et al. 2002	1:8,000 (1892)	1:20,000	warping	?	4.8–3.8 (RMS)
Hjort Caspersen 2002, Fabech et al. 2002 and Grau Møller 2004	1:4,000 (1770–1810)	1:25,000	warping	vector	10–20 m
Bender et al. 2005	1:5,000 (1808–1853)	1:25,000	? – vector	vector	?
Domaas & Ihse 2005	1:2,000 (1874, 1910)	1:5,000	affine – vector	vector	<2.0 m (PME-line), 4.0 and 2.5 (RMS)
Hamre et al. 2007	1:2,000 (1865)	±10 cm (field survey)	affine – vector	vector	1.7 m (SD)

based on the modern map sheet or survey, it will still be justifiable to consider these to be representations of the same object. According to the Norwegian Mapping Authority's standard, it is acceptable for up to 5% of the elements to be drawn more than 2*SD away from their real location (Statens Kartverk 1999).

The problems related to metadata in work that involves digitising and georeferencing historical maps were discussed at a workshop held by the Danish HisKIS network (Domaas 2004). The participants doubted whether detailed accuracy standards such as those described above are the way to go at present. Instead, it was suggested that it would be better to start developing a guide to good practice in this research field.

HisKIS (Historik-Kartografisk InformationsSystem): *www.hiskis.net*

5 EXAMPLES OF USES OF THE DIGITAL MAPS

5.1 *Theme 'land use'*

In Norway, the information provided by a land consolidation process is of crucial importance in obtaining a better understanding of the history, dynamics, and development of a farm and identifying older traces of human activity back to the 16th century and which areas are most important to protect and manage suitably. If this is not available, the oldest situation which can be reconstructed geographically without archaeological excavation will depend on which informants are available. They are usually the farmer and his family, and it is therefore becoming increasingly difficult to obtain information about land use and management before the Second World War. Property areas and boundaries can be traced back to the result of the latest land consolidation process, but not usually any further back. This means that it is only the "modern" information in the landscape that is readily available without data from a land consolidation process.

The digitised cadastral map provides a snapshot of the situation when the land consolidation process took place. The information collected was used to ensure that each owner's property was equal in value before and after land reallocation, and not for military or taxation purposes. Cadastral material is therefore considered to be very exact and a good historical source.

This way of digitising the cadastre maps makes it possible to illustrate specific landscapes – even in detail – and to make calculations for bigger areas. It is possible to calculate how much forest and meadow there is in each settlement area, and to illustrate on a cartographic graph (for instance figure 6). This Danish example shows the relative distribution of the respective land uses with the circle indicating the extent of a settlement area (relating to the underlying map). It becomes obvious that two different landscape types are present: to the south a forest area with widespread forest and meadow, and in the northern part cultivated fields dominate, but with a certain amount of meadows, which can be seen as essential in the agriculture around 1800.

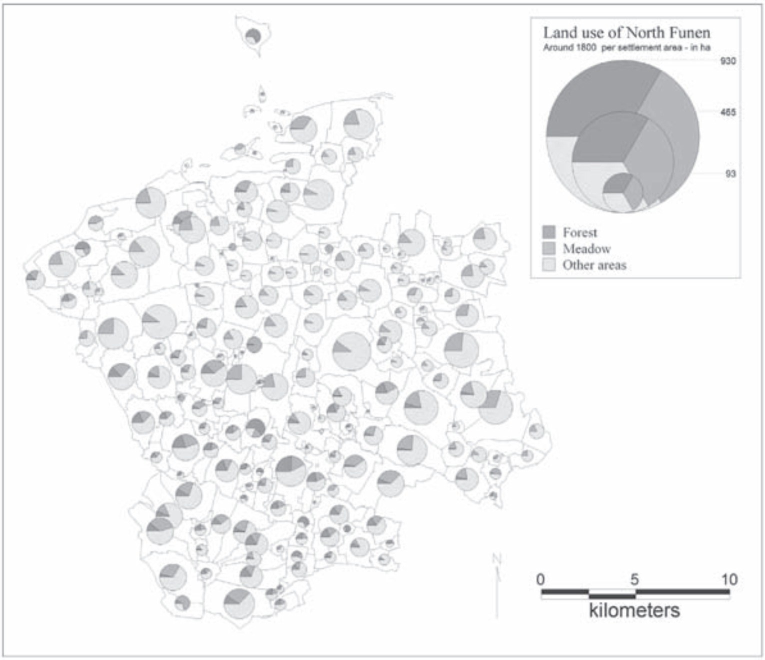


Figure 6. Calculation of forest, meadow and other areas on North Funen – village level. The software MapInfo enables this very detailed calculation and presentation.

Another theme may be a total calculation and relation with other periods in order to show how land use developed over a 200 years period. This is shown in the graph of figure 7. Essentially there is a radical change in land use after 1800, when cultivation increased especially on areas of former meadows and heathland. Normally, only data from 1880 and onwards are available in landscape management, but this example shows that a very essential phase is missing, if data from around 1800 are not integrated into, for instance, “nature restoration” projects.

5.2 *Theme ‘soil quality’*

The evaluation of Danish soil quality can be used for giving an overview of the potentiality of cultivation around 1820 with the contemporary agrarian technology. Even if it was used for taxation and thought to be a universal evaluation, it was clearly dependent on the settlement and cultivation situation at that time. The scale was a national one from 0 to 24 – and therefore very useful for comparisons with the help of GIS-technology. One of the criteria was the composition of the soil (clay, sand, chalk); another and more easily used was the depth of the layer of mould. This is actually very dependent on the intensity of cultivation of the passed centuries (Fabech et al. 2002).

In figure 8a, an overview is shown of the investigated area in East Jutland. The scaling of the values in the GIS gives a clear indication of

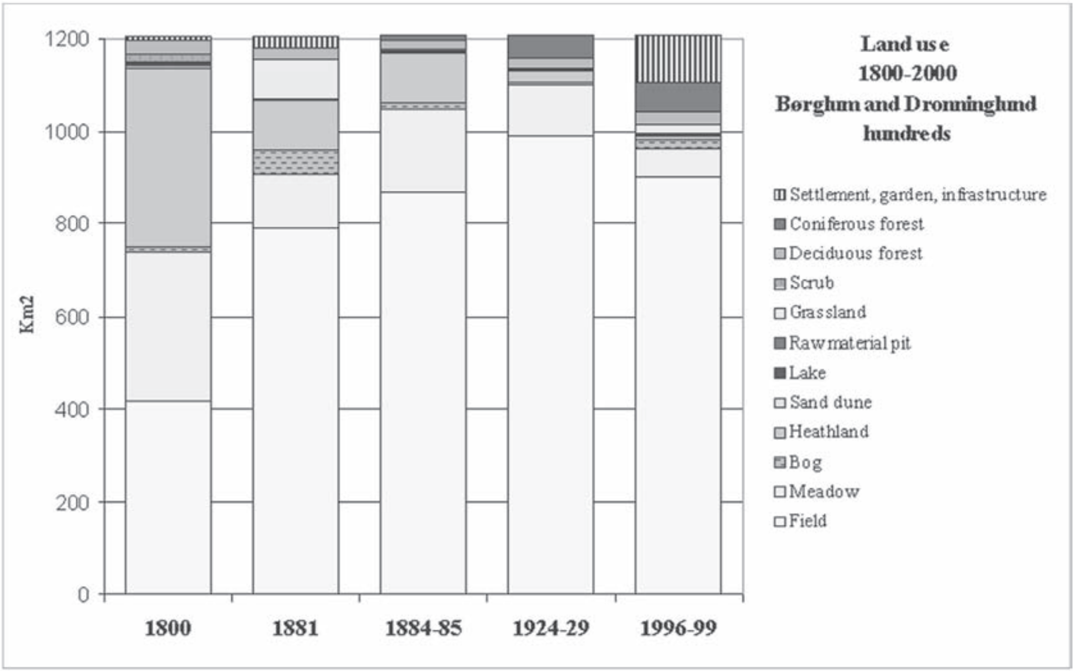


Figure 7. Statistics on land use in an area of Vendsyssel (North Jutland) 1800–2000 (compiled by Morten Stenak – unpublished).

the differences. Here, it becomes clear that the eastern part had a better soil quality than the western part, which also contains more forest and heathland. In figure 8b is shown an example from the south eastern part. Around the village Hørning presents a good example of the standard pattern: a village with the highest values and gradually decreasing values to the neighbouring village. But in the centre of the figure is a small exception of this pattern: to the North of the small village Bering are areas where the soil quality is as high as near the village (16). This might indicate that a settlement with intensive cultivation was situated here, either in the medieval period or in the Iron Age. When this now deserted settlement was active can only be verified by archaeological investigations, but these means and the GIS-tool might be a good indicative help in this landscape investigation.

The Norwegian written protocol matching the map provides information on production capacity for each parcel. Production capacity was used to classify parcels of land according to how much they could produce, to ensure that when a farmer lost a particular area during land consolidation, the land received in compensation would give an equivalent amount of agricultural production. The scale is a fraction scale, so an area of land in class 2 would produce half as much as an equal-sized area in class 1. The production capacity scale is unique for each area that performed a land consolidation process, i.e., each map. It is therefore impossible to compare directly different cadastral maps regarding production capacity.

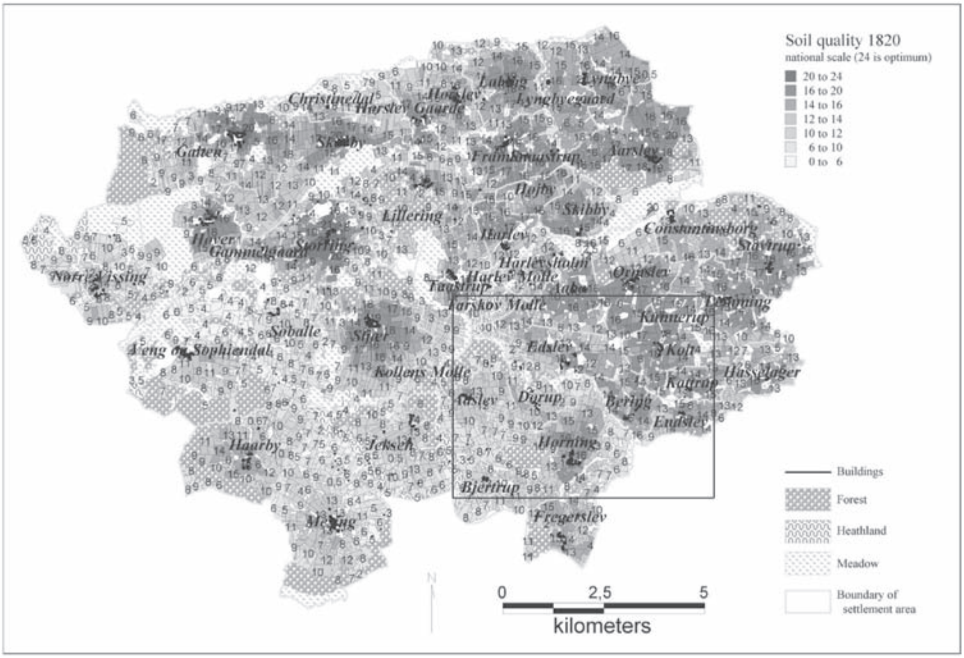


Figure 8a. Soil quality in the Tåstrup area west of Århus in East Jutland.

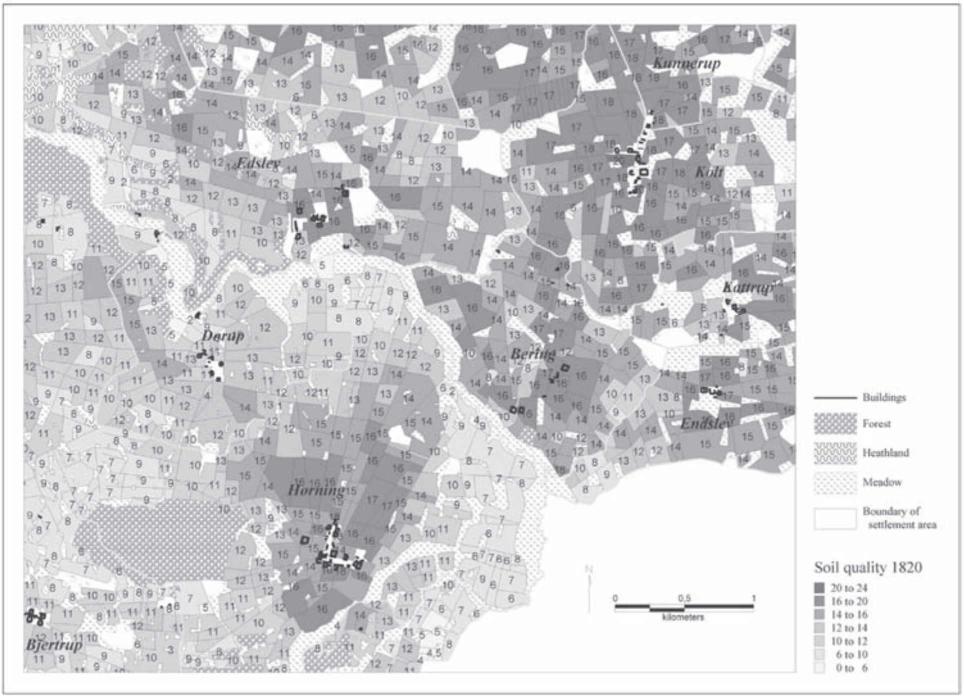


Figure 8b. Study of the eastern part of the Tåstrup area (cf. figure 8a).

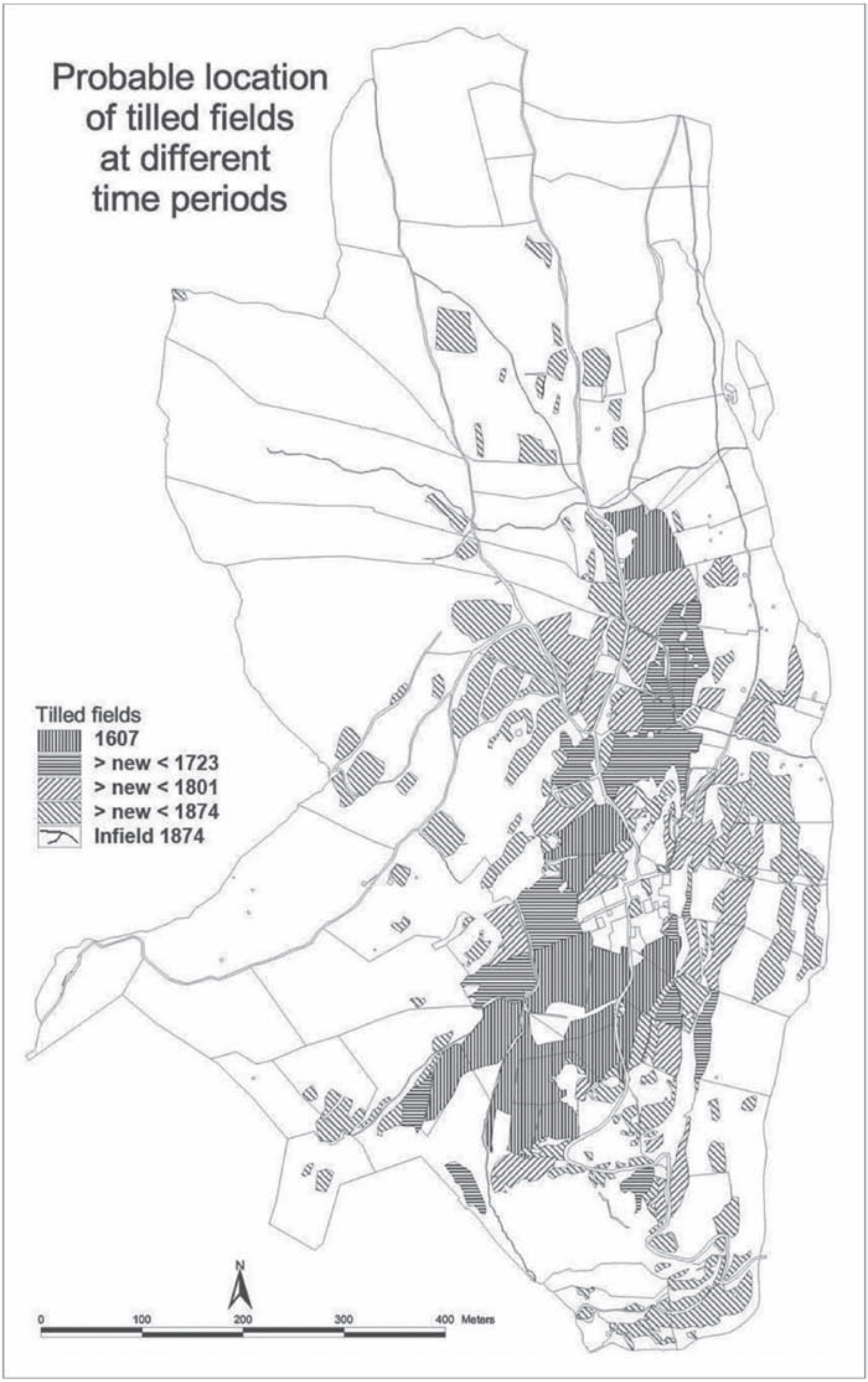


Figure 9. Geographical distribution of area of tilled fields in 1874 at the farm Grinde divided into four categories (based on production capacity) that approximate to the area of tilled fields in four different periods represented by the years 1607, 1723, 1801 and 1874 (Domaas 2007).

In one case, production capacity was divided into 46 classes on a scale from 1 to 300. The most valuable areas (tilled fields and high quality hay meadows) were finely divided, so that 17 steps were used for the quality classes between 1 and 2, while only seven steps were used between 50 and 300.

In another case, production capacity was divided into 44 steps on a scale from 1 to 200. The most valuable areas were here divided, so that 12 steps were used between 1 and 2. On the other hand, only six steps were used between 50 and 200 (50, 60, 70, 80, 100, and 200).

6 CONCLUSIONS

Digital historical cadastral maps can also be combined with other types of mapped information like vegetation surveys, quaternary geology and analysed in 3D models (figure 9) (Domaas 2007, Hamre et al. 2007). This opens up for the possibility to an even deeper understanding of the information contained in the cadastral maps, and it can be used as a tool for different types of landscape studies, like identifying key biotopes in the cultural landscape.

Provided that the theoretical considerations described above are kept in mind, the use of GIS allows for exciting advances in landscape studies and a number of other fields. A landscape may appear to be ancient and to contain old man-made structures even if this is not the whole truth. Changes in property areas and boundaries are relatively infrequent and are often difficult to trace geographically, and alterations in land use and management change the appearance of the landscape. The appearance of the landscape today is the result of all changes that have taken place over the years (Widgren 1998). Structures have been moved, removed, replaced and added. New users often introduce new land use and management regimes.

The information provided by a land consolidation process is of crucial importance in obtaining a better understanding of the history, dynamics and development of a farm. It helps to identify older traces of human activity back to the 16th century, and to decide which areas it is most important to protect and manage suitably.

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Part III

Data analysis and interpretation

The workflow of a historic landscape analysis using GIS with examples from Central Europe

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ABSTRACT

Based upon the Historic Landscape Analysis (HLA) concept presented earlier in this book, methods for investigating "historic" landscape structures and related development processes are now discussed in more detail. However, beginning with the identification and analysis of recent structures and changes, these methods of generally supporting landscape planning processes may well be arranged to a complete workflow in the course of this volume. Hence, this part consists of a quantification and description of landscape changes as well as an exploration of their causes and interrelationships. Furthermore, ideas of an assessment and evaluation of traditional structures in recent landscapes are proposed. The second part of this workflow analysis deals with the exploration of future landscapes and approaches to a landscape management support. Approached this way, however, the extent to which geoinformation technology explicitly supports the production of an added value in HLA will be demonstrated in detail. Additionally, both a detailed discussion of the existing related scientific approaches and an overview of further research needs will be given significant attention.

Concept of historic landscape analysis with GIS:
cf. chapter "The concept of a historic land-scape analysis with GIS" of Bender.

1 INTRODUCTION

The landscape information system (LIS) designed for an HLA both methodologically and functionally exceeds the cultural landscape cadastre currently proposed by advocates of applied historical geography. This is because of its emphasis upon the analysis of structures, functions and processes within landscape and its ability to extract additional information from the data originally implemented into the system.

Without any doubt, however, current research into landscape (still) rarely constitutes a purpose of its own. Instead, it evidently appears to focus more narrowly on delivering a contribution to landscape planning and management within the given legal frameworks (see Burggraaff & Kleefeld 2002). Depending on the scales of analysis, they may even discover their adoption within the different dimensions of public planning. Typically, their beneficiaries not only consist of nature conservationists (landscape planning), but may also include other sector planners (i.e., agrarian and forestry planning) and even overall-planning teams (i.e., regional and municipal land-use planning). Hence surveys conducted in this fashion should provide (at least) one systematic foundational piece of information both on the location and on the (historical) evolution of cultural landscape qualities, i.e., in the shape of landscape elements, patterns or ecological processes.

The demands of planning on the spatial sciences are to capture, to explain and to assess the recent landscape state. Landscape history plays a role insofar it is materially reflected in the present with its traditional elements and structures (“landscape as an archive of the past”; Schenk 2002), or it offers an exemplary function for future developments (historical ‘Leitbild’ or general principle), or it generally enables understanding from already known processes for the future (monitoring, planning; cf. Antrop 1997, Marcucci 2000). The latter is especially accepted in vegetation-ecological succession research (Jedicke 1998, Pahl-Wostl 1995; cf. the succession scheme related to land use types in Bender 1994b).

2 IDENTIFYING AND ANALYSING LANDSCAPE STRUCTURE AND CHANGE

2.1 *Quantification and description of landscape structure and change*

Overlay techniques:
a process of superimposing two or more layers in a GIS with the aim to do visual or analytical operations.

GIS principally allows for evaluating changes and assessing land use units. ‘Overlay’ techniques enable us to gain new data, and compared to a purely statistical evaluation (plot use assessment), a georelational approach has the advantage to assess development trends. With the help of the “change types” concept (the types result from the connection of the earlier and the later land use type) true assessment of change can be accounted.

Intersection:
a GIS operation which uses the features from two input vector layers and computes the intersection between their geometries resulting in a new layer.

The change of the landscape over time is described by means of temporal layer maps (figure 1). Maps of landscape change (figure 2) are produced by a successive intersection of the different temporal layers. New polygons, so-called lowest common geometries, arise by intersections of the plots in the temporal layers (Ott & Swiaczny 2001).

During this process, “sub-plots” are created reflecting the type of land use change, e.g. from pasture to woodland. Thereafter, the type of change between any two time slices can be visualised for every land use unit. Thus, the LIS offers more than simply a visual interpretation of thematic maps or statistical evaluation.

Such kind of analyses can focus, for instance, on anthropogenic habitat loss affecting threatened plant communities (Bender et al. 2005b). Rough pastures located on limestone and gneiss formations can be defined as potential sites of the endangered gentian-hairgrass turf (Gentiano-Koelerietum). The reduction of this traditional land use type equally represents a loss in potential habitats for plants and animals characteristic for those landscapes, and can be used as a measure of habitat

Figure 1. Time slice maps of the land use distribution in Wüstenstein (Franconian Alb) 1900, 1960, 2000 and a scenario of 2020 (simulation based on future land use requirements, identified by interviews with farmers in the respective village district) (Bender et al. 2005b).

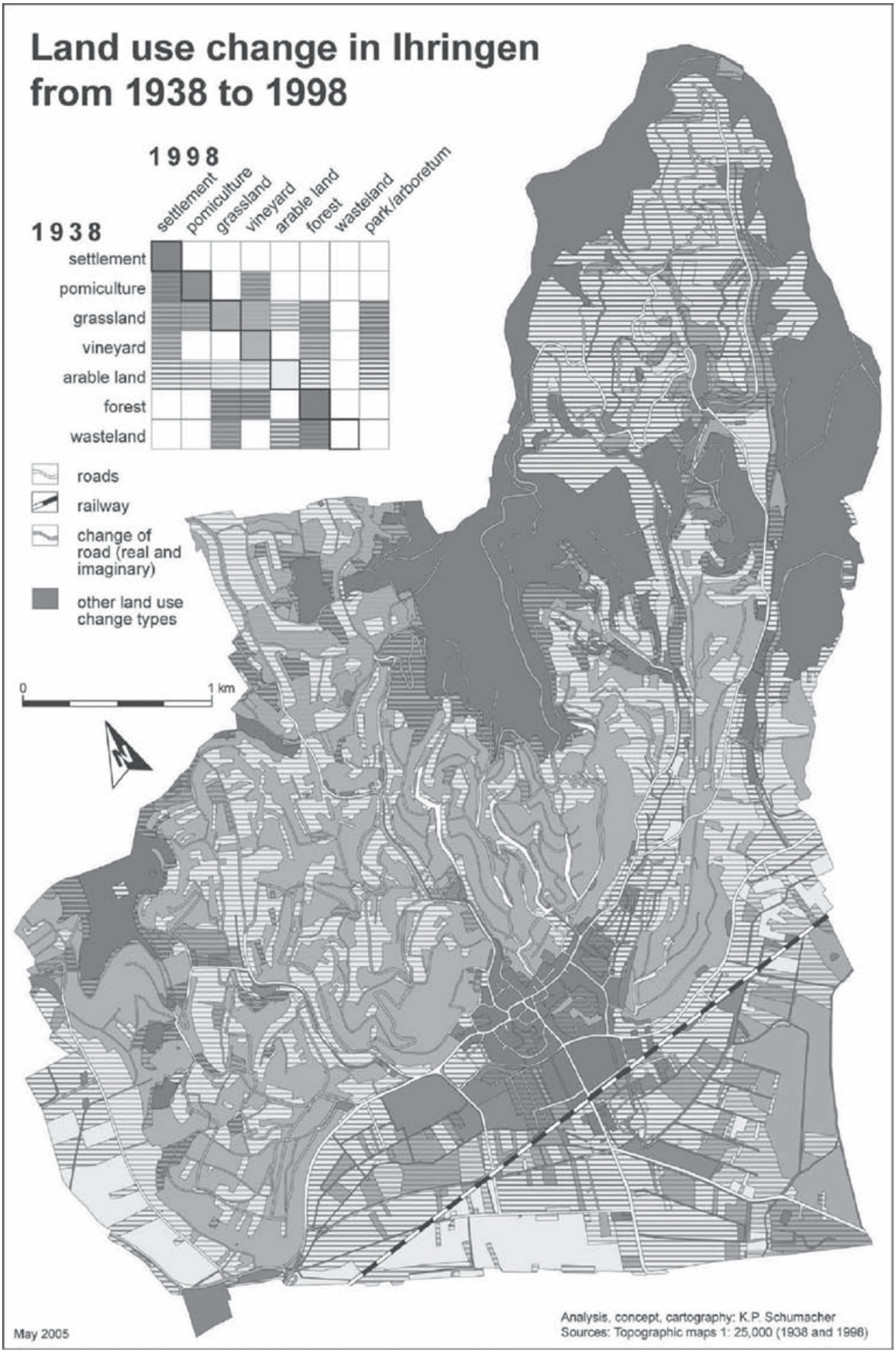

Figure 2. Map of land use change in Ihringen (Kaiserstuhl) (Schumacher 2006, original in colour).

fragmentation. Furthermore, with the assistance of diachronic LIS, it is possible to clarify the historical perspectives of nature conservation: was the "pristine landscape" of former times, which today often serves as an ideal, merely a result or an intermediate stage of anthropogenic processes? Hedgerows that are frequently regarded as a former, characteristic feature of the Franconian Alb, appear to have been planted not before the 20th century, as the cadastral maps recorded these hedges as grass verges until 1900. Conversely, the mesoxerophytic meadows of South Germany's mountainous regions are still regarded as a characteristic landscape feature, despite the fact that they became atypical a long time ago (Bender et al. 2005a).

2.2 *Causes and interrelationships of landscape change – the application of geostatistics*

Knowledge of different effects on cultural landscape dynamics is indispensable for the understanding of the landscape change and for landscape protection and planning. Bätzing (1996) stated that such knowledge already exists for large-scale and long-lasting development. At local level, where explicit decisions are made on land use changes and landscape planning, only little is known about the reason why a specific plot is affected by land use change or assignment at a particular time. Early attempts at analysing the impacts of both groups of factors, socio-economic conditions as well as the natural environment come from France.

Thus, Lamarche & Romane (1982) wanted to work out ecological and socio-ecological parameters such as the geology, the slope gradient and aspect, or the profession of the land owner, which are important for the landscape development. They tried to quantify the respective significance of in total 45 variables applying a factor analysis, but the approach failed. In the end they used "simple methods" for the visualisation and interpretation, such as raster maps for the spatial presentation of the land use, diagrams for the illustration of temporal developments of specific vegetation, and land use units in relation to different variable characteristics, for instance the subsoil.

Factor analysis:
a multivariate statistical process that relates a multitude of variables to common basic dimensions based on their mutual correlative relationships.

Cousins (2001) proceeded in a similar way in South Sweden, as she related the temporal change of the percentage of arable land and grassland with the respective substrate. Apan et al. (2003) succeeded in proving the correlation between property situation and the riparian vegetation development in Queensland (Australia) by means of a correspondence analysis. In that study, further statistical relations were only suggested by the assignment of types of land use change to slope and waters classes. Taillefumier & Piégay (2003) were the first who attained results in their study in the French Pre-Alps beyond the approach of Lamarche & Romane (1982). They gathered specific characteristics of eight environment-relevant variables, such as type of bedrock, altitude or slope, and applied a barycentric discriminant analysis (cf. Lebart et al. 1995). Thus, the environmental conditions clearly vary within a single land use type; however, the differences between the land use types are statistically significant and

Correspondence analysis:
an exploratory technique for analysing simple two-way and multi-way tables containing some measure of correspondence between the rows and columns.

certain characteristics of some variables strongly correlate with specific types. Only the developments of the local population and the farm animal were included as anthropogenic impact and these could not be correlated to the investigated area units (a test site of 3000 ha divided into raster cells of 2500 m^2). Thus, the request of Taillefumier & Piégay (2003), that there is a need for research with the objective to gather the significance of anthropogenic and natural factors for the cultural landscape change, remains valid.

A further research approach was submitted by Bender (2007). He analysed plot-related attributes for four time slices (1850, 1900, 1960, 2000) aiming at their effects on the distribution and the change of the land use in rural Bavarian cultural landscapes. Such causal analyses are realised by multivariate statistics, so-called structure-proving algorithms. The requirement for the application of such methods is that the user a priori originated a well established concept of the causal relationship between the variables. The scale level of the variables decides on the structure-proven algorithm that will be used. Erb (1990) pointed out that the discriminant analysis developed by Fisher (1936) is particularly suitable for the solution of space-relevant problems. The algorithm is used for the analysis of class differences with the assumption that the dependent variables are nominally-scaled and the independent variables are rationally-scaled. However, it is possible to handle dichotomous properties like metrically-scaled variables and to convert nominally-scaled characteristics into dichotomous coded so-called dummy-variables. Apart from that, the discriminate analysis is working rather robustly, even breaking the normal distribution rule, and presents satisfying results (Lachenbruch 1975).

Discriminant analysis:
classifies a categorical dependent which has more than two categories using a number of interval or dummy independent variables as predictors.

Interdependences of independent variables may warp the results of a discriminant analysis. For that reason the set of variables is taken for a bivariate correlation analysis after Pearson's correlation coefficient (P). In a first analysis step, a mean comparison and a discriminant analysis are applied on the main land use types, arable land, meadows, rough pasture, and forest with their respective plot attributes for all investigated time slices. In a second step, types of change are chosen concerning their respective frequencies. Main land use types of "no-change" (e.g. in 1850 arable field, in 1900 arable field) are contrasted with one or two types of change (e.g. in 1850 arable field, in 1900 forest). On the basis of the standardised canonical discriminant function coefficient (DFC) it can be assessed, to what degree the plot properties are crucial to or at least typical for the characteristics of the land use (figure 3).

Correlation analysis:
measures the relationship between two variables. The resulting value (called the "correlation coefficient") shows if changes in one variable result in changes in the other one.

Pearson's correlation coefficient:
determines the strength of an item associated with a set of variables.

Discriminant function coefficient:
denotes the unique contribution of each variable to the discriminant function.

Statistical science acknowledges that the causal explanation of such complex constructs like the cultural landscape change can in no case succeed absolutely unerring. The aim of the discriminant analysis should rather be working out the environmental conditions which might disproportionally often expect a specific land use or changing type. In this sense, the discriminant analysis shows – as expected – a complex impact with various effects on the land use structure. To what extent the causalities or the interdependence influences are present is dependent on the

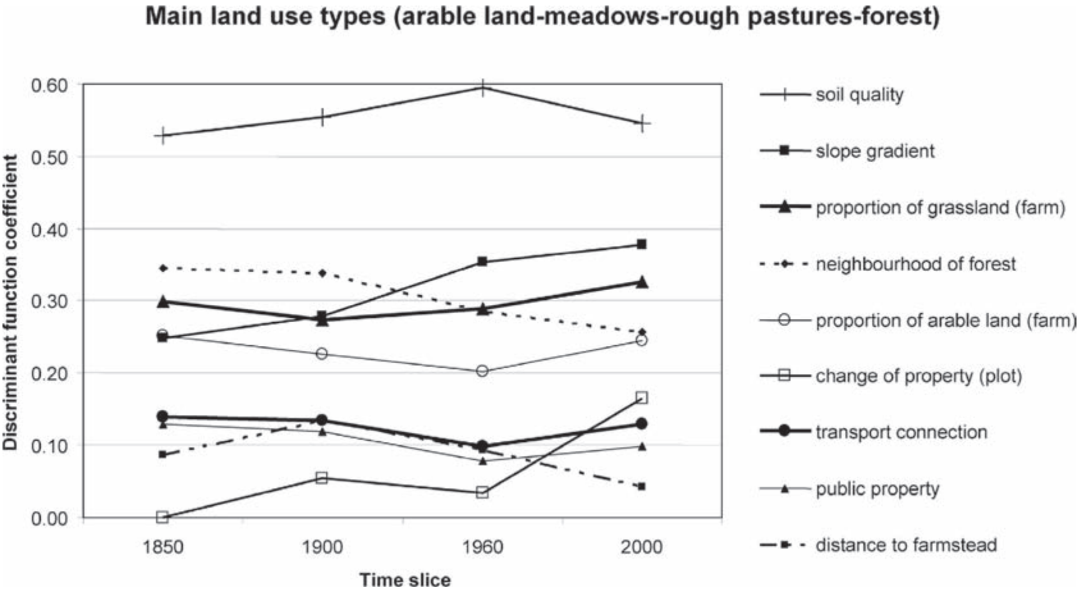

Figure 3. Temporal development of the most important land use structure variables after a discriminant analysis of major land use types. The discriminant function coefficient (DFC) indicates the relative importance of the respective variables (Bender 2005b).

respective variables. For instance, the relief can be considered as largely pre-characterised and as such causal for a specific differentiation of the land use types. However, the ownerships could be the cause as well as the effect of the land use.

The set of variables finally used has to be adapted to the respective study area as well. For the mentioned reasons, comparison studies are needed to assess the impact variables and the method. Only further similar studies in different areas will clear up the question which factors are crucial for which landscape types among which general conditions.

2.3 *Landscape assessment and evaluation*

Evaluation is used in several landscape disciplines for various purposes. Some methods have been used for a long time (e.g. agricultural soil taxation), others occur during a cultural landscape inventory, while more are still being intensively debated in science (e.g. application of landscape metrics for questions about nature protection; Lang & Blaschke 2007). However, landscape assessment, especially in the context of HLA, aims at understanding the ‘historic quality’ of the cultural landscape elements and sections.

Clearly subjective evaluation techniques result from perception and acceptance research, e.g. the in-situ assessment of succession stages (Hunziker & Kienast 1999) or scenarios of landscape development via photo-simulation. Various dimensions of landscape perception (e.g.

Scenario:
a specific assumed future state of a landscape according to defined conditions.

tradition, ecology, yield, and mood) have to be considered and explanations for preferences worked out. Another general approach is the contingent valuation method (Hanemann 1994).

Contingent valuation method: *uses surveys of individuals to elicit their preferences, measured in monetary terms (willingness to pay), for a specified improvement in their health outcomes.*

Qualitative-objective techniques often use a segregating method. With this method, according to certain rules, the area is divided into smaller units, e.g. “scenery units” (Paschkewitz 2001), which then have to be sorted with regard to comparable attribute data values. Because of the psychological dimension of such qualitative assessment methods, it is difficult to proceed in this way in the present day. The best basis for the assessment of former landscape conditions are detailed 4D landscape models with photo-realistic simulations.

Quantitative-objective assessments do not have this problem; they normally use aggregation techniques, where specific characteristics of landscape elements are added and related to each another. In recent times, these assessments are often obtained by employing geo-information technology, e.g. with the help of the landscape metrics approach (Lang & Blaschke 2007). This approach supports the examination of the area-wide landscape as well as individual parts, such as landscape elements (patch) or element types (class). Steinhardt et al. (2005) argue that a total evaluation of landscapes is not possible. However, in many cases it is possible to assess a total value for a larger landscape unit in a medium scale (“choric dimension”), which can be limited to a single criterion of evaluation.

Landscape metrics approach: *cf. chapter “Landscape metrics – a toolbox for assessing past, present and future landscape structures” by Lang et al.*

Finally, mainly for assessing current conditions, a diachronic evaluation is compared to the past with the aim to achieve possible values or appropriate development potential. Temporal landscape conditions can be evaluated in each case (structure), or during the course of development (process), where the differences between two temporal landscape conditions are measured and the difference is evaluated.

With regard to monument protection, the monument worth is assessed by applying an object evaluation (after Gunzelmann 1987) or a landscape evaluation. Monument conservators are interested in former conditions of a landscape as long as they can give a reason for an actual monument worth. The object evaluation techniques have been copied from the catalogue criteria and from the proceedings used in nature protection in the 1980s (cf. Plachter 1991). Historic certification, rarity, and characteristic trait, age, state of preservation, as well as possibility of replication are generally used as assessment criteria (e.g. BayLfU 2004, Gunzelmann 1987, von den Driesch 1988). In the evaluation, the assessed landscape element receives a numerical value, and the total numbers result in the index of its cultural historic significance.

Landscape assessment techniques are formally similar to object assessment techniques, with the difference that the spatial connection is evaluated: “For the overall impression, it is thus important to show the genetic causality and the network of the individual landscape elements. The cultural landscape areas will be evaluated in their cultural historic significance according to criteria of historic certification and characteristic traits (appearance and density) as well as functionally considering their use and the concurrence of historic cultural landscape elements" (BayLfU 2004). As a method, the problem of documenting spatial connections still remains unclear (as already mentioned by Bender 1994a). There is no question of a transparent, reproducible approach. For the rest, the assessment approaches deal largely in the present because early time slices which should serve in comparison are not documented to the same extent.

The cultural historic quality of a landscape ultimately depends on the quantity, complexity, and quality of persistent historic landscape elements. An assessment of the consequences of planned and unplanned landscape changes, however (and in singular landscape structures as well as in the entire cultural landscape), requires a quantification of the current cultural value of the landscape, which so far has not been done (von den Driesch 1988a). Bender (1994a) proposed a differentiation between "general structure value" and "historic-geographic structure" value (HGS) in order to achieve such quantification. It should be possible to determine the "general structure value" by the number, length, and area of the available element types, and recent research approaches also suggest that the diversity concept (within landscape metrics) could be applied.

Diversity within landscape metrics:
a composite measure of richness (simply the number of different patch types) and evenness (the relative abundance of different patch types).

The analysis of persistence (e.g. the persistence index after Häuber & Schütz 2001) can ascertain which structures or landscape elements (e.g. plot boundaries, anthropogenic ridges, forest edges, hedgerows) in which proportion (number, length, area) remained in-situ over spans of time. An example exists in the cultural landscape inventory of the federal GIS of Tyrol (TIRIS) in which areas of persistent land use in the agricultural landscape were examined on the basis of periodically repeated aerial surveys, in order to document the proportion of the largely unchanged farmlands to the total agricultural area. Areas were assessed according to the four ratings as "primary", "largely traditional", "conditionally traditional" or "modern." In order to permit a conclusion about cultural-historic value, a comparison can be made between the actual state and the historic state and an HGS value can be deduced (Bender 1994a); Bender (2007) gives a simplified formula (see also figure 4):

GIS of Tyrol (TIRIS):
Cultural landscape inventarisation:
http://gis3.tirol.gv.at/scripts/esrimap.dll?Name=natur2&Cmd=Start

$$\text{HGS} = (\text{persistence of land use} + \text{persistence of ground plan})/2 \qquad (1)$$

Finally, the above-mentioned assessment approaches generally can be advanced in three stages for the documentation of historic landscape types (Bender 2003) by:

– filtering out areas without or with only few changes in land use or in the ground plan (e.g. plot boundaries), according to the HGS value,
– selecting 'traditional' landscape types (e.g. hedgerow landscapes) by differentiating areas with (quantitatively) dominating historic landscape elements (cf. Wrbka et al. 2002), and
– evaluating the stability of landscape diversity by a study of land use mosaics (with the help of landscape metrics, e.g. Shannon diversity index) and their changes (cf. Bender 2007).

Shannon diversity index:
a diversity index taking into account the number of individuals as well as number of classes (or taxa in biology).

Figure 4. “Historic-geographic structure” value (HGS) in the study area Franconian Alb (Bender 2005a, after Bender 1994a).

3 ANALYSING AND MANAGING "HISTORY" OF FUTURE LANDSCAPES

3.1 *Exploration of future landscapes*

From a planning point of view, it is desirable to achieve an idea of the future landscape development. By means of trend extrapolations (prognoses) based on socio-economic developments derived from official statistics, a rough orientation can be worked out for large scales, for instance for the landscape framework planning. There seems to be no lack of such studies (cf. Schenk 2002).

Trend extrapolations: *a forecasting technique which uses statistical methods (such as exponential smoothing or moving averages) to project the future pattern of a time series data.*

Scenarios are not suited for the prediction of most probable developments, but rather for the task to structure several problems and impact relations which are corresponded to spatial planning in the future (Stiens 1996). It opens up the possibility to design "if–then" future sights by systematically varying of applied assumptions. In this process, factors can be integrated which are excluded from traditional (quantitative) approaches, because they are not measurable or allocable by any data. However, 'Leitbilder' or general principles as (target-) conditions are the result of normative restriction and in turn cannot represent an immediate output of scientific work. Especially at the local level of cultural landscape research (scale 1:5,000), the exploration of future landscapes is still unusual or not best practise, because of either missing or inaccessible data or an insufficient application of the geo-information technology (for instance, manually coloured maps with "scenarios" or simple "photo-simulations", both generated without a spatio-temporal deduction).

Hence, the aim is that respective future explorations for small-scale landscape sections as far as possible are aligned more quantitatively also by means of so-called simulations. As such, they have a closer relation to prognoses or at least to "integrated general principles" (Hawkins & Selman 2002). It requires a database integrating many natural disciplines (soil, vegetation etc.) and cultural disciplines (settlement structure, economy, etc.) that are geo-relationally linked with appropriate small-structured landscape units (most likely land use plots, maybe raster cells too) in a LIS (Bender 2007).

After the natural and socio-economic impact factors have been statistically analysed for the recent landscape change, a target-oriented variation of the fundamental data can result in a comprehensible identification of future land uses. Since a simultaneous simulation of all land use types is very elaborate in a larger test site due to the modelling and data processing, it is easier to concentrate on those development processes that are expected to be regionally important. These could be planned changes such as the development of residential areas (Aigner et al. 1999) or the establishment of biotopes. Furthermore, spatial decision support systems (SDSS) can be deployed for the search of optimal land use locations or for the assessment of cost-benefit relations, for instance in biotope planning (cf. section 3.2).

The simulation model of Bender (2007) deals with changes in peripheral agrarian landscapes where planning instruments are not extensively applied. The model takes in consideration that the future land use is dependent on specific plot properties whose effects on historical and recent developments (trends) have been already analysed (cf. section 2.2 in this chapter). If there is any economically reason for conversion, it can be assessed for every single land use area (according to its land use type) whether a further use or a conversion or a cessation of farming activities is expected (figure 1). In this way, discrepancies between the general principles and the probable developments can be pointed out using the "simulations". That implies a chance for the landscape and sectoral planning to react on endangerments and undesirable developments at an early stage. The dynamic approach provides not only criteria for protection and maintenance arrangements, but also for integrating and segregating protection of development processes (Decker et al. 2001).

3.2 *Landscape management support*

Since cultural landscape change entails serious ecological consequences, such as fragmentation and loss of habitats, specific knowledge about the

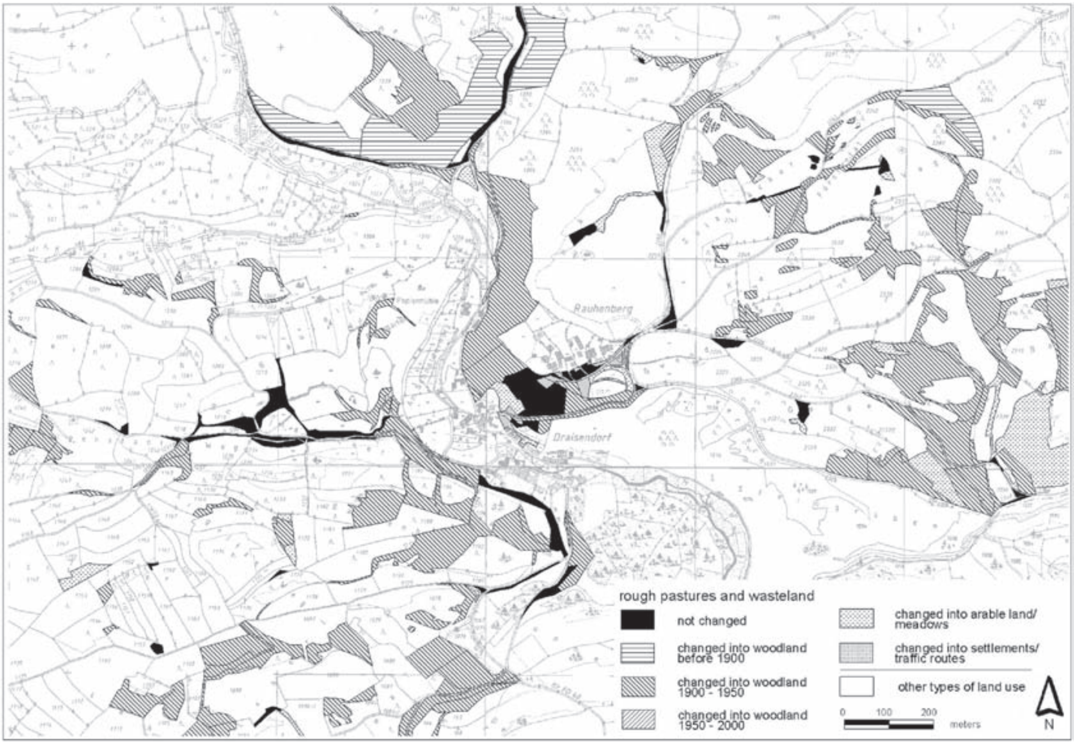

Figure 5. Categories of change in rough pastures and wastelands in the district of Wuestenstein (Franconian Alb) indicating potential sheep grazing areas (Bender et al. 2005b).

background of disadvantageous processes is fundamental for the success of nature conservation measures. Particularly conservation concepts for endangered species and communities that are supported by traditional land use systems (e.g. sheep grazing) have to consider the historical distribution of suitable habitats. A land plot-based multi-temporal LIS facilitates the precise reconstruction of habitat patterns and human disturbance regimes since the 19th century.

One example is the ability to re-establish a desirable habitat such as limestone grassland. It is possible to determine whether the envisioned aggregate (which may now be shrub-like, forested, or tilled) was formerly a rough pasture, and when the change in use occurred (figure 5). Historical drove tracks can be accurately reconstructed. This makes it possible to evaluate the probability of success in re-establishing a mesoxerophytic meadow at the site in question. Thus, the categories of change represent a tool for decision-making, and can help to determine the effort involved in achieving a desired result in a given area (“spatial decision support”; cf. Prato 1999 and 2001). In general, it is possible to forecast the time required for certain vegetation elements to arise, including the potential natural vegetation (Lindacher 1996).

4 CONCLUSIONS AND FURTHER RESEARCH NEEDS

It was shown that the approach of a quantitative HLA using GIS is advantageous particularly for a description and quantification of land use change at the local and regional level. Thus, this method can be employed, for instance, on detailed reconstruction of ancient landscapes, on quantification and description of landscape changes, on identification and explanation of human induced processes, and on landscape conservation or planning purposes as well.

Finally, the quantitative approach used to explain historical landscape change is an essential component for the prediction of future landscape changes. Integrating data from both the natural and the social sciences is a basic requirement for constructing a realistic simulation of the future local-level landscape development (Vogt et al. 2002). A diachronic LIS also facilitates feasibility estimations of development concepts in the planning of land use or habitat aggregates.

Despite the described LIS which are already successfully implemented, the existing analysis instruments have to be enhanced and new ones need to be created. Under comparable conditions of landscape development and with comparable data sources, these instruments are open to any kind of extension and can be used area-wide (Bender 2007). Thus, all relevant functional claims on the landscape can be considered in an inter- and transdisciplinary sense and, thanks to a large-scale cadastre-based approach, they should be integrated directly into communal planning. Likewise, after cartographic generalisation, they can support comparative studies of different landscapes.

Cartographic generalisation: *the process of abstracting/simplifying cartographic information as a result of changing scales accompanied by increasing complexity.*

Furthermore, the potential of a database and GIS solutions which has been rarely used sufficiently in historic landscape research up to now should be emphasised. A GIS is useful for:

- selecting specific contents (geocultural objects with their attributes) and their relational connection to the database (various field definitions including images and texts),
- varying scales, and developing generalisation rules in order to integrate the geo-cultural objects into various planning dimensions (cf. Burnett & Blaschke 2003),
- exploring spatial connections of landscape elements, e.g. with the landscape metrics approach (cf. Lang & Blaschke 2007),
- explaining landscape change by time-integrative combinations or overlays of physiognomic (e.g. land cover types), functional (e.g. land use, land owner, etc.), and ecological information (e.g. land value by soil taxation) and qualitative and statistical examination of the results (Bender 2007, Lamarche & Romane 1982),
- providing spatial information to support planning and management decisions, e.g. GIS analysis to define landscape conservation measures, land use or the demarcation of (nature) reserves (cf. Bender 2007),
- compiling didactic contributions with GIS support, e.g. planning and virtual representation of cultural historic excursion routes or ecomuseums.

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Spatial interpolation and terrain analysis

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ABSTRACT

This chapter presents basic principles of spatial interpolation and terrain analysis that may be used effectively in geoarchaeology and other related geospatial applications. Explanation of spatial interpolation and terrain analysis methodology is supplemented by an overview of basic techniques that are available in current GIS and other software packages. The selection of appropriate methods is explained, along with differences, problems and applications using various data.

1 INTRODUCTION

Modern geospatial technology provides much point data representing the values of a studied phenomenon at certain locations. While traditional methods based on slow, manual techniques (e.g. vectorisation of topographic maps, tachymetry) provided files with tens, or thousands of measured points, recent technology (e.g. 3D laser scanner) produces tens and hundreds of millions of points over relatively small areas. Hence, the demand for reliable, quick and flexible spatial interpolation techniques is growing. The sampled phenomena include elevation, soil properties, chemical concentrations in water and air, or even socio-economic phenomena. While most of these phenomena are measured by point data, often irregularly distributed in space and time, modelling, analysis and visualisation are usually based on a raster representation. Moreover, the phenomena may be measured using various data collection methods (remote sensing and site sampling) leading to heterogeneous datasets with different digital representations, resolutions and data densities which need to be used together to form a single spatial model of the phenomenon.

Vectorisation:
a process of converting analogue maps into a digital vector representation, by the coordinate geometry of points, lines, and/or polygons.

Spatial interpolation:
an estimation of continuous phenomenon values in areas between measured locations.

Raster representation:
a regular digital representation (grid) as an array of equally sized square cells arranged in rows and columns which are referenced by their x, y location.

Many interpolation methods have been developed to predict values of spatial phenomena in unsampled locations. Comprehensive reviews of available interpolation methods may be found, for example, in Burrough (1986), Lam (1983) and Mitas & Mitasova (1999). These methods are being used to support transformations between different discrete and continuous representations of spatial and spatio-temporal fields, typically to transform irregular point or line data to raster representation, or to resample between different raster resolutions.

2 SPATIAL INTERPOLATION

2.1 *Problem formulation*

Spatial interpolation is the mathematical method of estimating the values of a studied phenomenon at unsampled locations in areas between the sampled locations. The locations may be defined as points in space and time, hence interpolation need not be necessarily defined as one- or two-dimensional. While the most common application is terrain modelling with two-dimensional data, there are increasingly new data and approaches that use multidimensional (also multivariate) interpolation methods. In fact, three-dimensionality is a common feature of all landscape components (e.g. atmosphere, hydrosphere, etc.). Moreover, new interpolation approaches have shown that the inclusion of an additional variable influencing the modelled phenomenon often improves the result of interpolation, so multivariate methods are gaining popularity (Hofierka et al. 2002).

The definition of the interpolation problem include the task of finding a mathematical function which passes through the given points and, at the same time, provides sufficiently accurate estimation of values between these points. The trade-off between interpolation accuracy in given points and unsampled area has lead to the use of methods that are, in a mathematical sense, approximations (i.e., they do not pass exactly through the given points). The lower accuracy in given points provides a better accuracy and reliability in unsampled areas. This utilises the belief that many data sets contains recorded values with a certain level of noise (uncertainty, error) that should be smoothed out (eliminated or minimised).

Remote sensing:
cf. chapter "The use of satellite remote sensing for detecting and analysing cultural heritages" of Heinrich et al.

Choosing appropriate interpolation methods for landscape applications poses several challenges. The phenomena being modelled are usually very complex; data are spatially heterogeneous and often poorly sampled with a significant noise. In addition, data sets may be very large originating from various sources with different accuracies. Reliable interpolation tools, suitable for landscape modelling and analysis, should therefore satisfy several important requirements: sufficient accuracy and reliability in describing various types of phenomena, multidimensional formulation, applicability to data from various sources (e.g. contours, remote sensing, geodetic methods, etc.), applicability to large data sets, computational efficiency, and ease of use. Currently, it is difficult to find a sufficiently versatile method which fulfils all of the above-mentioned requirements for a wide range of georeferenced data. Therefore, the selection and proper parameterisation of an appropriate method for particular application is crucial. Different methods may produce quite different spatial representations and in-depth knowledge is needed to evaluate which method produces a result closest to reality. The use of an unsuitable method or inappropriate parameters may result in a distorted model of spatial distribution, leading to potentially wrong decisions based on misleading spatial information (Mitas & Mitasova 1999). Some evaluation tools, for example cross-validation, may help to select the appropriate method and its optimal parameters, but their application domain is often limited to well-sampled phenomena (Hofierka et al. 2007). The art of successful application of spatial interpolation is still based on good knowledge of available methods, modelled phenomenon and a trial-and-error procedure including advanced visualisation and terrain analysis that help to detect interpolation errors and geometrical distortions (Mitas & Mitasova 1999).

Cross-validation:
a model evaluation method for approximating the error of a model by training a subset of data and testing this performance on the other unlearned part.

2.2 *Interpolation methods*

There are many interpolation methods that are available in various software packages. Specialised software usually provides several methods with sufficient options and parameters to optimise the interpolation result. More comprehensive software include geographic information systems (GIS) in which the interpolation methods are part of a wider spatial modelling toolbox.

Despite a plethora of available methods, the following three main groups of interpolation methods may be recognised: local neighbourhood, kriging and variational methods (Mitas & Mitasova 1999).

2.2.1 Local neighbourhood interpolation

Local methods are based on the assumption that each known point influences the values of neighbourhood points only up to a certain finite distance. Values at unsampled points are computed by various functions. The most common methods in this group are:

- inverse distance weighted (IDW) interpolation,
- natural neighbour interpolation,
- triangulated irregular network (TIN) interpolation.

The methods are usually quite fast, but often at expense of lower accuracy and unwanted interpolation artifacts for datasets with variable data density (figure 1). For example, the IDW interpolation produces “bull’s-eye” effects (local extrema at the data points), while the TIN interpolation is very sensitive to a correct construction of triangles.

IDW (Inverse distance weighted):
a method based on the assumption that the nearest known points have a higher influence on the interpolated value than the distant points.

Natural neighbour:
a method based on Voroni polygons to smoothly interpolate between points on the surface.

2.2.2 Kriging methods

The principles of geostatistics and interpolation were developed by G. Matheron, as the “theory of regionalised variables”, and D.G. Krige as an optimal method of interpolation for use in the mining industry. Kriging is based on a concept of random functions. The resulting surface or volume is a realisation of the function with a certain spatial covariance (Matheron 1971).

An important step in the kriging procedure is the assessment of the rate at which the variance between points changes over space. This is expressed in the semivariogram which shows how the average difference between values at points changes with distance between the points. The experiment semivariogram may be approximated by the theoretical

Triangulated irregular network (TIN):
a method of irregular tesselation of triangles based on a set of points. A speical case is the Delaunay triangulation.

Random function:
a collection of dependent random variables, or alternatively, a random variable whose values are functions rather than numbers.

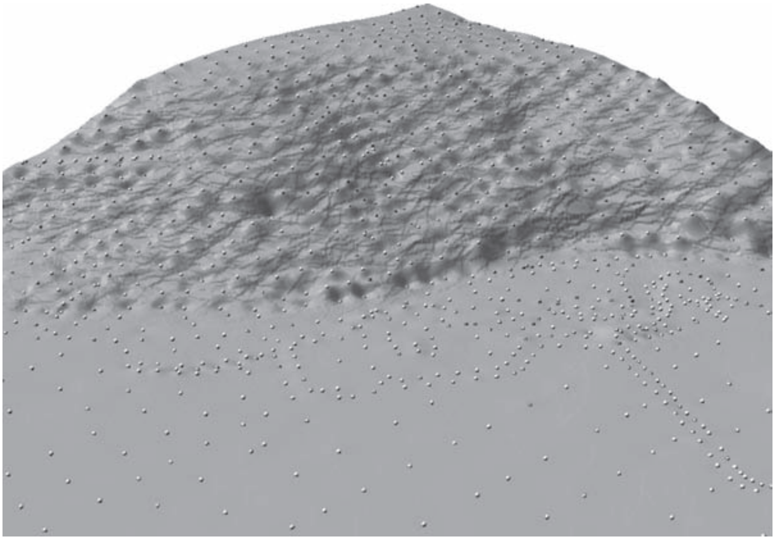

Figure 1. Interpolation artifacts (peaks and pits) around the data points (IDW interpolation).

Semivariogram:
a mathematical function used to quantify the spatial correlation in observations measured at sample locations.

semivariogram (e.g. spherical, exponential, Gaussian, Bessel, etc.). The parameters for these functions are then optimised for the best fit of the experimental semivariogram. In developing the semivariogram, it is necessary to make some assumptions about the nature of the observed variation on the surface (the existence of the trend in data). The interpolated surface is then constructed using statistical conditions of unbiasedness and minimum variance.

Co-Kriging:
a form of kriging in which the distribution of a second, highly correlated variable is used along with the primary variable to provide interpolation estimates (ESRI GIS dictionary, http://support.esri.com/knowledgebase/).

Various extensions enhance its flexibility and the range of applicability (Cressie 1993). For example, co-kriging includes information about correlations of two or more attributes to improve the quality of interpolation, while disjunctive kriging is used for applications where the probability that the measured values exceed a certain threshold is of interest (Rivoirard 1994). For cases in which the assumption of stationarity is deemed not to be valid, zonal kriging may be used (Burrough 1986). Approaches for spatio-temporal kriging reflect the different behaviour of the modelled phenomenon in the time dimension. Time is treated either as an additional dimension with geometric or zonal anisotropy, or as a combination of the space and time correlation functions with a space-time stationarity hypothesis (Bogaert 1996, Rouhani & Myers 1990).

Kriging:
an interpolation technique in which the surrounding measured values are weighted to derive a predicted value for an unmeasured location (ESRI GIS dictionary, http://support.esri.com/knowledgebase/).

The main strengths of kriging are in the statistical quality of its predictions (e.g. unbiasedness) and in the ability to predict the spatial distribution of uncertainty (Mitas & Mitasova 1999). It is often used in the mining and petroleum industries, geochemistry, geology, soil science and ecology, where its statistical properties are of great value (Burrough 1986, Cressie 1993, Isaaks & Srivastava 1989, Oliver & Webster 1990). It has been less successful for applications where local geometry and smoothness are the key issues and other methods proved to be competitive or even better (Hardy 1990, Deutsch & Journel 1992). Other problems with this method include high computational demands for large datasets, often a difficult estimation of the variogram, and sufficient experiences of the user in order to make several crucial assumptions about the statistical nature of the variation, so the results from this technique may never be absolute (Mitas & Mitasova 1999).

2.2.3 Variational methods

The variational methods are based on the assumption that the interpolation function should pass through (or close to) the data points and, at the same time, should be as smooth as possible. These two requirements are combined into a single condition of minimising the sum of the deviations from the measured points and the smoothness seminorm of the spline function (Mitas & Mitasova 1999).

A bivariate smoothness seminorm with squares of second derivatives leads to a thin plate spline (TPS) function (Duchon 1976, Harder & Desmarais 1972). The TPS function minimises the surface curvature and imitates a steel plate forced to pass through the data points: the equilibrium shape of the plate minimises the bending energy which is closely related to the surface curvature. There are at least two deficiencies of the TPS function: (1) the plate stiffness causes the function to overshoot in regions where data create large gradients; and (2) the second order derivatives diverge in the data points, causing difficulties in surface geometry analysis (Mitas & Mitasova 1999). These two deficiencies may be eliminated by adding the first and higher order derivatives into the seminorm (Franke 1985, Hutchinson 1989, Mitas & Mitasova 1988).

Thin plate spline (TPS):
a smooth function which interpolates a surface that is fixed at points at a specific height.

Mitasova et al. (1995) have proposed regularised spline with tension (RST) that synthesise the desired properties into a single function. The tension parameter tunes the surface from a stiff steel plate into an elastic membrane. The function has regular derivatives of all orders and therefore is suitable for differential analysis and direct calculations of curvatures (Mitasova & Hofierka 1993, Mitasova et al. 1995). The method is implemented in GRASS GIS as *v.surf.rst* module for bivariate case (terrain application). The trivariate version of RST has been implemented in GRASS GIS as *v.vol.rst* module (Neteler & Mitasova 2004). Both modules may be used to produce raster-based surfaces and volumes from scattered or regular input data distributions. The behaviour of RST interpolation in the modules is controlled by a set of parameters that may be selected empirically, based on the knowledge of the modelled phenomenon and function, or automatically, by minimisation of the predictive error estimated by a cross-validation procedure (Hofierka et al. 2002, Hofierka et al. 2007).

Regularised spline with tension (RST):
a smooth function which is tunable by a tension parameter and suitable for terrain analysis.

GRASS GIS (Geographic Resources Analysis Support System):
an open source GIS used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualisation.
http://grass.osgeo.org

As it has been pointed out by several authors (Cressie 1993, Hutchinson & Gessler 1993, Matheron 1981, Mitas & Mitasova 1990, Wahba 1990), splines are formally equivalent to universal kriging with the choice of the covariance function determined by the spline seminorm. Therefore, many of the geostatistical concepts may be exploited within the spline framework. However, the physical interpretation of splines makes their application easier and more intuitive. The thin plate with tension analogy helps to understand the behaviour of the function also in higher dimensions where the interpolation function models an elastic medium with a tunable tension (Mitas & Mitasova 1999). The RST control parameters such as tension and smoothing proved to be useful and effective in elimination or minimisation of common interpolation artifacts such as artificial peaks, pits around given data points, waves along the contours, or overshoots in areas with high gradient often found in results of less sophisticated interpolation techniques (Hofierka & Cebecauer 2007).

2.2.4 Choice of interpolation method

Current software packages and GIS's provide numerous methods that may be used in interpolation tasks for landscape modelling and geoarchaeology. The user often faces the problem which method to use in a concrete application.

The choice of proper interpolation method depends on various factors: spatial distribution of the modelled phenomenon, data collection method, data density and homogeneity, and further application of the interpolated surface/volume.

There are several groups of spatial phenomena that may be modelled using interpolation methods. Probably the most widely used is land surface represented by digital elevation models (DEM) with various elevation data sources. Other applications include data from various naturally continuous variables (e.g. temperature). While most of the phenomena gradually change over space and time, some areas may exhibit very abrupt changes (strong gradients). For example, geologic faults often influence a distribution of certain substances and visible topographic forms. Technical applications require a preservation of breaklines, or man-made topographic features in the resulting DEM.

Data collection methods strongly influence the choice of method. Data derived from digitised contour maps are unevenly distributed with high data density along the contours and low data density between the contours. A similar situation may be found in GPS measurements and photogrammetry data (Hofierka & Cebecauer 2007). The variable data density may lead to unwanted interpolation artifacts, such as artificial peaks and pits around the data points (figure 1), or waves along the contours (figure 2).

LIDAR provides huge datasets with tens and hundreds of millions data points that are virtually impossible to process by current software packages without a pre-processing including a data density reduction. If several data points fall into one raster cell, it is necessary to select only one or two points to be used in the interpolation process. Other data sources (e.g. IFSAR, SRTM radar data) also provide data that need to pre-processed. They often contain void areas (no data in shadowed areas during the recording, etc.) and the values represent a surface that includes also vegetation and man-made objects. All these factors should taken into consideration before the selection of interpolation method. Some methods are easy to use because of a minimum of parameters, but often at expense of low flexibility and low accuracy

LIDAR (Light Detection and Ranging):
an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target.

cf. chapter "Shedding light on the past: using LIDAR to understand ancient landscapes"of Crutchley.

IFSAR (Interferometric Synthetic Aperture Radar):
a radar technology for acquiring elevation data.

SRTM (Shuttle Radar Topography Mission):
the acquisition of remotely sensed data of the Earth's surface from space in February 2000 for the generation of a homogeneous digital elevation model.
www2.jpl.nasa.gov/srtm

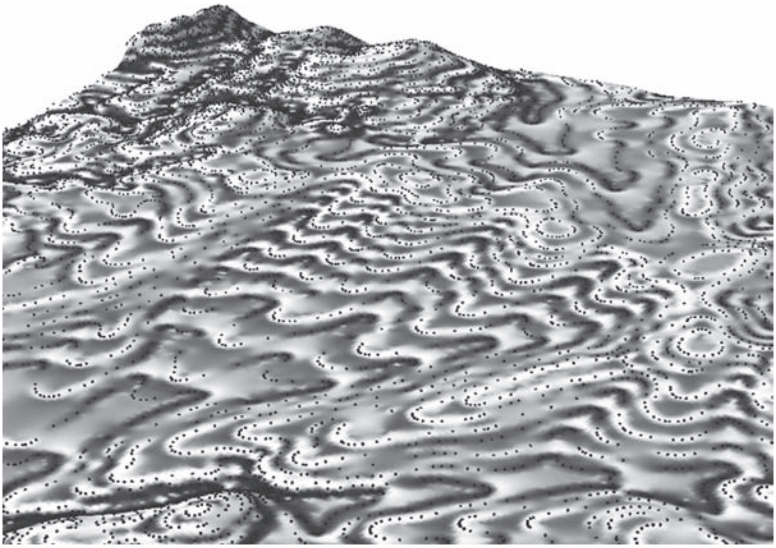

Figure 2. Interpolation artifacts (waves along the contours) showed using profile curvature draped over the terrain surface (RST interpolation).

(e.g. TIN, IDW). Other methods provide a set of parameters that may be used to minimise the interpolation errors and tune up the result according to the character of the phenomenon. However, the user must be sufficiently familiar with the method, its behaviour and parameterisation (e.g. RST, kriging).

The best practice for successful application of interpolation is to use two or three methods for the same data set, evaluate results in the terms of interpolation accuracy and intended further application and then try to parametrise the selected method to tune-up the final result.

2.2.5 Selection of interpolation parameters and evaluation of interpolation accuracy

Generally, almost every interpolation method is controlled by a set of parameters that enable the modification of the behaviour of the mathematical function so that a resulting surface meets the criteria of specific applications. Often, a proper setting of these parameters is difficult and not clear to those who are responsible for the DEM data processing.

The interpolation methods implemented in GIS software often have control parameters set up as default constants. Their functionality may be poorly explained and their influence on results may be unclear. Instead of a clearly controlled procedure, the spatial interpolation becomes a black box for the user. In such cases it is difficult to provide the end user with information on the uncertainty associated with the estimates generated during the interpolation. Therefore, robust interpolation methods are needed that offer comprehensible parameterisation.

There are various approaches to finding optimal interpolation parameters. In practice, a trial-and-error method is often used, but much effort is needed, and less-experienced users may get quite poor results. There are also user-independent computational approaches that are focused on minimising the interpolation errors.

The interpolation accuracy may be measured by different methods. The most straightforward is to evaluate deviations between interpolated surface and the input points. The overall error, measured e.g. by Root Mean Squared Error (RMSE) then characterises the interpolation accuracy in the given points. However, this approach does not provide information about the accuracy in areas between these points. The interpolation accuracy in areas between the input points is actually a predictive accuracy of the interpolation method.

Root mean squared error (RMSE):
is the error of the predicted values to the actual value (e.g. reference image) expressed as the square root of the mean sum of the square errors.

One of the options to evaluate the predictive accuracy is to use an evaluation dataset that contains data not used in the interpolation. For each evaluation point the deviation between actual and interpolated value are calculated and the overall accuracy is tested. However, in many applications due to a limited number of input points, such an independent evaluation dataset is difficult to select. Moreover, the accuracy information is available only for these independent points and they rarely cover the entire area of interest with a sufficient density.

Another method widely used in interpolation applications is a cross-validation (CV). The CV method is based on removing one input data point at a time, performing the interpolation for the location of the removed point using the remaining samples and calculating the residual between the actual value of the removed data point and its estimate. The procedure is repeated until every sample has been, in turn, removed. This form of CV is also known as the “leave-one-out” method (Tomczak 1998). The main advantage of the method is a clearly defined and user-independent algorithm that may be easily implemented in the software. The method is less reliable for surfaces with insufficient data density since removing points from already under-sampled areas may lead to misrepresentation of the surface to be interpolated (Hofierka 2005, Hofierka et al. 2007, Jeffrey et al. 2001).

The overall performance of the interpolator is then evaluated by statistical means such as the Root Mean of Squared Residuals, Mean Absolute Error (MAE) or Mean Error. Low RMSE indicates an interpolator that is likely to give most reliable estimates in the areas with no data. The minimum RMSE calculated by CV can be used to find the optimum interpolation control parameters (Hofierka 2005, Hofierka & Cebecauer 2007, Hofierka et al. 2002, Hofierka et al. 2007). However, Hutchinson (1998) has found that CV does not always represent a reliable estimate of the model error, especially when a short-range correlation in data is present. Therefore it is appropriate to use additional evaluation methods to ensure the reliability and consistency of the predictions (Hofierka et al. 2002).

2.3 *Spatial interpolation in a geoinformation technology*

Depending on application, spatial interpolation may be performed at three levels of integration with geoinformation technology (Mitas &

Mitasova 1999): (1) within a more general programme/command; (2) as a specialised command; or (3) using linkage to specialised software. Interpolation integrated at a 'sub-command' level may be found in many GIS application programmes such as computation of slope and aspect, automatic raster resampling, flow-tracing, hydrological modelling, etc. Mostly simple and fast local interpolations such as IDW bilinear, or local polynomial methods are used in this case. The interpolation is fully automatic, hidden from the user, and while it is sufficient for most applications, it may result in artefacts in surfaces if an improper method is implemented.

Resampling: *the process of interpolating new cell values when transforming rasters to a new coordinate space or cell size (ESRI GIS dictionary, http://support.esri.com/knowledgebase/).*

Interpolations integrated at a command level serve as data transformation functions. A limited set of basic and some advanced methods have been integrated within GIS, most often the simpler versions of IDW, TIN, kriging and splines. Compromises in numerical efficiency, accuracy, and robustness are common and upgrades to improved modifications of methods are slow, especially for commercial systems. Therefore, it is necessary to evaluate the results carefully and, if possible, to use more than one independent interpolation procedure. Although interpolations performed by specialised software linked to a GIS provide the most advanced and flexible tools, a time-consuming import/export of data, or inconvenient work in a different software environment might be necessary. This approach still may be preferable, especially when data are complex and high accuracy is required.

3 TERRAIN ANALYSIS

Terrain analysis (also known as geomorphometry) is closely related to interpolation and digital elevation models (DEMs). It provides morphometric parameters that quantify geometrical properties of the interpolated surface or identify specific land surface features (e.g. peaks, landforms). A comprehensive review of basic morphometric parameters and possible applications may be found in Hengl & Reuter (2008), Moore et al. (1991), and Wilson & Gallant (2000).

Morphometric parameters and features may be grouped according to various criteria. For example, Wilson and Gallant (2000) distinguish primary and secondary morphometric parameters depending on whether they are derived directly from a DEM, or additional processing steps are required. Alternatively, the areal extent may be used to distinguish local and regional parameters.

Local parameters describe land surface properties at a point and its infinitesimal surrounding. They may be computed based on the principles of differential geometry using partial derivatives of the mathematical function representing the surface. Local approximation methods are usually applied to estimate derivatives on a regular grid. A surface defined by the given grid point and its 3 × 3 neighbourhood is approximated by a second-order polynomial and partial derivatives for the given centre grid point are computed using one of the common finite difference equations, for example

Second-order polynomial: *a quadratic, bivariate mathematical function.*

(Hengl & Reuter 2008, Jordan 2007). This approach works well for smooth and non-flat areas. However, for high resolution data representing relatively flat areas with small differences in elevations or noisy surfaces, the small neighbourhood may not be sufficient to adequately capture the geometry of land surface features. Also the approximation needs to be modified to estimate derivatives for grid cells on edges of the study area, where the complete 3×3 neighbourhood is not available.

3 × 3 neighbourhood: *eight cells surrounding the central cell in a raster representation.*

A more general approach to the partial derivatives estimation is to use a differentiable function for DEM interpolation. Then the local surface parameters may be computed using an explicit form of the function derivatives, usually simultaneously with interpolation. However, this task is not trivial because the interpolation function must, at the same time, fulfil several important conditions necessary for reliable land surface modelling (Hofierka et al. 2008).

3.1 *Local parameters*

Land surface substantially influences many landscape processes. For example, steep slopes often undergo erosion and landslide processes, slope and aspect influence the intake of solar energy and then hydrothermal balance of soils and vegetation. To quantify the influence of geometric properties of land surface on landscape processes, a complex methodology based on the concept of physical fields and differential geometry must be used (Krcho 1973 and 1990, Mitasova & Hofierka 1993). The land surface is expressed as a physical, scalar field of elevations that may be described by a continuous function of two variables in the form $z = f(x,y)$, where z is the elevation and x,y are independent variables defining a horizontal position of the point on the land surface. Then, the morphometric parameters describing geometric properties of land surface at a given point and its small, infinitesimal surrounding area may be expressed using partial derivatives of this function. Basic local morphometric parameters are slope, aspect, profile, and tangential curvatures (figure 3).

Profile and tangential curvatures: *morphometric parameters expressing the shape of terrain in a direction of slope line and contour line, respectively.*

Slope and aspect are defined by the elevation gradient. The slope angle (size of gradient) is usualy expressed in degrees in the range of 0°–90°. Aspect is expressed in degrees in the range of 0°–360° with a defined angle counting method (e.g. North = 0°, clockwise). A land surface with zero slope has no aspect. Curvatures express the land surface shape in certain directions. The land surface has different curvatures in different directions. Two directions are the most relevant: gradient direction and direction of contour tangent, which is perpendicular to the gradient direction. The curvatures are expressed in m^{-1} and may have positive and negative values expressing convex and concave forms of land surface in given directions.

Morphometric parameters play an important role in landscape processes. The general influence of the morphometric parameters on hydrologic and geomorphic processes is as follows:

- slope influences a velocity of mass flows,
- aspect influences a direction of mass flow,

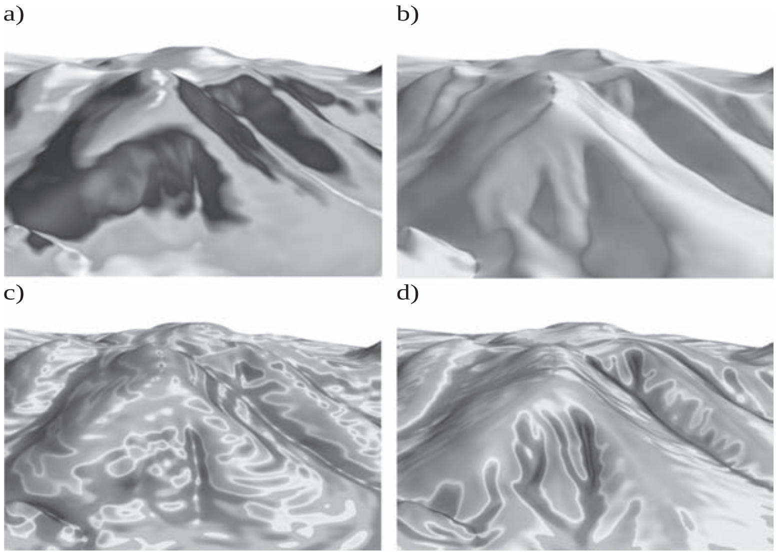

Figure 3. Morphometric parameters draped over the land surface: a) slope, b) aspect, c) profile curvature, d) tangential curvature.

- profile curvature influences an acceleration and deceleration of mass flow,
- tangential curvature influences a concentration and dispersion of mass flow.

It is important to note that land surface parameters (especially curvatures based on second-order derivatives) are very sensitive to the quality of interpolation process. For example, interpolation from contours may lead to a false pattern of waves along the contours that may be fully visible only on a profile curvature map (figure 2). This is caused by very uneven distribution of input data – the distances between points on the contour are relatively small, while they are large between the contours. These artifacts may be minimised by tuning the interpolation parameters or inserting additional points in undersampled areas to obtain more even distribution of data (Hofierka & Cebecauer 2007, Neteler & Mitasova 2004).

Computation of curvatures from densely sampled or noisy data, such as LIDAR and SRTM, poses a different type of challenge. Without adequate smoothing, curvatures will reflect the noise rather than the real surface geometry (Hofierka et al. 2008).

Noisy data: *data with a high degree of uncertainty (error).*

3.2 *Regional parameters*

Landscape processes are also influenced by landscape configuration that reflects broad-scale geometry of the terrain. The magnitude of the transporting agent (e.g. water) affects its carrying capacity or defines the occurrence of specific phenomena such as floods or gullying. It is often related to the spatial extent of the land surface from which the transporting agent is flowing downslope. Thus, the movement may be traced by flowlines and currents.

3.2.1 Flow parameters

Topography has a profound influence on mass and energy fluxes in landscape and is often a major factor in many geospatial models and applications. Flow parameters are derived by flow tracing algorithms that approximate the route of water or other liquid over the surface represented by DEM (figure 4). Many algorithms have been developed for flow routing, based on the approach for estimation of the steepest slope direction and water movement to the downslope cells (Hofierka et al. 2008). Usually, the following basic flow parameters may be computed using a GIS or other specialised software package:

- flow accumulation,
- upslope contributing areas,
- stream network,
- watershed (basin) areas,
- flowpath length.

Flow routing algorithms are often negatively influenced by the quality of DEMs. Numerous local depressions in valleys or flat areas stop the flow tracing algorithm that leads to an incorrect pattern of flow accumulation (upslope contributing areas), stream networks, flowpath lengths and other flow parameters. Specific algorithms may be used to remove depressions (sinks) and lakes on DEMs (Hutchinson 1989). However, these depression-filling algorithms also introduce locational errors, create artificial features (e.g. flats leading to parallel streams) and the flow parameters then do not fit with values of other land surface parameters computed from the original DEM. Basically, the choice of the module and operations depends on the application.

Flow parameters represent a potential of land surface to generate overland water flow. These parameters do not take into account infiltration or land cover. Therefore, topographical indexes derived from these parameters often represent a steady-state situation or maximal values of overland flow assuming uniform soil and land cover properties (Mitasova et al. 1996). Thus, in some areas the estimated patterns of net erosion and deposition based on upslope contributing areas may contradict with data from field inspection.

3.2.2 Ray-tracing parameters

Solar radiation influences many landscape processes and is a source of renewable energy that attracts attention of many researchers, energy companies, governments and consumers. Many GIS and specialised software provide functionality related to solar radiation: calculation of a position of the sun and maps of shadows for specified time and Earth position, and solar irradiance/radiation (beam, diffuse and reflected)

Figure 4. Flow accumulation (in dark grey) draped over the land surface computed using the *r.terraflow* module in GRASS GIS.

for clear-sky and/or overcast conditions (Hengl & Reuter 2008, Šúri & Hofierka 2004).

Another application of terrain analysis is viewshed analysis that generates a map containing marked areas visible from a user-specified observer location and representing the vertical angle (in degrees) required to see this area (viewshed).

3.3 *Volume parameters*

Terrain often represents a surface of a 3D object. The volume algorithm may be used, for example, to estimate a volume of soil that needs to by excavated for archaeological or construction purposes.

Moreover, many landscape phenomena may be investigated using differential geometry tools extended to three dimensions (Hofierka & Zlocha 1993). For example, GRASS GIS provides several tools for 3-dimensional (volume) modelling including a trivariate interpolation using regularised spline with tension. Similarly to the bivariate version, trivariate RST may compute a number of geometric parameters related to the gradient and curvatures of the volume model: magnitude and direction of gradient, directional change of gradient, Gauss-Kronecker and mean curvatures. Mathematical definitions and explanation of volume parameters have been studied by Hofierka & Zlocha (1993) and Neteler & Mitasova (2004).

Spline:
mathematical function used for smoothing of polylines in order to achieve visual enhancement.

Moreover, trivariate interpolation may also be helpful in spatial interpolation of natural phenomena influenced by the land surface. For example, Hofierka et al. (2002) present an application of trivariate RST in precipitation modelling. Elevation, aspect, slope, or other land surface parameter may be incorporated in the trivariate interpolation as a third variable. The approach requires volume data (x, y, z, w) and a raster DEM. The phenomenon is modelled by a trivariate interpolation function $w = f(x,y,z)$. Then the phenomenon values on the land surface is computed as an intersection of the volume model with the land surface represented by a DEM.

4 APPLICATION TO GEOARCHAEOLOGICAL AND GEOCULTURAL RESEARCH

The study of human history is inevitably associated with the landscape. The landscape has always provided necessary resources and space for living. At the same time, it has been modified and shaped by human activities. The human interaction transformed the original natural landscape to cultural landscape containing many man-made features that are a subject of study of archaeology or other disciplines.

On a short time scale (tens of years) terrain may present a stable landscape feature, but over the long term it exhibits changes that are caused by various landscape processes. During the relatively short period of a man's existence on Earth many of these processes were caused or initiated by human activities. For example, deforestations have started many landscape processes that changed the topography over large areas. The unprotected soil was removed by heavy rainfalls and water eroded deep linear terrain features – gullies. Although the abandonment of the degradated land may again lead to afforestation, such terrain features usually persist for hundreds of years (e.g. Bork 1991 and 2006).

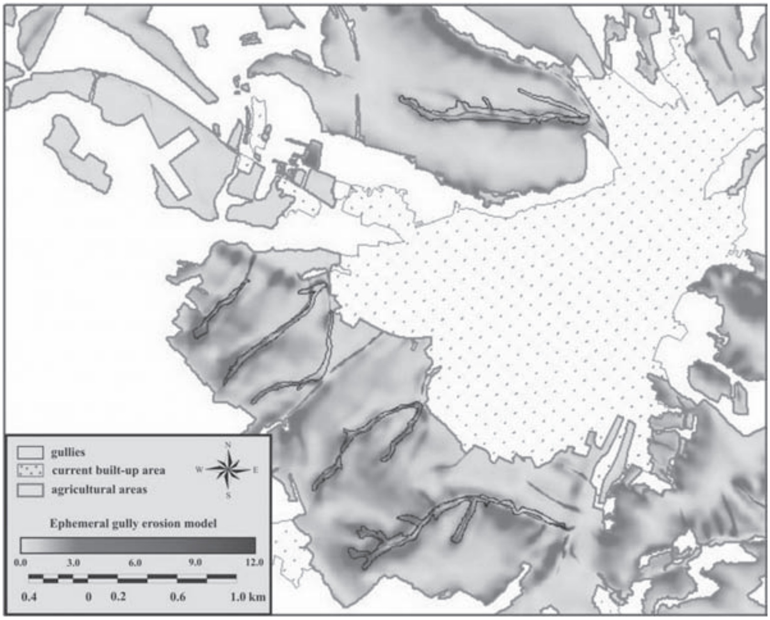

Figure 5. Modelling gully formation using geospatial technology.

Hofierka and Koco (2008) studied the existing gullies in eastern Slovakia that were formed in medieval times when the extensive deforestations and climate change occurred. The results of this study showed that the locations of old permanent gullies are strongly associated with topography and anticipated land use at the time of gully incision (figure 5). To reconstruct the assumed topography and land use that lead to the gully formation, the geospatial technology used included spatial interpolation and terrain analysis. Similar applications of spatial interpolation and terrain analysis can be found in numerous studies with spatially distributed geoarchaeological data.

5 CONCLUSION

This chapter has presented a brief overview of the main spatial interpolation methods which are relevant for geoarchaeological and landscape research. The selection of proper interpolation methods is still a highly subjective decision that depends on various factors. Each interpolation method has intrinsic properties that influence the interpolation result. The proper application of the method depends on data and the purpose of interpolation. Evaluation of interpolation accuracy is an important part of the interpolation process. The available evaluation procedures may help to assess the interpolation accuracy, find the optimal interpolation parameters and tune-up the interpolation method.

Terrain analysis is closely related to interpolation. It provides morphometric parameters that quantify geometrical properties of the land surface. Morphometric parameters like slopes, curvatures and various topographic indexes may help to understand the structures of the terrain or analyse landscape processes (e.g. soil erosion invoked by deforestation). They may help to find subtle changes in the terrain surface, identify landscape processes that occur in the landscape or evaluate the processes that formed historic landscapes.

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Landscape metrics – A toolbox for assessing past, present and future landscape structures

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ABSTRACT

This chapter provides an overview of the development, the potential and some limitations of landscape metrics in the context of historical landscape analysis and landscape planning. Starting with a review of the background and motivation of landscape structure assessment, followed by a brief overview of major concepts of this approach, the chapter discusses the major components of landscape structure to be quantified in a comprehensive way: the analysis of area, density, edge, form, core area, proximity, diversity, and subdivision. It then gives insights into some practical experiences from the use of landscape metrics for assessing historical landscapes, and points out specific implications such as the stepwise backward editing and the most suitable metrics. In a complementary way, the potential and usability of landscape metrics for planning purposes and for the comparison of different future is examined. The chapter closes with a short statement on the achievements thus far, followed by a look at future tasks and provides a link to a discussion of sustainable landscapes and the question of whether a specific landscape structure may be of relevance to it. One of the most important challenges is to find and publish standardised and widely agreed measures for planners and authorities.

1 MEASURING LANDSCAPE PATTERN

1.1 *Spatial context matters*

The quantitative assessment of landscape structure is of increasing importance for a wide range of landscape ecological applications (Blaschke 2006, McGarigal 2002, Turner 1990). As one of the primary research questions, landscape ecology investigates the relationships between pattern and process, i.e., how ecological processes are influenced or even

Landscape structure: *spatial characteristics of a landscape or a portion of a landscape as being attributed to the spatial arrangement of landscape elements or units.*

driven by the spatial configuration of ecological units (Turner et al. 2001). Landscapes exhibit specific patterns or mosaics of constituting elements, commonly referred to as patches, and this heterogeneity is measurable and can be quantified. As Forman (1995) and others point out, ecological processes and functions are strongly interlinked with the structural properties of the landscape. Analysis of the landscape pattern gives insight into underlying processes, potentials, and functions (see below). It has been widely argued that the arrangement of ecological units (i.e. patch mosaic) rather than the mere quality of patches is crucial for the integrity of e.g. protected areas (see Blaschke 2006 for an overview). A decade ago or so, findings in the assessment of habitat integrity and the suitability of habitat arrangements convinced ecologists that the spatial context is crucial (Wiens 1997). Originating from the quantitative branch of North American landscape ecology, these ideas have since settled in European landscape applications and spatial ecological research (Blaschke 2000, Walz 1999 and 2001). A broad set of quantitative measures, called landscape metrics, has been elaborated within this approach. Structural indicators, based on landscape metrics, describe landscapes in terms of size, shape, and neighbourhood relations (Lang & Klug 2006). They express in mathematical terms the arrangement and configuration of landscape

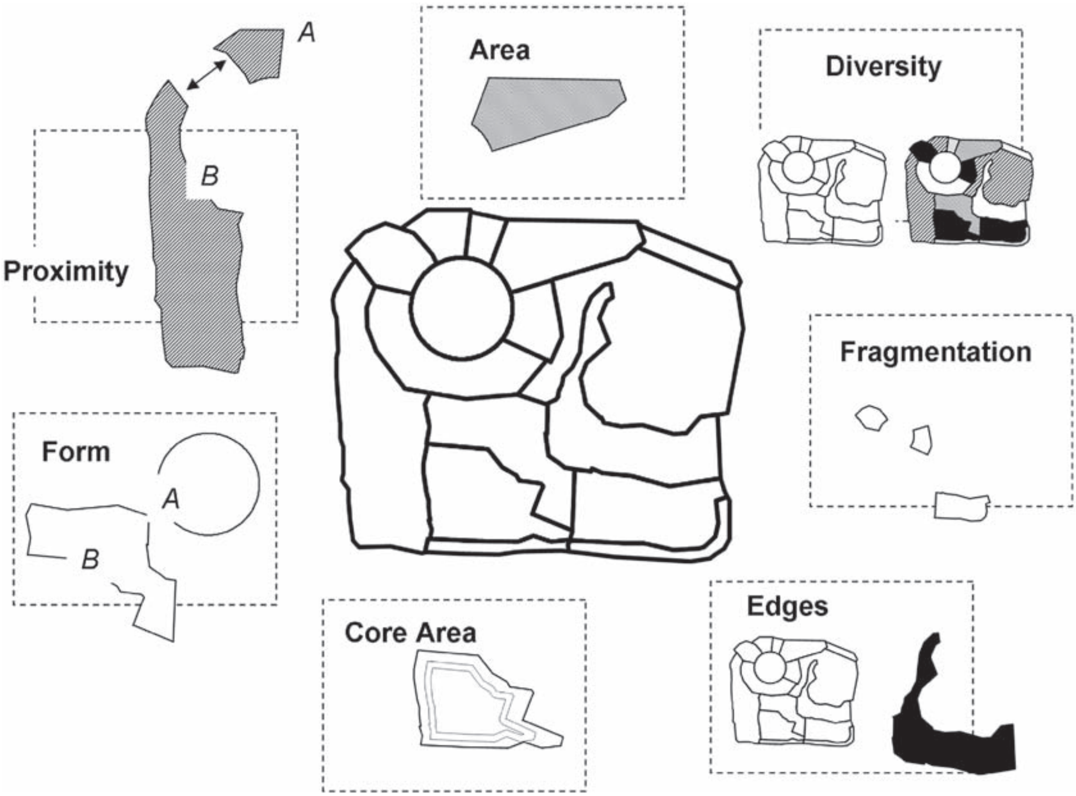


Figure 1. Facets of landscape structure analysis (Lang & Blaschke 2007, modified).

elements in a specific area of interest. They characterise different spatial properties of landscape units (cf. figure 1) by specific measures or in an aggregated manner using basic statistical values (mean, standard deviation, etc.).

1.2 *Landscape structure and scale*

Scale:
a broad terminological concept encompassing, depending on the context, the specific granularity of observation or description of a process, the resolution and level of detail of an imaged representation or the degree of generalisation and the minimum mapping unit in a mapping exercise.

Earth neither exhibits a uniform coverage nor an unstructured, chaotic surface. Views from above, captured on aerial photographs or satellite imagery, reveal regular structures and patterns. Such structures are perceived as an arrangement of homogenous units, but appear in different scales. Landscape ecologists relate the genesis of landscape structures to, first, the spatial variability of supplied resources (e.g. water, different soil types, micro-climate, topography, etc.) and, second, to systemic processes that lead to spatial organisation. “Patch context matters” – this short and comprehensive formula represents an emerging paradigm in spatial ecology. Investigating spatially explicit characteristics of a given landscape portion draws from the notion that observed patterns and underlying processes are closely interlinked. This notion is by no means new (Lang et al. 2004): traditionally, landscape ecological research has been strongly influenced by airphoto interpretation methodologies developed in the early decades of the 20th century (Troll 1966). The bird’s eye perspective opened ecologists the way to characterise and compare the spatial arrangements of landscape patterns, on a broader, an overview scale. This has enabled, and still does, complementing ground investigations and in situ measurements. When Troll (1939) coined the term ‘landscape ecology’, specific patterns and arrangements of landscape units (German: ‘Verbreitungsbild’) were related to respective processes. A complex cause-effect network was considered interlinked with these observable patterns (Leser 1997). Later, Troll proposed the term ‘ecotope’, including functional relationships between organisms and their environment (a kind of spatial manifestation of ‘ecosystem’ as defined by Tansley in 1935).

The ecotope concept was revised and adapted to incorporate hierarchical concepts, meaning that units reflect multiple scales of process and pattern in the landscape (Carol 1956). The idea of geographical dimensions was born at the same time by defining specific cause-effect feedbacks on several scales of investigation (Neef 1967). The dimension in which uniform processes take place (and can be measured locally at one specific site) was since called the topological dimension. Above that, the chorological dimension refers to various heterogeneous aggregates in broader scales. Whereas this idea implies a hierarchical concept, it is less flexible than recent multiscale approaches. Wu (1999) has introduced the hierarchical patch dynamics paradigm (HPDP), which rests upon two principles: (1) patches (as landscape units) are hierarchically structured and ‘homogenous’ under specific aspects only; and (2) within a hierarchical set of patches, at least three levels should be taken into consideration, i.e., the focal level (level under investigation), Level +1 which controls the focal level, and Level –1 which is controlled by it. In other words, level –1 provides explanatory variables for the focal level, and Level +1 constraints (Burnett & Blaschke 2003).

1.3 *Landscape elements: patches, corridors, matrix*

The smallest, homogenous landscape unit (according to scale) is referred to as ecotope, patch, or cell (Zonneveld 1989), or more general as landscape element (Forman & Godron 1986), or as land unit (ibid., Lavers & Haines-Young 1993, Wiens 1989). Within landscape structure analysis, the most commonly used (and straightforward) term is 'patch' which is defined as a "relatively homogeneous area that differs from its surroundings" (Forman 1995). In a morphogenetic view we differentiate between several types of patches: disturbance patches, remnant patches, environmental resource patches, introduced patches, ephemeral patches (Forman & Godron 1986). The term 'patchiness' describes the spatial arrangement of patches reflecting the way patches are distributed in space. Patchiness is a scale-dependent phenomenon meaning that scaled representations lead to different kinds of patchiness. Patches considered homogenous in a given scale, may be composed by a set of patches in a finer scale ('within-patch-heterogeneity', Blaschke 1995, see HPDP above).

According to the conceptualisation of Forman & Godron (1986) and Turner (1989), there are – next to patches – other, complementary types of landscape elements, namely corridors and the (landscape) matrix. Both types are scale-dependent. The matrix is defined as the dominant surface type, either in terms of area coverage (at least 50% of a given landscape under investigation), or in terms of its connectivity or the degree of control-over dynamic. The concept becomes clear, when looking at the type of landscapes in Northern America which functioned as prototypes for this concept: Large, extended forested areas (matrix) intermingled with small clear cut islands (patches). However, in highly managed cultural landscapes in Central Europe with their small structures, the landscape matrix is often not clearly definable (Lang & Blaschke 2007). Corridors, instead, are abundant here or there. The term 'corridor' comprises all elongated structural elements, which appear as linear elements, caused by their specific length/width ratio. Usually, corridors play important roles as conduits of matter and organisms to allow for functional and physical connectivity (Forman 1995, Noss 1993), but could similarly function as barriers. All patch edges may be considered barriers (boundaries) to a certain degree. Knauer (2001) for example highlights the ecological importance of hedges in otherwise agrarian landscapes.

1.4 *Structure, function and change*

The 'landscape structural approach' (Dollinger 2002) investigates the specific arrangement of landscape units, and the resulting landscape mosaic as a whole. It characterises status and temporal changes of prevailing spatial structures in the landscape. As mentioned earlier, these structures are considered spatio-temporal manifestations of processes that occur in various scale domains (Forman 1995, Levin 1992, McGarigal & Marks 1995, Meentemeyer & Box 1987, Turner 1989 and 1990, Wiens 1989). These processes include fluxes of substances, matter and energy, as well as interactions among organisms. Pattern and related processes are encapsulated in a cause-and-consequence relation, which is non-linear and, to a certain degree, bi-directional. In other words, the observable pattern is often a product of spatially constrained processes (e.g. a groundwater influenced bog area); vice versa do prevailing structures influence processes (e.g. a new road may be a barrier for former animal dispersal routes).

Scale domain:
a portion of a scale continuum, in which processes and other observable phenomena are considered uniform.

Structure, function and change (or development) are three profound aspects of landscape research, already highlighted by Neef (1967). These aspects are central in recent literature as well (Forman 1995, Forman & Godron 1986, Risser 1987, Turner et al. 2001, Volk & Steinhardt 2002). The landscape structure results from a cluster of interrelations (synchorical occurrence, Neef 1967) between different landscape compartments (e.g. soil, water, climate/air, relief) at specific local sites (vertical structure of the landscape). Structure is measurable by investigating the specific configuration and arrangement of landscape elements, with respect to their size, form, spatial distribution. These arrangements are indicative of fluxes of substances, energy and matter, as well as organisms and information.

Landscapes fulfill a range of different functions, directed towards specific ecological and societal purposes; according to Marks et al. (1992) there are several landscape functions including habitation function, protection function, control and other abiotic process functions (like buffer function, filter function, or transformation of matter and energy), development and regeneration. Costanza et al. (1997), Costanza et al. (1998), de Groot et al. (2002) and Steinhardt et al. (2005) add several other functions from a human-centered perspective, such as information function, production and recreational function. Further functions include social and economic values such as aesthetic values, which reflect the subjective sensing of landscapes by humans. The production functions are confined by the respective capacity of landscapes to meet the demand of humans (and other organisms). Natural capital is a recent approach looking specifically at the potential of landscapes to fulfill the demand for a set of functions (Potschin & Haines-Young 2003).

In reality, we often face a plurality of functions, i.e., landscapes exhibit a multifunctional character (Brandt et al. 2000, Klug & Zeil 2006). This applies under four aspects: (1) integrated (vertical) multifunctionality meaning there is a spatial overlap of different functions on the same land unit simultaneously; (2) spatial/scale dependent (horizontal) multifunctionality, which can be considered as a mixture of different land use types in one spatial layer; (3) temporal/sequential multifunctionality which is a spatial overlap of functions on the same land unit at successive periods (dynamic). Here, we consider the changing expression of system qualities caused by e.g. crop rotation. (4) The temporal-integrated multifunctionality, where the priority function is changing without restricting other functions at the same land unit and time.

Cultural landscapes are highly integrated, multifunctional landscapes, with a complicated pattern of combined functions, visible as the prevailing land use pattern. The intensity of the cultural (i.e., human) influence has been measured by so-called stages of hemeroby (Blume & Sukopp 1976), ranging from a-hemerob (near-natural) to meta-hemerob (highly modified or degraded). From a perspective of landscape structures, one often assumes that with increasing human influence the structures become less convoluted, less 'natural'. Measures like rectification of river runs (e.g. Klug & Blaschke 2003), land consolidation, road alignments, tunnels, etc. all provide simpler structures, it seems. On the other hand, first impacts in otherwise natural landscapes (e.g. clear cuts) may produce more complex structures as before. So, the transition from 'historic' to 'modern' landscapes does not necessarily imply a trend to simpler, more monotonous structures.

Finally, landscapes are dynamic: they undergo development and are subject to change. There are different qualities of changes, ranging from seasonal, cyclic changes (phenological course, crop rotation systems), through episodic, but still repetitive changes (e.g. forest fires, avalanches, floods and the like), to more pertinent changes, often directed by a trend. This trend may be caused by changing land use patterns due to changing climatic regime (e.g. desertification, decreasing average temperature) or especially economic-political changes such as for instance changes

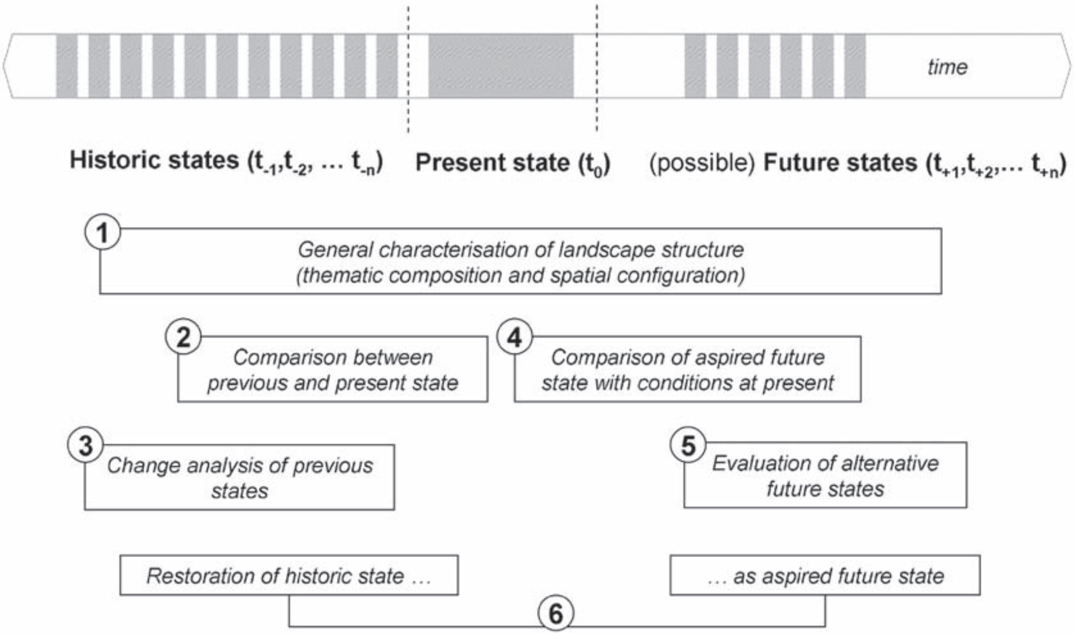


Figure 2. Present state, historic states, and future states. Structure assessment for investigating landscapes from different perspectives (see text for explanation).

caused due to declining subsidy payments in agriculture. Changing landscape structures can be identified and quantified; they offer valuable hints for changing processes in the background. For instance, habitat fragmentation may lead to loss in biodiversity due to decline in dispersal space and limited possibilities for foraging or mating.

As figure 2 portrays in a schematic way, characterising structural characteristics of landscapes under present state conditions (t_0, see 1) is only one possible focus of landscape structure assessment. Present state conditions may be compared against historic conditions (2) and likely future states (4) of landscapes. By applying time series reflecting past landscape conditions, the historic development of landscapes may be analysed, trends and drivers identified (3). Different future scenarios may be evaluated (5) in order to identify a most favourable one. Previous time slices may be compared among each other. Irrespective of the given state at present, a future state may be oriented towards a previous state requiring restoration measures and management (6).

Time series:
a technique to sequentially observe the development of a specific area by standardised data sets and analysis.

cf. section 1.3 of chapter "The concept of a historic landscpe analysis using GIS" of Bender.

Scenario:
a specific future state of a landscape according to defined conditions.

2 LANDSCAPE METRICS – THE TOOLBOX FOR QUANTIFYING LANDSCAPE STRUCTURE

2.1 *The rationale of landscape structure assessment*

The landscape structural approach has been influenced through and supported by tools, methods and concepts from geographical information science and digital image analysis. Today, the toolbox of 'landscape metrics' provides a set of formulae for the quantitative spatial analysis of landscape structure. Since the development of landscape metrics in the 1980s and 1990s, in which conceptual considerations were of primary concern (Blaschke 2000, Gustafson 1998, O'Neill et al. 1988, Turner 1990), today the approach is established in various workflows and utilised in decision making and planning (Botequilha Leitão & Ahern 2002). Recent works (e.g. Banko et al. 2000, Blaschke 2000, Bock et al. 2004, Jooß et al. 2005, Klug & Blaschke 2003, Lang et al. 2002, Langanke et al. 2005, Langanke & Lang 2004, Pernkopf & Lang 2007, Schöpfer & Lang 2004, Walz 2006, Walz et al. 2001, Weiers et al. 2004) show off the potential of the approach for a variety of applications, including studies on

- biodiversity, habitat integrity, fragmentation;
- landscape planning and environmental assessments;
- landscape modelling and change analysis of land use patterns;
- catchment management;
- planning and landscape design.

Clearly, the objective of applying landscape metrics goes beyond describing and measuring patterns: its aim is to "[...] explain and understand the processes that occur. Thus the description of landscape pattern as an end in itself is limited" (Haines-Young 1999). In other words, the potential of the approach resides in its complementary use with other, more field-based investigations (Dollinger 2002).

Measures taken from the toolbox of landscape metrics describe spatial properties of a certain portion of a landscape. This 'portion' is often defined pragmatically (for example represented by an administrative unit boundaries or sometimes simply a rectangle; see figures 3b and 3c). Consequently, landscape limits representing ecological boundaries are often missing. Consequently, talking about 'the landscape' is often misleading when simply referring to an area of investigation. On the level of single patches, so-called patch metrics calculate basic geometric properties, e.g. area, edge length or shape (see figure 3, left). As patches are usually categorised according to a certain classification key, other metrics address the level of unique classes and their instances (i.e., patches assigned to these classes). On the level of classes any patch metric can be statistically aggregated (mean, standard deviation, etc.). We call these metrics class-aggregated. Furthermore, there are class-specific metrics, e.g. the summation of area-weighted distances (proximity). On the landscape level, we have landscape-aggregated metrics and landscape-specific ones. The latter comprise measures for assessing the overall spatial distribution of patches, either spatially implicit (composition, i.e., based on area percentages of classes) or spatially explicit (configuration). For a concise overview of the levels of landscape structure assessment see Lang & Blaschke (2007) or McGarigal (2002).

Spatially implicit:
measures which do not or only implicitly consider the actual spatial arrangement.

In many cases, neighbouring patches of the same category are separated by border lines. These lines may have important landscape functions and represent ecological boundaries (e.g. barriers, corridors, etc.). Such boundaries, due to their specific length-width ratio are often not represented as polygons but as line features. For practical reasons, neighbouring patches may be combined, the boundaries between them 'dissolved'. As shown in figure 3 (middle and right), this has implications for the application of landscape metrics. In order to avoid this effect the line features can be buffered, transferring them into disjunctive polygons.

Polygons:
a way of representing area features in a vector GIS.

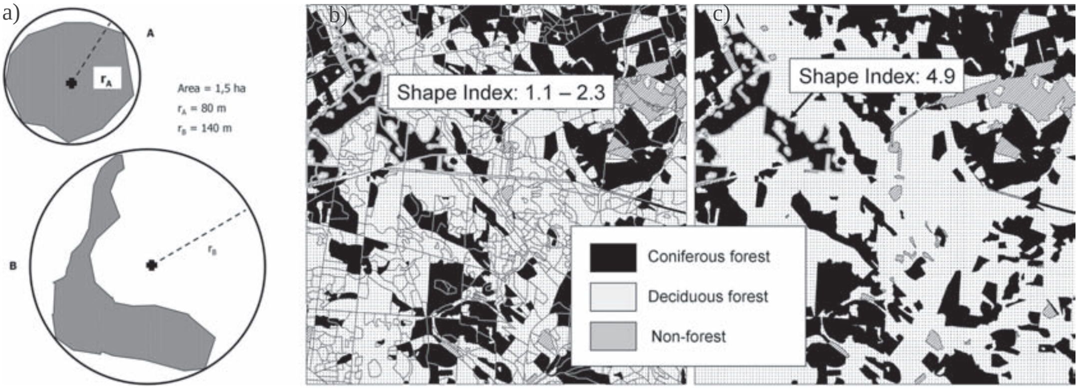


Figure 3. (a) Form metrics (radius of gyration). Note that patch A and B have the same size, i.e. 1.5 ha. (b) Original land use mapping with three classes for a 16 ha subset of a landscape. NP (number of patches): 1299. (c) Neighbouring patches of the same class are dissolved, NP drops to 200. Shape index for coniferous forest patches for the same landscape clipping. Shape index (SI) was calculated for a dissolved forest patch (right, SI = 4.9), and the 27 corresponding, non-dissolved patches (middle, SI ranges between 1.1 and 2.3).

2.2 *Categories of structural characteristics*

The exact number of potentially available metrics is difficult to estimate, as with any metric there are statistical derivatives attached to it. Statistically, many metrics are correlated and there have been attempts to de-correlate them and identify factors through e.g. principal component analysis (Lausch & Herzog 2002, Riitters et al. 1995, Walz 2001). Other approaches try to semantically narrow down the sheer number of metrics according to ecological (or other) aspects (Klug et al. 2003, Lang et al. 2002). Under the following subheadings six categories of landscape metrics are portrayed in a condensed form corresponding to main structural aspects. A selection of established metrics is given as representatives of particular sub-aspects (for a detailed overview see Lang & Blaschke 2007).

PCA (Principal Component Analysis):
a multivariate statistical method to identify and extract principal components in correlated datasets.

2.2.1 Area, density and edge metrics

Basic measures of patch size, perimeter, class, area in total or as a share are used for the calculation of most other landscape metrics. Particularly, patch area is often used in more complex metrics in order to enhance the effect of larger patches against the smallest. Concerning edges, the difference between adjacent patches can also be evaluated. Several metrics exist to measure heterogeneity under this aspect via edge length and edge density. Edges may be valuable transition zones between patches (ecotones, see below) and highly favourable, or function as barriers or borders. Thus, when not explicitly considering the quality of the linear elements, misleading results can be easily obtained. For example, when edges mainly consist of little roads or other barriers, the landscape needs to be considered as being highly fragmented instead of highly structured.

2.2.2 Form analysis

Patch size does not provide explicit information about the particular shape of a patch, but the latter can be measured in various ways. A categorisation of patch shape and the respective ecological implications is given by Forman (1995). The most common and intuitive measures are based on area-to-edge relations according the formula of circular area. ‘Shape Index’ (SI, cf. figure 3) values close to 1 indicate rather compact patches (close to a circle), whereas elongated patches yield higher values. More advanced metrics detect, for instance, the proportion of medial axis, the dissection of body or edge, and the curvature of the borderline (Moser et al. 2002).

2.2.3 Core area analysis

Boundaries between patches are often transition zones (ecotones) with a particular species mix (Forman 1995) or of any other abiotic buffer function. We can consider the interior of a patch as being ‘protected’ against influences from outside. For example, when looking at edge sensitive species that avoid boundaries, the effective area of a patch differs from its actual size by a specified core area distance. Methodologically, core areas are constructed by negative buffers. In cases where the initial patch is very small, no core area may be left over by this procedure. On the other hand, elongated and complex shaped patches like alluvial forests along a river may be split up in a larger number of small, disjunct core areas.

Buffer:
a GIS technique to construct a corridor around an outline or line with a specific distance.

Disjunct:
spatially non-adjacent.

2.2.4 Proximity and neighbourhood analysis

The proximity of patches may be influential to any processes depending on distance. For instance, proximity among neighbouring habitat patches may have a strong ecological influence on the viability of metapopulations (Hanski & Simberloff 1997, Wiens 1997). The metapopulation may be no longer viable, when functional exchange between suitable habitats through animal dispersal is not guaranteed. The ‘Proximity Index’ measures “both the degree of patch isolation and the degree of fragmentation” (McGarigal & Marks 1995). It is implemented as distance-weighted area in several variations (Lang & Blaschke 2007). A specific search distance (proximity buffer) reflects the potential dispersal range of the respective species or the range of any other abiotic process. It is assumed that larger neighbouring patches are more influential to smaller patches than vice versa. This results in higher values for smaller nearest-neighbour patches sharing the same distance. A zero (0) value is assigned to patches, which are situated outside the buffer distance. Alternatively, the least cost path edge to edge distance can be analysed, as well as other neighbourhood measures evaluating the coaction of adjacent or distant patches.

Least cost path:
a technique to calculate an optimised path based on cost minimising, whereas ‘cost’ is taken as a generic concept (e.g. distance, altitude, etc.).

2.2.5 Diversity analysis

Still, another aspect of landscape heterogeneity is addressed by the group of Diversity metrics. For instance, based on information theory (Shannon & Weaver 1949), the ‘Shannon Index’ quantifies landscape composition. The basic element of the formula is area percentage of classes. Diversity metrics should be taken with care when interpreting absolute values; they prove more suitable for comparative studies. Due to the fact that the number of classes (increasing potential richness) influences diversity, this group of metrics strongly depends on the number of potential categories provided by the classification scheme (thematic resolution). Evenness metrics detect the share of class proportions, excluding the thematic resolution.

Thematic resolution:
the degree of detail of a given classification scheme.

2.2.6 Subdivision analysis

The group of subdivision metrics measure landscape dissection and fragmentation on the level of specified classes (Jaeger 2000). Landscape dissection (e.g. by roads) does not imply significant loss of area, as the portion of land covered by the dissecting lineaments is comparatively small. Still, every dissecting element has an effect on the coherence of the (remaining) landscape, and the influence of the subdivision effect is measurable by the so-called effective mesh size and related measures.

2.3 *Landscape metrics as structural indicators*

Indicators can be of different temporal and spatial scale, but even local level indicators are very often not spatially explicit. But many applications on the local scale require decisions to be supported by spatial explicit indicators (Blaschke 2001) as, for instance, landscape metrics. In many cases a certain metric is difficult to interpret, simply because we know little about the links between measured structure and underlying processes. This in particular applies to the complexity of culturally grown, small-scaled landscapes within Europe. In terms of a non-ambiguous interpretation, there are at least three aspects to be considered:

- Firstly, there may be certain cases, in which increasing or decreasing values do not unambiguously indicate the improvement (or deterioration) of a certain status. For example, when determining *Edge density* at t_0 and then looking at respective values at t_1, higher values may indicate a richer and more complex structure, which from an ecological point of view may be considered more valuable than a poorer, more uniform structure. On the other hand, higher values may also be triggered by an increase of dissecting linear structures (roads, transmission lines, etc.), which leads to an unfavourable status as compared to t_0.
- Secondly, results often cannot be interpreted by looking at absolute values alone, but need to be seen in relation to specific requirements, such as the needs of a species with respect to its habitats. Using *Area* as an indicator may reveal critical values for some particular species with given minimum habitat requirements, whereas the same values may prove insignificant to other species which react invariant to a certain patch size. Related to this, additional parameterisation may be needed in order to calculate certain metrics (e.g. specific distances when assessing proximity or isolation).
- Thirdly, results may be dependent on the interpretation key and the number of classes being used when a spatial representation of a certain landscape is established. For example, the comparison of two landscape portions with significant differences in forest cover may reveal inverted results if diversity is calculated on land use classifications of different details.

There are few structural measures used in operational monitoring of ecosystems in the European Union, but suggestions by the Joint Research Centre of the EU promote the use of landscape metrics at a landscape level based on remote sensing images (JRC 1999). Lausch & Herzog (2002) review existing land use indicators and see potential for indicators that quantify landscape pattern in this context. However, they stress the need for harmonisation of landscape metrics regarding input data, data processing and the selection of landscape metrics in order to make standard applications of those metrics in land use monitoring effective (Langanke et al. 2005).

Being aware of the shortcomings and interpretational problems of some landscape metrics, a carefully selected set of spatially explicit landscape metrics may be used as target-oriented structural indicators. For

Land use monitoring: *observation of certain land use patterns in regular time intervals applying standardised methods.*

IDEFIX (Indicator Database for Scientific Exchange):
www.geo.sbg.ac.at/larg/idefix.htm

SPIN (Spatial Indicators for European Nature Conservation) project:
duration: 2001–2004.
www.spin-project.org

ArcGIS:
a GIS and Mapping Software provided by the company ESRI. ArcGIS is a complete system und integrated collection of GIS software products.
www.esri.com

V-LATE (Vector-based Landscape Analysis Tools Extension):
provides a selected set of the most common metrics to cover basic ecological and structure-related investigations.
www.geo.sbg.ac.at/larg/vlate.htm

selection criteria of metrics see for example Syrbe (1999). Based on a comprehensive literature study, metrics have been identified and transferred to a database named IDEFIX (Indicator Database for Scientific Exchange) within the SPIN project (EVG1-CT-2000–00019) (Klug et al. 2003). The database facilitates research and provides assistance in interpreting structural indicators. IDEFIX users get familiar with the metrics available, their behaviour, biases, and limitations. The focus is set on semantic content and the relationship to specific ecological issues rather than on mathematical discourse. The database allows for an appropriate choice of a delimited and sound set of metrics. The IDEFIX database has been designed for pan-European issues related to the Natura 2000 concept, especially in the context of monitoring and change detection tasks, but can be utilised in any other context. For the calculation of selected measures, the database has been linked to the ArcGIS extension V-LATE (vector-based landscape analysis tools extension, Lang & Tiede 2003).

3 IMPLICATIONS FOR CHARACTERISING HISTORIC LANDSCAPES

Changes of land use often take place as small-scale measures with local impact, and maybe insignificant if taken in isolation and assessed independently. However, by cumulative effects under both spatial (neighbourhood) and temporal (accumulation) aspects they can lead to significant changes of regional structures and environmental conditions. Therefore, important tasks of landscape ecological research at present are to monitor and assess natural resources, to examine impacts and effects of human intervention and, last but not least, to observe the state of the environment over long time periods.

Current main processes of landscape change result in alteration of landscape structure. One of these processes in central Europe is the suburbanisation around urban areas, while another process affects the rural areas by increasing fragmentation through infrastructure and communication lines. In addition, in many European regions the actual trend in agriculture leads to intensively used large field plots. Structural changes have consequences for landscape functions, like biodiversity, potential for food production or human recreation. Therefore, investigating changes of landscape structure aims at the following questions:

- How have land use and the landscape structure changed over historical time periods?
- How have these changes affected the ecosystem pattern and biophysical processes?
- Can general trends be deduced on structural land use changes over the next few decades?

Against this background, it is important to use landscape metrics for the evaluation of the effects of structural changes on selected environmental protection goods.

3.1 *Historical maps and other data sources*

Digital preparation and analysis of historical maps and subsequent digital land use mapping using GIS techniques are the basis for such evaluations of historic landscape structure. This enables the spatial and statistical appraisal of large time series and allows connecting them with natural-spatial data.

Preprocessing:
a set of methods to prepare and integrate digital datasets used for GIS analyses.

Since the 18th century land surveys in Europe have provided suitable cartographic bases for historical landscape analysis. Examples are the Swedish Register Maps (1692–1709), the "Topographic maps" of the Prussian land survey since 1830, the "Saxon Milesheets" since 1780 or the First Austrian land survey (1764–87), the latter covering large parts of Eastern and Central Europe. Similar map series are also available for other parts of Europe. These maps have sufficient resolution in terms of geometry and content for medium-scale studies and allows landscape development over more than 200 years to be investigated. Older maps are rarely accurate enough and should at most be used for supplementary information.

Historical landscape analysis:
cf. chapters "The concept of a historic landscape analysis using GIS" by Bender and "Use of historical cadastral maps in modern landscape research and management" by Domaas & Grau Møller.

It is important to consider the specific quality when comparing map contents from different times. Special attention should be paid to geometrical accuracy (measurement errors), the differing information content and the scale dependency of the spatial accuracy. The study of land use change at national level can serve for statistical purpose and the determination of overall trends only. At the regional scale, general trends of land use classes may vary due to the specific bio-physical settings. Furthermore, especially for the calculation of landscape metrics the accuracy of the data is important. The generalisation on larger cartographic scales can bias the results.

Geometrical accuracy:
spatial measurement errors or uncertainties residing in the data source.

Generalisation:
is the process of abstracting/simplifying cartographic information as a result of changing scales accompanied by increasing complexity.

Studying landscape change in periods of recent centuries should also be supported by means of other sources and materials documenting land use and the reasons why it changed. For example, additional useful information is contained in historical landscape descriptions, local chronicles, street maps, register maps, and increasingly remotely sensed data as well as landscape paintings and special lawsuit map sections. In addition, geomorphologic and stratigraphic-pedologic studies can contribute to the analysis of previous landscape changes.

Remotely sensed data:
cf. chapter "The use of satellite remote sensing for detecting and analysing cultural heritages" by Heinrich et al.

3.2 *Notes on data preparation for analysis of landscape structure*

As a first step, the historic maps need to be georeferenced. The second step is the digitising or vectorisation of the land use information taken from the historical maps. This can be done by "backward editing". For this method, the present (existing) land use vector-layer on the screen is underlain by the historical map while only the changes in the geometry have to be edited. This process is repeated for all historical maps used, beginning with the newest and incrementally proceeding to prior maps. For the further analysis of land use and its development over time, a combined dataset consisting of cartographic linear and polygon features is essential. This is important because polygon features are often divided by linear objects, like roads, streams, hedges that exhibit a certain width and thus area. Also for the analysis of ecological processes, for example soil erosion, it is necessary to combine lines and polygons for instance, to delineate such important erosion barriers as field boundary ridges or hedges within the polygons (Neubert et al. 2008).

3.3 *Problems of comparability*

Legend:
the reference area on a map that lists and explains the colours, symbols, line patterns, shadings, and annotation used on the map.

When processing and comparing available maps, it must be borne in mind that they vary in terms of survey techniques, map contents and given details depending on the time when they were produced. Moreover, old maps often do not include legends or any other form of explanation. The introduction of the Prussian legend in the new edition of the survey maps around 1870 was the first time that clear, uniform map symbols were used (in fact a modified set of the same symbols is still employed nowadays). Other difficulties result from the different areas covered owing to the changing borders of the several states. Any analysis of historical maps must therefore start with an examination to determine congruence and comparability between modern and historical maps. For the analysis a unified legend should be compiled (Neubert & Walz 2002, Walz et al. 2001).

3.4 *Metrics as indicators for land use change*

The results of an investigation into historical landscape development primarily consist of quantitative statistical information on historical states. Only by standardisation, it is possible to assure the comparability and reproducibility in different investigation areas. The difficulty is the selection of metrics which provide universally valid results, independent from the specific situation of the test site.

In most cases relatively simple, straightforward landscape metrics are used (table 1), because they are easy to interpret and comprehensible for presentations in the public.

3.5 *Examples of investigations*

Studies on land cover change can be found at very different levels of scale, from European across nationwide over to very local for single communities. For example, in a research project on cultural landscape in Austria, landscape metrics were used for an appraisal of the whole state (Wrbka et al. 2002). At the European scale, landscape metrics were mainly used for the description of biological diversity (European Commission 2000) and as indicators for changes in agricultural landscapes (European Environmental Agency 2001). Different research studies in Germany evaluated the effects of land use changes on landscape function on the medium scale (Haase et al. 2007, Neubert et al. 2008). At the local scale, there are investigations of Bender et al. (2005), who assessed landscape change on the basis of land register maps for different communities in Bavaria. Cousins (2001) conducted a study on change of agriculture in Sweden also on basis of cadastral maps and on additional aerial photos. The development of the National park region “Saxon Switzerland”

Table 1. Landscape metrics as indicators for landscape change (cf. Neubert & Walz 2006).

Information	Indicator
Division of landscape into small patches	Measurement of areas: Mean Patch Size Measurement of edges: Edge Density
Heterogeneity of patch areas	Variation of patch area: Patch Size Standard Deviation, Patch Size Coefficient of Variation
Fragmentation (e.g. by infrastructure)	Measurement of edges: e.g. Mean Patch Edge Measurement of areas: Effective mesh size, area of unfragmented spaces
Shape and complexity of land use patches	Shape indices: Mean Perimeter-Area Ratio, Mean Shape Index, Mean Fractal Dimension, Double Log Fractal Dimension
Richness of a landscape	Dominating land use class
Distribution/regularity of arrangement and alteration of land use patches	Interspersion and Juxtaposition Index Diversity- and evenness indices: Shannons' Diversity/Evenness
Degree of isolation of patches within same land use classes	Mean Proximity Index

(figure 4) showed the 'loss' not only of land in terms of total area but also of resources and landscape functionality even in such a nature protected area (Walz 2005a).

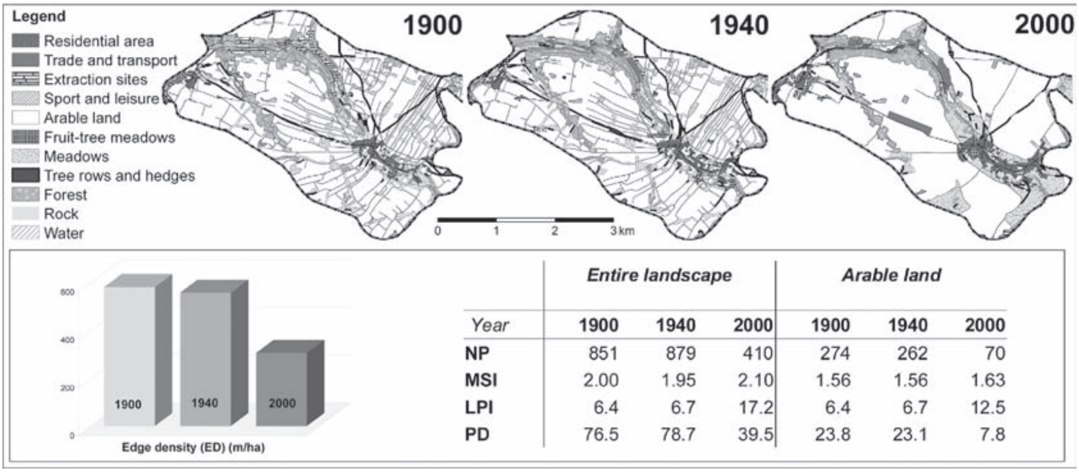
3.6 *Further work*

Further works need to focus on the development of complex evaluation methods for the impact of land use changes on the functionality of landscapes. Considering the landscape structure is one important issue, but a lot of other information is necessary for its assessment. The actual trend in the field of landscape metrics shows the direction. Landscape metrics are often part of complex ecological models, however it can hardly be expected that landscape metrics themselves can deliver information as an assessment indicator.

4 LOOKING INTO THE FUTURE – LANDSCAPE METRICS AND LANDSCAPE PLANNING

4.1 *Integration of landscape metrics in landscape planning*

As technological progress and ever growing human demands make the world change rapidly, time periods of significant change seem to be occurring more rapidly than in previous decades (Bastian & Bernhardt 1993). Consequently, people permanently try to adapt themselves to their local environment to make life easier or even more profitable. Adaptation



	Entire landscape			Arable land		
Year	1900	1940	2000	1900	1940	2000
NP	851	879	410	274	262	70
MSI	2.00	1.95	2.10	1.56	1.56	1.63
LPI	6.4	6.7	17.2	6.4	6.7	12.5
PD	76.5	78.7	39.5	23.8	23.1	7.8

Figure 4. Landscape change in the National park region “Saxon Switzerland”. Natural unit “Wehlener Ebenheit”. (Processing: U. Walz, IÖR). NP = number of patches, MSI = mean shape index, LPI = largest patch index, PD = patch density.

to new situations means shaping the landscape and thus having an impact on the landscape structure. From a spatial perspective landscape planning is similar to the adaptation to new situations. The important tasks in landscape planning exercises are to examine the cumulative spatial impacts and the effects of human intervention on processes and functions with consequences in their substance, matter and energy exchange mentioned above. Considering landscape planning as a means to provide scenarios of how the future may be, an upcoming challenge in future applications using landscape metrics will be to structurally describe, analyse and evaluate planning results. Comparing them with the present status will enable forecasting and prediction of the question: “What planning option may result in which positive or negative effect?”

4.2 *Strength and weaknesses of landscape metrics in planning studies*

Given the rapid rate of change and the decreasing time horizon for reaction, understanding the complexity of landscapes and their pattern is an essential requirement to devise pro-active rather than re-active strategies for landscape development and future scenarios. Therefore, landscape planning – as an endeavour to design best suited spatial arrangements of landscape elements – is strongly coupled with landscape development. Landscape development relies on modelling outcomes supported by empirical evidence. It is based on decisions made within a landscape planning procedure with the aim to predict long-term social, economic and ecological effects of landscape alteration to maintain future demands to multifunctional landscape resources.

In order to structure the complex system of landscape planning for an achievable future state (German: ‘Leitbild’), landscape metrics can be used to support decisions between alternative planning solutions. In response to this challenge, this section briefly highlights some major obstacles and potentials the landscape metrics approach holds for describing, classifying and planning landscape visions embedded in a trans-disciplinary, holistic concept.

For assessing future planning states of landscapes, landscape metrics are supportive in comparing present states and conditions with aspired future land use allocations. They are useful for deriving potential process-based scenarios and showing the functional consequences of changes being diagnosed. As Tischendorf (2001) noted, landscape metrics are able to effectively predict ecological consequences resulting from land use changes and changes in landscape pattern. Furthermore, landscape metrics may be a useful toolbox for characterising differences among planned alternative development strategies (Jongman 1999). As an example, Pernkopf & Lang (2007) analysed alternative road infrastructure developments using the effective mesh size (Jaeger 2000) to find a suitable route with less impact on landscape fragmentation (figure 5).

However, the quantification and unique characterisation of present and future states, or the comparison between alternative futures are the main challenge of using landscape metrics. A comprehensive understanding of landscape processes and functions as well as their interconnections are necessary to give qualitative value to the spatial characteristics derived from the given landscape pattern (Klug et al. 2003). The linkage between ecological processes and landscape metrics has been paid too little attention in many studies (Thompson & McGarigal 2002). Nevertheless, a range of publications have demonstrated the applicability of landscape pattern indices for characterising landscapes (Corry & Nassauer 2005, O'Neill et al. 1988), but limited knowledge has been derived from the quantifications in various case study areas (Botequilha Leitao & Ahern 2002). Accordingly, there is a certain lack of evidence that pattern-based indices are directly interlinked with ecological processes. In addition, the transfer

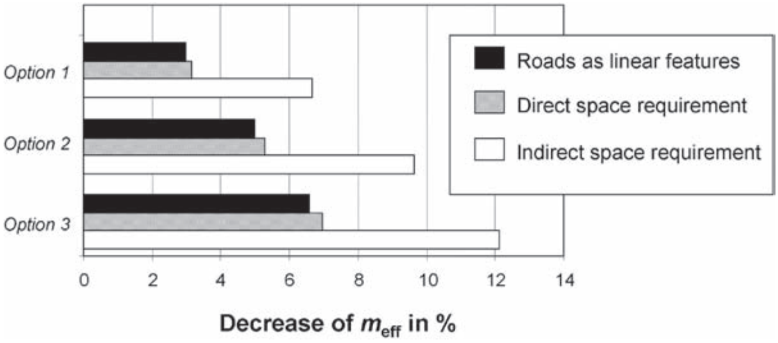


Figure 5. Comparison of the impact three scenarios for road construction using the indicator Effective Mesh Size (m_{eff}) under three different options: (1) roads taken as linear feature only (black bars), (2) considering direct space requirement of road construction (dashed bars), (3) considering indirect space requirement due to noise and other ecological disturbances (white bars) (Pernkopf & Lang 2007, modified).

of knowledge about the behaviour of landscape metrics to different case study areas is still limited, as is the scalability of landscape metrics in different scale domains (upscaling, downscaling) (Corry & Nassauer 2005, Gustafson 1998, Thompson & McGarigal 2002, Turner et al. 2001).

Klug & Blaschke (2003) and Klug & Zeil (2004) give a practical example using landscape metrics for catchment-level planning and catchment management. They examine relationships between land use allocations and water pollution distribution and discuss how different kinds of metrics can contribute to answer different questions from the European Water Framework Directive (Directive 2000/60/EG). Buffer stripe implementation as a contribution for preventing surface waters from eutrophication, and retention area for water to minimise high water impact on downstream villages and cities were analysed. They conclude that despite the fact that a common ecological interpretation of the metrics used is lacking, the usability of landscape metrics for tracking the consequences and impacts of the measures being planned is high.

But there are more challenges to tackle. Many applications of landscape metrics focus on habitat models, dealing with the quality and connectivity of habitats with special attention to certain species. In many such studies habitat structures and process-based behaviours of single species have been analysed without considering the impact on other species and habitats nearby or at the same place, or on other compartments such as water, soil, relief or climate. The multifunctional character of cause-and-consequence relationships requires a more pronounced focus on pattern and process.

As a conclusion, landscape metrics serve landscape planning purposes to contribute to the evaluation of future scenarios and compare them with present situations, but cautious use in making inferences from landscape patterns to alternative landscape scenarios is recommended. On the other hand, landscape metrics are not supposed to fulfil the objectives of landscape planning when used in isolation. Landscape planning has many disciplinary and organisational facets. According to the latest standards, landscape planning should involve the public in a transdisciplinary planning process to consider social, economic and ecological perspectives in equal parts. Spatial planning concepts should be enriched with socio-cultural and financial aspects which cannot be assessed by landscape metrics alone. Hence, landscape metrics can only play an important, but not exclusive role in measuring the spatial distribution and arrangement of land use or land cover. They may help drawing better conclusions for the better steering of the processes and functions that depend on the change of landscape pattern.

4.3 *Further research requirements*

Further research in applying landscape metrics need to go beyond a mere experimental stage to equip alternative future plans with quantitative values that can be evaluated and compared. What is required is a shared knowledge stock with evidence-based explanations and hints on the interpretation of results having been achieved and metrics successfully applied as indicators. There are tools available (e.g. Fragstats 2.0, V-LATE, Landscape Analyst, see Lang et al. 2004), but to make them fully available and operable for designers and planners is still a challenge (Botequilha Leitao & Ahern 2002). What is needed is more assistance in evaluating alternative plans to give decision makers support to effect informed decisions. We need to elaborate knowledge on how landscape metrics are related to landscape quality objectives. These aggregated objectives should be tracked by landscape metrics as indicators to predict future scenarios consistently.

5 CONCLUSION & OUTLOOK

We can conclude that landscape metrics are "doable" by any GIS-literate person. But the existence of a satisfactory amount of methods and tools does not guarantee any improvement of the investigations carried out. We may compare it to statistics: figures about distributions of numbers or instances alone may only partially, or in certain cases, help explain or solve a problem. A trivial but sometimes overlooked fact is that the computer will always generate numerical results or – more specifically – landscape metrics. Only if we find standardised and widely agreed "measures" with the reality, then landscape metrics may become operational part of landscape planning processes. Like the accuracy assessment in remote sensing every set of metrics may then be accompanied by standardised and widely known accuracy measures. Since there is no "right" or "wrong" we may aim for "relevant" or "irrelevant" as major categories of such a metrics. In figure 6 the two landscapes represent roughly the same landscape metrics. Researchers may want to find out whether or not either of the two particular distributions may be relevant to the problem under investigation.

Especially when it comes to the concept of "sustainable landscapes" (Antrop 2006, Blaschke 2006, Potschin & Haines-Young 2006) the particular realisations of similar statistical pattern as shown in figure 6 may make a difference. The term 'spatial quality' has been introduced to underline this phenomenon. Antrop (2006) states that the notion of sustainable landscapes involves a contradiction. Landscapes because of their unpredictable and evolutionary nature, may contribute to sustainability, but they are not sustainable in themselves. Therefore sustainability is positioned in the character of change, and not in terms of any optimal state (Vanautgaerden 2005). As landscape changes, also its meaning and significance changes and consequently its management should be adapted.

As methods for habitat patch delineation have improved significantly over the last 20+ years to better inform our understanding of landscape metrics, we witness now an increasing amount of empirical studies investigating organism-specific use of habitat patches (Girvetz & Greko 2007). Similarly, measures are needed at a landscape-level which are "ecosystem

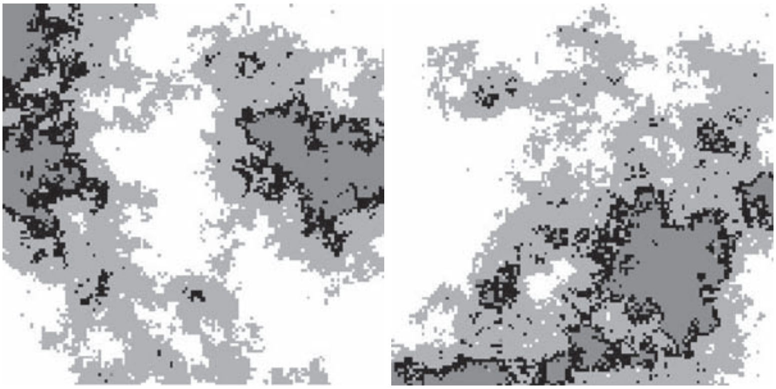


Figure 6. Two artificial landscapes (so called "Neutral landscapes") with similar landscape metrics generated randomly using the same distribution and spatial clumping functions.

Neutral landscapes: *landscapes generated (mostly randomly) by special algorithms varying the portions of contributing classes for testing landscape metrics.*

function sensitive". This observation goes hand in hand with the recognised need for a parsimonious core set of metrics, a requirement stated from the 'early days' of landscape metrics (Blaschke & Petch 1999, Cain et al. 1997, Griffith et al. 2000, Lausch & Herzog 2002, McGarigal & McComb 1995, Neel et al. 2004, Riitters et al. 1995, Scanes & Bunce 1997, Tinker et al. 1998). These studies and many others suggested that patterns can be characterised by relatively few components. But a brief review of these studies does not reveal a concordance in the identification of important landscape structure components. These facts lead to the conclusion that there may be no fundamentally important aspects of landscape structure *per se.* With some caution we may conclude instead that structure patterns are discriminatory to specific landscapes. Some of the authors cited above argue that the problems of comparability are more likely a consequence of the fact that the different studies did not use the same pool of metrics, the same data types and accuracies, and that they used different methods to identify components. But if our skepticism holds true, comparisons between landscapes based on landscape metrics stay difficult.

The authors believe that we do need less severe restrictions for comparisons within the same landscape or region. This is a positive message to the readers: rather reducing comparative assessments of landscapes across Europe to mere quantitative measures, we may concentrate on the concept of "sustainable landscapes". Given the complexity of real landscapes and real world communities a future research need is to develop alternative solutions in the planning cycle serving the needs for multiple uses and – consequently – multiple scales. Conceptually and in accordance with Blaschke (2006), the authors believe that a key issue will be the ability to take into account the multiplicity of (spatial) scales of study so that each phenomenon studied at its specific level can be integrated through hierarchically organised spatial concepts.

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Part IV

Case studies

Geomorphological study of Thera and the Akrotiri archaeological site

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ABSTRACT

This chapter concerns the application of computing technologies in Geoarchaeology. The main issue is the combination of GIS and remote sensing technologies with on-site observations of the archaeological, geomorphological and geological characteristics of the area. This combination involves gathering all the necessary information of the spatial structures: geological, topographical, geomorphological and archaeological data. The main target is the composition of the palaeolandscape in order to reveal the paleotopography of Thera and the archaeological site of Akrotiri before the Minoan eruption. GIS analytical tools may help to recreate the different phases of landform evolution of Thera before the Minoan era till nowadays. Thus, 3D models before the Minoan, during the Minoan and after the Minoan phase were produced. Furthermore, the chapter focuses on the geomorphology of Akrotiri site, the most important archaeological site on Thera. The geological formations and the dominant erosion and deposition processes were mapped in order to understand the geomorphological evolution of the area. The extensive reworking and adaptation of the geomorphology from sustained volcanic activity over a long period has resulted in huge physical changes: loss of a central area of the island, coastline modifications, soil loss, deposition and abandonment of valleys and settlement sites. This abrupt evolution have played a major role to the land use change and land cultivation, strongly affecting the local communities, perhaps emphasising and coinciding with distinctive periods of cultural expansion and contraction.

1 INTRODUCTION

This study focuses on the application of new technologies to study how geomorphological processes are affecting ancient settlements. Emphasis is placed on the meaningful combination of geomorphological and environmental data with archaeological features, within Geographic Information Systems. The application of modern technologies and GIS in the fields of archaeology and, more generally, cultural heritage has become widespread in recent decades within the international scientific sphere.

Thera is situated in the Aegean Sea, and is part of Cyclades area (figure 1). Thera, along with Therassia and Aspronissi, form a circle and are the remains of the boundary of a caldera created by past volcanic activity. The caldera is partly submerged and its centre is occupied by two volcanic islands, New Kameni and Old Kameni. The caldera of Thera is one of the largest in the world: 11 km (N–S) by 7.5 km (E–W). The volcano has erupted numerous times during Quaternary, forming a distinctive landscape which may be characterised by major geomorphological events. The topography of Minoan Thera has been modified through the deposition of volcanic tuffs, both in the valleys and on the coast line, radically reshaping the island.

The geological structure of Thera is characterised by a non-volcanic substratum, a complex of volcanic series and alluvial deposits. The basement of Thera is composed of Triassic crystallic limestones and dolomites, phyllites of Eocene age (Tataris 1964) and a Miocene Granitic Intrusion (Skarpelis & Liati 1990). These formations are highly deformed (folded and thrusted), while the granitic intrusion seems to be the dominant lithological formation of the substratum, according to the results of many drillings (Kourmoulis 1990). The second category of rocks dominating Thera is a continuous series of volcanic products dated from 1.6 million years (Ferrara et al. 1980) until modern times. The volcanic series of Thera are characterised by an alternation of volcanic lavas and pumice (Druitt et al. 1989, Pichler & Kussmaul 1980). Generally, the various writers distinguish

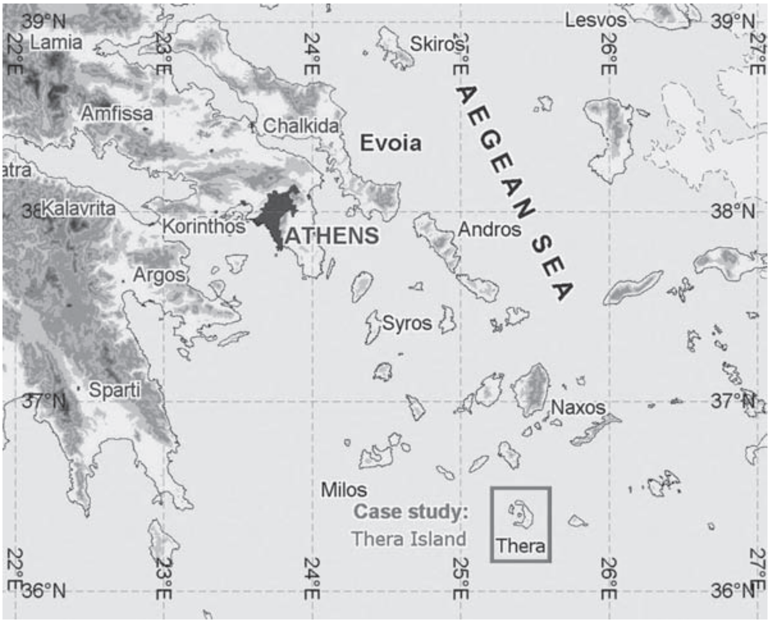

Figure 1. Location of Thera Island in the Aegean sea.

three horizons of pumice: the lower, the medium and the upper. The volcanic activity is probably related to the extensive tectonism, orientated in a NE–SW direction, the so-called Kameni line (Druitt et al. 1989).

Thera contains a range of different types of archaeological sites dating from the Neolithic Era onwards. Buildings, walls, graves, and ceramics, discovered under the pumice, have revealed settlements such as Akrotiri (ca. 7000–1670 BC), which was found buried under ash and pumice. Potentially, according to comparative studies and spatial analysis of the available land for settlement development, 62 such sites may have existed in Thera. Though it is likely that only 39 are preserved; areas on the slopes north of Oia and on the western side of Therassia are likely to contain some of them.

Archaeological data testify that during the last centuries of the 3rd millennium BC, Akrotiri had become an urban settlement and its harbour had begun to play an important role in communication with the rest of the Aegean. The harbour of the settlement was totally submerged after the Minoan eruption. According to a theory of Marinatos (1972), the coastline in the prehistoric period could be found roughly 800 m further south than today. On the contrary, Doumas (1983) believes that the beach was situated 50 m to the north of the current one.

This chapter analyses the geomorphological evolution of Thera Island and describes the processes which have modified the ancient settlement at Akrotiri. Many projects in a wide spectrum of sciences have studied the island of Thera (Friedrich 1980 and 1990, Fytikas et al. 1984, Galanopoulos 1958 and 1971, Heiken & McCoy 1984, Lagios et al. 1990, Lohmann 1998 and 2005, Marinatos 1968 and 1972, Ninkovich & Heezen 1965, Skarpelis & Liati 1990, Velitzelos 1990 and 1991). Despite the aforementioned studies, the geomorphological references are relatively rare (Gournelos et al. 1995).

The main tool of this study was a Geographical Information System. This has been used in many different stages, in order to form the geomorphological and archaeological database and to analyse the spatially referenced parameters. Different scale topographic maps (1:50,000, 1:25,000 and 1:5,000) provided by the Hellenic Military Geographical Service (1990) and the geological map of the Geological Institute for Mineral Exploration (I.G.M.E. 1980) were vectorised and used as input data. The database was completed using data derived from interpretation of aerial photography and satellite imagery as well as from detailed field work.

Secondary maps have been produced by analysing primary data layers; further quantitative analysis of the altitudinal data has been carried out. Models of modern landscape settings (digital elevation model, slope maps, morphological features) have been developed in order to be compared to the island's palaeorelief. The GIS software MapInfo Professional (V8.5) and ERDAS IMAGINE have been also used for the data analysis (figure 2).

MapInfo Professional:
GIS software for mapping and geographic analysis.
www.mapinfo.com

ERDAS IMAGINE:
a suite of software tools designed specificially to process geospatial imagery.
www.erdas.com

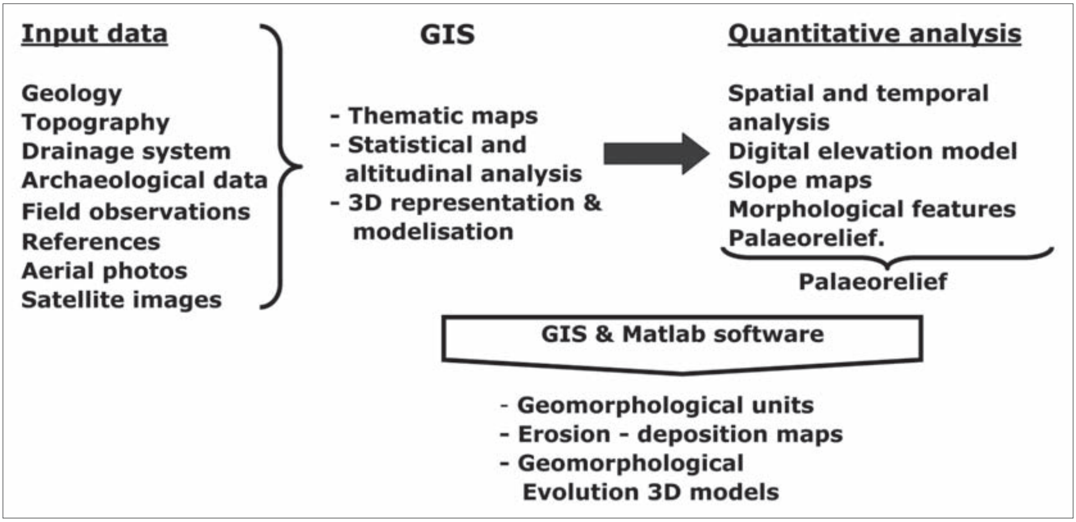

Figure 2. Flow diagram of the procedures involved in this work.

2 RESULTS

2.1 *Geomorphology of Thera Island*

The present relief of Thera is the result of intense tectonic and volcanic, as well as erosional-depositional processes. The drainage network of the islands of Thera and Therassia is generally radial. Secondary watersheds are also of the same orientation, apart from the area of Prophet Ilia.

Five geomorphological units have been distinguished in the Thera Island (figure 3):

1. The Limestone-schist Unit (Prophet Ilia – Vlychada). This formation is found in the south-eastern part of the island and mainly constitutes of crystalic limestones, dolomites and phyllites that represent the pre-volcanic relief of Thera.
2. The volcanic clusters (M. Vouno – Small Prophet Ilias – Skarou) which are located in the Northern part of the island are mainly formed by andesitic lavas.
3. The Minoan volcanic relief which has a crescent form in Thera as well as in Therassia. This unit may be further divided in two sub-units, the one having a smooth relief and the other presenting a rough relief.
4. The Caldera which is the most impressive landform in Thera and has attracted many researchers over time.
5. The Unit of the newer volcanic islands, Old and New Kammeni, whose recent creation expresses the most recent volcanic activity.

For the caldera area, a detailed altitudinal analysis has been undertaken. Thus, altitude histograms for seven areas of the Caldera have been developed: three for the northern part, three for the southern part and one for Therassia (figure 4).

Figure 3. The five geomorphological units of Thera complex.

From the distribution of the altitudes three caldera sub-units may be grouped, which reflect paleotopographic similarities:

1. The Therassia northern part (Th3, N1)
2. The central part (N2, N3, S1)
3. The southern part (S2, S3)

The first sub-unit presents a mean altitudinal value of 97 m with maximum value about 300 m. The second sub-unit is characterised by mean altitudes of 135 m and maximum values about 320 m. Finally, the last sub-unit presents a mean value of 65 m and maximum altitude about 180 m (tables 1 and 2). These three caldera sub-units indsicate the topography of the island before the Minoan eruption and are the fractured remains of the complex volcanic cone. This cone was characterised by a central higher part (sub-units N2, N3, S1) and two lower parts (Therassia northern part and southern part). In general, the whole topography of the caldera may be visualised taking into account its submarine relief (Heiken & McCoy 1984, Perisoratis 1990).

2.2 *The three stages of the evolution of the Thera topography*

The geomorphology of Thera, considering its structure and its dynamical multistage evolution, have been divided in three main periods: 1) before the Minoan period, 2) the Minoan eruption, and 3) after the Minoan eruption.

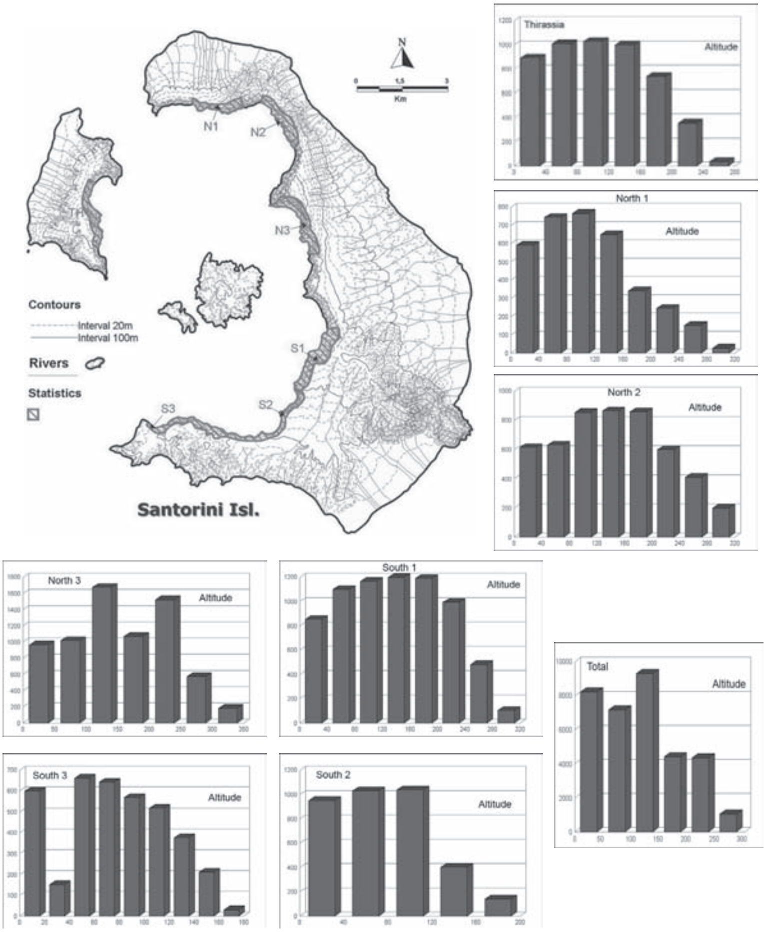

Figure 4. a) Spatial distribution of the caldera subunits. b) Altitudinal histograms of each subunit.

Table 1. Statistics of the caldera subunits.

	Th3	N1	N2	N3
Count	5056	3518	5035	7007
Minimum	0	0	0	0
Maximum	260	300	300	320
Range	260	300	300	320
Sum	487720	348420	658660	1010980
Mean	96.46	99.04	130.82	144.281
Variance	3888.92	4740.75	6138.34	6649.29
Standard Deviation	62.36	68.85	78.35	81.54

2.2.1 The topography of Thera Island before the Minoan eruption

Referring to relief before the Minoan period (figure 5), it is possible to describe the characteristics of the volcanic landscape just before the destructive eruption. The pre-Minoan relief of Thera is under

Table 2. Statistics of the caldera subunits.

	S1	S2	S3	Average
Count	7089	3560	3758	5003.3
Minimum	0	0	0	0
Maximum	280	180	160	257.14
Range	280	180	160	257.14
Sum	881480	221900	244640	550543
Mean	124.35	62.33	65.10	103.2
Variance	5520.18	2078.72	1761.34	4396.8
Standard Deviation	74.30	45.59	41.97	64.71

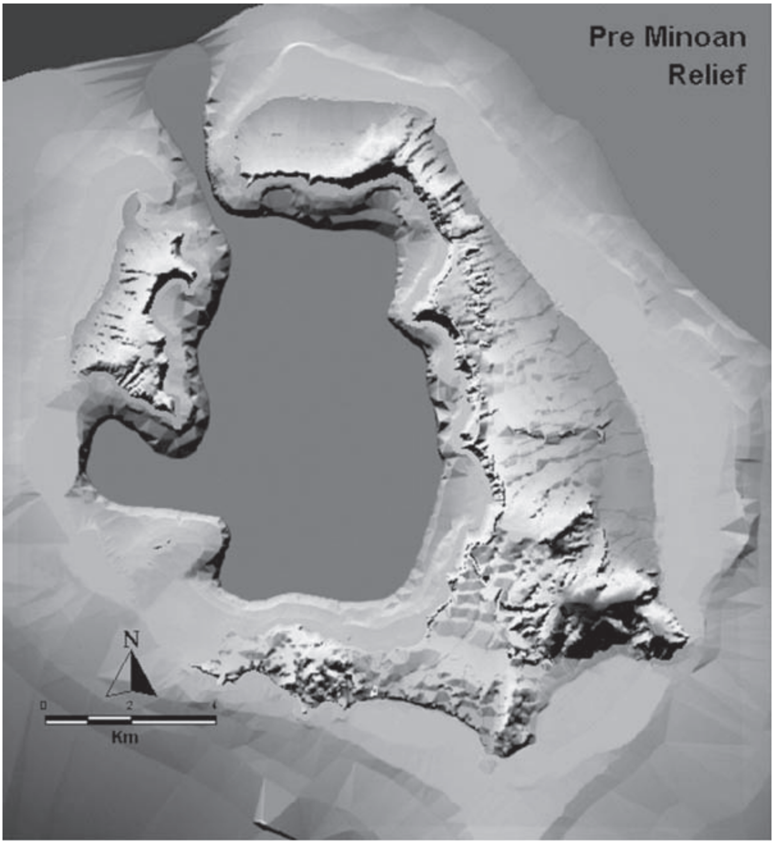

Figure 5. Thera’s relief just before the last great Minoan eruption.

investigation by many scientists. The pre-Minoan relief discussed in this chapter comprises of the common areas existing during and after the Minoan eruption period as well. The drainage network was, in general, radial. Most of this ancient topography had been covered by the middle pumice deposits. The age of these series is between 110,000 ± 21,000 years (Seward et al. 1980) and 110,000 ± 13,000 years (Pichler & Friedrich 1976). In some places, especially in the northern part of the island, lava shields are interbedded in the Middle series. The palaeotopography of this period has been suggested using fossils in the middle pumice series and paleosoils. Stomatolite remnants of 17,000 years have been found in the northern part of Thera (Friedrich et al. 1990) showing the existence of a shallow caldera area. Furthermore, different plant remnants (Friedrich 1980, Friedrich & Velitzelos 1986, Velitzelos 1991) suggest that a topography poor in trees and bushes had developed in climatic conditions similar to today's. The stages of the caldera formation are very complicated and there are controversial opinions concerning its evolution (Druitt & Francaviglia 1990, Druitt et al. 1989, Heiken & McCoy 1984, Pichler & Friedrich 1980).

Erosion processes were dominant upslope, while deposition occurred in the footslope areas. This became obvious by mapping the small palaeo-valleys and the palaeo-gullies in both sides of the caldera. In general, many volcanic structures dominate the north-central part of the island. These structures are steeper than in the southern part, except the area of Prophet Ilias which is the limestone mountainous area in the

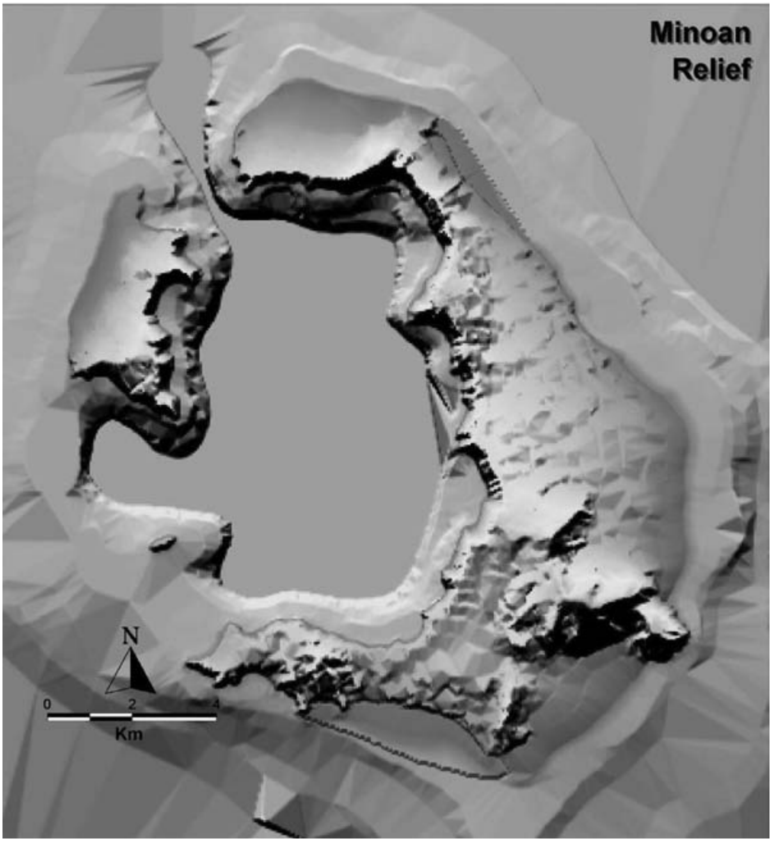

Figure 6. Thera's Minoan relief right after the last great eruption.

southeast of the island. The weathering processes have been active in some places where a palaeo-soil horizon has been observed.

2.2.2 Minoan topography

The Minoan activity produced a thick complex deposit of pumice and ash (Bond & Spark 1976, Druitt et al. 1989, Heiken & McCoy 1984, Pichler & Friedrich 1980). According to Druitt et al. (1989) a sequence of different phases describes the Minoan eruption:

- Plinian pumice fall,
- Base-surge deposits,
- Mud-flows, and
- Ignimbrites.

This eruption is dated around 1649 BC (Friedrich et al. 2006, Hammer et al. 1987, Keller et al. 1990). Thus, the Minoan relief (figure 6) was characterised by a depositional phase and the relief of Thera at this exact period was relatively smooth except for the caldera area. The poor relatively inclined drainage system had been covered by the volcanic product. Also, the coastline of the whole island had progressed seawards except for the parts around the caldera.

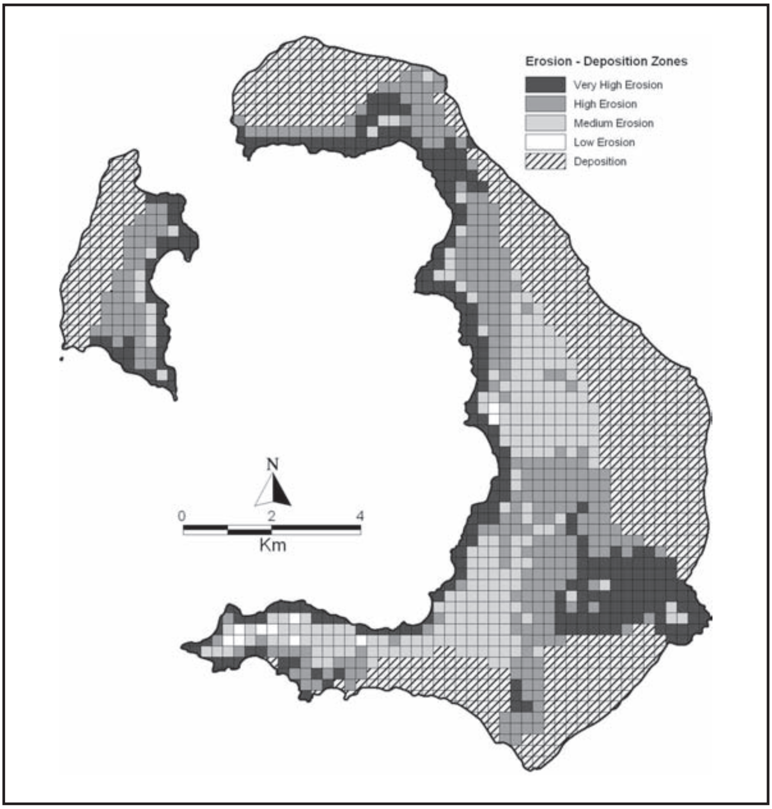

Figure 7. Erosion-deposition map of Thera Island, immediately after the Minoan phase.

Table 3. Logical rules which have been used to transform input variables to output zones (Erosion – deposition zones).

If	lithology is very erodible (pumice)	&	upslope	&	low slope gradient	then	zone of low erosion
If	lithology is very erodible (pumice)	&	upslope	&	medium slope gradient	then	zone of medium erosion
If	lithology is very erodible (pumice)	&	midslope	&	low slope gradient	then	zone of medium erosion
If	lithology is very erodible (pumice)	&	midslope	&	medium slope gradient	then	zone of high erosion
If	lithology is very erodible (pumice)	&	midslope	&	high slope gradient	then	zone of very high erosion
If	lithology is very erodible (pumice)	&	footslope			then	zone of deposition

2.2.3 *Evolution after the Minoan eruption*

Contemporary to the final phase of pumice deposition, an erosional phase has started. While in the first stage the entire island had been covered by pumice, the denudation processes was also very active. To study this erosional phase, an erosion-deposition zone map of this period (figure 7) was constructed. This was achieved using as input variables: the lithology, the slope gradient, and the slope characteristics (upslope, midslope, footslope). The above input variables have been transformed by using an inference mechanism of logical rules (table 3) based on expert knowledge (Gournelos et al. 2004). The map of figure 7 shows the spatial distribution of erosion and deposition zones. Erosional processes are dominant upslope and midslope and deposition in footslope area. The erosional processes are very obvious in the Prophet Ilias area, where most of Minoan deposits have been removed. Deposition has been occurred in low-land areas (figure 7). An indication of the deposition rates in the Kamari and Perissa area may be concluded by the alluviation about 1.5 m in an early Byzantine church (Papageorgiou et al. 1990).

Finally, the whole coastal area has been progressively changed. After the initial coastal advance, wave action has modified this very vulnerable area. Thereby, the observed high coastal erosion in Akrotiri area may be explained.

It is obvious that the geomorphological processes which took place before the Minoan eruption are different from those of the period after the eruption. Thus, after the Minoan eruption, a more smooth relief and fertile surface deposits (soils) have been formed on the most part of the island (figure 8). This fact is of great importance for change and the expansion of land use and the related cultural modification. This may be confirmed by studying all the ancient settlements of Thera which dates back to the prehistoric times.

2.3 *The Akrotiri archaeological site and its geomorphological evolution*

Akrotiri is one of the most important prehistoric settlements of the Aegean. The first habitation at the site dates back in the Late Neolithic times (at least the 4th millennium BC). In the Middle and early Late Bronze Age (ca. 20th–17th centuries BC), it was extended and gradually developed into one of the main urban centres and ports of the Aegean Sea. The

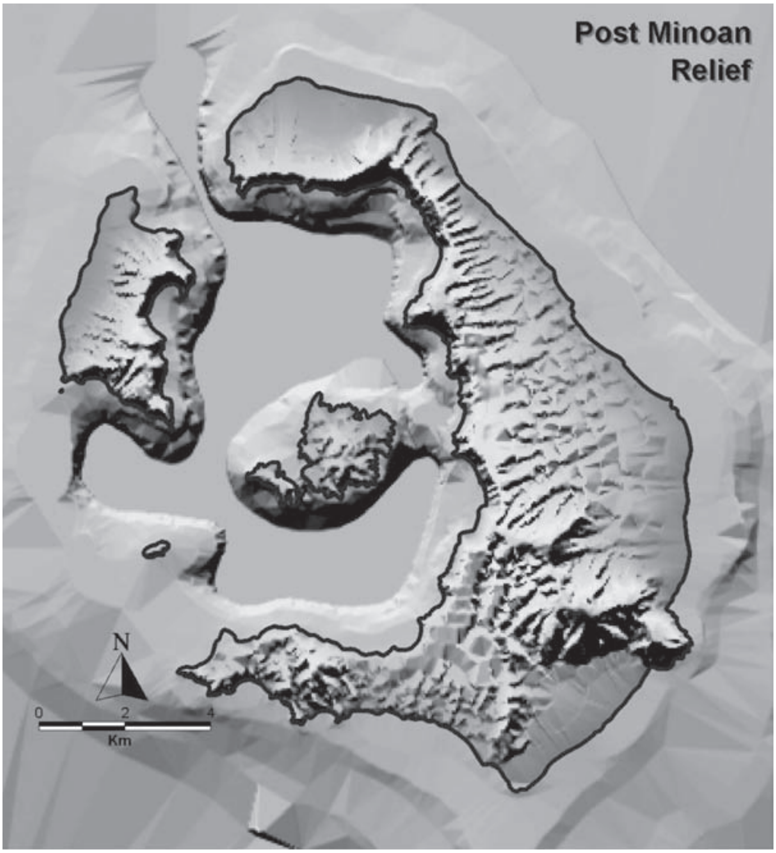

Figure 8. Thera’s relief after the Minoan eruption.

large extent of the settlement (ca. 20 hectares), the elaborate drainage system, the sophisticated multi-storied buildings with the magnificent wall-paintings, furniture and vessels, show its great development and prosperity. The various imported objects found in the buildings indicate the wide network of its external relations. Akrotiri was in contact with Crete, but also communicated with the Greek mainland, the Dodecanese, Cyprus, Syria, and Egypt. The town’s life came to an abrupt end in the last quarter of the 17th century BC when the inhabitants were obliged to abandon it as a result of severe earthquakes. The eruption followed. Volcanic material covered the entire island and the town itself. But it was this material that preserved the buildings and their contents up to nowadays.

Evidence of habitation at Akrotiri first came to light in the second half of the 19th century. However, the systematic excavations begun much later, in 1967, by Spyridon Marinatos, under the auspices of the Archaeological Society of Athens. Sample trenches were excavated during the period of June 21st–26th when a great building complex, which may have constituted a palace, came to light. Walls with their plaster, paved floors, potteries, stones pots, and many other archaeological and architectural remains have also been found (Marinatos 1968). Intact buildings with second floors and ceramics have been found under the pumice layer. The most important finds were the wall paintings, with images of birds and flowers. All these finds would lead to the deepest knowledge of the Copper civilisation in the Eastern Mediterranean. The following year (1969), more decorative wall paintings, tools, ceramics, and fire traces have been found. The findings are numerous and very important. In 1970, precious finds have been also discovered, like copper pots incised with writings in Linear A and coloured wall paintings of large dimensions with images of ancient celebrations praising nature and monkeys that still lived then in the Eastern Mediterranean (Marinatos 1976). Since his death in 1974, the excavations have been continued under the direction of Christos Doumas (Doumas 1983).

In the small valley of Akrotiri (figure 9), the three main phases of the geomorphological evolution of the island, that have been described above, may also be distinguished: a) firstly, the drainage system before the Minoan eruption defined by the Akrotiri volcanoes in the west, b) the topography of the volcanic area in the north and c) the Perissa limestone in the east. A part of this small drainage system was the valley of ancient Akrotiri. The location of the settlement was

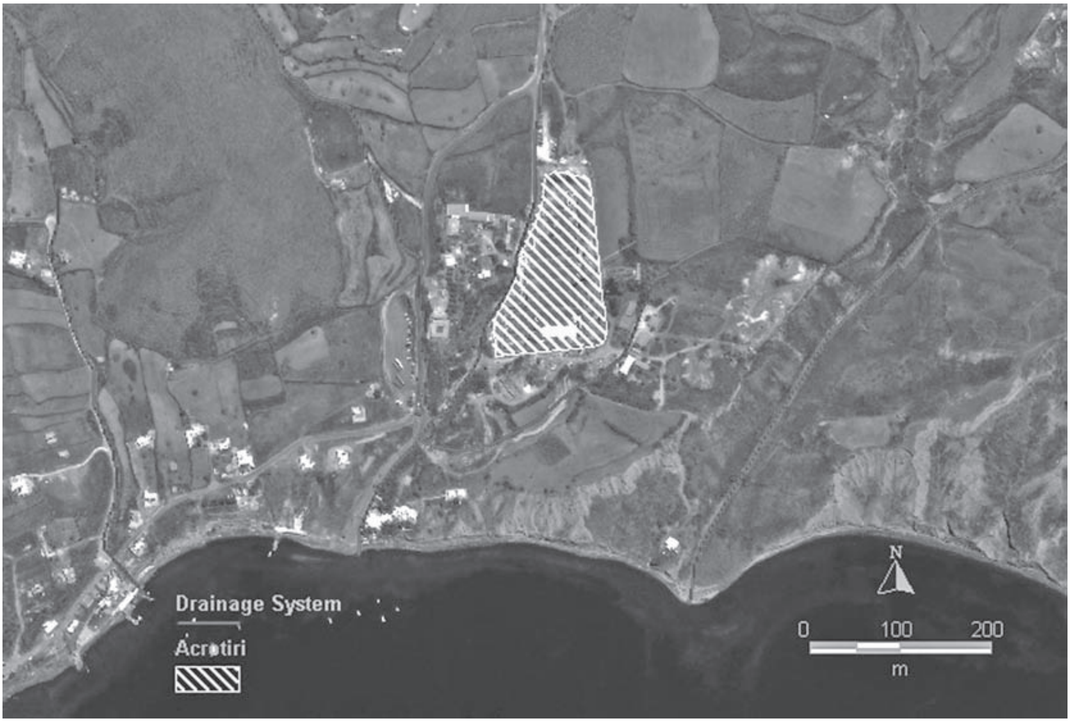

Figure 9. Satellite image of the modern archaeological site of Akrotiri.

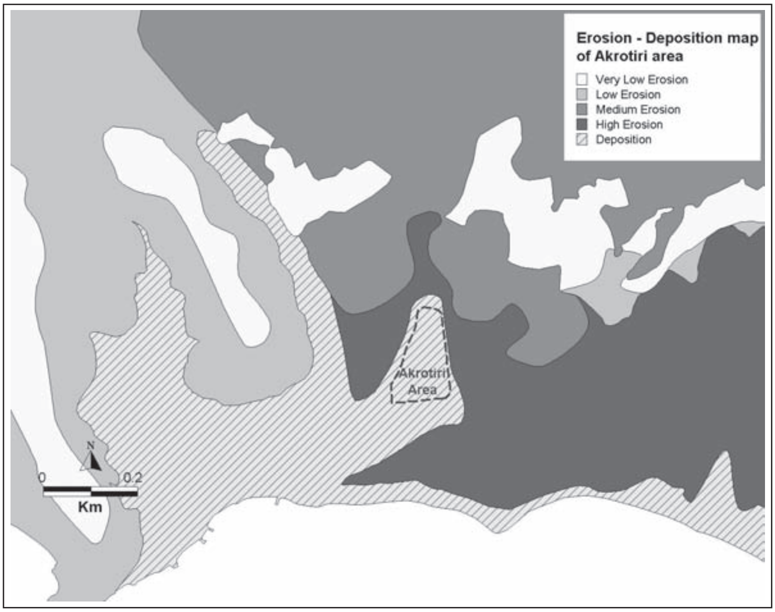

Figure 10. Erosion-deposition map of Akrotiri archaeological site.

on a gently inclined southern slope, close to the sea. The Minoan eruption filled the small valley and covered the low divides of the relief that previously existed. Before the Minoan eruption, a strong earthquake occurred. This is concluded from the destruction of the buildings in Akrotiri (Doumas 1983). Hence, the beginning of the Minoan eruption took place with percussive earthquakes and volcanic activity.

For this area, the geology, the drainage system, and the geomorphological processes have been studied. The dominant formations are the volcanic rocks before the Minoan deposits (figure 3). An erosion-deposition map of this area (figure 10) has been constructed, based on the same rules (table 3) as the ones applied for the erosion-deposition map of Thera itself (figure 7). In figure 10, the spatial distribution of erosion-deposition zones in Akrotiri area is shown. It is obvious that apart from the volcanic formations before the Minoan eruption, all deposits present medium and high erosion rates. All eroded material is still being removed to the small valleys and to the coastal area. Analysing all data within GIS, it has been estimated that in this valley (figure 10) the thickness of pumice was, at some places, more than 10 meters. The topography during this stage was gently inclined and coastal, bordered towards the north by a relatively steep gradient relief. The final period of evolution at Akrotiri was the beginning of the erosional phase. Today, the intense down-cutting erosion is obvious in the field around the archaeological site and is reflected by the drainage density distribution values, which are very high in the area.

3 DISCUSSION

The study of geomorphological evolution is a difficult task and many different stages, methods, and multiple data sets are necessary. This all contributed to a general research programme on the geomorphological evolution in Thera and the Akrotiri archaeological site, in which analytical methods, modelling, and field work were used in order to cross validate the results. The combination of geomorphological and archaeological investigation provided a vast amount of data. This was needed to determine the temporal phases and evolution of the studied area. The use of different level GIS methods made possible our main task: to study the geomorphological evolution of an area of major archaeological interest.

The volcanic island of Thera has a complicated geomorphological history. Three geomorphological stages have been distinguished: the geomorphological evolution before the Minoan eruption, the Minoan eruption period, and the geomorphological evolution after the Minoan eruption.

The geomorphological evolution before the Minoan eruption was the result of tectonic processes and complex volcanic activity. The altitudinal distribution of the present caldera suggests that before the main faulting phase, a complex volcanic cone was present with its highest elevations in the central part of the island. The altitudinal statistical analysis shows that the caldera has formed just before the Minoan eruption, as it has also been suggested by many writers; still the fracturing process is not known. The area of the island, just before the Minoan eruption, was smaller and the coastlines of the southern and eastern part appeared regressed. The topography of the island was lower than the current one, but it was also characterised by the existence of the caldera.

The Minoan landscape was covered by the pumice sediments. Thick layers of pumice had been deposited in the local topographical depressions and in the relatively deep palaeo-valleys. In some places, the Minoan coastline had vanished under thick tuff depositions, and in others, recent coastlines were extended towards the sea.

After the Minoan eruption, the geomorphology of the island is characterised by an intense erosional phase; the pumice has been progressively removed from the higher altitudes towards the lower ones.

These geomorphological processes have also affected the archaeological site of Akrotiri. Initially, a drainage system before the Minoan eruption had been established. A part of this small drainage system was the valley of ancient Akrotiri. The location of the settlement was on a gently inclined southern slope close to the sea. Then, the Minoan eruption filled the small valley and had covered the low divides of the pre-existing relief. Thus, the whole settlement and its harbour was covered by pumice layers.

The final period of evolution at Akrotiri begins with the erosional phase, especially the re-opening at a small valley in the Akrotiri area. The nature of the geological formations of Akrotiri (Minoan deposition) make them very vulnerable to erosion processes. Thus, parts of the Minoan deposition have been progressively transported in the small valleys and in the coastal areas.

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GIS landscape models for the study of preindustrial settlement patterns in Mediterranean areas

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ABSTRACT

This chapter presents a landscape archaeology approach for the study of the logic underlying location of rural pre-industrial settlements in a Mediterranean region. This task entails the use of GIS for managing and analysing information. The authors apply a non-reconstructive methodology that studies past societies without the need to recreate the morphology of past landscapes. They use landscape information relating to two topics: settlement and geographic data. The latter include several kinds of features. Two of them stand out: terrain morphology (studied through digital terrain model analysis) and land use, for which digital processing of remote sensing images is an important tool. Information is analysed at two scales: surroundings and region. Surroundings are landscape features that relate to settlement location; region refers to relations among settlements. Two ways of interaction between individuals and landscape are considered: mobility and visibility – respectively treated in GIS through cost models and visibility analysis.

1 INTRODUCTION

This chapter presents a research strategy involving the use of GIS technology in the elaboration and management of landscape models in order to test hypotheses relative to social and economic organisation of preindustrial agrarian societies in Mediterranean environments. This strategy is based on the analysis of the locational logic of settlements in a specific area within a fixed chronological range, understanding *locational logic* as the set of social factors that explain the position of a settlement in landscape (Vicent 1991). A generic methodological scheme is described that has been drawn from a series of works developed within the Department of Prehistory (Madrid), the Instititute of Archaeology (Mérida) of the Consejo Superior de Investigaciones Científicas (CSIC), and the Department of Prehistory of the Universidad Complutense (Madrid). This has been applied in different regions, such as Eastern Andalusia (Chapa et al. 1998, Mayoral 1998 and 2004, Uriarte 2005), Madrid (Bermúdez et al. 2006, Chapa et al. 2004 and 2005, Mayoral et al. 2004) and, recently, Extremadura. GIS technology is applied in the Laboratorio de Teledetección y Proceso Digital de Imagen (LabTel), of the Department of Prehistory of the CSIC, and in the Laboratorio para el Análisis Arqueológico del Territorio y la Arquitectura, of the Institute of Archaeology (Mérida) of CSIC.

This line of research is linked to the introduction of spatial analysis and the study of agrarian landscapes in Spanish archaeology during the eighties and nineties (Burillo 1984, Gilman & Thornes 1985, Molinos et al. 1994, Vicent 1991). It has experienced a new impulse with the application of GIS technology (Baena et al. 1997, Grau 2006a). Similar methodological approaches have been applied in other Iberian regions (Grau 2002, 2004, 2005 and 2006b, Molinos et al. 1994, Parcero 2002, Parcero & Fábregas 2006).The methodology is based on an inferential approach, consisting of hypotheses formulation and testing, as Gilman & Thornes (1985) and Vicent (1991) propose for the field of landscape archaeology. It includes two phases: a theoretic one consisting of the hypotheses definition construction, and an empirical one consisting of information recording, its integration, and the testing of the hypotheses.

2 THEORETIC PART: HYPOTHESES FORMULATION

This is not the place to expose with detail the hypotheses and the theoretical models on which these lean, so just the basic topics are presented. It is dealt with the dynamics of a certain type of society (agrarian preindustrial) in a specific environmental setting (Mediterranean). Agrarian preindustrial societies comprise a wide spectrum of socioeconomic and sociopolitical forms (Johnson & Earle 1987), ranging from tribal segmentary societies (Sahlins 1968) to tributary states (Haldon 1993, Wolf 1966). Mediterranean environments have structural features that condition economic practices, including sparse and irregular rainfall and hydrology, marked variation of landscape with altitude, intensely active erosion, and land degradation.

The evolution of a specific society in a certain region entails a series of social and economic structural changes. These have a spatial dimension that can be detected through landscape archaeology. For example, we can research significant changes in the following aspects:

- emergence or disappearance of specific types of settlements;
- settlement preference for specific classes of terrain or soil, according to economic strategies;

- strategic locations of certain settlements, in an attempt to control routes or crucial points;
- settlement networks due to formation of political territories.

3 EMPIRICAL PART: DATA ACQUISITION

It is in the empirical phase in which GIS technology plays its role. The research was undertaken using varied softwares, such as IDRISI, ESRI (ArcView, ArcGIS), and GRASS.

The GIS allows to construct and manage a landscape model that will allow to obtain the necessary information for the testing of hypotheses. The 'landscape factorial model' proposed by Díaz (1984), later adapted to archaeology by Vicent (1991: 40–47), was applied. A landscape factorial model takes shape in a 'landscape factorial matrix', formed by elements and factors. 'Elements' are the observable components of a landscape, this is, the features that can be defined, distinguished and described. 'Factors' are the explanatory components of a landscape, the geographic variables that determine the configuration of its elements. In the factorial matrix each factor has a specific value for each element.

In the present case, the elements of the matrix are the settlements, while the factors correspond to all those landscape variables that describe them. The analysis of the landscape factorial matrix allows to compare the location of the settlements, to observe regular patterns in this location, and to search for the logic underlying these patterns. The empirical work consists of the following steps:

1. Data recording: obtaining data and integrating them in the GIS;
2. GIS analysis: description of the settlements using a defined series of landscape variables in the GIS, and subsequent construction of the landscape factorial matrix;
3. Matrix analysis: analysis of the landscape factorial matrix using statistical techniques.

Landscape variables belong to one of these two scales:

1. *Surroundings*: With this term it is referred to the landscape immediately found next to a specific settlement, with which their inhabitants would have had direct contact.
2. *Region*: This term is applied to the landscape beyond the surroundings, the potential scene of a network of relations among contemporary settlements.

Two types of information are needed: about settlements and about geographic variables.

IDRISI:
an integrated GIS and image processing software solution for the analysis and display of digital spatial data.
www.idrisi.com

ESRI:
a provider of GIS and mapping software. ArcGIS is a complete system and integrated collection of GIS software products.
www.esri.com

GRASS GIS (Geographic Resources Analysis Support System):
an open source GIS used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualisation.
www.grass.itc.it

3.1 *Settlements*

During the research project, archaeological information is used for characterising settlements using a varied set of data sources, both existing documents (bibliographies, archaeological reports, inventories of sites) and data registered. This means a great heterogeneity that has to be analysed, refined and synthesised. For this task, one positive factor is the progressive development and normalisation of inventories of sites and their migration to GIS (García Sanjuán & Wheatley 2002), e.g. in Andalusia (Amores et al. 1997 and 1999, Fernández et al. 2000) and Madrid (Blasco & Baena 1997).

Most of the archaeological data used in landscape archaeology come from surface survey. This gives a general and representative sample of settlements for wide areas and long time spans and therefore allows to undertake regional and long-term research (Barker 1995, Cherry et al. 1991, Jameson et al. 1995). Nevertheless, surface data sometimes are not sufficiently precise for determining aspects of site character, such as chronology or function.

The recovery of the information leads to the creation of a settlement database, with the following aspects: x, y coordinates, chronology and functional type. x, y coordinates have to be sufficiently accurate, according to the chosen map scale. The human eye cannot distinguish differences below a 0.2 mm threshold. Multiplied this value by the scale denominator, the minimum accuracy necessary is obtained. Thus, for 1:25,000 and 1:100,000 scales, accuracies of at least 5 and 20 m are needed, respectively.

Global Positioning System (GPS):
a satellite based navigation system that allows the determination of the exact geographical location on Earth with accuracies up to one metre.

cf. chapter "Using digital field data acquisition (FDA) in archaeological prospection" of Garcia et al.

Coordinates can be obtained from existing documentary information about the site or during the fieldwork, using either cartography or GPS. GPS has become an accurate and fast tool for obtaining coordinates of archaeological features (Amado 1997, Chapman & van de Noort 2001, Estrada-Belli 1997). Low cost GPS receivers offer enough accuracy to position archaeological sites on landscape within a 1:50,000 scale (Ortiz n.d.), with standard errors ranging from 10 to 20 m, and below 5 m if they are able to receive correction signals, e.g. by the WAAS/EGNOS system.

It is necessary to define a series of chronological stages and to assign one or more of them to each settlement. The chronological resolution of the defined stages will depend on the precision of the data. Regarding functionality, the aim is to establish a typology of settlements according to their archaeological features (size, structures, artefacts, etc.). Of course, it is necessary to be aware that this typology is an abstraction that is based on the research criteria and the interpretation of the archaeological record.

3.2 *Geographic variables*

Relevant landscape variables are incorporated into the GIS in the form of layers, in order to build up the landscape factorial matrix and to analyse the logic of location of settlements. Depending on the aims of research and on social and economic models, different aspects of landscape must be considered.

In relation to temporality, there are two types of geographic information that must be taken into account: information that describes the landscape as it currently is, and information that may be obtained and processed for the reconstruction of some dimension of ancient landscapes. The first type is mainly obtained through analog and digital cartography produced by research and administrative institutions. The second type includes historical information (e.g. cadastres) (Gilman & Thornes 1985) and data obtained through so-called paleoenvironment reconstruction methodologies such as provided by geomorphology, sedimentology, pedology, palynology etc. (cf. GIS applications in Aguilella 2006, Evelpidou 2003 and 2006, Fyfe 2006, Spikins 2002, Vicent et al. 2000 and 2006). Here, the potential of the information is stressed drawn from current landscape features for the study of past societies, without denying the fundamental role that ancient landscape information plays in landscape archaeology studies.

The use of information derived from the landscape as it is in the present entails the issue of actualism. Is it appropriate to use present landscape data for the study of past societies? From a solely reconstructive standpoint, the answer is "no": ancient landscape features should be reconstructed before studying ancient societies linked to them. Nevertheless, landscape modelling can be an alternative to a reconstructive approach. The key point would not be the reconstructed character of information, but its suitability for the testing of hypotheses. This strategy does not generate variables useful to show the characteristics of past landscapes; it is, on the contrary, useful to answer questions about the relations among different communities and their landscape in the past (see a discussion in Vicent 1991: 48–50).

For this aim, it is necessary to work with geographic variables that make sense of structural aspects of the landscape, so that they can be extrapolated to past times. To accomplish this task, a variable has to fulfil at least one of the following requirements:

1. Its values have remained stable along time. An example is topography.
2. Its values have varied homogeneously, so that relative differences stay stable along time. Some examples are climatic variables, such as pluviometry and temperature.
3. Its values have varied heterogeneously, but recent variation can be removed using other variables that have remained stable.
4. Historical traditional features whose existence cannot be extrapolated to the investigated research periods, but are incorporated into the analysis in order to see if there are significant spatial relations between them and the settlements. If there is a significant relation, it is possible to think that the historical features "fossilise" some reality relevant to the investigated settlement patterns. An example is traditional road network (e.g. Fairén et al. 2006).

Of course, this is valid for general views and comparative studies, never for fine-grained descriptions or small portions of landscape. The variables to be used depend on the research objectives. Here it is focused on two main aspects:

1. Land cultivation: There are many variables that have to do with the possibilities that land offers to be exploited (terrain, geology, soil,

hydrography etc.). Their interaction can be synthetically expressed through a potential land use layer.
2. Control of surroundings: The idea is accepted that visibility is an essential factor for the strategic potential of settlements. Its study requires a digital elevation model (DEM).

Digital elevation model (DEM): *the digital representation of the Earth' surface and providing information about it's elevation.*

Beginning with the elaboration of the DEM, the stability of elevation along time is assumed; therefore, it is possible to extrapolate its values to the past. DEMs generated and used in the research project are organised according to a raster model. There is an extensive bibliography on DEM generation and operation, both at a general level and archaeological applications (see a synthesis in Burrough & McDonnell 1998: chapter 5, Conolly & Lake 2006: chapter 6). In this research project, DEMs obtained from two sources are used:

1. DEMs generated through linear interpolation from digitised contours;
2. DEMs distributed by institutions, e.g. the one generated by the Shuttle Radar Topography Mission (SRTM), created by interferometric synthetic aperture radar technique. It covers approximately 80% of Earth's terrestrial surface and has a spatial resolution of around 90 m which makes it suitable for studies in large regions, with 1:100,000 or 1:200,000 scales.

SRTM (Shuttle Radar Topography Mission): *the acquisition of remotely sensed data of the Earth's surface from space in February 2000 for the generation of a homogeneous digital elevation model.*
www2.jpl.nasa.gov/srtm/

Interferometric synthetic aperture radar (IfSAR): *a technique involving phase measurements from successive aircraft or satellite SAR images to infer differential range and range changes for the purpose of detecting very subtle changes on or of the Earth's surface.*
www.ccrs.nrcan.gc.ca/glossary/index_e.php

Map of Cultivation and Land use:
www.mapa.es/mca2/inicio.htm

Interpolation from digitised contours is based on the following steps (figure 1):

1. Contour digitisation to vector format from analog cartography on paper. In some cases this first step is not necessary, since digital topographical maps are available;
2. Contour rasterisation;
3. DEM generation through linear interpolation.

The potential land use map is a qualitative raster layer composed by three classes, representing three basic uses within Mediterranean agrarian economies (Gilman & Thornes 1985: 38–40): a) woodland and pasture, b) dry land agriculture, and c) irrigated land agriculture. Two possible ways are followed to generate it:

1. One is based on edaphological or agrological cartography.
2. The second is based on current land uses and their conversion to potential past land uses through the use of stable variables.

The first way consists of assigning each original class to one of the three above mentioned, following reclassification procedures. Mayoral (2004: 75–76) based on Molinos et al. (1994: 108–114) uses the soil map (scale 1:200,000) produced by the Department of Edaphology and Agricultural Chemistry of the University of Granada, which is based on FAO Soil Classification (FAO 2006). The soil map groups 15 edaphological associations into eight potential productivity categories. These eight categories are reclassified into three basic potential land uses: woodland and pasture (low productivity), dry arable land (medium productivity) and irrigated land (high productivity). There are similar applications by

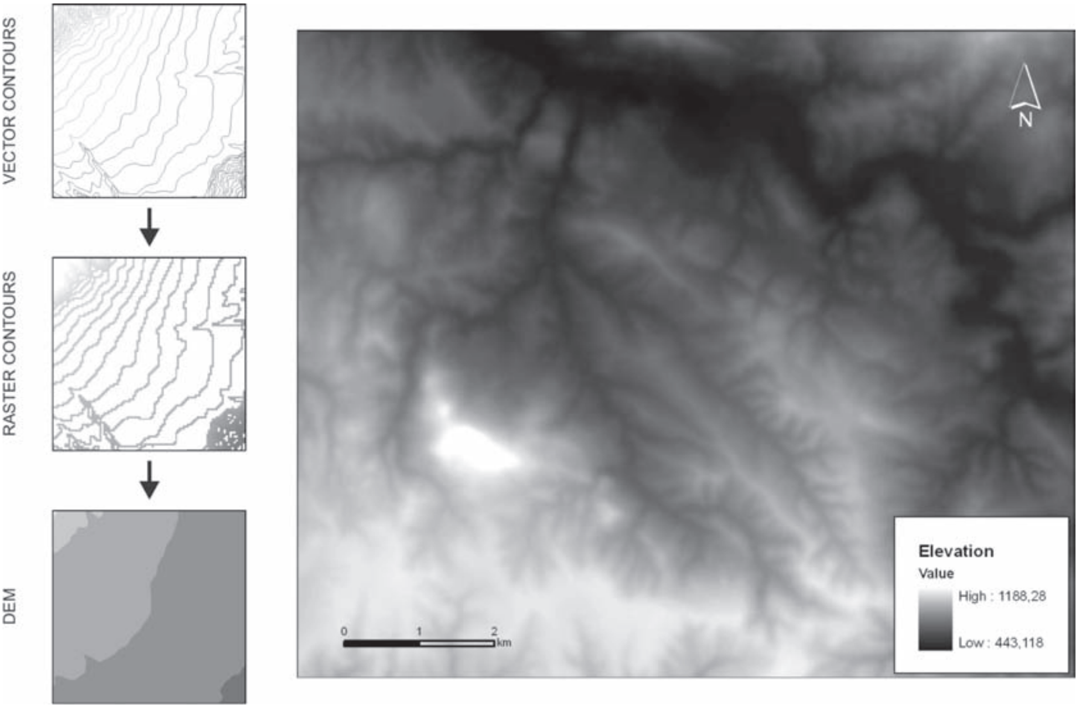


Figure 1. DEM elaboration from digitised contours.

Grau (2002: 138–140), Parcero (2002: 62–64), and Parcero & Fábregas (2006: 78–79).

To support the second approach, there are several land use maps available, such as the Map of Cultivation and Land Use published by the Spanish Ministry of Agriculture (1:50,000 and 1:200,000 scale) or Corine Land Cover 2000, a European land cover digital map generated from remote sensing images.

It is also possible to create a land use layer in a customised way through digital analysis of remote sensing images, specifically Landsat imagery. The software used is ER Mapper Pro and, more recently, ERDAS IMAGINE. Analysis of remote sensing images allows to categorise landscape according to the research aims and the specific geographic features of the study area.

Remote sensing applications in archaeology are numerous and varied (Campana & Forte 2006). Most of them are oriented to the recognition and description of archaeological features. Another line of research is followed, oriented to the study of land cover within a landscape archaeology approach through the use of multispectral satellite imagery (Clark et al. 1998, Cox 1992, Custer et al. 1986, Rodríguez 1998, Vicent et al. 2000 and 2006).

Digital image classification techniques are applied to Landsat imagery to generate land cover maps, specifically using the supervised classification (Lillesand & Kiefer 2000), which considers the a priori knowledge

Corine Land Cover 2000:
a Europe-wide project which provides homogeneous and comparable land cover data of Europe on a scale of 1:100,000 derived from satellite imagery. The first acquisition in 1990 comprised 44 classes. In 2000 the data was updated.
www.eea.europa.eu/themes/landuse/clc-download

ER Mapper Pro:
a geospatial imagery processing application. All ER Mapper products have been included in the ERDAS portfolio.
www.ermapper.com

ERDAS IMAGINE:
a suite of software tools designed specifically to process geospatial imagery.
www.erdas.com

Landsat imagery:
http://landsat.gsfc.nasa.gov

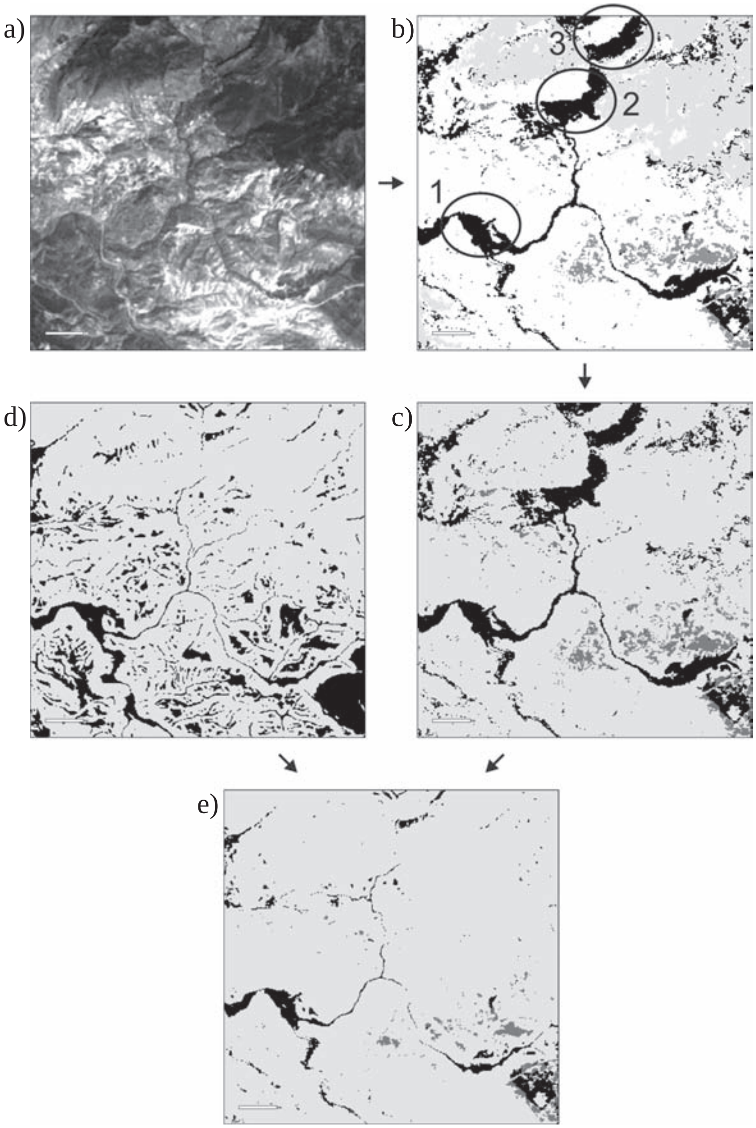


Figure 2. Creation of a potential land use layer using Landsat imagery and slope: a) Landsat image; b) Supervised classification of Landsat image. White colour groups several classes of badlands and xerophytic vegetation; light grey represents pine wood; dark grey, dry land agriculture; black, green vegetation. Green vegetation class groups different land uses: irrigated land agriculture in lowlands (1), irrigate land agriculture with terraces (2), and some areas of pine wood (3). c) Reclassification. Light grey represents woodland and pasture; dark grey: dry land agriculture; black: green vegetation. Green vegetation mixes two different potential land uses for an Iron Age economy: woodland and pasture (current pine wood and irrigated land agriculture with terraces) and irrigated land agriculture (current irrigated land agriculture in lowlands). d) A slope layer to distinguish which green vegetation pixels are suitable for irrigated land agriculture in Iron Age. A 15% slope threshold helps to distinguish cultivable (black) and not cultivable land (light grey). e) Potential land uses: woodland and pasture (light grey), dry land agriculture (dark grey) and irrigated land agriculture (black).

about the classes to guide the classification procedure. It consists of the following steps:

1. Selection of training fields: Training fields are pixel clusters delimited on the image by the analyst in order to collect a representative sample of each relevant class. Each class is represented by a group of training areas. The selection of training areas requires that the analyst knows the study region and is able to recognise each one of the land coverages.
2. Spectral definition of the classes: Each class is characterised through numerical summaries of the spectral information of its respective training fields.
3. Image classification: Each pixel is assigned to a class through the application of a classification algorithm. The algorithm uses the a priori knowledge elaborated through training fields.

Supervised classification: *a method for identifying spectrally similar areas on an image by defining "training sites" of known targets and extrapolating those spectral signatures to other areas of unknown targets. www.ccrs.nrcan.gc.ca/glossary/index_e.php*

However, when researchers produce maps, this information usually derives from the current landscape. Therefore, it is necessary to "filter" it using stable features as auxiliary variables, so that it is possible to establish the potential land uses in the context of a paleo-technical economy, and to tell apart those due to the introduction of industrial technologies. For this, one useful feature is topography. This involves the development and use of a digital terrain model (DTM) and its following layers:

1. Elevation (DEM): establishing an upper threshold for agriculture depending on the altitude;
2. Slope: establishing an upper threshold for agriculture depending on the slope without the construction of terracing systems (figure 2);
3. Flow accumulation: In this layer, each cell value expresses how many cells drain to it in case of surface runoff. It is reasonable to assume that high values mean favourable conditions for irrigated land agriculture (cf. another approach in Esteve 2006).

Digital Terrain Model (DTM): *is a "bare-earth" model that represents the natural ground surface (topography). This term is commonly used interchangeably with digital elevation model (DEM).*

4 EMPIRICAL PART: GIS ANALYSIS

Once the layers are integrated that comprise the landscape model, it is necessary to characterise each settlement using that information, both at the surroundings and the regional scale. Here, a matrix is built and used in the analysis.

Assuming that there exist two ways in which the inhabitants of a settlement shape their relation to landscape: mobility and visibility. In other words, the underlying logic to explain the location of a settlement has much to do with what is accessible and visible from it. Van Leusen (2002: 6–3) explains this phenomenon by means of the concept of 'focus', defined as the point where an individual is located and has a certain level of visibility and accessibility. This results in two types of surroundings: catchment area (what is near) and viewshed (what is visible).

4.1 *Catchment area*

Catchment area is closely related to the site catchment analysis (SCA) (Jarman et al. 1972, Vita-Finzi & Higgs 1970). There are later revisions of the concept and the methodology (Gilman & Thornes 1985, Mayoral 2004: 41–42, Molinos et al. 1994: chapter 4, Ruiz y Molinos 1984, Vicent 1991: 53–65) and GIS applications (Gaffney & Stancic 1991, Hunt 1992). Accordingly, the catchment area can be understood in the following terms:

1. The catchment area is not an effective reconstruction of the economic use of the surroundings of a settlement, but the expression of the possibilities that the landscape offers for certain economic practices within a certain distance range.
2. Its interpretation depends on socio-economic models and hypotheses.

A catchment area was originally defined using a radius whose origin was in the settlement. More recent works (e.g. Gilman & Thornes 1985) have added the influence of the terrain on modelling individual movement. Thus, the distance that may be walked is a function of time, but also of the characteristics of the terrain. This has promoted the use of irregular catchment areas that the GIS technology allows to shape through the use of cost surface models (e.g. Bell et al. 2002). In this modelling of displacement, a key factor is slope, although other factors could be considered, such as lithology or vegetation. The elaboration of the cost layer from the slope layer is as follows (figure 3):

Cost surface model: *represents a spatial distribution of a cost variable, which can be based on a single factor or a combination of criteria (e.g. time, distance, degree of difficulty) relevant to movement for instance in a landscape.*

1. Starting with DEM, a slope layer is created.
2. A cost layer is created from the slope layer. The steeper the slope, the higher the cost. Cost uses to be expressed in time units: in the cost layer, each cell value indicates how long it takes to walk through that portion of terrain.

There are several ways to calculate costs from a slope:

1. One way is to establish slope intervals and to assign a fixed cost value to each one (Mayoral 1998: 424–425).
2. Another way is to use a mathematical function that relates both variables.

There are several functions for calculating cost (Grau 2006b: 216, Parcero 2002: 66). In this study a linear function (Uriarte 2005: 613–614) was developed from data contributed by Gilman & Thornes (1985: 36–38). Gilman & Thornes establish a table that relates number of contours crossed (in the topographic map) and distance crossed in 12 minutes. It was transformed into a table that relates slope and time. With this data, a linear regression analysis was performed (figure 4), obtaining a function for calculating the time it takes to cross a specific distance depending on specific slope (equation 1),

Linear regression: *a statistical technique for finding a linear relationship between a dependent variable and one or multiple independent variables.*

$$T = 0.0277\,RP + 0.6115\,R \tag{1}$$

where T = cost (in seconds), P = slope (in percentage), and R = spatial resolution (in metres) of the raster layer.

Once the cost layer has been created, the catchment area of each settlement may be generated. As a first step, an accumulated cost surface

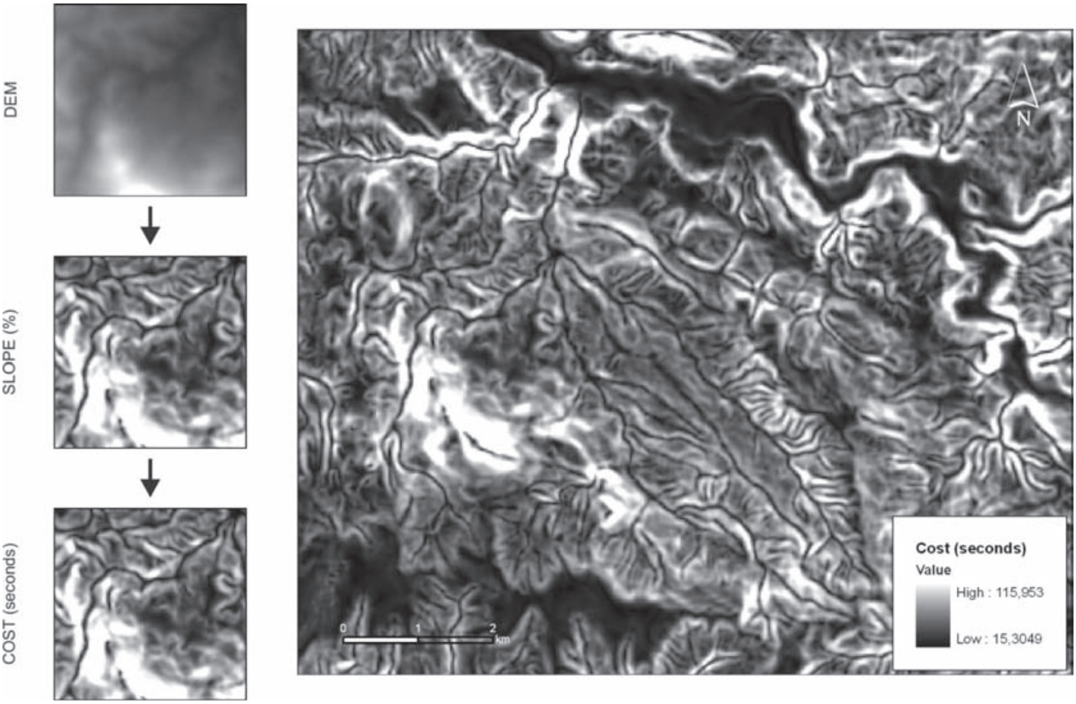
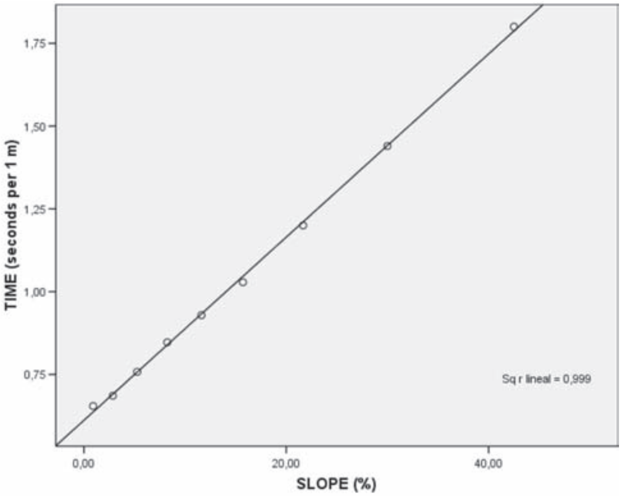


Figure 3. Elaboration of a cost layer.

SLOPE (%)	TIME (seconds per 1 m)
0.91	0.65
2.86	0.69
5.26	0.76
8.24	0.85
11.61	0.93
15.71	1.03
21.67	1.20
30.00	1.44
42.50	1.80



Resumen del modelo

Modelo	R	R cuadrado	R cuadrado corregida	Error típ. de la estimación
1	1,000[a]	,999	,999	,01203

a. Variables predictoras: (Constante), SLOPE (%)

Coeficientes[a]

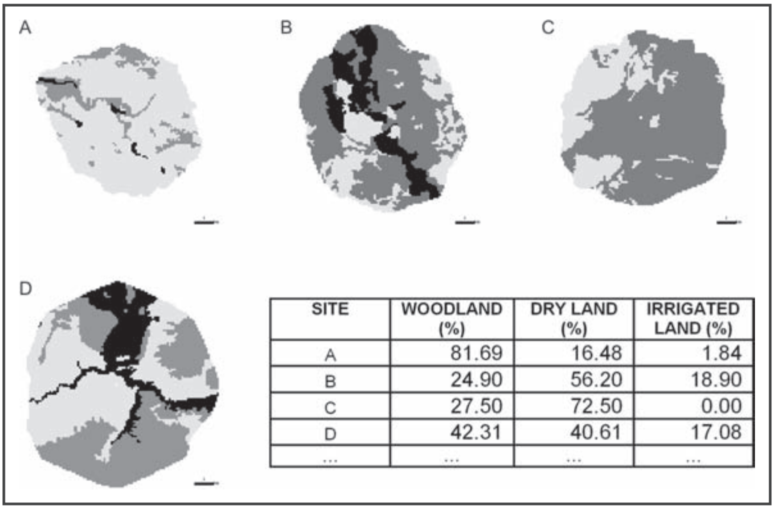
		Coeficientes no estandarizados		Coeficientes estandarizados		
Modelo		B	Error típ.	Beta	t	Sig.
1	(Constante)	,612	,006		98,330	,000
	SLOPE (%)	,028	,000	1,000	89,733	,000

a. Variable dependiente: TIME (seconds per 1 m)

Figure 4. Linear regression model that establishes the function for calculating time from slope.

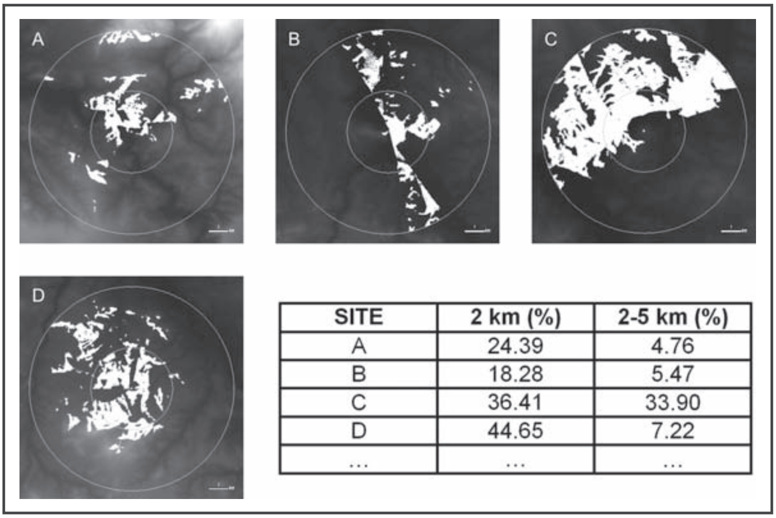
layer for each settlement is generated, in which each cell value expresses how long it takes to get to it from the origin. The boundary of the catchment area is defined by those cells whose value exceeds the time limit set for the displacement. Limit values most used vary between 15 minutes and 1 hour.

After the catchment areas have been established, each of them is described as a function of the chosen landscape variables, using the appropriate numerical summaries (mean, median, percentage, etc.). In this case, the percentage of each type of potential land use within the area was used (figure 5).



SITE	WOODLAND (%)	DRY LAND (%)	IRRIGATED LAND (%)
A	81.69	16.48	1.84
B	24.90	56.20	18.90
C	27.50	72.50	0.00
D	42.31	40.61	17.08
...	...	...	...

Figure 5. Characterisation of 1 hour catchment areas through potential land uses.



SITE	2 km (%)	2-5 km (%)
A	24.39	4.76
B	18.28	5.47
C	36.41	33.90
D	44.65	7.22
...	...	...

Figure 6. Viewsheds in 2 and 5 km radii.

4.2 *Viewshed*

There is an extensive bibliography about visibility, its GIS implementation and its application in landscape archaeology (e.g. Wheatley 1995, Zamora 2006). Here, it is dealt with the viewshed generated from a specific point within a specific radius. Once the viewshed has been defined, it is possible to work with it in two different ways:

1. First, it is possible to handle it like catchment areas, this is, to characterise it after some specific landscape variables (Parcero 2002, Parcero & Fábregas 2006). Working this way, it may be possible to get known the aspects of the landscape which are visible from each settlement and the extent.
2. Second, the surface covered by the viewshed can be quantified, either in absolute terms or in percentage of the circle defined by the radius (figure 6).

4.3 *Regional analysis*

The distance between two settlements is a decisive variable for evaluating the relation between them. In this sense, it is interesting to characterise each settlement in terms of how distant (in time) it is from others. This characterisation may be done in three steps:

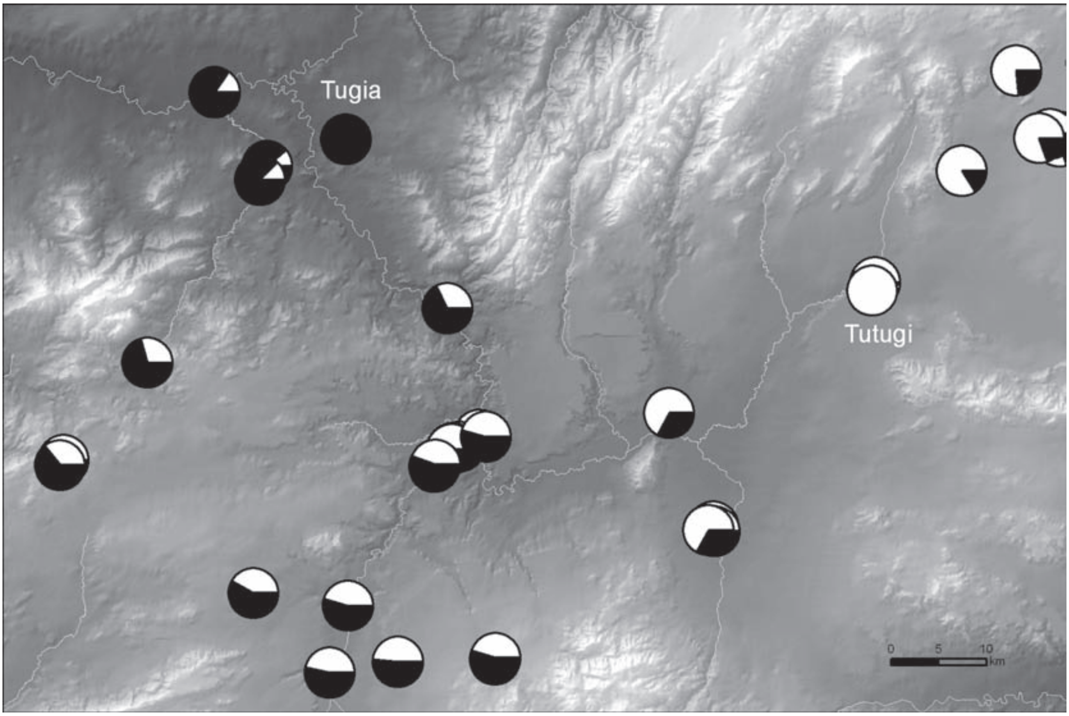


Figure 7. Comparison between distances (in time) to two Iron Age oppida from a set of contemporary settlements. It helps to estimate the potential influence of each oppidum.

1. Development of the cost layer (see above);
2. Generation of the accumulated cost model for each settlement;
3. Each settlement receives a value accumulated cost, according to its position in relation to others (figure 7).

5 EMPIRICAL PART: MATRIX ANALYSIS

The statistical analysis of the factorial matrix of a landscape allows to compare the underlying logic of location of settlements and, in turn, to test the hypotheses.

Descriptive statistics: *basic statistics to describe and summarise data including measures of average values (e.g. mean or median) and dispersions of variables.*

The analysis of the matrix can be addressed through either descriptive statistics or inferential statistics. Descriptive statistics allow to explore and summarise the data structure, in order to describe, synthetically, the basic characteristics of the information set. This allows to study the independent behaviour of each variable (univariate statistics), its relation to another variable (bivariate statistics), or a combination of several variables (multivariate statistics). When this analysis is applied to a landscape model, it is possible to observe which economic and strategic practices were being undertaken from each settlement, and the similarities or dissimilarities among settlements, in relation to those practices. Thus, a typology of different rationalities (based primarily on location) can eventually be proposed.

Inferential statistics: *calculations for deriving inferences about the population. It allows to draw conclusions that apply not only to the data, but the group under study.*

Inferential statistics allow to establish, after probability theory, if significant differences exist between groups of elements. In other words, they allow to test the significance of the differences found through descriptive statistics. Comparisons can be made in two ways:

1. Between groups of settlements established a priori after archaeological criteria, such as chronology or functionality;
2. Between the settlements and a sample of points randomly generated in the GIS that stand for the whole landscape. Random points and settlements must be characterised using the same variables, in order to observe how the settlements behave in relation to the landscape, and if they present any dominant trend in relation to any specific feature.

6 CONCLUSIONS

The basic guidelines of a landscape archaeology approach have been presented for the study of social and economic organisation and dynamics of preindustrial societies in Mediterranean environments. They have the following structure: (1) theoretical stage, consisting of hypotheses formulation, and (2) empirical stage, consisting of data acquisition and analysis with the use of GIS technology. This second stage has three phases: (a) data acquisition, (b) GIS data analysis and landscape matrix elaboration, and (c) landscape matrix analysis by means of statistical techniques.

This proposal has some characteristics which can be stressed as follows:

1. It has an inferential nature, in which empirical work is subordinated to theoretical design. Data and applications used depend on the historical questions to be answered.
2. Empirical information is synthesised in numerical models susceptible of mathematical analysis.
3. It is a methodology valid for the study of global structures and dynamics, appropriate for regional long-term research.
4. It allows a wide variety of archaeological and geographical data, depending on which research questions one wants to investigate.

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Mapping and analysis of linear landscape features

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ABSTRACT

The author presents case studies relating to historic land use in the Roman province of Pannonia, and shows how geospatial methods can be used in archaeological research for the detection and analysis of linear features. The methodology is based on remote sensing, GIS and statistical methods. The data used for the analysis are a collection of satellite images, orthophotos, historic and current cadastral maps. The results of the analysis are visualised in the form of maps and diagrams. The main topics of the chapter are how to characterise, by their orientation, the lineations created by land use and to analyse change between ancient and recent linear landscape elements.

1 INTRODUCTION

The main research questions of this chapter deal with the detection and analysis of possible Roman centuriation systems which are still preserved in the modern landscape. Roman centuriation grids are good examples of 'planned landscapes' which rely on perpendicularly aligned surveying axes and are formed by square moduli (centuriae), on average measuring between 703 and 710 m (Clavel-Lévêque & Vignot 1998, Clavel-Lévêque & Orejas 2002).

In Northwest-Pannonia (figure 1), from the first century AD until now these planned landscapes changed in such a way that their remains are sometimes difficult to recognise. Several attempts have been made to identify Roman surveying axes or to reconstruct these centuriation grids. The data used for these reconstructions is based on current linear landscape elements and on those extracted from historic maps of the 19th and 20th century.

2 RESEARCH ON PLANNED ROMAN LANDSCAPES: METHODOLOGICAL APPROACHES

The detection and interpretation of ideal Roman "centuriated" landscapes which are characterised by their orthogonal land division, is closely related to the development of surveying and mapping techniques. After the Second

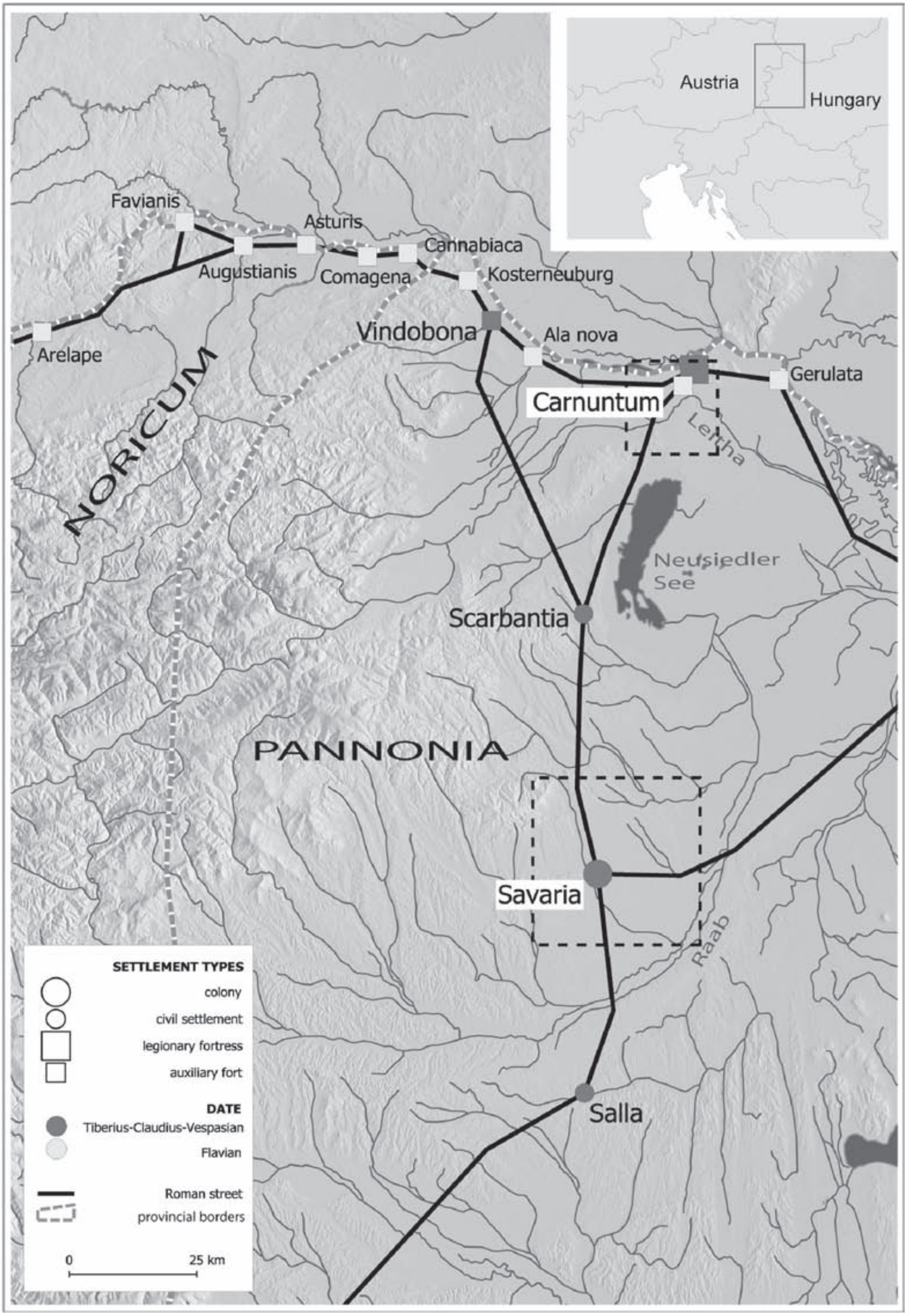


Figure 1. North-western Pannonia in the first century AD. The research areas mentioned in the text are marked with squares, © 2006 Gugl (ÖAW).

World War, aerial photography became more important in archaeological research and was established as a major technique of archaeological prospection. In the 1950s and 1960s, there was a strong focus on the identification of Greek and Roman landscape elements which still survived today, especially in Mediterranean countries. Before this approach from the air, archaeologists and ancient historians relied on the cartographic work of regional topographic survey units and the maps they provided. Although aerial photography made it possible to survey large areas, rectifying and interpreting the images remained a time consuming process due to the analogue photogrammetric methods in use. Nevertheless, it was an important step for landscape studies that relevant landscape features could be extracted from topographic maps and (rectified) air photos by a visual interpretation process (Bradford 1947 and 1957).

In the 1980s, statistical methods were introduced into Roman landscape studies. Most extensively used were descriptive statistical parameters, for instance to analyse orientation data which was manually extracted from analogue maps, and frequency distributions illustrating the summed up length of selected line structures per area. Correspondence analysis helped to quantify the relations between grid systems and different soil types (Compatangelo 1989). In general, it was regarded as sufficient to obtain a good visual fit of postulated centuriations with road tracks and footpaths. With the spread of information systems, it became much easier to perform statistical tests, like Kolmogorov-Smirnov-tests (K-S-tests) which try to determine if two datasets differ significantly. Peterson (1988a and 1988b) used K-S-tests to calculate the association of points to a hypothetical grid.

A new step in Roman landscape studies was reached in the second half of the 1990s with the introduction of CAD and GIS systems with sophisticated graphical user interfaces. This new technology was well suited to the study of ancient linear features. In this specific context, GIS technology became an integral part of many geoarchaeological projects, best illustrated by a case study in the Civitas Menapiorum in Western Belgium, conducted by a research team of Ghent University between 1997 and 1999 (Vermeulen 2006). By the integration of raster and vector data in a GIS system, these different types of information were explored, particularly by use of visual overlay techniques. The intention was to calculate the orientation of the vectorised line segments with the help of spreadsheet programs, to classify them according to their orientation values, and to visualise these results within the GIS (Clavel-Lévêque et al. 2001). In all these studies, only the position parameters and dispersion measures of classical statistics were used for the characterisation of the line features (normal distribution, mean value, standard deviation).

3 RECENT RESEARCH ON ROMAN CADASTRES IN NORTH-WESTERN PANNONIA: THE RESEARCH PROBLEMS

Among the Roman provinces on the mid-Danube, Pannonia offers the most favourable conditions for historic landscape studies (figure 1). The

Aerial photography:
cf. chapter "The application of digital vertical aerial photogrammetry in the recording and analysis of archaeological landscape" of Corns & Shaw.

Image rectification:
a process of transforming a distorted image into a defined coordinate system.

cf. chapter "Use of historical cadastral maps in modern landscape research and management" of Domaas & Grau Møller.

CAD (Computer Aided Design):
A computer-based information processing system which supports engineering, planning and illustrating activities. New versions include basic GIS functionalities.

Graphical user interface:
an interface which allows to interact directly between a computer (or a PDA, etc.) and its user on the basis of textual or graphical elements.

Overlay techniques:
a process of superimposing two or more layers in a GIS with the aim to do visual or analytical operations.

flat to slightly hilly terrain of the Pannonian landscape is in general not densely populated and vast parts of the countryside are open, so there is a great potential for archaeological prospection.

First attempts to detect centuriation grids in the area of the Roman colony of Savaria/Szombathely (Vas megye, Hungary) and in the hinterland of the legionary fortress of Carnuntum (Petronell – Bad Deutsch-Altenburg, Lower Austria), both founded around the mid first century AD, were made in the 1960s and 1970s. Andras Mócsy (1965: 34, fig. 11), Emre Tóth (1977: 80, fig. 3) and Manfred Kandler (1977) were inspired by the well known historical sources, especially Hyginus Gromaticus, who refers several times to Roman land surveying activities in the province. This author writing in the early second century AD, gives only general information on land surveying in Pannonia and so the location of centuriated areas is not specified in his text (Guillaumin 2005: 119–120).

From the methodological point of view, several problems now appear in this work. Only small scale maps were available, which were used to manually extract linear elements of the modern landscape, such as field boundaries and roads. The reconstructions of Mócsy and Tóth consist of rather suggestive maps which contain only the lines fitting into the proposed grid system. Nowadays it is impossible to evaluate the representativeness of the lines selection they presented on their maps. Such interpretations are not transparent and intersubjectively comprehensible. Therefore, the reliability of the research results remains unclear.

Another point is the deep impact of agriculture on the landscape. In west Hungary and in the eastern parts of Austria, we know that land consolidation measures of the last 200 years affected the landscape, although this has not been studied in detail yet. There are studies offering a general overview of these phenomena in Austria (Seger & Kofler 1998 and 2005), but this is not sufficient to understand the effects on the development of the historic landscapes at a micro-regional level. Hence, before trying to reconstruct the Roman centuriation, it seems necessary to evaluate the changing face of the landscape, or at least those changes in the orientation of field systems and the road network, that have occurred during the last 200 years. For this period, we have adequate data to perform structural analysis of these landscapes using GIS.

4 THE DATA

Because of the long tradition of aerial prospection around Carnuntum, abundant remote sensing data is available. Archaeological activities since the 1970s have concentrated on the legionary fortress and the Roman town, disregarding the vast hinterland of this archaeological site. The aerial archive at the Department for Prehistory and Medieval Archaeology of Vienna University provides the data basis, but so far geophysical prospection has only been conducted in minor parts of the Roman town. Nevertheless, by combining these data with the excavation results of the last 130 years, we can now draw a very precise map of Roman Carnuntum with much topographic detail (Doneus 2006, Kandler 2004).

In contrast, far less spatial thematic data is available from Savaria. As with many other Roman towns, Savaria is facing the problems of urban archaeology, because the Roman colony lies immediately under the modern town of Szombathely. No prospection results from Savaria and its territory are published, so our knowledge of the town layout and the surroundings of the Roman colony is currently very limited (Scherrer 2003).

For this research, the availability of spatial base data such as orthophotos and panchromatic SPOT-satellite images is almost essential. The regional government of Lower Austria provides both black-and-white orthophotos (with a pixel resolution of 0.5 m on the ground) as well as colour orthophotos with a resolution of 0.25 m per pixel. These cover the entire Carnuntum area whereas from the Savaria region only the SPOT data with a pixel resolution of 10 m can be used.

Orthophoto:
a rectified photograph, typically an aerial photograph, showing image features corrected for variations in scale and height displacements.

In general, it is much more difficult to obtain historic data which already has been scanned and vectorised. If historic maps and cadastres are available at all, it is often only in an analogue version. In the study area, the earliest surveys with a sufficient geodetic accuracy date back to the early 19th century. For the whole territory of the former kingdom of Hungary there are now more than 1,100 scanned and georeferenced map sheets available, drawn during the second military survey of the Habsburg Empire (1806–1869) at a scale of 1:28,800 (figure 6). The georeferenced version of the digitised map sheets provided by Arcanum (Budapest) has an accuracy of 50–100 m. However, in the Carnuntum area which was situated in the Austrian part of the Habsburg monarchy, we have to go back to the original map sheets. The original coloured map sheets of the cadastre of 1819 were produced at a scale of 1:2,880. They offer much more details concerning land parcelling at an average RMS accuracy of 4–5 m, but all had to be laboriously scanned and georeferenced.

Historic maps and cadastres:
cf. chapters "Use of historical cadastral maps in modern landscape research and management" of Domaas & Grau Møller and "The concept of a historic landscape analysis using GIS" of Bender.

RMS (Root mean square) accuracy:
is the mean derivation of a map to geomet-rically correct reference data expressed as the square root of the mean sum of the square errors.

5 METHODOLOGY AND RESULTS

In studies on Roman land parcelling, the geographic features involved are frequently linear. In structural geology, the commonly used term for linear or curvilinear landscape elements visible from the air is photolineations (Kronberg 1984: 251–252). Whereas photogeology is interested in structural features (tectonic structures), in Roman landscape archaeology other forms of lineations created or influenced by land use are studied (roads, footpaths, hedgerows, borders of land parcels, boundaries of forests, canals, etc.). In a vector GIS database, linear geographic features of the real world can be represented most appropriately by lines or polylines.

Within a GIS environment, linear features have both their geometric characteristics and their specific spatial attributes. A line object may consist of a single line segment or a sequence of line segments linked together

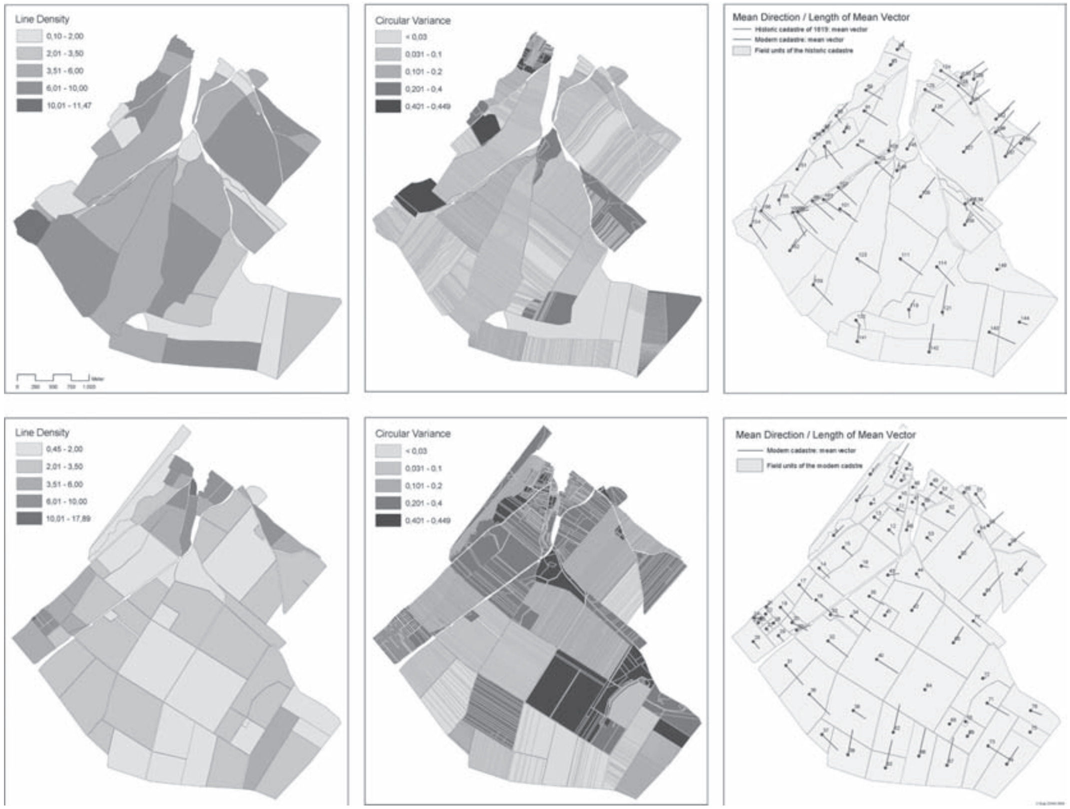


Figure 2. Comparison between the his-toric cadastre of 1819 (upper row) and to-day (below) in the municipality of Bad Deutsch-Altenburg. Mapping descriptive statistics: line density, circular variance, and mean direction, © 2004 Gugl (ÖAW).

which is generally called a chain. With the help of software tools, spatial attributes like the length of the line segments and their orientation can be easily derived from linear features (DeMers 2000: 311–317, Lee & Wong 2001: 91–131).

Especially in the geosciences, a broad range of statistical techniques has been developed to analyse linear geographic features (figure 2 and 3). In contrast to line length which can be described by standard statistics, orientation data (uni- or bidirectional) belong to the so called circular data type. In this case circular statistics have to be used (Mardia & Jupp 2000, Lee & Wong 2001: 104–114). One of the basic concepts of circular statistics is the concept of the mean vector which shows two attributes: the mean angle (directional mean) and the length of mean vector. From the latter, the circular variance can be computed. This measure characterises the variability of orientation of line segments whereas the first shows the general direction of a linear data sample.

Circular histograms and rose diagrams are common ways of visualising the analysis results. They can illustrate the azimuth frequency and

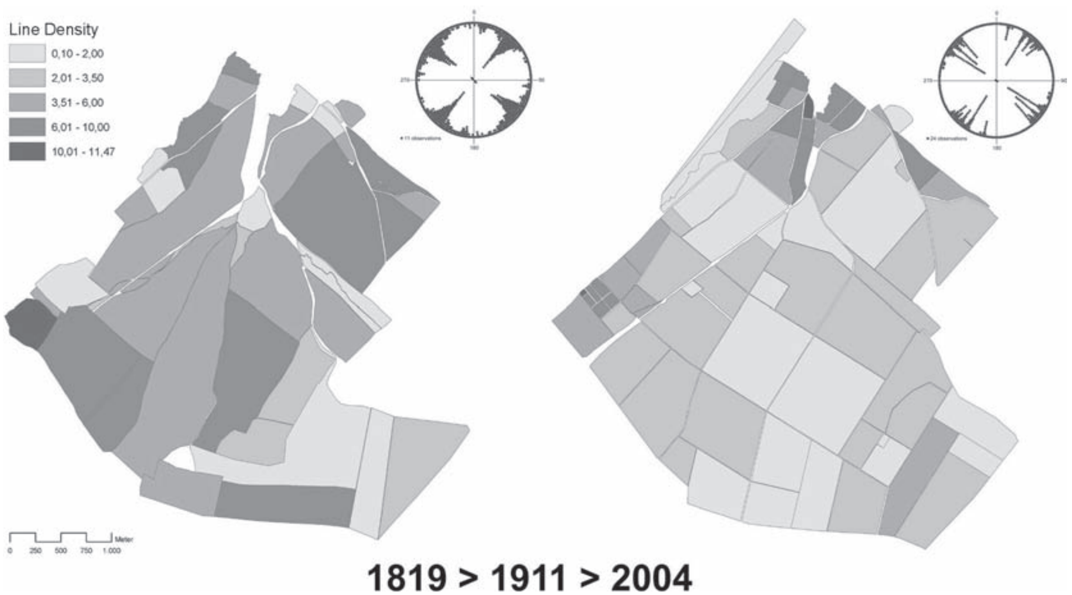


Figure 3. Orientation analysis of field boundaries in the municipality of Bad Deutsch-Altenburg. Decreasing line density and increasing orientational uniformity between 1819 and today. The most striking changes took place in 1911 due to land consolidation measures, © 2004 Gugl (ÖAW).

the length distribution of the lineations according to their orientation (Kovach 2003: 53–62). GIS systems offer several ways for the graphical presentation of line (and point) density, for example mapping density by area or creating a density surface (Mitchell 1999: 69–85).

In the context of our studies on Roman land survey in north-western Pannonia, several of these GIS and statistical techniques have been used to compare historic and current cadastre maps and to analyse the change between ancient and recent field boundaries. The first step includes the definition of important Roman roads and surveying axes postulated by archaeological theory. The coordinate system chosen must be based on a conformal map projection which preserves angles locally. In the case of Carnuntum, the orientation analysis of field boundaries focused first on the immediate vicinity of the legionary fortress. The whole research area covered 1,280 ha, from which areas covered with modern buildings and roads had been excluded. For a quantitative analysis of the regional differences, it is advantageous to define smaller sampling units according to the existing land parcels. Of course this is a subjective process, but the data sample of the whole research area will in general only deliver unsatisfying statistical results.

Cadastre:
a public register of the value and ownership of the land of a country, state, or municipality.

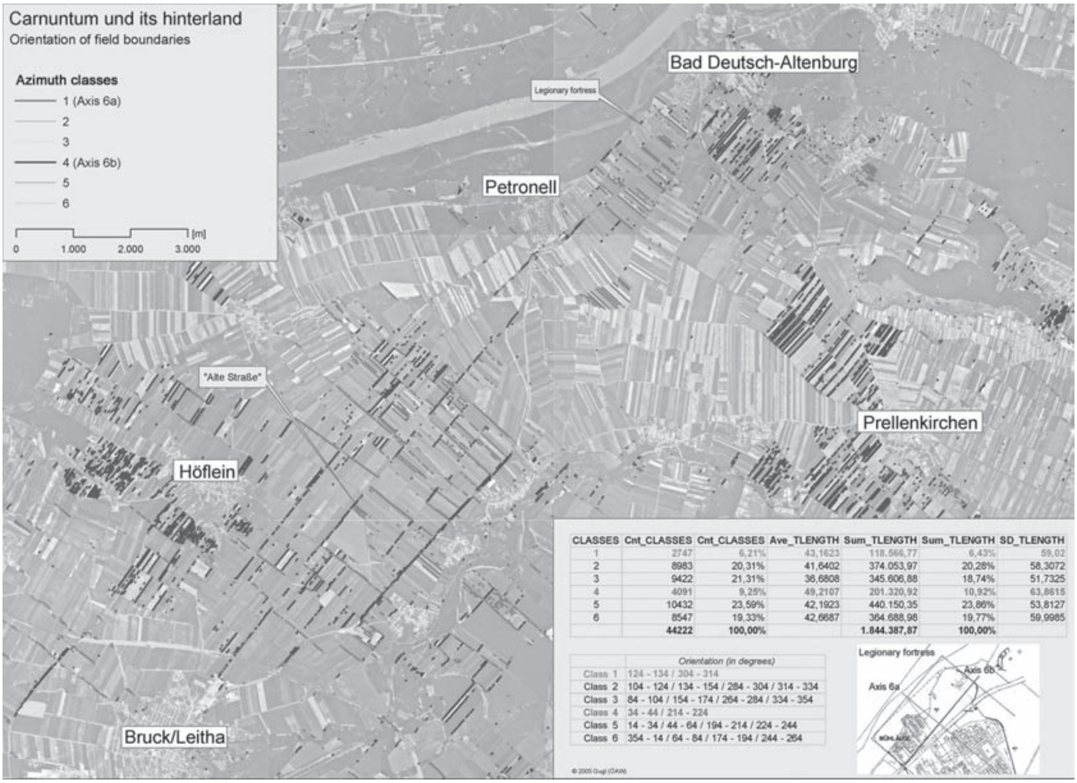
As in environmental sciences, for instance in hydrology (Burn 1997: 214–222, fig. 3 and 4, Uhlenbrook et al. 2001: 193, fig. 8 and 9), this approach seems to be a suitable method for measuring the distribution and orientation of field boundaries in time and space. The line segments of each sampling unit can easily be selected using the clip operator in a

Clip operator:
a GIS tool for selecting and cutting GIS objects by overlay of another object. Therefore, the clip command works like a cookie cutter.

ESRI's ArcView 3:
the predecessor GIS and mapping software of ArcGIS provided by ESRI.
www.esri.com/arcview3x

vector GIS. A simple way is to calculate length and orientation of all line segments with the help of several scripts, written for ESRI's ArcView 3 GIS package. Software specially developed for analysis of orientation and direction, such as Oriana, calculate these basic statistics and perform single- and multi-sample tests as well as circular correlations (Kovach 2003: 43–51). In this way, it is possible to determine several statistics, such as line density, circular variance, mean direction and length of mean vector, and therefore to characterise the line elements in the past and present landscape at the defined regional level (figure 2).

Description of linear features by their length and azimuth is a well established technique. Experience shows that the definition of the class range should be appropriate to the nature of the proposed grid axes. This includes a certain angle tolerance due to the spatial accuracy of the data. In the majority of cases, a tolerance value of ±5˚ should be sufficient, so a class range of 10˚ seems appropriate (Wiedemann et al. 2001: 117–118). One research aim is to distinguish between sets of lineations with orientation close to that of a predefined (centuriation) grid or axis. So, the extracted orientations might be classified using a varying range for each azimuth class, for instance a class with a width of 10˚ for the lines which



CLASSES	Cnt_CLASSES	Cnt_CLASSES	Ave_TLENGTH	Sum_TLENGTH	Sum_TLENGTH	SD_TLENGTH
1	2747	6,21%	43,1623	118.566,77	6,43%	59,02
2	8983	20,31%	41,6402	374.053,97	20,28%	58,3072
3	9422	21,31%	36,6808	345.606,88	18,74%	51,7325
4	4091	9,25%	49,2107	201.320,92	10,92%	63,8615
5	10432	23,59%	42,1923	440.150,35	23,86%	53,8127
6	8547	19,33%	42,6687	364.688,98	19,77%	59,9985
	44222	**100,00%**		**1.844.387,87**	**100,00%**	

	Orientation (in degrees)
Class 1	124 - 134 / 304 - 314
Class 2	104 - 124 / 134 - 154 / 284 - 304 / 314 - 334
Class 3	84 - 104 / 154 - 174 / 264 - 284 / 334 - 354
Class 4	34 - 44 / 214 - 224
Class 5	14 - 34 / 44 - 64 / 194 - 214 / 224 - 244
Class 6	354 - 14 / 64 - 84 / 174 - 194 / 244 - 264

Figure 4. Automated vectorisation of orthophotos of the Carnuntum area indicating field boundaries which correspond to the two possible Roman surveying axes, © 2004 Gugl (ÖAW); Base maps: © BEV EB 2003/01203.

fit most to the expected orientation and a larger value for all the other classes (figure 4).

For visual data inspection and the presentation of analysis results, special forms of visualisation have been developed. Scientific disciplines like photogeology which deal a lot with the detection and interpretation of lineations, have been very innovative in developing and adopting special graph types and data plots. For this purpose powerful software programs like Grapher (Golden Software) or Oriana (Kovach Computing) should be integrated into the work flow. They are capable of graphing the data in a variety of ways, including rose diagrams, circular histograms, raw data plots and other forms of distribution plots, allowing easy detection of patterns and visualisation of similarities and differences between two or more sets of observations (figure 3). Of special interest are two-variable histograms with stacked bars which show the relative proportions of subsets within the data by dividing up the second variable into frequency classes. For example, lineations may be classified by azimuth and total line length, using segments of the multiple bars to represent the frequency of observations of each length class at that azimuth (figure 5).

Grapher (Golden Software): *a graphing programme for all of most complex graphing needs (2D and 3D graphs from simple and complex equa-tions). www.goldensoftware.com/products/grapher/graphers.shtml*

Oriana (Kovach Computing): *a software which calculates the special forms of sample and inter-sample statistics required for circular data. www.kovcomp.co.uk/ oriana*

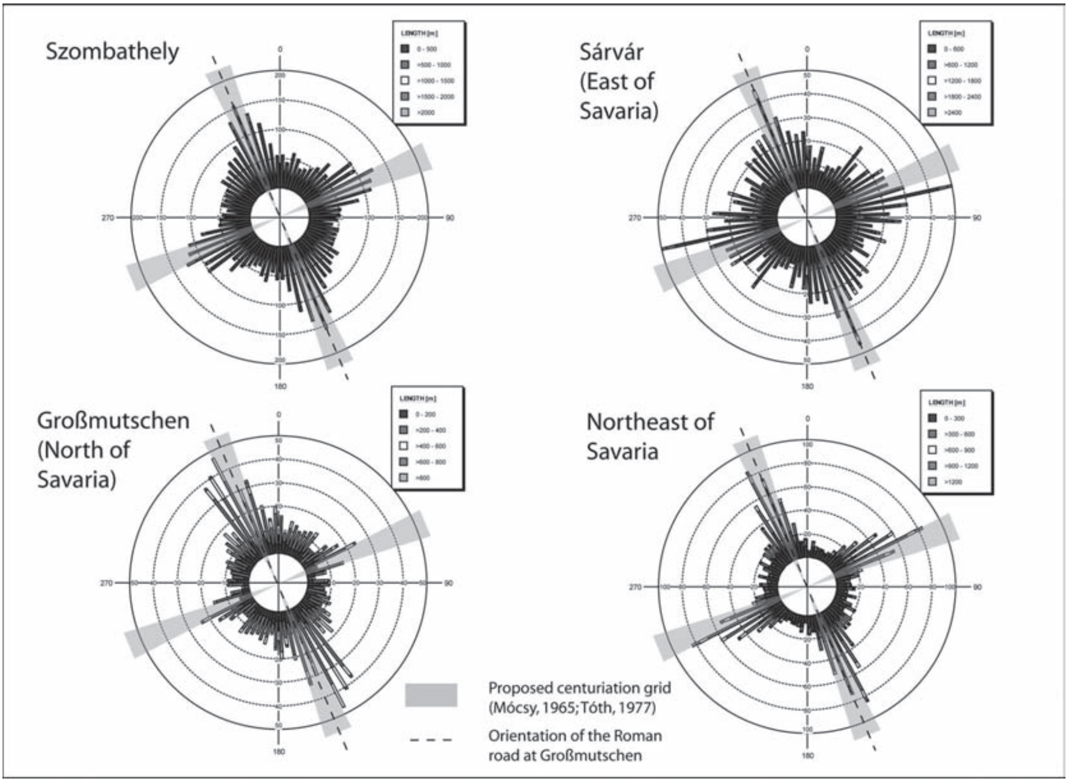


Figure 5. Orientation analysis of 19th century roads and tracks around Szombathely (Savaria), Sárvár (Vas megye, Hungary) and Großmutschen (Burgenland, Austria). The data was generated out from the cadastre maps of the second military survey in the Habsburg Empire shown in figure 6.

GIS mapping techniques combined with the use of sophisticated graphs greatly accelerate the process of visual data exploration. However, research in the field of historic landscape analysis remains complicated by the process of data acquisition. Current cadastre maps are in general available in digital form, whereas historic ones, especially in the required map scale and with a sufficient spatial accuracy, are often not. For the study of microregions, historic maps can be scanned and georeferenced with a reasonable amount of work. When the interest focuses on larger areas, other solutions have to be considered. In the late 1970s, first attempts of automatic linear recognition were carried out in geological and environmental remote sensing. LIRA was the first commercially available software package for the automatic detection of linear features in a digital image (Vincent 1997: 151–155). Concerning Roman landscape studies, a French research group made experiments with the optical filtering of light spectra constructing elaborate devices (banc du filtrage) to extract the orientation of field boundaries from analogue air photos and satellite images (Favory 1980, Darbandi & Guy 1981).

In the hinterland of Carnuntum, black-and-white orthophotos were used to perform automatic linear feature mapping in an area of 225 km^2 (figure 4). This supplemented the in-depth analysis of historic map sheets from the vicinity of the legionary fortress, covering only approximately 13 km^2 (figure 2–3) (Gugl 2005: 95–104). Nine tiles of 8-bit greyscale bitmaps, each covering an area of 25 km^2, were used to generate vector data by (semi-)automated processes. Before making a raster to vector conversion, several techniques of image enhancement may be used. These include contrast stretching and digital filtering, such as Sobel or Canny edge detection, to isolate lineations and directional trends in the image (Jähne 2005: 349–372). After these necessary preparations follows a binarisation of the greyscale images. Most of this workflow can be done within commercial raster analysis GIS packages such as IDRISI as well as open source image processing tools, for example ImageJ. For converting these enhanced 1-bit images into vector files suitable for GIS, there are specialised raster-to-vector software applications, for instance WinTopo which is also freeware. Depending on the properties of the input-images, in most cases it is useful to perform raster thinning using thinning algorithms which skeletonise the edges down to single pixel width (Nischwitz et al. 2004: 486–495). Afterwards the vectorisation can be done, generally combined with algorithms for simplification to smooth or reduce polylines. Most conversion programs allow the results to be saved in interchangeable vector formats such as dxf (AutoCAD) or shp (ESRI).

Finally, it is advisable to optimise the vectorisation and to reduce the total number of polylines by removing those who wouldn't make any sense in a further orientation analysis. Vectors might only reflect uninteresting details of obscured areas or forests; this kind of noise could be selected for exclusion by using a polygon to represent them. Within the GIS, this is done by a polyline-polygon overlay. Curvilinear polylines should also be removed, because the spread of the orientation of their

Image enhancement:
cf. chapter "The use of satellite remote sensing for detecting and analysing cultural heritages" of Heinrich et al.

IDRISI:
an integrated GIS and image processing software solution for the analysis and dis-play of digital spatial data.
www.idrisi.com

ImageJ:
a public domain Java image processing program developed on Macintosh for dis-playing, editing, analysing, processing, saving, and printing 8-bit, 16-bit and 32-bit images.
http://rsbweb.nih.gov/ij

WinTopo:
a free raster to vector imaging software.
http://wintopo.com

Autodesk AutoCAD:
a CAD software application for 2D and 3D design and drafting of vector objects, de-veloped and sold by Autodesk, Inc.
www.autodesk.co.uk/adsk/servlet/index?siteID=452932&id=10480967

segments may be too large to be acceptable. The complexity of a polyline can be measured by the length ratio which is based on the difference between the straight line length and the true length of the chain. Selected polylines with a high length ratio could either be deleted or they may be modestly simplified (to be closely spaced around their main directions).

An important issue is the evaluation of the vectorisation results. Joppe (1998: 104–105, fig. 14) presents a method of evaluating geological lineations by comparing the results of automated vectorisation with those of a conventional visual interpretation. This evaluation method has two goals: to perform a plausibility check and to test the completeness of the automatically detected features. First, in a limited test area in the GIS a buffer was created around the manually extracted lineations (reference data) and the automatically generated lines lying in the buffered area were counted (test data). Then, for evaluating the completeness, the same procedure was done the other way round, with the automatically mapped lineations as reference data and the visually mapped ones as test data.

Buffer:
a GIS technique to construct a zone with a defined distance around discrete spatial objects, e.g. points, lines, or polygons.

In the Carnuntum case study, the vectorisation results of two software products were compared: GRASS GIS, an open source GIS package, and MapScan, developed by the United Nations/UN-IOIT between 1996 and 1999 (Gugl 2005: 97–104). In a test area, the lineations, automatically detected on the black-and-white orthophotos, were compared with the modern digital cadastre map. An artificial orthogonal grid with 82 squares of 500 m × 500 m was created, the line density in each square calculated and compared. This could be visualised by a graph that showed the frequency distribution of the lineations for each sector. Furthermore, the relations of the lines orientations could be determined by a circular-circular correlation of the 82 mean vectors of the digital cadastre map and the two vectorisation attempts.

GRASS GIS (Geographic Resources Analysis Support System):
an open source GIS used for geospatial data management and analysis, image processing, graphics/maps production, spatial modelling, and visualisation.
http://grass.osgeo.org

MapScan:
a software package developed by the United Nations Statistics Division for con-verting raster data into vector format.
http://netgis.geo.uw.edu.pl/free/mapscan/

Finally, a reconstruction of the centuriation in the Carnuntum area was attempted (Gugl 2005: 104–108). The use of GIS not only makes it possible to select polylines according to their orientation and to discuss different postulated grids by comparing them in a visual overlay, but also to quantify the plausibility of competing models. Six hypothetical centuriation grids were established, differing slightly in their orientation, but particularly in their point of origin and in the side length of the reconstructed squares (centuriae of 703 or 710 m). A buffer of ±15 m was added to the axes of the grids. The line segments within the buffered area were counted and compared. Unfortunately, the six proposed models don't show significant differences, so one can be judged as good or bad as the other.

In general, conventional visual interpretation profits from the human cognitive abilities of pattern recognition and the personal experiences of the interpreter (Joppe 1998: 80–81), who can directly classify lineations by assigning attributes to the mapped features. Even with the use of high resolution imagery, like colour orthophotos, it remains problematic to produce more satisfying results. High resolution data does not lead to an easier classification process concerning the detection of edges caused by land use. Although these photos show a high level of spatial details, the represented objects are far less homogenous which makes the extraction of relevant land use patterns much more difficult. So at present, it is doubtful if automatic linear feature mapping, which is based on changes in the greyscale values of raster images, delivers adequate results for executing successfully metrological studies. It is not possible to distinguish between different kinds of edges which may represent (temporary) field borders or more permanent hedgerows, fences, border

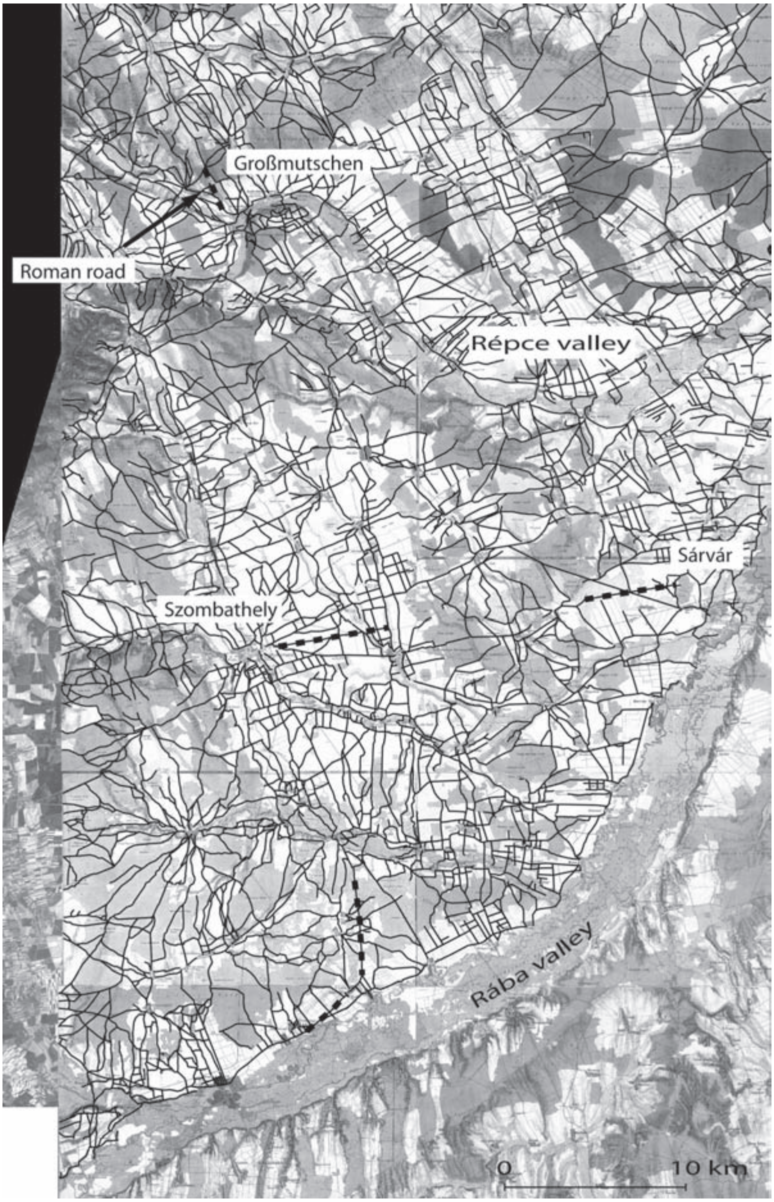


Figure 6. 19th century cadastral maps of Western Hungary. The main Roman roads around Savaria (Szombathely) are indi-cated with dashed lines. © 2006 Gugl (ÖAW).

walls, etc. Nevertheless, automatic feature mapping can deliver regional structural trend information, not just for a limited area, but on a larger scale. This would be impossible with conventional methods.

6 FUTURE PERSPECTIVES

Recent research on historic field patterns in Austria showed that the land consolidation measures from the end of the 19th century onwards could have had a considerable impact on the structure of the landscape. The flat country in north-eastern Austria was dominated by systems of strip-fields, identical to those in the municipality of Bad Deutsch-Altenburg. Especially there, the land consolidation measures of the last century resulted in field patterns in block-form, looking sometimes at first glance similar to relics of a Roman centuriation grid. The small-scale cadastral maps of Hungary from the first half of the 19th century, now available in digital form (figure 6), make it possible to get a general idea on the structure of the historic road and path network from the time before the land consolidation was executed. Around Szombathely, the former Roman colony of Savaria, roads, tracks and paths as well as segments of known Roman roads could be manually vectorised covering an area of approximately 2,000 km^2. When analysing these polylines with the techniques described above, the data were grouped according to well defined study areas depending on the regional topography and on the research questions. The aim was to identify any possible sub-regional trends in the data (figure 5).

Historical cadastral maps of Hungary:
II. Military Surveying of the Kingdom of Hungary and Temes, provided by Arcanum Adatbázis Kft., Budapest, available as DVD: www.arcanum.hu/idegennyelvu/iny_mkf1.html

For further research, additional data would be necessary to have independent evidence for the Roman origin of these features appearing in the modern landscape. For example, we could analyse the relationship of the proposed grid systems to archaeological evidence of rural settlement and field systems. We currently lack a gazetteer of archaeological remains in north-western Pannonia, as well as systematic research on the relationship between them and the Roman survey axes and roads. First attempts in this regard are at present being carried out in the Leitha valley, southwest of Carnuntum (Gugl et al., in print, Ployer 2006).

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