MODELLING AND MONITORING OF COASTAL MARINE PROCESSES

Edited by
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Springer

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Foreword

The majority of personnel responsible for coastal zone management and coastal environmental impact analysis are drawn mainly from traditional fields of physical, biological and engineering sciences. Many of them are not exposed to specialized training in dealing with complex problems of the coastal zone. Therefore, there is a growing need for trained marine professionals in countries of the central Indian Ocean (IOCINDIO) region to deal with the coastal marine pollution and related issues arising out of accelerated developmental activities. Modelling and Monitoring of Coastal Marine Processes (MAMCOMP) was first initiated by the UNESCO's Intergovernmental Oceanographic Council (IOC) for the IOCINDIO region in 1994 as a training programme in Integrated Coastal Area Management (ICAM). It has been successfully conducted every year, with the exception of 1998, at Indian Institute of Technology Delhi, India. Recognizing the growing need for trained marine professionals in the Regional Organization for the Protection of the Marine Environment (ROPME) Sea Area (RSA) to deal with emerging marine pollution, and other related issues arising out of accelerated land-based and offshore developmental activities at the third session of the IOCINDIO region meeting during 2000 in Tehran, I.R. of Iran, it was decided to conduct the MAMCOMP-ICAM training programme in the RSA region in collaboration with the ROPME. The IOC and ROPME in co-operation with the UAE Federal Environmental Agency and UAE University conducted MAMCOMP-2001 at Al Ain, UAE and MAMCOMP-2003 and 2007 at Tehran in collaboration with ROPME and Iranian National Center for Oceanography. The IOC was responsible for planning and conducting all aspects of the MAMCOMP training programmes.

The IOC sponsorship of MAMCOMP was essentially based on the concept of national and regional "capacity building" of scientifically trained marine science professionals. The participants for the training programme are usually selected by a Programme Committee comprising senior scientists/administrators from various institutions dealing with marine issues. About 20-30 participants were selected per year from the marine pollution control agencies and boards, R&D organizations dealing with marine science and environmental engineering, and academic institutions interested in marine science studies. While most of the participants were from the host country, on occasions, a limited number of participants from the IOCINDIO region countries and international participants were sponsored by the IOC. Although the training programme was originally intended to provide broad-based theoretical and experimental aspects of coastal marine science for working scientists, it has also served well as an introductory graduate course for students pursuing advanced university degrees at the Masters and Doctoral levels. MAMCOMP training programme is now reasonably known in marine science laboratories, academic institutions, marine environmental centres such as coastal pollution boards, and it has generated considerable interest in the IOCINDIO region in Integrated Coastal Area Management.

Julian Barbiere
ICAM Coordinator
UNESCO-IOC

Preface

This book deals with a collection of overview articles on two aspects of coastal oceanography: monitoring and modelling of coastal marine processes. Although numerous books have been written on both monitoring and modelling of coastal oceans, there is a practical need for an introductory multi-disciplinary volume to non-specialists in the field. The text is intended for graduate students and professionals who do not have extensive training in marine sciences and coastal zone management. This book will also support instruction of modelling and monitoring of coastal marine processes for short courses to mid-level scientists. As such, the articles in this monograph can be a valuable reference for practicing professionals.

The articles in the book, organized into four major themes, are written by experts in their disciplines. The first section introduces the complex physical processes with main emphasis on waste disposal in the coastal ocean. The articles in this section provide an overview of transport and diffusion processes in the marine environment. The review of fundamentals at this stage provides a common foundation of mathematical and field observational knowledge upon which the rest of the course is developed. Following this, examples of instrumentation techniques that are commonly used for measuring different properties of oceans are described with several examples of both in-situ and remotely sensed instrumentation. Coastal and estuarine transport and dispersion modelling is introduced in the next section with examples from different parts of the world. The last section provides an overview of coastal disasters such as tropical cyclones, storm surges and oil spills. Finally, we provide some overview articles on integrated coastal management with some regional examples and the application of GIS techniques for coastal zone management.

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INTRODUCTION

The coastal ocean extends from shorelines, beaches and estuaries across continental shelves and slopes to where exchanges and interactions occur with the deep ocean. Although the inshore boundary is normally the coastline, it may extend in some cases such as estuaries as far upstream as riverine cross-section where unidirectional downstream flows always occur irrespective of tidal flow conditions. The general offshore boundary is the continental shelf-break and the inshore boundary may extend as far as the river plains. Functionally it is the broad interface between land and water where production, consumption and exchange processes occur at high rates of intensity. Ecologically it is an area of dynamic biological activity, but with limited capacity for supporting various forms of human interactions.

The coastal ocean—where land, air and sea meet—is a region of very high physical energy and biological diversity that is heavily exploited by man. The coastal zone occupies only about 8% of the earth's surface but approximately 26% of the total global primary production occurs in this area and as much as 85-90% of the present world fisheries production is derived from the Exclusive Economic Zone (EEZ). Much of the world's arable lands and industrial development lie on the coastal plains and in lower river valleys. As a consequence, about 60% of the present world's population lives within 60 kilometres of the shoreline. It is estimated that in a few decades 75% of the world population will live within 60 kilometres of the coast. Over two thirds of the world's cities with populations greater than 1.6 million inhabitants are located in coastal areas, often in the vicinity of highly productive estuaries or coastal wetlands. In Southeast Asia, 65% of all major cities are on the coast. Population growth and population density are highest near the coastal zone and in many countries the coastal population growth rate is twice the growth rate inland due to heavy migration to coastal locations and cities. Urban coastal ocean problems pose serious threats to marine water quality and resources.

Therefore, the coastal ocean regions are the areas of most immediate interest to the public and most direct human impact occurs there. The coastal ocean and the adjoining terrestrial areas interact intimately. The coastal ecological systems are already stressed and degraded and the driving forces in these environments are no doubt anthropogenic. Through deliberate dumping and inadvertent action, coastal oceans have become the depositories of human and industrial wastes. Also, the rivers serve as natural conduits in transporting materials to the coastal ocean. The present quantity of domestic municipal and industrial wastes discharged into the coastal waters, estuaries and the open ocean precludes the possibility of economic alternative methods of waste disposal. All waste water used in man's activities ultimately finds its way to the aquatic and oceanic environments.

The coastal ocean is the focal point of inter-related water resources systems and should receive much greater attention in water resources research, planning and management. It is the coastline where the river meets the sea, where fresh groundwater is subject to salt-water intrusion, where the majority of urban centres' industrial complexes are located. Sustainable development of the coastal ocean must be based on interdisciplinary studies including socio-economic and political aspects. Coastal oceans are very important in several ways, not mutually compatible if carried to extremes and each with differing policy and management objectives. Neither total exploitation, nor complete conservation is an acceptable goal and hence a balance must be maintained. Ecological rehabilitation must now be an integral part of any new coastal ocean development programme. Integrated environmental and socio-economic studies must be initiated with a broad view of formulating coastal ocean management policies and strategies.

Chapter 17 of UNCED's Agenda 21 specifically calls for innovative approaches to "Integrated Management and Sustainable Development of Coastal and Marine Areas, including Exclusive Economic Zones, EEZ". It also calls upon countries to "co-operate in the development of co-ordinated, systematic observations, research, and management of coastal systems". In view of world-wide interest in coastal ocean issues, several international agencies have proposed activities to tackle coastal zone management.

COASTAL MARINE PROCESSES

The coastal zone is truly a dynamic ecological system with continuous natural erosion and accretion at the shoreline. At the coastal interface, the sea is shallow and the land is low. Sand and mud flats receive daily tidal floods and river run-off, while wind and waves bring continual change to the shoreline. However, it is man's activities which cause the greatest and most rapid change, and which are the primary reason for the concern with coastal resources management. The coastal ocean is particularly vulnerable to global changes such as climate change, sea level change, which is in itself a derivative of the climate change, and changes in uses of land and fresh water. These global changes may fundamentally modify geomorphologic, hydrodynamic, geochemical and biological processes in the coastal ocean and affect significantly transport of materials from the land to rivers and seas.

The physical transport processes are dominant in mediating geochemical and biological processes in the coastal ocean environment. Thus, it is very important to have a thorough understanding of the coastal physical processes responsible for the distribution and redistribution of chemical and biological species in the coastal ocean. The transport and fate of nutrients and contaminants discharged into the coastal zone is just one example. Their residence time and their degree of accumulation in the sediments (suspended as well as bottom) are partly by the physical exchange processes and partly by biotic processes active in the coastal regions. The coastal regions are not, however, isolated but are coupled to a greater or lesser degree by exchanges across the shelf-break involving transport of materials, momentum and energy.

Several physical factors combine to make the coastal ocean complex and unique in its hydrodynamics, and the associated physical transport and dispersal processes of the coastal flow field are equally quite complex to deal with. The first characteristic feature of the coastal ocean is its shallow depth, typically less than 200 m, compared with depths of 4000 m in the deep ocean. The edge of the continental shelf is usually marked by an abrupt increase in the bottom slope from an average of 1 in 500 to about 1 in 20. Because of the presence of bottom at a relatively shallow depth, currents near the bottom are often much larger than deep ocean. The bottom friction, which is negligible in the deep ocean, plays a significant role in their dynamics.

The presence of shoreline acts as a lateral constraint on water movements, tending to divert currents so that they flow nearly parallel to the shoreline. The shoreline also causes surface slopes to develop, which in turn react on and modify the water movements. The influx of freshwater run-off from the land, often after passing through the estuaries, has the effect of reducing the salinity, and hence also density of the coastal water. For a similar heat flux through the sea surface, the shallower water near the coast undergoes larger changes in temperature than deeper water. Because of these effects, coastal water exhibits large horizontal gradients of density, often associated with changes in currents.

Tide and Tidal Currents

The tides, which produce the rise and fall of water in the coastal zones, are generated in the deep oceans. But due to the above characteristics of coastal waters, the tides and tidal currents are considerably modified in the coastal zone compared to deep-ocean. Their magnitude is usually increased, sometimes by a large factor when resonance occurs between a tidal period and the natural period of oscillation of a coastal body of water.

Wind-driven Motions

Wind-driven currents are strongly affected by the presence of the coastline and the bottom. In some areas this gives rise to storm surges, while in others new effects are produced, such as occurrences of upwelling and downwelling or the generation of coastal jets.

Surface Waves: Surface waves are an important feature of oceans that get modified in the coastal waters. As waves travel into shallower water, the proximity of the bottom induces considerable changes in them and eventually causes them to break, dissipating most of their energy on the shore. The release of energy from the waves leads to the movement of large amounts of beach material in some areas and exerts considerable forces on natural and man-made structures.

Seiches: Standing waves cause much greater water displacements than surface waves and are, therefore, much more important in physical oceanography and limnology. Standing waves are a phenomenon occurring in all inland water bodies, but only in large basins we observe periodic rise and fall of the water surface. They are generally known as 'seiches'. The seiches are free surface waves, governed by similar dynamics as short, wind generated waves. The principal ingredients in the wave dynamics are acceleration of the water particles and pressure gradients generated by displacement of the free surface and the force of gravity.

Storm surges: A sudden strong wind will produce not only oscillating seiches, but also cause the water surface to set up or tilt, more or less in opposition to the wind stress, and for the duration of the wind. These changes in water level observed in response to extremely vigorous wind forcing are known as storm surges. The largest change in water level is produced by the sum of storm surge and tide. Storm surges are largest at the ends of an elongated basin, particularly when the long axis of the basin is aligned with the wind. In low-lying shores such events may cause flooding and increased erosion, with property damages and risk to human lives.

Topographic gyres: The wind drag is transferred from the surface downward by turbulent friction. In the closed basins, the transport of water through any cross-section averaged over the period of fundamental seiche is zero. Surface wind-driven flow must be balanced by a subsurface flow that is driven by pressure gradients. Close to the shore, wind drag is experienced all the way to the bottom, and this water is accelerated in the direction of the alongshore component of the wind. The balancing return transport occurs in the middle of the basin. Thus the forced, vertically averaged circulation takes the form of double gyre. The complicated vertical shear maintained during the active wind-forcing soon dies out, leaving this two-gyre motion behind. Within such cross-shore flows, the earth's rotational force and pressure gradients do not balance and a wave-like motion sets up. The two-gyre motion rotates counter-clockwise around the basin in the Northern Hemisphere. These motions are called topographic or vorticity waves. Unlike the influence of topography, the curl of the wind stress generates a single basin-wide gyre that can rotate around the basin, depending on the wind stress.

Coastal Jet: During strongly stratified regions the force of gravity suppresses turbulence. The vertical transfer of wind-imparted momentum is thus inhibited so much so that the shear stress in the horizontal planes within the thermocline is usually small. This is not true all of the time or everywhere; however, it has been observed in the coastal regions that at least at some distances from the shore the momentum of the wind induced coastal current is concentrated in the top, warm portion of the water column above the thermocline. This concentration of momentum in relatively shallow layer resulted in increased velocities, compared to their depth-averaged values. The region where such concentration was pronounced occupied a band of 5 km width. Their high velocity, shallow depth, and narrow width make it appear to describe the flow structure as 'coastal jets'.

Upwelling and downwelling: When wind blows over the stratified coastal waters, the initial transport is confined to the upper layer, which slides over the unperturbed lower layer. At the shores, accumulations of warm water force the thermocline down (downwelling), and where the warm water moved offshore, the thermocline must rise (upwelling). The strong tendency for the Coriolis force to steer flows in such a way that the pressure gradients are balanced by the Coriolis force limits the upwelling and downwelling zones to a narrow band along the shore line typically within the Rossby radius of deformation. The Rossby radius of deformation can be defined as the ratio between the typical velocity scale of surface or internal waves, and the Coriolis frequency.

Internal Kelvin waves: When the wind stops, the initial unbalanced state described above relaxes through the mechanism of internal Kelvin waves. Kelvin waves propagate along shore in a counter-clockwise direction in the Northern Hemisphere. Internal Kelvin waves are confined to a few kilometres from the shore, and with no motion in the perpendicular direction to the coast. The near-surface currents that moved in the downwind direction during the active wind phase now reverses during the propagation of these waves.

Near-Inertial motions: In large lakes and oceans the earth's rotation is often important and may influence the water motion. When the natural period of the oscillation is comparable to or greater than the inertial period ($12/\sin\varphi$), the motions are affected by the earth's rotation. The inertial period is dependent on the latitude (φ) of the lake. During the stratified season away from the near-coastal regions, currents exhibit clockwise rotary motions close to the inertial period. The main features may be explained in terms of balance between the Coriolis force and the centrifugal force. A sudden wind impulse lasting less than half the inertial period is favourable to the creation of inertial motions. Observations also showed similar motions in the deeper layers where the direction is generally opposite to that of surface oscillations. These motions are called Poincare waves, which are similar to internal seiches in lakes and inland seas. The currents are accompanied by vertical oscillations of thermocline at the wave period. These waves are hybrid between pure inertial motion described above and gravity waves; the current vector rotates in clockwise direction at a frequency close to but usually larger than local inertial frequency.

Vertical convection currents: Apart from wind- or river-induced circulation, currents can also be generated internally due to stratification effects. These currents draw their energy from changes in density due to surface cooling and heating. Differential cooling and heating is also very important in shallow zones and may be responsible for flushing of littoral waters.

There are several conceptual models and theoretical ideas concerning the hydrodynamics and transport and dispersion in the coastal ocean. However, it is difficult to identify the relative effects of different physical processes in any specific situation to arrive at a predictive deterministic model. Recognising this difficulty, it is therefore not surprising that coastal marine research places considerable emphasis on carefully designed large scale field experiments at several coastal sites with a view to formulate a climatology of the coastal physical environment in terms of the dominant circulation features and transport and dispersion processes. The results and data obtained from the experiments facilitate in parameterising the coastal marine physical processes necessary for developing predictive coastal transport models. Generally there are several interrelated objectives for such coastal marine experimental programmes. Some objectives are site-specific in nature (for example siting Sewage Outfalls in the coastal ocean) and others are towards the understanding of fundamental coastal marine processes.

WASTE DISPOSAL

Waste disposal into the ocean has come a long way from the time when there was unplanned and indiscriminate dumping of wastes. The alarming marine pollution that resulted from such practice has, in most places, been minimised in recent years in many countries. Now, waste disposal into the coastal ocean is a carefully controlled operation based on extensive scientific and engineering research and design. However, indiscriminate dumping still occurs in many countries even today.

In the early stages of waste disposal into the coastal ocean, it was the usual practice to discharge effluents from the end of a pipe or submarine outfall in a single large stream. The buoyancy of such a flow was so strong in relation to its mixing rate that the effluent plume would invariably rise to the surface and spread as a surface current. Pollution of the shoreline was likely when onshore currents occurred. Two significant advances in techniques of waste disposal into the coastal ocean have minimised this possibility of shoreline and beach pollution:

(i) Introduction of multi-port diffusers: Very large multiple jet diffusers have been successfully designed and operated without clogging and mal-distribution of flow. Diffusers greatly enhance initial dilution of waste effluent with receiving waters and dilution ratios of 200:1 or even 300:1 are commonly achieved with well designed diffuser systems within a very short distance from the point of discharge.

(ii) Concept of submergence: The natural density stratification of the ocean has been used to a great benefit in keeping waste discharges submerged in the lower layers of the ocean. A remarkable change in the flow pattern occurs when there is a slight density gradient in the receiving waters, caused by temperature and salinity changes with depth. In the ocean, the stratification is almost always hydrodynamically stable, with warmer (or less saline) layers at the top. The buoyant plume may no longer rise to the surface because the plume loses its buoyancy before it gets there. Initial dilution of the plume due to multiport diffuser is responsible for the loss of buoyancy of the plume. In actuality, however, the density of the entrained fluid decreases as the plume rises; nonetheless, a point of neutral buoyancy will be reached at some depth. Theoretical prediction of the maximum height of rise of a plume in a stratified environment is possible and of special interest in the coastal ocean, where submergence of the cloud of mixed sewage and sea water is beneficial in controlling marine pollution. The maximum height of rise may be made less than the total depth by making the discharge per port sufficiently small in relation to the density gradient. To produce a submerged sewage cloud one must first measure the natural density stratification in the ocean and then design a diffuser system to produce small enough jets so that the stratification may act as a brake on the buoyant rise of the wastewater plume. Essentially three stages of mixing and dilution of the wastewater field are encountered: (i) Initial jet or plume mixing: initial dilution; (ii) Development of a homogenous waste field following initial jet mixing: transition zone; and (iii) Dispersion of the waste field due to natural oceanic turbulence and current shear: far-field dilution.

Planning new coastal waste disposal systems in the coastal ocean should consider the following: (i) Water quality standards to be met in the receiving waters; (ii) Degree of treatment: primary treatment: screening, sedimentation from removal of settleable and floatable solids, and chlorinating as required to control bacteria and viruses; secondary treatment to achieve the necessary biodegradation which is often expensive. Properly designed marine outfall systems can provide the secondary treatment, for example, organic wastes are digested by the natural ocean life; (iii) Detailed oceanographic surveys: salinity, temperature and density stratification; coastal flow and dispersion climatology: current speeds, directions, persistency of currents, coastal dispersion coefficients etc.; submarine topography and geology and the characteristics of marine biology, turbidity, DO levels; and (iv) Dilution predictions using well established outfall diffusion models.

In the actual design of a waste disposal system, which is unique for each site, the engineer can choose the location, depth, and the length of the diffuser and the number and size of its discharge ports. Receiving water quality objectives have the major effect on the design. Design decisions can be made only in a systems context, taking into account the degree of treatment, outfall and diffuser hydraulics, the various stages of dilution, the decay rate of bacteria and other substances, and the density stratification, prediction of submergence and the current regimes in the receiving water body. In some instances a submerged waste field may be desirable, while in areas such as estuaries and large lakes it may not be desirable.

Ocean outfalls will not become obsolete even when much of the waste water is reclaimed for reuse. With growing demands for waste water, there will undoubtedly be extensive reclamation, because such water is much cheaper. But there will always be substantial outflows to the ocean because only part of the waste water can be reclaimed and reused and many types of industrial wastes are unsuitable for reclamation. Further, waste products from waste water reclamation plants must go somewhere, and the ocean is the most suitable place.

Deepwater ocean outfalls have virtually eliminated many coastal marine pollution problems. In some cases, one would have difficulty in finding any evidence at all of waste outfall disposal. Although, waste field is submerged most of the time and therefore out of sight, there are subtle ecological changes taking place in the ocean environment. These ecological changes should be identified and evaluated through biochemical and water quality monitoring and research; we cannot eliminate all ecological changes. However, by applying fluid mechanics, oceanography, and careful engineering research and design, we can obtain high dilution through dispersion and thus minimise the long range ecological effects. In heavily industrialised and urban coastal areas of India, the direct disposal of industrial and municipal effluents into the coastal ocean and the indiscriminate use of urban waterways, canals, streams and rivers as carriers of the waste effluents pose a threat to marine water quality and thus depriving alternate uses of coastal areas for recreation, tourism, and fisheries development and management. In some situations coastal marine environments have been stressed beyond their natural assimilative capacity to absorb the waste effluents with noticeable detrimental effects on the water quality and aesthetic value. The scientific and engineering aspects of the design, construction, maintenance and operation of marine outfall systems in India are very much in their infant stage at the present time. Therefore, the majority of the recently laid marine outfalls have been plagued with frequent malfunction and in some cases total failure.

Introduction to Transport Phenomena

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INTRODUCTION

The study of transport phenomena—i.e., transfer of mass, momentum and energy—is increasingly recognized as a unified description of fundamental importance. It is a topical extension of the concepts and laws of mechanics, thermodynamics and fluid mechanics. The prediction of the mechanical transport of substances in the ocean is a difficult task since it requires knowledge of many other interrelated factors. These factors include convection (transport by the moving waters of the ocean), physical (transition between different states, nuclear decay), chemical (chemical decay of substances, reaction with other substances) and biological (accumulation and transport of substances by living organisms). The transport is not only by the mean current velocities but also by the presence of random chaotic fluctuations in the velocity field. For calculating advective transport of substances, data on the vector field of mean current velocities for the ocean region are needed as well as their variations with time.

The transfer process typified by a diffusion process may be defined as the tendency towards equilibrium—a process which tends to establish equilibrium. For example, when a small amount of perfume vapour is sprayed into a room, the mass transfer process causes the perfume vapour to diffuse throughout the room until its concentration is uniform—an equilibrium condition. In all transfer processes, we are chiefly concerned with rates at which changes in properties of a system occur. In the flow of a viscous fluid, the frictional phenomenon or viscous stresses may be related to the rate of change of momentum of a system. Likewise, mass diffusion in any one of the various forms may be related to the rate of change of composition of a mixture due to transfer of one of the component species.

Microscopic theories of transfer processes are based on the phenomenological approach in which the basic transfer relations are postulated from experience without reference to the details of mechanisms of transfer.

By definition, a transfer process consists of net flow of a property under the influence of a driving force. The rate of transfer is the flux and the intensity of the driving force is the potential gradient. The transfer process (or flux) takes place in the direction of decreasing potential.

We give below the phenomenological rate equations for transfer of *momentum* and *mass*.

(a) Newton's Equation of Viscocity

Consider the motion of a fluid between two very long parallel plates, one of which is at rest and the other moving with a constant velocity parallel to itself. Let the distance between the plates be h, the pressure being constant throughout the fields. Since the fluid adheres to both the walls, its velocity at the lower plate is zero and that at the upper plate is equal to the velocity of the plate, U. Moreover, the velocity distribution in the fluid between the plates is linear, so that the fluid velocity is proportional to the distance y from the lower plate. Thus we have,

$$u(y) = \frac{y}{h}U \tag{1a}$$

$$\left(\tau + \frac{\partial \tau}{\partial y} dy\right) dx - \tau dx = \frac{\partial \tau}{\partial y} dx\, dy \tag{1b}$$

In order to support the motion, it is necessary to apply a tangential force to the upper plate, the force being in equilibrium with the frictional forces in the fluid. It is known from experiments that this force per unit area of the plate is proportional to the velocity U of the upper plate and inversely proportional to the distance h. The frictional force per unit area denoted by τ (frictional shearing stress) is, therefore, proportional to U/h, for which, in general, we may also substitute $\frac{du}{dy}$. The proportionality factor between τ and $\frac{du}{dy}$ which we shall denote by μ, depends on the nature of the fluid. It is small for "thin" fluids, such as water or alcohol, but large in the case of very viscous liquids such as oil or glycerin. Thus, we have obtained the fundamental relation for fluid friction in the form

$$\tau = \mu \frac{du}{dy} \tag{2}$$

The quantity μ is a property of the fluid and depends to a great extent on its temperature. It is a measure of the *viscocity* of the fluid. The law of friction given by equation (2) is known as *Newton's law of friction.* Equation (2) can be regarded as the definition of viscocity.

The dimensions of μ from (2) are

$$\frac{FT}{L^2} \text{ or } \frac{M}{LT} \tag{3}$$

where symbols F, T, L and M represent the primary dimensions of force, time, length and mass respectively. Thus in CGS units, μ may be expressed in gm/cm.sec.

It has been found useful to define another quantity known as kinematic viscosity and denoted by v:

$$v = \frac{\mu}{\rho} \tag{4}$$

where ρ is the fluid density. It is readily seen that v has the dimensions of L^2/T or cm^2/sec.

We shall confine our attention to Newtonian fluids, which includes all gases and most liquids. It should be understood, however, that many industrially important fluids, such as molten plastics are non-Newtonian.

(b) Ficks' Equation of Diffusion

Consider two parallel plates with initially dry air between them, the bottom plate being covered with gauge and the top plate coated with a substance such as silica gel which absorbs essentially all water vapour which it contacts. Suddenly the gauge is wetted with water so that the partial density of the water vapour at the wet surface is maintained at C gms water vapour per cm^3. Then diffusion takes place until a steady state is reached. At the silica gel surface, c is assumed to be zero

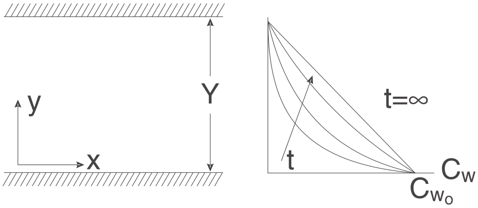

Fig. 1: Concentration distribution in a viscous fluid between two parallel plates.

Experimental evidence indicates a direct proportionality between the diffusion rate of water vapour and the concentration gradient. In the steady state or in general, at any position during the transient, the flux J is given by

$$J = -D\frac{\partial c}{\partial y} \tag{5}$$

where D is called the diffusivity or coefficient of diffusion and has the units L^2/T such as cm^2/sec. Equation (5) is called the Ficks' equation.

The equations (2) and (5) are not in fact laws of nature, but rather definitions of μ and D, which are found experimentally to be properties of the material.

(c) Diffusivities

Among the transfer coefficients defined by the rate equations, we note that the kinematic viscosity v and the diffusion coefficient D have the same dimension L^2/T. Clearly, a dimensionless number can be formed from the ratio of any two of these quantities. Thus, the

$$\text{Schmidt number } Sc = \frac{\nu}{D} = \frac{\mu}{\rho D} \tag{6}$$

It is a significant parameter of isothermal systems undergoing simultaneous momentum and mass transfer processes. It is approximately unity in gases, but is large for liquids.

CONSERVATION LAWS FOR ONE-DIMENSIONAL CASES

In transfer processes, we are chiefly concerned with finding out the rates at which some property of a system changes. In most instances, we are interested in changes due to fluxes of that property crossing a control surface, and in some special cases we are able to postulate from experience that the property is conserved. We shall formulate a mathematical statement of the conservation laws for certain one-dimensional cases.

Consider the two systems discussed in the previous section. For a fluid particle whose direction of motion coincides with x direction, it is found that the resulting shearing force is equal to

$$\left(\tau + \frac{\partial \tau}{\partial y} dy\right) dx - \tau \ dx = \frac{\partial \tau}{\partial y} dx \ dy \tag{7}$$

Hence the frictional force per unit volume is equal to $\dfrac{\partial \tau}{\partial y}$, or from (2)

$$\frac{\partial \tau}{\partial y} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \tag{8}$$

By the principle of conservation of momentum, this should equal the rate of increase of momentum of the fluid in the element, or $\dfrac{\partial}{\partial t}(\rho \Delta x \ \Delta y \ \Delta z\, u)$ or $\dfrac{\partial}{\partial t}(\rho u)$ per unit volume.

Equating these for constant ρ, we get

$$\rho \frac{\partial u}{\partial t} = \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) \tag{9}$$

The conservation equation for mass transfer follows a similar development. If the space between $y = 0$ and $y = h$ is air with water vapour in dilute concentration diffusing from one wall to the other, the net rate of mass of water vapour diffusing into the element $\Delta x\ \Delta y\ \Delta z$ is $\frac{\partial}{\partial y}\ (D\ \Delta x\ \Delta y\ \Delta z)$. Then, by conservation of mass this should equal the rate of accumulation of water vapour in the element, $\frac{\partial}{\partial t}\ (c\ \Delta x\ \Delta y\ \Delta z)$. Equating the two we get,

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial y}\left(D\frac{\partial c}{\partial y}\right) \tag{10}$$

Equations (9) and (10) have a striking similarity. This comparison shows the desirability of interpreting τ as a *flux of momentum*. This similarity of mathematical form plus similarity of boundary conditions defines a group of processes which are said to be analogous. It must be emphasized that this one-to-one correspondence, although valid for certain of the simple cases, cannot be extended to all cases. The conservation equations and rate equations applicable to the general processes in three-dimensional and including external force fields, chemical reactions, coupling phenomena etc. are not analogous in form.

CONTINUITY EQUATIONS

Relations expressing the overall continuity of matter in flowing systems will be useful in simplifying conservation equations for transfer processes in non-stationary systems. Consider a flow of a single-phase single-component fluid with velocity $\bar{v}$ having u, v and w components. The x direction flow rates entering and leaving a control volume $\Delta x\ \Delta y\ \Delta z$ fixed in space are shown in Fig. 2.

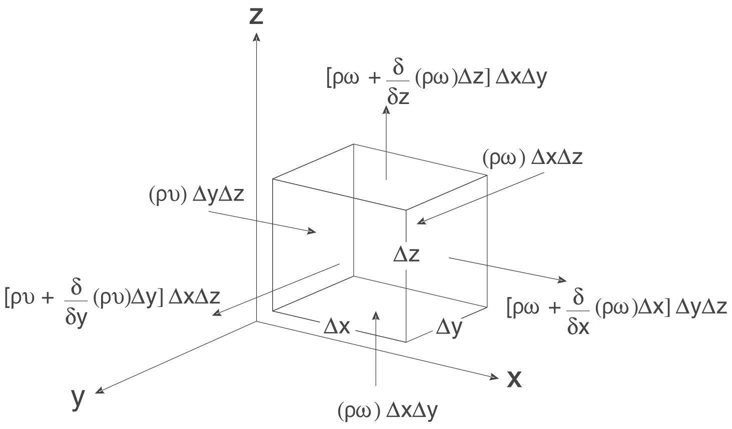

Fig. 2: Volume element for deriving continuity equation.

The net fluxes of mass in three component directions are then:

$$\left.\begin{array}{l} x \text{ direction}: \dfrac{\partial}{\partial x}(\rho u)\,\Delta x\ \Delta y\ \Delta z \\ y \text{ direction}: \dfrac{\partial}{\partial y}(\rho V)\,\Delta x\ \Delta y\ \Delta z \\ z \text{ direction}: \dfrac{\partial}{\partial z}(\rho w)\,\Delta x\ \Delta y\ \Delta z \end{array}\right] \tag{11}$$

The sum of these will equal the rate of change (decrease) of mass within the control volume, $-\left(\dfrac{\partial \rho}{\partial t}\right)\Delta x\ \Delta y\ \Delta z$, or dividing by $\Delta x\ \Delta y\ \Delta z$,

$$-\frac{\partial \rho}{\partial t} = \frac{\partial}{\partial x}(\rho u)+\frac{\partial}{\partial y}(\rho V)+\frac{\partial}{\partial z}(\rho w) \tag{12}$$

or

$$\frac{\partial \rho}{\partial t}+(\nabla.\rho\bar{V}) = 0 \tag{13}$$

This is known as the continuity equation or equation of conservation of mass. If the density is constant in time and space, equations (12) and (13) are reduced to

$$\frac{\partial u}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial w}{\partial z} = 0 \tag{14}$$

or

$$\nabla.\bar{\nabla} = 0 \tag{15}$$

EQUATION OF MASS DIFFUSION IN STATIONARY MEDIA

The mass balance for component diffusing through a control volume with sides in a solid may be obtained as follows, where J_x, J_y, J_z are the mass fluxes in the x, y, and z directions respectively.

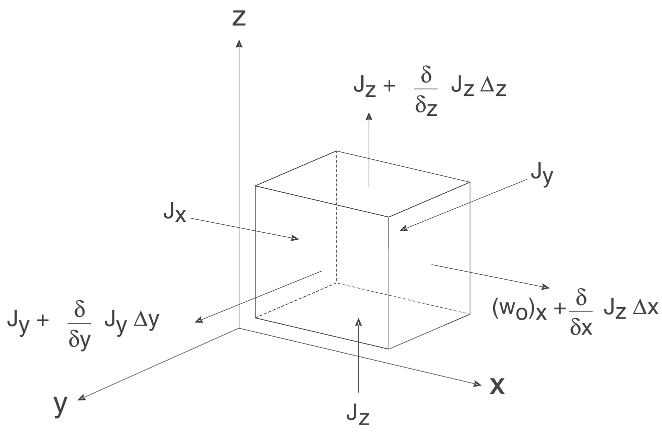

Fig. 3: Volume element for deriving mass diffusion equation.

Net transfer of C_a by diffusion in the x-direction

$$\frac{\partial}{\partial x}(J_x)\Delta x\ \Delta y\ \Delta z \tag{16}$$

Similar expressions may be written in the y and z directions. Rate of production or immobilization of C_a within the volume:

$Q_{a=}$ $\Delta x\ \Delta y\ \Delta z$ where Q_a is the rate of production per unit volume.

Rate of change of concentration of C_a within the volume

$$\frac{\partial C_a}{\partial t}\Delta x\ \Delta y\ \Delta z \tag{17}$$

The mass balance, dividing throughout by $\Delta x\ \Delta y\ \Delta z$, is given by

$$\begin{aligned}\frac{\partial C_a}{\partial t} &= -\frac{\partial J_x}{\partial x} - \frac{\partial J_y}{\partial y} - \frac{\partial J_z}{\partial z} + Q_a \\ &= -\frac{\partial}{\partial x}\left(D\frac{\partial C_a}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial C_a}{\partial y}\right) + \frac{\partial}{\partial z}\left(D\frac{\partial C_a}{\partial z}\right) + Q_a\end{aligned} \tag{18}$$

or

$$\frac{\partial C_a}{\partial t} = (D\,\nabla.C_a) + Q_a \tag{19}$$

If D were independent of x, y, z and C_a and Q_a were zero, then

$$+\frac{\partial C_a}{\partial t} = D\ \nabla^2 C_a \tag{20}$$

MOMENTUM TRANSFER IN LAMINAR FLOW

General momentum conservation equations–Navier Stokes Equations

In deriving equations (1)-(10), we presented a one-dimensional statement of the momentum conservation law, our purpose then being to emphasize the area of similarity among the conservation laws of various transferable properties. We considered only viscous shear forces (or equivalent momentum transfer), expressed by the simple one-dimensional rate equation. We now write a more general form of the momentum conservation equations in three dimensions.

In general, forces acting on a fluid system may be classified as body forces proportional to the volume or mass of the system such as gravity, and surface forces proportional to the area of surface on which they act, such as pressure and viscous forces.

The presence of viscous force in a fluid system gives rise to three-dimensional stress-strain relations analogous to the well known stress-strain relations (Hooke's law) for an elastic solid. However, whereas in an elastic solid stresses are proportional to strain, in fluids stresses are empirically found to be proportional to the rate of strain, expressible in terms of velocity gradients. Physically, this means a fluid offers no resistance to change of shape but resists time rate of change of shape. The general three-dimensional stress-strain relations for a viscous fluid are given below. We shall accept them as empirical formulations, although precise expressions for gases can be derived from the kinetic theory.

Fig. 4: Volume element with arrows indicating the positive direction of x-direction stresses.

Figure 4 shows the assumed positive direction of x-direction shear stresses. Similar sets exist in other two directions.

$$\left.\begin{aligned}
\sigma_x &= -p + 2\mu\frac{\partial u}{\partial x} - \frac{2}{3}\mu\nabla.\bar{V} \\
\sigma_y &= -p + 2\mu\frac{\partial v}{\partial y} - \frac{2}{3}\mu\nabla.\bar{V} \\
\sigma_z &= -p + 2\mu\frac{\partial w}{\partial z} - \frac{2}{3}\mu\nabla.\bar{V} \\
\tau_{xy} &= \mu\left(\frac{\partial u}{\partial y} + \frac{\partial V}{\partial x}\right) = \tau_{yx} \\
\tau_{yz} &= \mu\left(\frac{\partial V}{\partial z} + \frac{\partial w}{\partial y}\right) = \tau_{zy} \\
\tau_{xz} &= \mu\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right) = \tau_{zx}
\end{aligned}\right] \qquad (21)$$

In these equations, μ is a constant of proportionality called, as before, coefficients of viscosity; its definition is more general than that given by equation (1). σ's are normal stresses, composed of nontrivial normal stresses or pressures p, and viscous normal stresses (terms containing μ). τ's are viscous shear stresses with their first suffix corresponding to the plane on which they act and the second suffix corresponding to the direction of action.

The equations of motion can be written in the following vector form:

$$\rho \frac{D\bar{V}}{Dt} = \bar{F} + \rho \tag{22}$$

where $\bar{F}$ is the body force (X, Y, Z) and Δ is the surface force. Resolving the forces in the three directions, we get the equations of motion as,

$$\begin{aligned}
\rho \frac{Du}{Dt} &= X + \frac{\partial \sigma_x}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} \\
\rho \frac{Dv}{Dt} &= Y + \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial \sigma_y}{\partial \tau} + \frac{\partial \tau_{zy}}{\partial z} \\
\rho \frac{Dw}{Dt} &= Z + \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial \sigma_z}{\partial z}
\end{aligned} \tag{23}$$

Substituting (21) in (23) we get,

$$\begin{aligned}
\rho \frac{Du}{Dt} = X - \frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left\{\mu\left[2\frac{\partial u}{\partial x} + \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial w}{\partial z}\right)\right]\right\} \\
+ \frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial y} + \frac{\partial V}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left[\mu\left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)\right]
\end{aligned} \tag{24}$$

Similar expressions for y and z directions can be readily written down.

Equation (24) is known as the *Navier-Stokes* equation. For constant ρ and r (incompressible fluid), equations (24) combined with the equation for an incompressible fluid simplifies to

$$\begin{aligned}
\rho\left[\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + V\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right] &= -\frac{\partial p}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) + X \\
\rho\left[\frac{\partial v}{\partial t} + u\frac{\partial u}{\partial x} + V\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right] &= -\frac{\partial p}{\partial y} + \mu\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right) + Y \\
\rho\left[\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + V\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right] &= -\frac{\partial p}{\partial z} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) + Z
\end{aligned} \tag{25}$$

or, in vector notation,

$$\rho \frac{D\bar{V}}{Dt} = -\nabla p + \mu \nabla^2 \bar{V} + \bar{F} \tag{26}$$

The solutions of the above equations become fully determined physically when the boundary and initial conditions are specified.

We give in the next section a few examples in which exact solutions of Navier Stokes equations and the equation of mass diffusion can be obtained.

Parallel flow through a straight channel and Couette flow

A very simple solution of the Navier-Stokes equation is obtained for the case of steady flow in a channel with two parallel flat walls. Let the distance between the walls be denoted by $2b$ so that equation (25) can be written as

$$\frac{dp}{dx} = \mu \frac{d^2u}{dy^2} \tag{27}$$

with the boundary conditions $u = 0$ for $y \pm b$. Since $\frac{\partial p}{\partial y} = 0$, the pressure gradient in the direction of flow is constant. Thus, $\frac{dp}{\partial x} =$ constant and the solution is

$$u = -\frac{1}{2\mu}\frac{dp}{dx}(b^2 - y^2) \tag{28}$$

The resulting velocity profile is parabolic.

Another simple solution is obtained for the so-called Couette flow between two parallel flat walls, one of which is at rest, the other moving in its own plane with a velocity U. With the boundary conditions

$$y = 0,\ u = 0;\ y = h,\ u = U \tag{29}$$

we obtain the solution

$$u = \frac{y}{h}U - \frac{h^2}{2\mu}\frac{dp}{dx}\frac{y}{h}(1-\frac{y}{h}) \tag{30}$$

In particular, for a vanishing pressure gradient, we have

$$u = \frac{y}{h}U \tag{31}$$

This particular case is known as simple Couette flow, or simple shear flow. The shape of the velocity profile is determined by the dimensionless pressure gradient

$$P = \frac{h^2}{2\mu U}\left(-\frac{dp}{dx}\right) \tag{32}$$

For $\Delta > 0$, i.e., for a pressure decreasing in the direction of motion, the velocity is positive over the whole width of the channel. For negative values of P, the velocity over a portion of the channel width can become negative, that is, back flow may occur near the wall which is at rest and this happens when $P < -1$. In this case, the dragging action of the faster layers exerted on fluid particles in the neighbourhood of the wall is insufficient to overcome the influence of the adverse pressure gradient.

One-dimensional contaminant diffusion

The one-dimensional case given by equation (20) can be simplified as the contaminant diffusion equation,

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial z^2} \tag{33}$$

In ocean conditions, such situations occur at lower values of horizontal contaminant gradient. (It is assumed that it is possible to neglect the vertical advection of the contaminant.)

The solution of the equation (33) under the boundary conditions of zero concentration C at $|z|= 0$ at the moment of time $t = 0$, has the form

$$X(z, t) = \frac{1}{2\sqrt{\pi Dt}}\exp(-\frac{z^2}{4Dt}) \tag{34}$$

This solution (34) is known as the fundamental solution of one-dimensional equation of diffusion.

Distributions of contaminant concentrations along the axis for certain values of Dt are displayed in Fig. 5.

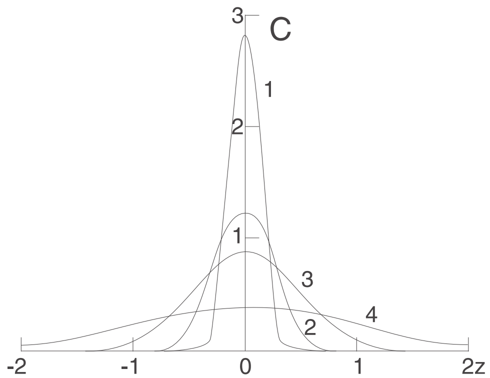

Fig. 5: Curves of normalized one-dimensional distribution of the concentration of a contaminant diffusion from an instantaneous point source of unit intensity. Curves 1, 2, 3, and 4 refer to the contaminant distribution at diffusion times exceeding that for Curves 1, 5-, 10- and 50-fold, respectively.

Coastal Marine Diffusion Processes

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INTRODUCTION

The fluid flows in the natural environment such as the atmosphere, oceans, lakes and rivers are generally complex turbulent movements. Superimposed on a mean flow circulation pattern are turbulent eddy-like motions of varying intensities and temporal and spatial scales. These eddy-like motions exist in both horizontal and vertical directions. The scale of horizontal eddies, however, is much larger than the vertical eddies because in the natural environment horizontal dimensions are greater than the vertical dimension. A direct consequence of the turbulent diffusion processes in the natural environment is the transport and dispersion of chemical and biological species from one area to another. Pollution problems created by the practice of indiscriminate discharge of municipal and industrial pollutants into the environment provided impetus for extensive theoretical and experimental studies of turbulent diffusion processes in the natural environments in recent years. However, turbulent transport and diffusion processes in the natural environment are very complex and theoretical predictions of concentration distributions of pollutants are far from satisfactory. Thus, an understanding of the various manifestations of turbulent transport and diffusion processes in the natural environments is heavily dependent on the practical approach of conducting large-scale experiments under actual field conditions.

Since the horizontal scales of motions in the natural environment are much greater than the vertical scales, their effect on turbulent transport and dispersion may be considered separately. In this approach, it is assumed that the introduced substance is subject to horizontal mixing within a sufficiently thin homogeneous layer so that vertical variations in both concentrations and velocities may be neglected. However, the importance of vertical diffusion cannot be neglected even though the diffusing substance is, for practical purposes, confined to a very thin layer. The combined action of vertical shear in the horizontal mean flow and vertical diffusion may produce effective horizontal diffusion of the substance.

In this article, we will present an over-view of some fundamental turbulent diffusion processes largely inferred from large scale field experiments in the oceanic and aquatic environments. However, the discussions are general enough to apply to other natural environments such as the atmosphere.

DIFFUSION PROCESSES

Mean Concentration Field

When a marked tracer is released continuously into a turbulent environment such as oceanic coastal currents, the subsequent transport and diffusion of the tracer may be studied either in a frame of reference moving with the centre of gravity of the plume or in a frame of reference fixed to the stationary source. Conventionally the former is referred to as “relative” diffusion and the latter as “absolute” diffusion. The interlink between the two concepts is explained by the random movements of the centre of gravity of the diffusing plume usually referred to as the “meandering”. One may regard absolute diffusion as a superposition of the two component processes of relative diffusion, i.e., diffusion relative to the centre of gravity of the plume and meandering or bodily displacements of the diffusing plume parcels due to turbulent eddies larger than the plume size. In studies of turbulent diffusion in the coastal ocean, both formulations have been applied (Murthy and Miners, 1980). We will present examples here to elucidate some detailed properties of relative and absolute diffusion based on measurements of concentration distributions of diffusing continuous fluorescent tracer plumes in oceanic coastal environment.

Figure 1 shows a mosaic of the diffusing fluorescent dye plume in the coastal ocean taken from time-sequence aerial photography and illustrates quite vividly the two component processes of diffusion relative to the centre of gravity and lateral meandering. In this particular experiment, meandering of the dye plume may be observed beyond about 100 m or so from the dye source. In dealing with turbulent diffusion problems in the coastal ocean both formulations are useful. Here we will attempt to delineate some fundamental characteristics of ‘relative’ and ‘absolute’ diffusion and parameterize the diffusion parameters such as eddy diffusivity, in terms of the governing oceanographic parameters, appropriate to model sub-grid turbulent fluid motions in coastal pollutant transport models.

The concentration distribution $c(x, t)$ measured at a fixed point within the diffusing dye plume in the coastal ocean is a random variable. Thus, instantaneous concentration profiles measured at different times, under what seemed to be identical environmental conditions, showed considerable irregularity. This poses a fundamental difficulty in elucidating the relative

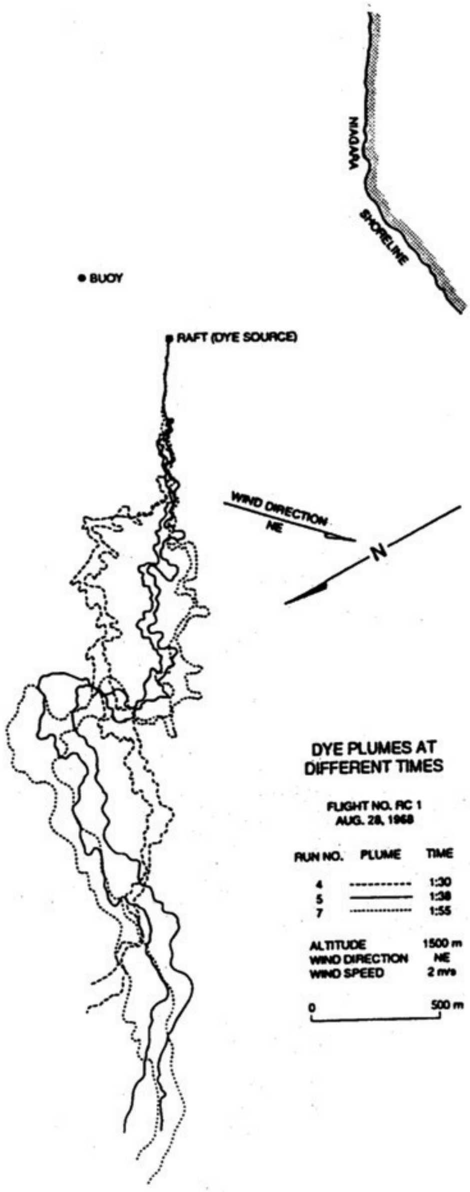

Fig. 1: Mosaic of aerial photographs of diffusing dye plume in coastal currents.

diffusion characteristics reliably. One way of overcoming this difficulty is to average the individual concentration distributions obtained at different times. In order to remove the irregularities, the instantaneous concentration profiles were overlapped such that their centres of gravity coincided, and then the averaging was carried out at fixed distances from the centre of gravity. This process effectively filters out the random movements of the centre of gravity. Figure 2 shows experimentally determined 'relative' mean concentration distribution from 50 individual realizations. Quite often the measured relative mean concentration distributions have been approximated with equivalent 'Gaussian' distributions. For this reason, Gaussian diffusion models have been extensively used for quantitative estimates of dilution of pollutant sources in the coastal ocean (Lam and Murthy, 1978).

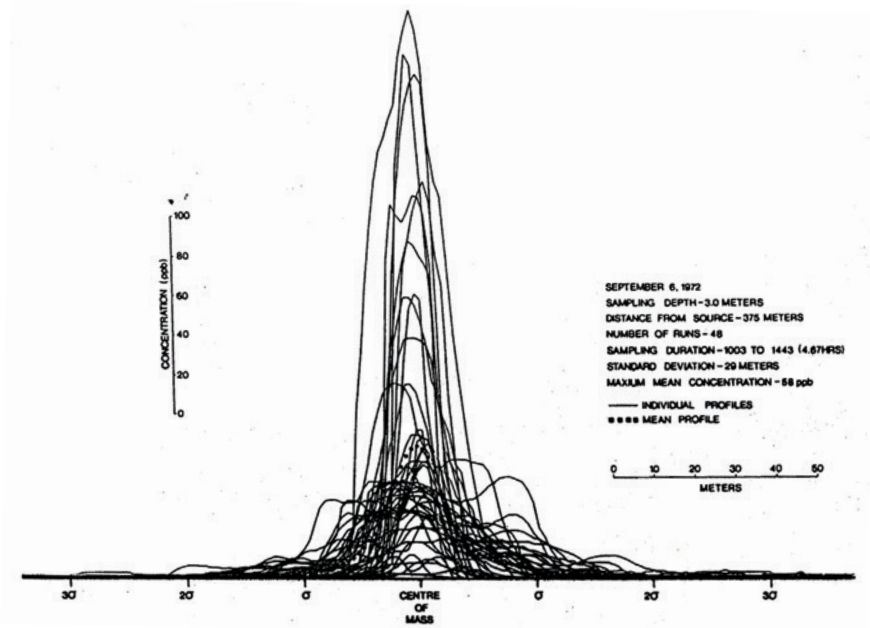

Fig. 2: Cross-plume mean concentration distribution: relative diffusion.

As remarked earlier, absolute diffusion is a superposition of the two component processes of 'relative' diffusion and 'meandering' diffusion caused by the random movements of the centre of gravity. Large-scale turbulent eddies comparable to or larger than the source itself are responsible for meandering diffusion. The mean concentration distribution, constructed by merely averaging the individual concentration profiles in the absolute coordinate system is shown in Fig. 3. The growth of the variance of the concentration distribution (or its square root, the standard deviation) with diffusion time is an indication of the range of turbulent eddy sizes contributing to the diffusion process. Figure 4 shows such a plot of growth of variance as a function of diffusion time corresponding to the data in Figs 2 and 3. It is interesting to note that the variance in 'relative' diffusion attains a constant value almost immediately indicating that the physical size of the diffusing field sets a clear limit to the eddy sizes available for diffusion. The variance in absolute diffusion, on the other hand, shows no sign of attaining a constant value, meaning that some very large-scale eddies are still present in the flow field and contributing to the diffusion process. One would expect, eventually, that the variance in 'absolute' diffusion will also settle down to a constant value if sampling is extended for a longer period. The effective eddy diffusivity calculated from the experimental data in absolute diffusion is greater by a factor of 2 as compared to relative diffusion. This is particularly important in modelling turbulent diffusion processes in the natural environment.

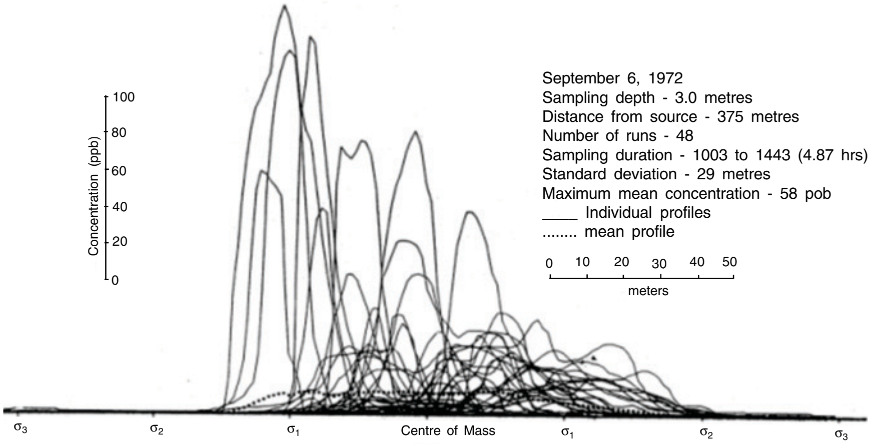

Fig. 3: Cross-plume mean concentration distribution: absolute diffusion.

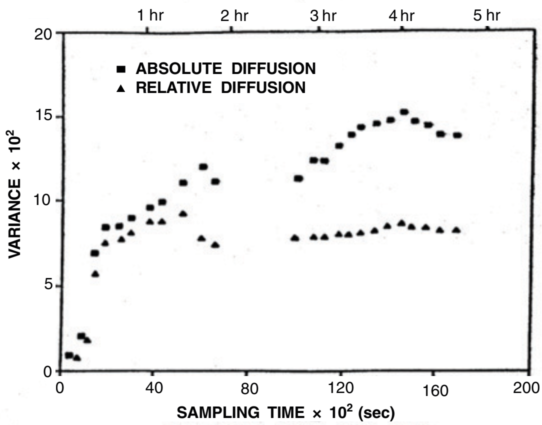

Fig. 4: Dispersion variance versus diffusion time in relative and absolute diffusion.

Diffusion Characteristics

Experimental data from large scale field diffusion studies have contributed a great deal to examine critically the dependence of horizontal diffusion process on the properties of turbulent eddies. Richardson's "four-thirds power law" has been the basis to interpret natural environmental diffusion data and results in view of the widely accepted physical basis on which it is derived by applying the concepts of the similarity theory of turbulence. In the inertial sub-range the similarity theory predicts that the turbulent kinetic-energy spectrum $E(k)$ is given by the familiar "-5/3 power law"

$$E(k) = c\,\varepsilon^{2/3} k^{-5/3} \tag{1}$$

where c is a universal dimensionless constant, ε is the rate of dissipation of turbulent kinetic energy, and k is the wave number.

If turbulent eddies larger than the size of the diffusing cloud do not contribute much to the diffusion process and further if we designate a length scale $l = k^{-1}$ to the eddies responsible for the diffusion of the cloud, then for a point source initially released into a turbulent medium consisting of a spectrum of eddies of several sizes, the turbulent kinetic energy available for diffusion of the cloud would be:

$$\overline{q'^2} \propto \int_k^{\infty} \varepsilon(k)\ dk \tag{2}$$

Combining (1) and (2), the turbulent velocity associated with length scale, l, is given by:

$$\left(\overline{q'^2}\right)^{1/2} = c\,\varepsilon^{1/3} l^{1/3} \tag{3}$$

Following mixing length arguments an effective horizontal diffusivity of the diffusion process can be defined by:

$$K = \text{const.}\,\varepsilon^{1/3} l^{4/3} \tag{4}$$

which is the Richardson's "4/3 power law" of diffusion. The physical meaning of the Richardson's "4/3 power law" is that the inertial sub-range eddies are active and the diffusion process is characterized by two parameters: ε, the rate of turbulent energy dissipation, and, l, the length scale of eddies.

Experimental diffusion data from the oceanic and aquatic environment validate the Richardson's "4/3 power law" of diffusion quite well. Figure 5 shows on logarithmic scale the effective diffusivity versus the length scale of diffusion from experimental diffusion data obtained in widely varying environmental conditions in the oceanic and aquatic

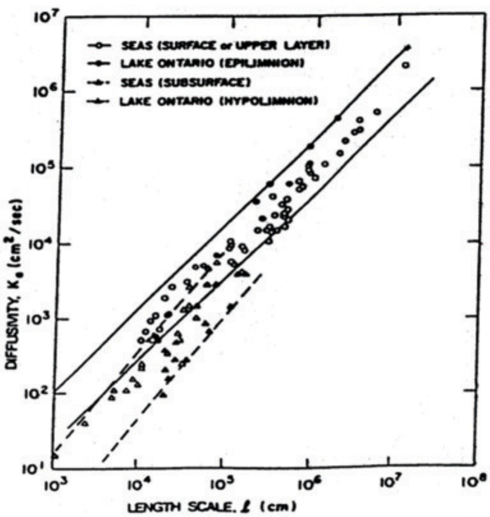

Fig. 5: Horizontal eddy diffusion coefficient versus length scale of diffusion.

environments (Murthy, 1976). The dependence of the effective diffusivity on the length scale provides useful guidelines for modelling of practical diffusion problems in the natural environment.

In contrast to the horizontal diffusion in the natural environment, the process of vertical diffusion is controlled primarily by the small-scale fluid motions characteristic of a stable stratified flow. Unlike the horizontal eddy diffusivity, the vertical eddy diffusivity does not depend uniquely on the scale of diffusion. Efforts have been made to relate the vertical diffusivity to the governing environmental factors relevant for vertical mixing (Kullenberg et al., 1973, 1974). One such example again for the oceanic and aquatic environment is given by

$$K_z = 4.0\times10^{-4}\,\overline{q'^2}\left(\overline{N^2}\right)^{-1}\left|\frac{\overline{dq}}{dz}\right| \tag{5}$$

where $\overline{q'^2} = \left(\overline{u'^2} + \overline{v'^2}\right)$ is the turbulent kinetic energy of the flow, N is the Brunt Vaisala frequency defined by $\overline{N^2} = (g/\bar{\rho})(d\bar{\rho}/dz)$, $\bar{\rho}$ is the mean density and $\overline{dq}/dz$ is the absolute value of the mean shear in the flow. Experimental data from the oceanic and aquatic environment agrees quite well with this formulation as shown in Fig. 6. These semi-empirical formulations of vertical diffusion provide practical guidelines in numerical calculations of dispersion of pollutants in the natural environment.

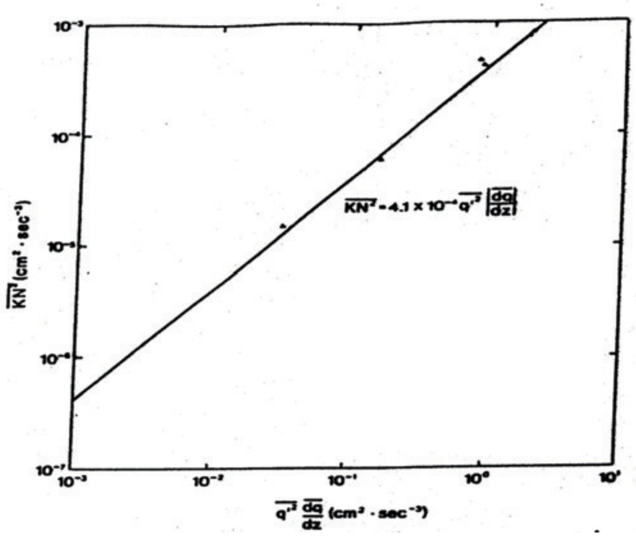

Fig. 6: Vertical diffusion coefficient versus stability parameter, current shear and turbulent kinetic energy.

Concentration Fluctuations

The concentration field of any diffusing substance in a turbulent flow field is a random variable. In turbulent diffusion studies one ordinarily attempts to predict the mean concentration distributions, the first moment of the probability distribution of the random variable. However, the variance of the concentration distribution, the magnitude and duration of the concentration peaks and the frequency of occurrence of concentration levels are all important parameters in order to assess the possible effects of the diffusing cloud on living organisms in the natural environment. Local effects of pollutants are determined by the random short-term fluctuations of the concentration rather than by the mean values. Short-term concentration fluctuations observed at a fixed point in the wake of a continuous release of some diffusing substance are generally very high and often of the same order of magnitude as the local mean (Murthy and Csanady, 1971; El-Shaarawi and Murthy, 1976 and Murthy and Miners, 1981). A parameter to characterize this is the local peak/mean concentration ratio. Figure 7 shows the observed peak/mean concentration ratios at the centre of the diffusing plume with diffusion time corresponding to the experimental data in Figs 2 and 3. As expected, very high peak/mean concentration ratios ranging from 1 to 15 were observed. From this, one can calculate the frequency of attaining peak/mean concentrations. In this example the peak concentration exceeded the mean concentration by an order of magnitude 25 per cent of the time. As remarked earlier, mean concentration levels alone are obviously not sufficient in assessing the local effects of the pollutants released into the coastal ocean.

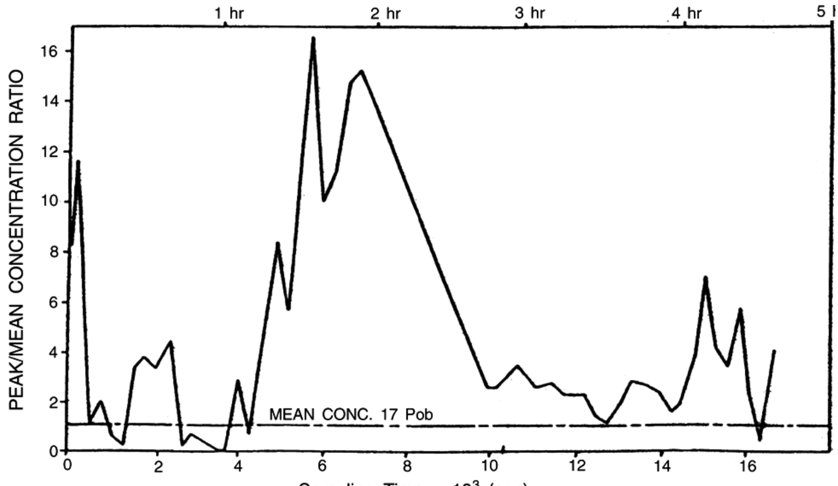

Fig. 7: Peak/Mean concentration ratio at the centre of the diffusing dye phase.

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Measurement of Currents in the Coastal Oceans

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INTRODUCTION

The term 'currents' in water bodies refers to the time variation of water movements. Currents are generated by a complex interaction of forces acting on the water surface. In general, water movement results from the mechanical mixing due to wind stress and thermal effects due to alternate heating and cooling through the surface. In oceans and lakes, accurate measurement of the local current structure is fundamental for predicting the physical and biochemical characteristics of a given region. Historically, current measurements were used for shipping and oceanographic applications. Contemporary research, however, has seen the extension of this analysis to include the study of water movement in the coastal areas of the oceans and in large lakes. In this, coastal engineers and limnologists have benefited from the experience gained in the development of ocean-scale technology. With some modification to comply with the constraint imposed by shallow waters, practical means have evolved to study processes and potential problems imposed by industrial and municipal pressures—especially in the near-shore regime.

There are numerous methods by which current characteristics can be determined. Measurement approaches can be categorized as indirect or direct. Indirect methods rely on the detection of phenomena which correlate with water movement but are not themselves observations of motion. Remote sensing of such scalar quantities as temperature or silt transport are examples of such procedures. Alternatively, direct measurement of water motion can be used. In contrast to an indirect method of obtaining flow by measuring some property of the medium from which the current may be calculated, the water motion itself is measured. There are two types of current measurements. In the Lagrangian techniques current magnitude and directions are obtained by noting the sequential position of a drifting device as a function of time. In contrast to this, an Eulerian device is fixed in space and measures the motion of the passing water. Generally, Eulerian techniques are used to study the dynamics of water movements, whereas Lagrangian measurements are more amenable to describing diffusive and mass transport phenomena.

LAGRANGIAN TECHNIQUES

Drift devices are probably the oldest instrument used by scientists for measuring currents. Perhaps the most familiar drifter design consists of a closed bottle containing a note urging the finder to communicate the time and place of his discovery. Using these, if the finder complied, the trajectory of a water parcel could be determined. This process may be enhanced somewhat by placing a drag-producing device beneath the buoyant portion of the bottle in order that the resultant motion of the bottle will be determined by the water motion a meter or so below the surface. This general idea is still used today, with both bottles and small plastic cards being used. The cards are designed to reduce the surface area under the influence of the wind with respect to the influence of the moving water.

Water masses can also be traced with a naturally occurring characteristic that can be measured in low concentrations, or artificially ‘tagged’ by injecting tracer materials. Typically, artificial tags are either dyes or radioactive tracers placed on or near the surface or within the water column at depths of interest. In either case, the concentration of the tracer is measured over a period of time, or the point of its maximum concentration is charted as the tracer moves and disperses through the water column. In this manner, not only can trajectories be determined, but also a great deal can be learned about turbulence from a study of the dispersion patterns. Such techniques have been powerful tools in recent years because of the low detection levels of concentration by modern instruments.

With modern electronic equipment it is also possible to track drifting objects, such as radio or ultrasonic buoys, placed either at the surface or at some intermediate depth and allowed to move under the influence of the local water masses. Those placed at intermediate depths are usually called swallow floats, after John Swallow, who first developed the concept of a neutrally buoyant float. Submerged floats are tracked by means of sonic signals, while those at the surface may be followed more readily by radar, radio transmission, satellite positioning systems and/or modern positioning systems such as Loran-C and the GPS.

The types of tracers which have been employed to infer mean current speed and direction have been varied. For example, some of the contemporary tracers used on the Great Lakes are given by Palmer (1972). These have included:

1. marginally buoyant objects
2. subsurface drogues suspended from surface floats
3. variable buoyancy devices
4. simple bottles used in mail-in experiments
5. natural tracers such as silt
6. various artificial tracers such as dyes.

Whereas many of these tracer types have been used in various studies in the lakes or oceans, it appears that the use of drogues and Florescent dyes have found the most general application.

The evolution of drogues has been documented in great detail (e.g. Monahan and Monahan, 1973; Monahan, Hawkins and Monahan, 1974; Terhune, 1968). In general, a drogue is an object or device, the trajectory of which can be followed with wide cross-sectional area to the current so that it may be carried by the current. The principle of operation is that the object will drift in the direction of the net force caused by wind and water (Yachon, 1973). In designing drogues, the cross-section of the area above the water surface is minimized to reduce the wind-drag component (Fig. 1).

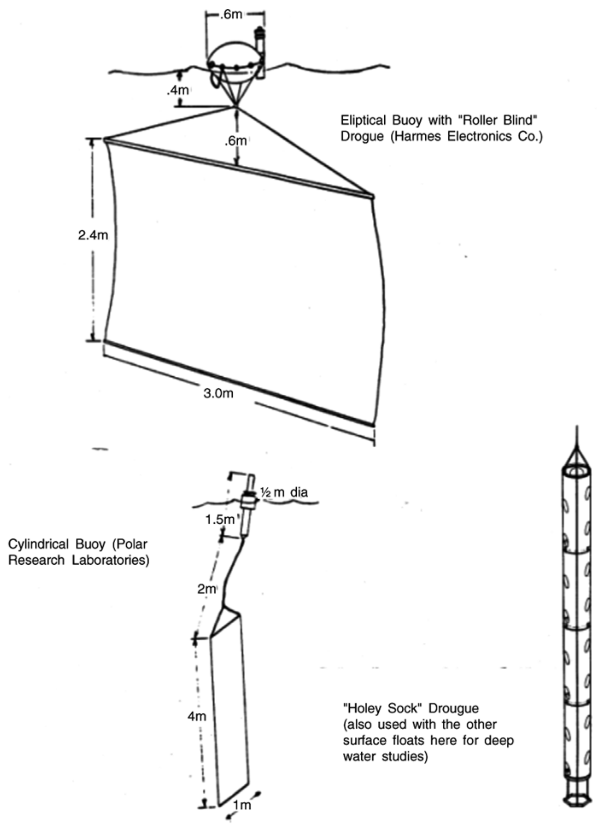

Fig. 1: Configuration sketch of two ARGOS Satellite Tracked Drifters.

Drogues can be categorized according to geometry. To be practical for use in field operations, the modern drogue must conform to specific constraints imposed by the study objectives and limitations. In general, these considerations can be summarized as the following:

1. simplicity
2. cost
3. deployability (size and weight)
4. constancy of drag area and orientation to the flow
5. available resources for position fixing.

A Langrangian database resulting from drogue studies consists of a number of sequential position fixes with the time of each fix. The drogue position may be determined by various means, e.g., triangulation of fixes from shore-based observation positions, by radar fixes from a ship or launch in the study area, employing small boats equipped with various receivers for range-range systems (e.g., Motorola's Mini-Ranger), LORAN-C or GPS receivers to take fixes alongside of the drogue buoy, or by variations on acoustic bottom-mounted position fixing systems. Many of the more modern drogue-buoy pairs contain sophisticated electronics for internal recording and/or the transmission of data via the ARGOS satellite system. Position fixing can be accomplished by on-board GPS systems, and/or by position fixing at time of receipt of transmission by the ARGOS system. In addition, sensors in the buoy-hull or distributed along the drogue support cable can be included to record other parameters of interest (e.g., temperature or depth).

Drogues have a number of advantages and limitations. As indicated earlier, they are useful for determining the mean current at specific depths and dispersal characteristics for that specific layer. In any dispersive study, drogues set at different depths are recommended to infer the mean movement of a column of water. Some limitations that are encountered when using drogues are: (Murthy, 1975):

1. Due to drogue density, they are constrained to move in a horizontal plane and therefore respond only to the horizontal components of essentially three-dimensional flow. Consequently, the drogue cannot provide information on vertical transport and mixing unless as stated above, several drogues at many depths are employed.

2. Due to the finite physical size of the drogues there is a filtering effect meaning that smaller scale turbulent eddies are effectively damped out, and therefore do not contribute to the analysis of turbulent transport and diffusion. This limitation can be reduced by the use of smaller drogues but in light of other comments, the consequence of possible loss of performance must also be assessed.

Fluorescent Dyes

Dye injection studies have been employed extensively in the Great Lakes for the measurement of transport and diffusion (MURTHY, 1976). The types of tracers which are applicable to this type of study are:

1. Fluorescent
2. Rhodamine B
3. Pontacyl Brilliant Pink B
4. Rhodamine BA
5. Rhodamine WT

To be useful for Lagrangian studies, a dye should be readily detectable by fluorometry. The dye solution must be adjusted to the density of the water layer being sampled so that the dispersion observed in the dye is due only to the water movement itself. The fluorometer is calibrated in the field with in-situ water at constant temperature. The sensitivity of fluorometers are such that they can detect dye concentrations as low as 2×10^{-10}. With the use of special filters concentrations up to 2×10^{-7} can be measured beyond which the solutions become opaque to the exciting light (Murthy and Miners, 1978).

Radioactive substances can also be used to trace water masses. In a few cases, naturally occurring radio-isotopes (or those from industrial processes) of effluents entering into receiving waters can be utilized as water-mass tracers. In other cases, certain isotopes can be injected and traced over time. The latter activity is unlawful in many jurisdictions.

EULERIAN TECHNIQUES

The device employed to measure water motions at a fixed point in the water column is called a "current meter". The ideal current meter would respond to, and measure, the exact nature of the fluid motion as the fluid moves past the sensing element. The ideal device would exhibit an instantaneous response to changes in fluid motion in 3-dimensions, have the ability to measure motions down to tenths of millimetres per second accurately, and be capable of sampling frequencies to the order of 100's of samples per second in order to resolve the significant turbulent motions. In addition, because of the rather high data rates required here, such a current meter (if self-recording), would have to be equipped with a very large data storage capacity in order to obtain a data record of sufficient length to resolve the lower frequencies (longer periods) of advective motion.

The most common direct method of measuring current is by means of a current meter that is fastened securely at one point in space and that receives its excitation from the passing fluid. Since water currents are vector quantities, that is, are composed of a magnitude and a direction, current meters incorporate speed and direction sensors as a minimum sensor suite. In addition, a water temperature sensor is almost always included in commercially available systems. Physically, a current meter consists of a sensor set, a pressure case and, in some designs, a mechanical vane which serves to orient the meter in the direction of the flow. The pressure case contains the sensor electronics, controller, memory and batteries, and is mechanically configured to attach to, or form part of, a mooring line. In modern solid-state designs, an external connector is provided to allow communication between the internal controller and an external computer for purposes of software configuration and data downloading.

For the most part, current measurements are made by *recording* current meters. Those current meters that transmit information to a shore-based or surface-based recording system are used less frequently. The recording current meter has been designed to measure the speed and direction of water flow at the physical location of the instrument's flow sensors; or in the case of acoustic Doppler profiling systems, over a vertical section of the water column. Current meters are typically completely self-contained, battery powered, and are designed to be reasonably compact and lightweight to ensure easy handling in the severest of weather conditions. In older instrument technology, the recording media was typically magnetic tape or film. Since the mid-1980's, most of the current meter designs record in solid-state memories that have distinct advantages over other systems as the data is easily handled, stored, and retrieved using desktop computer technology. The in-sea deployment capability of a typical current meter can be up to a year, depending upon the number of physical parameters to be measured, the frequency of the sampling rate, the instruments memory size, and the internal battery capacity.

Current meters measure flow speeds using various techniques. The more common methods of current speed sensing are variations of the following technologies:

- by measuring the change in electrical resistance, over a period of time, of a potentiometer driven by a propeller or rotor being turned by the water current;
- by digitally counting propeller or rotor rotations by means of magnetically or optically coupled pulse counters;
- by measuring the tilt of the instrument and relating the tilt to the water speed through hydrodynamic calibrations;
- by measuring the time of flight or phase shift of an acoustic signal in two directions in quadrature;
- by acoustic or laser Doppler techniques;
- by electro-magnetic techniques that measure the low-level EMF created by a moving conductor (the water) in the presence of a magnetic field;
- by employing strain gauges to measure stress on two or three-dimensional members and relating to water motion;

- by sensing the electrical current required to maintain a probe at a constant temperature in the presence of cooling by flowing water (no directional component); and
- HF radar and other spatially averaged systems.

By consensus within the ocean community, current direction is specified in the direction toward which the flow is going. Current direction is typically measured by a comparison between a flow-direction orientating element and that of a compass. Various techniques are used to accomplish this comparison, but most involve sensing the alignment of the current meter or part of the current meter with respect to the flow. Some mechanical designs incorporate an external "alignment" vane to ensure that the current meter body is orientated parallel to the flow. Other designs have incorporated small vanes as part of the design for this purpose; i.e., rather than orient at the entire current meter into the flow, a small vane is employed which aligns itself with the direction of the current. In each case, the relative direction of the vane is measured, or compared to, a compass reading.

For the family of current meters employing two or more directional speed sensors set at right angles to each other, a compass (typically a "flux-gate" compass) is employed to measure the relative angle between the orthogonal speed sensors and the magnetic north. Since, in these designs, the orthogonal speed sensors are at a fixed position with respect to the pressure case, it suffices to measure the orientation of the case to magnetic north. Typically these units measure an "x" and "y" component of current, and an angle "alpha" which is the orientation of one of these components to magnetic north. These measurements are then mathematically manipulated to provide a "north" and "east" component of current.

Classes of Current Meters

Generally speaking, the technology of current meters can be categorized into two classes: the dynamic type, which has a rotating sensor, such as a propeller or rotor; and the static type, which has no moving parts. The more modern designs are tending towards the static type, acoustic technology being a primary example.

Dynamic Current Meters

Dynamic current meters are mechanical in nature. The flow speed measurement generally depends on the water flow to rotate a rotor or propeller as a water speed "sensor". In a typical instrument, the number of turns of a rotating sensor measured over a precise time-interval is recorded and, through a calibration, is directly related to the current speed.

Historically, the first true current meter satisfactorily used at sea was introduced by V.W. Ekman in 1905. It consisted of a propeller connected, by means of a gearing arrangement, to a tube which allowed a small bronze ball to fall into a container for every 100 revolutions of the propeller. In addition, the container into which the bronze balls fell was compartmentalised and magnetised so that it oriented itself toward magnetic north. Current magnitude could be determined by simply counting the number of balls dropped in a given time period, and direction could be determined by noting which compartment contained the most balls. To use this device, the entire unit, with its propeller locked, was lowered over the side. When it was desired to start measuring the current, a weight or "messenger" was dropped down the line used to lower the device over the side which unlocked the propeller. After a given period of time, another messenger was dropped to lock the propeller, and the measurement ended. The total time of operation (current averaging interval) was simply equal to the time between the dropping of the first and second messengers.

Current meters equipped with propellers are still used in many applications today. Limitations include inertia (flow must exceed a "threshold" value before the rotor will turn), potential for fouling by aquatic weeds etc. and sensitivity to vertical motion. Some designs locate the propellers in "ducts" or tubes in an attempt to isolate the propeller from vertical motions (primarily induced by mooring dynamics). Certain of these designs perform well in specific flow regimes. One design in particular, referred to as a 'Davis-Weller' type (after the original design team) or as a 'Vector Measuring Current Meter' (VMCM), is particularly adept at measuring small mean flows in the presence of high frequency oscillatory flow associated with surface waves and/or mooring motion. This design incorporates two sets of counter-rotating orthogonal propellers.

By the mid-1960's an 'S'-type rotor, typified by the Savonius rotor, came into popular use. The advantage of the Savonius rotor over the propeller was that the design response was omni-directional in the horizontal, with negligible response in the vertical. However, the major disadvantage of the Savonius rotor was in its response to orbital motions. Under such conditions, the omni-directional response to horizontal flow tends to pump-up the rotor giving an over-estimation of the actual current speed. Rotors that are "paddle" designs rather than propellers or Savonious rotors are also employed as speed sensors. The Aanderaa RCM-7/RCM-8 current meters are the best known and most widely used of these designs today.

A mechanical current meter without a rotor that is in use today utilizes form drag characteristics of the instrument to estimate flow speed. The current meter body contains a sensor designed to measure and record the angle of the instrument from the vertical; when deployed, and acted upon by a flow field, this angle, combined with knowledge of the mechanical drag form of the device, allows calculation of the current speed as a function of the inclination angle.

Static Current Meters

Static current meters employ static (i.e., non-moving) sensors to measure currents. Current meters with non-rotating sensors include: electromagnetic sensors; acoustic time-of-flight and Doppler technologies; laser Doppler devices; directional temperature dissipation systems; the pressure-plate type, wherein the fluid pressure on a plate is measured; the arrested-rotor type, which measures the torque necessary to constrain the rotor motion; systems employing tri-axial strain gauge sensors; and the pressure, or pitot-tube type, where the difference in pressure at two different points in the flow field is determined. Of these, only the electromagnetic and the acoustic current meters are commonly used outside of laboratory research applications.

The electromagnetic current meter (E.M.) is based on a simple principle. A conductor moving in a magnetic field produces a voltage (Faraday's Law). Similarly, if water (a conductor) moves in a magnetic field, a voltage is produced which is proportional to the water velocity. With advances in electronic design, modern electromagnetic current meters are available with a zero stability as good as 1.0 cm/sec. In certain situations, these instruments surpass the various rotor devices in both accuracy and sensitivity for water velocity measurements. In practice, electromagnetic current meters consist of either spheres or probes having sets of orthogonal external electrodes in contact with the water column. Current flow around the sensors intersects lines of magnetic flux causing voltages to be generated which are detected by the electrodes. These signals are amplified, processed and recorded as analogue voltages proportional to the X and Y components of velocity or, in partnership with direction measurements, processed through a microprocessor and recorded as the U and V component of velocity. Measurement of current direction relative to magnetic north is accomplished by sensing the direction of the instrument body and using the physical geometry of the probes relative to the instrument pressure case to calculate the current direction. The accuracy of E.M. sensors depends on the "electronic noise" of the system, linearity, zero drift and the errors in the calibration. Most instruments are accurate to 2% of reading +/- 1.0 cm/sec over a 300 cm/sec range, with increased resolution over smaller ranges. Performance at flow speeds under a few cm/sec is degraded.

The acoustic current meter came into general oceanographic use in the early 1970's with many designs commercially available today. Such devices can generally be divided into two classes of measurement techniques: the direct-path two or three-dimensional current meter and the acoustic backscatter device. Both techniques depend on the passage of acoustic signals through the water column the travel speed of which is a function of the local density of the water path. Although the measurement principle is simple in concept, the conversion of acoustic current meter measurements to current speed requires that the speed of sound in water be known to sufficient accuracy, i.e., knowledge of both the temperature and salinity of the water within the sample volume. Most acoustic current meters measure temperature as part of their sampling scheme, and salinity can be either estimated or measured.

In the direct-path acoustic measurement device, the speeds of sound in orthogonal directions of the flow are compared, in pairs, with the speed of sound in the opposite directions. These devices use the Doppler shift or time-of-flight of an acoustic signal between pairs of orthogonal transceivers to measure the current velocities. Since a moving fluid carries sound energy along with it, acoustic transmission will result in a difference in phase of signal received, or time-of-flight between transducer pairs, related to the speed of motion of the fluid. This technique lends itself to direct three-dimensional current measurements by mounting three pairs of sonic transducers at right angles to each other, so that the total vector current velocity can be obtained.

In order to keep the sample volume, and hence the instruments size, small, one early version of an acoustic current meter used an approach that saw orthogonal pairs of transceivers send and receive signals via a small path length (e.g., 10 cm) through the water and reflect from an acoustically impervious "mirror" to its opposite finger. Water movement within the sample volume causes a shift of the phase of the signal arriving at each of the transceivers which, in turn, is related to the current speed parallel to a line between the transceivers. This measurement technique is utilized in the EG&G Marine Instruments SACM current meter. As the ability to discriminate very short time-periods accurately became available, time-of-flight current meters were developed that transmitted directly between pairs of orthogonal transceivers eliminating the mirror. Both designs are presently available by various manufacturers.

The measurement principle of the acoustic backscatter systems is based on the fact that any naturally occurring fluid contains small organic or inorganic particles from which it is possible to reflect sound energy. These devices employ Doppler techniques which can allow for both very accurate measurement of current velocities at a single focused point away from the current meter (Acoustic Doppler Velocimeter - "ADV"), and for vertical profiling over a limited depth range below the instrument (Acoustic Doppler Current Profiler - "ADCP"). The ADCP devices have been used extensively in oceanographic practice, the ADV devices are relatively new and, at this time, used primarily in laboratory applications. Although very powerful in the utilitarian sense (i.e., for many measurement requirements, the ADCP can take the place of many individual current meters in a vertical string), the ADCP devices were quite expensive when first introduced. However, recent advances in design and the competitive market have reduced the capital cost of these systems to that of two or three times a single conventional current meter. Several manufacturers market ADCP's, for example, RDI and Aanderaa. An RDI narrow-band ADCP unit is shown in Fig. 2.

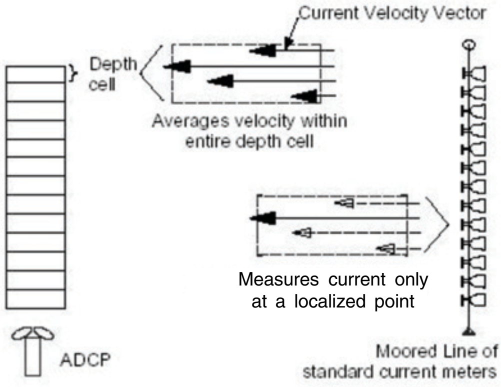

Fig. 2: Schematic of ADCP principle.

Surface currents can be measured by using HF radar (3-30 MHz). At these frequencies, the Doppler shift of back-scattered radar energy is proportional to the current. In order to obtain a map of two-dimensional current flow over a large area, it is necessary to obtain measurements from two radars located at different sites. Except for the baseline between the two sites, data from the two systems can be combined to estimate the vector current. Such systems have been used both from land-based sites and from systems operated from ships.

The practising ocean engineer should be acutely aware of the capabilities and limitations of the various types of current meters available. Performance expectations, flow conditions, mooring requirements, mission duration, device availability, logistical support requirements and financial constraints are all parameters that influence the choice of a specific current meter for a specific job. Depending on the expected flow regime and the performance requirement, a given measurement technology may be considered unsuitable for a particular flow regime or physical location. For example, mechanical designs, in general, cannot accurately respond to motions smaller than the physical size of the sensors, and may not be physically orientated into the flow properly in low current speeds or in highly dynamic situations. Similarly, the electro-magnetic devices, as a family, have an inherent problem in that their output is proportional to the magnetic field they generate, and this field decreases rapidly with distance from the coil. These devices are then sensitive to the flow in the immediate area of the coil, a flow which is itself modified due to the very presence of the current meter. Various manufacturers of these devices have used different mechanical techniques to reduce this effect, for example ensuring that the flow is turbulent across the sensing electrodes. Acoustic current meters have similar operational limitations. Vortices shed from sensor mounting rods or the pressure case may severely affect the measurement accuracy in highly dynamic flow conditions, for example in flow regimes consisting of significant wave induced motions. Acoustic direct path systems are extremely sensitive to bubbles that may be contained within the sensing volume. ADCP system performance degrades near the surface, near the bottom boundary, in the presence of large shear forces and in extremely clear water. In addition, fouling of acoustic transceivers may cause significant signal attenuation problems.

Data Processing

In order to accurately record the spectrum of motions at a given point in the water column, a current meter must sample at a rate at least twice the highest frequency significant motions in the flow. To accomplish this, many devices employ a "burst sampling' technique wherein the instrument rapidly samples and records a number of readings (typically 256, 512 etc.,) and then sits quiescently for the remainder of a sampling period before the burst process is repeated. In this manner, the higher frequency motions can be estimated. If the rate of the sampling is slow compared to the (significant) time-variations of the motions, the average of the data collected may not be accurate, and the user cannot recover his advective information. The spectrum of motions is then under-sampled, and the data set is said to be "aliased" with respect to those motions that are under-sampled.

In a typical current meter deployment, the current speed and direction is averaged over some time interval before recording. Many of the older current meters attempted to accomplish this averaging process mechanically, i.e., a rotor or propeller was allowed to rotate over a long period of time before sampling the results. In such systems, the direction sensor was designed with a long time-constant, and was typically sampled at the same time as the number of rotor rotations was sampled. Although some of these devices performed better than others, such designs gave, in general, poor results in those measurement areas with significant wave induced motions. In addition, the instrument can only respond to scales of motion that are physically larger than the mechanical size of the sensing elements (rotor and vane) itself, effectively ignoring any smaller scale fluctuations. For example, a large-vaned current meter, if properly designed, is capable of responding to average velocities of the order of a few cm/sec, but may exhibit poor response characteristics to orbital and small scale turbulent motions. Thus, the vane swings into currents that act on it for a long time (even small currents), but may exhibit a minimum response (if any) to motions which act on it for short periods (even large motions).

The measurement of currents in the presence of significant wave induced motions is a difficult task. For example, a current meter equipped with the well-known Savonius rotor can introduce large errors into the speed data when used in a near-surface coastal deployment because it rotates in one direction only (rectifying effect). Thus, in a flow regime in which the average horizontal velocity is low relative to the orbital motions present, the rotor will "pump-up" and over-estimate the actual current. The Davis-Weller arrangement has a much superior response characteristic under these conditions. Other flow measuring devices equipped with fast-response sensors can also be employed. For these systems, the speed and direction of the flow is sampled at a high enough frequency to capture all the significant wave induced fluctuations. Typically, for reasons of finite memory size within the instrument, the data is then vector averaged over a relatively long period of time before recording. In this process, orbital motions will average out to zero (as they should) and only the advective information will be recorded.

After a series of individual measurements of current magnitude and direction has been taken by a current meter, there can be problems associated with the averaging of the results. If the magnitude and direction are averaged separately over a given time period, the result obtained will (in general) be significantly different from that obtained by the vector averaging of the instantaneous current readings. Many of the current meters employing orthogonal speed sensors sample at rates to the order of a few Hz, and then average the north and east components over an averaging interval specified by the user. In most modern current meters, the availability of powerful on-board micro-processors enables a flexible sampling scheme combined with high-speed sampling and the possibility of both vector and scalar averaging of sensors.

Current Meter Mooring Configurations

There is no standard configuration for setting out a mooring from which current measurements will be taken. The configuration will depend on the measurement requirements, and on the water depth, the maximum expected flows, the current meter(s) used, and the logistical and financial resources available. Each situation requiring current measurements can be unique; but in practice are essentially variable on a few standard configurations.

A research study may set out many current meters within the study area. Figure 3 shows a typical mooring configuration used in a study in Lake Ontario; note the relatively shallow waters. The groundline is used to lower the mooring anchor, and later is present for dragging operations should it become necessary. In waters more than 100 metres deep, an acoustic release is often used above the anchor. The 'U'-shape is still retained as a redundant method of retrieval.

In deep ocean work, mooring depths can be several thousands of metres. For such depths, distributed buoyancy on a single point mooring equipped with an acoustic release is typically used. Current meters are often set out under surface floats, and mounted off structures such as towers and bridges. In addition, current measurements are taken over-the-side from stationary vessels, and in the case of acoustic profiling devices, from moving vessels.

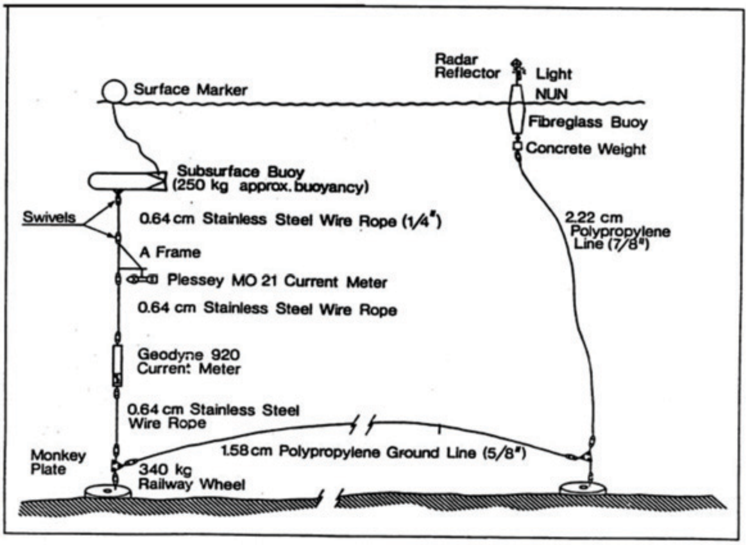

Fig. 3: A typical NWRI Shallow Water Mooring Configuration.

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Remote Sensing Applications to Coastal Oceanography

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INTRODUCTION

Remote sensing of coastal oceanography refers to analysis of various coastal processes using space-borne and air-borne sensors. Remote sensing provides many advantages over the conventional techniques such as synoptic coverage, repeated observations, and area averaging. However, satellite oceanography is constrained by its limited accuracy and largely depends upon manifestation of various underwater processes on the ocean surface due to its high altitude of observations. Here, we shall briefly discuss the utilization and need of remote sensing methods for the coastal applications and their present status.

India has a long coastline of approximately 7500 km. The monitoring of coastal environment is very important in sea level changes due to global warming, coral reeves' extent, shoreline changes and various industrial and engineering activities. The crucial features for these studies include waves, winds, currents, sea surface temperature, chlorophyll content and suspended sediment, coastal morphology, etc. Field of remote sensing has now emerged as one of the major discipline for acquisition of data over the oceans to support a large number of oceanographic applications. Sensors on-board space platforms use electromagnetic radiation in visible, near infra-red, thermal infra-red and microwave regions to measure diverse physical, biological and geological parameters of the ocean. Since the launch of SEASAT in 1978, having microwave payloads, the field of satellite oceanography has made rapid advances and, today, there are a number of space missions providing data on various sea state parameters such as waves, surface winds, ocean colour, sea surface temperature etc. with an accuracy suitable for various applications. The major advantage of the remote sensing observations is to provide synoptic and repetitive coverage of the ocean in contrast to the sparse and isolated in-situ ship observations. Despite the fact that measurements provided by the space-borne sensors pertain to the sea surface only, they do manifest the oceanic processes beneath. Currently a large number of orbiting platforms namely, ERS-1, ERS-2, TOPEX/POSEIDON, SeaWiFS, NOAA series of satellites are available for the research as well as for operational use. This paper mainly discusses about the waves transformation, wave power, coastal bathymetry, sea surface temperature and chlorophyll.

Monitoring of coastal bathymetry is vital for exploration and exploitation of non-living and living resources, operations on engineering structures and ocean circulation studies. The bathymetric measurements by ships and buoys over the vast stretches of coastal waters, though accurate, are found to be expensive and inadequate. These in-situ measurements can be synergistically complemented with those by remote sensing techniques. Use of the imageries over the coastal waters produced by Synthetic Aperture Radar (SAR) data to infer coastal depths could be a potential remote sensing method. The capability of SAR images to reproduce the changes in wavelengths and wave directions due to refraction processes was demonstrated earlier by Shuchman and Kasischhe (1981), who had used SEASAT SAR imageries to infer refracted wavelengths and directions in coastal waters with known depths, and compared these wave parameters with those computed using classical refraction theory. In this paper, the inverse objective of inferring depths using the wavelengths and directions of the incident and refracted ocean waves, estimated from the SAR images by applying Fast Fourier Techniques has been discussed.

WAVE MODELS

A coastal wave transformation model is very necessary to generate wave characteristics near the coast with known deep water wave characteristics. Due to action of generating forces (e.g. wind) and consequence of dynamic processes (e.g. shoaling etc.), sea waves are random and dynamic in nature and are rather difficult to define in mathematical terms (Weigel, 1964). When the waves enter in the region where the water depth is less or equal to half of the wave length, the waves start feeling the bottom. The shoaling, refraction, diffraction and other nonlinear process in the shallow water make their characteristics very complex.

A large number of wave theories are proposed to describe the behaviour of the ocean waves. Their merits and applicability is discussed by various researchers (Weigel, 1964; US Army, 1984). It is known that neither small amplitude (Airy) wave theory nor Stokes' wave theory is adequate to describe the behaviour of waves in very shallow water. In shallow water, Cnoidal wave theory is appropriate and near breaking solitary wave theory is more appropriate (Madsen, 1976). Lakhan (1989) has presented a comprehensive detail of the use of these theories in his work on computer simulation of shoreward propagating deep and shallow water waves. This paper also describes about the wave transformation model (Varma et al., 1997a). The technique to transform SAR image spectrum into direction `al wave height spectrum developed earlier (Varma et al., 1997b) has been utilized for wave power computation (Varma et al., 1997c; VARMA et al., 1997d; Raj Kumar et al., 1997).

The sea surface temperature is known to influence many atmospheric as well as oceanic processes on all scales, from short-term scales of cyclogenesis to mesoscale phenomenon of Indian monsoon and also climate through El Nino/La Nina effect on long-term scale. In numerical weather prediction models, the SST field exerts its influence in the calculation of surface fluxes over the oceans; this in turn affects the forecast of convection and convective rain. SST is one of the most crucial geophysical parameter in climate studies, as the behaviour of the atmosphere is strongly coupled to the ocean temperature. Improved estimation and monitoring of SST will not only lead to better understanding of many of these phenomena e.g., El Nino and Indian Monsoon but it will also help in the early detection of global warming due to greenhouse effect (Allen et al., 1994). With the TOGA study group on climate studies (TOGA, 1983) setting up a target accuracy of 0.3 K for SST, launching of Along Track Scanning Radiometer (ATSR) onboard ERS-1 and ERS-2 augurs well because simulation studies (Prata et al., 1990; Mathur and Agarwal, 1993) show that this accuracy can be attained with the enhanced water vapour correction in dry as well as moist conditions. On the other hand normal Multichannel Sea Surface Temperature Algorithm (MCSST) using NOAA AVHRR channels (McClain et al., 1985) produces an error of as large as 4K in very moist conditions. Although these errors can be minimized to get an accuracy of 0.7 K (Mathur and Agarwal, 1991) by using one more channel of High Resolution Infrared Sounder (HIRS) centring around 13.4 μm, yet the errors in colocating HIRS and AVHRR observations results in large errors in SST retrieval. Mutlow et al. (1994) have shown that ATSR is capable of retrieving SST with an accuracy of 0.3 K when it is compared with observations of ship-borne radiometer. But a similar study lacks in tropics where water vapour content and its vertical distribution plays a crucial role in attenuating the IR signal (Schluessel, 1989; Mathur et al., 1996). Here, an attempt to remove this effect by utilizing the spectral response of the forward scan of ATSR has been discussed.

EXAMPLES OF COASTAL APPLICATIONS OF REMOTE SENSING

Coastal Bathymetry from SAR Data

The bottom depth contours as shown in Fig. 1 are assumed to be straight and parallel to the shore line. A shoreward propagating ocean gravity wave field from deep water regions will start feeling the effects of the sea floor approximately at the point where the depth h equals half the deep water

α_d = deep water wave angle
α_2 = shallow water wave angle
L_d = deep water wavelength
L_2 = shallow water wavelength
C_d = deep water wave celerity
C_2 = shallow water wave celerity
h = water depth

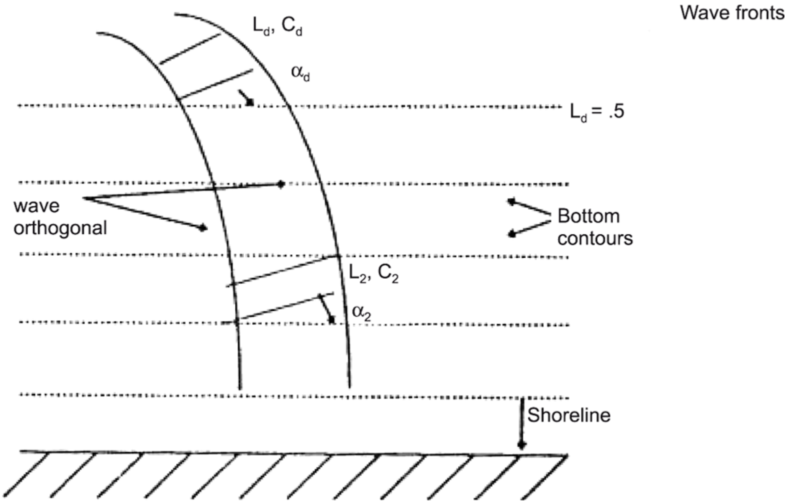

Fig. 1: Refraction of gravity waves.

wavelength L_o. If the angle between the wave front and the bottom contour, a is not zero, the shoreward portion of the wave will feel the bottom first (Fig. 1), causing reduction in its wave velocity due to frictional drag. This leads to decrease in wavelength between two successive waves, independent of the wave angle. Thus, as a wave propagates shoreward both its wavelength L and direction a decrease.

Assuming that the gravity waves are linear, the dispersion relationship (Leblond and Mysak, 1978) in the first approximation may be stated as

$$w^2 = gk \tanh (kh) \tag{1}$$

where w = wave frequency, k = wave number = $2\pi/L$, L = wave length, g = acceleration due to gravity, and h = water depth.

The equation (1) can be rewritten as follows:

$$L = (2\ p\ g/w^2) \tanh (2\pi\ h/L) \tag{2}$$

Within the limits of linear wave theory, the frequency w must remain constant as the waves approach the shore from deep waters. Deep-water approximation ($h/L >> 0.5$) provides the following condition:

$$\tanh (2\pi\ h/L_o) \sim 1 \tag{3}$$

where L_o denotes deep-water wave length.

Combining equations (2) and (3), following relationship is obtained

$$h = (L_h/2\pi) \tanh^{-1} (L_h/L_o) \quad (4)$$

where L_h denotes wave length in shallow waters at depth h. Equation (4) can thus be used to estimate coastal depths as a function of L_o and L_h.

To estimate wave spectrum (wavelengths and wave direction) in deep and shallow water regions, image is divided into smaller sizes of 128 × 128 pixels frames. For ERS-1 SAR image, each pixel corresponds to 15 m × 15 m area. Hence the total image covers an area of about 1.9 km × 1.9 km. Initially, the image is normalized and then a Fourier transform of the image is taken and squared to get power spectrum. Due to finite resolution, spectral response at high wave numbers reduces. So, a trend function has been estimated by computing 8th degree polynomial suggested by Tilley (1987), and subsequently response correction was applied. Due to coherent imaging system, SAR has the disadvantage of having speckle noise. The noise manifests itself on the SAR imagery as a white noise upon the actual spectrum. The noise is excluded from the data by excluding values with deviation more than 20% from average values. The spectrum thus obtained is an enhanced image spectrum, and is not identical to ocean wave height spectrum. The wave height spectrum $S_w(K_a, K_r)$ is derived from the noise free image spectrum $S_I(K_a, K_r)$ by dividing it by square of the Modulation Transfer Function (MTF) and multiplying it by square of wave number K^2 as shown below (Alpers et al., 1981; Raj Kumar et al., 1996).

$$S_w(K_a, K_r) = S_I(K_a, K_r)K^2/R^2_{SAR} \quad (5)$$

Here R_{SAR} is the Modulation Transfer Function and accounts for Hydrodynamic modulation, Tilt modulation and Velocity bunching effects.

ERS-1 SAR data for Kakinada, Goa and Trivandram coasts have been analysed. Fourier analyses revealed occurrence of waves with larger wavelengths in deep waters during the monsoon season. For example, waves with wavelengths of around 200 m are found to be prevalent in the deep-sea regions. Corresponding shallower regions show that waves with wavelengths in the range of 100 m are dominant (Fig. 2).

For the month of January, the sea is found to be quite calm, and not many dominant wave activities are seen; however in deep sea regions, the wavelengths calculated are around 200 m and near the coastal region the wavelengths reduce to 100 m range. To account for the effect of tides at the time of ERS-1 SAR data, we have calculated the tidal heights at the time of pass using Indian Tidal Tables. The effects of currents on the SAR data have not been taken into account in this analysis.

For a few areas near Goa, depth values were estimated at same locations by all three SAR images. Intercomparisons of estimated depths among themselves as well as with those provided by the NHO Charts (1990) were conducted. The depth values estimated on three different days were not only found consistent, but average departure of the estimated depths from the

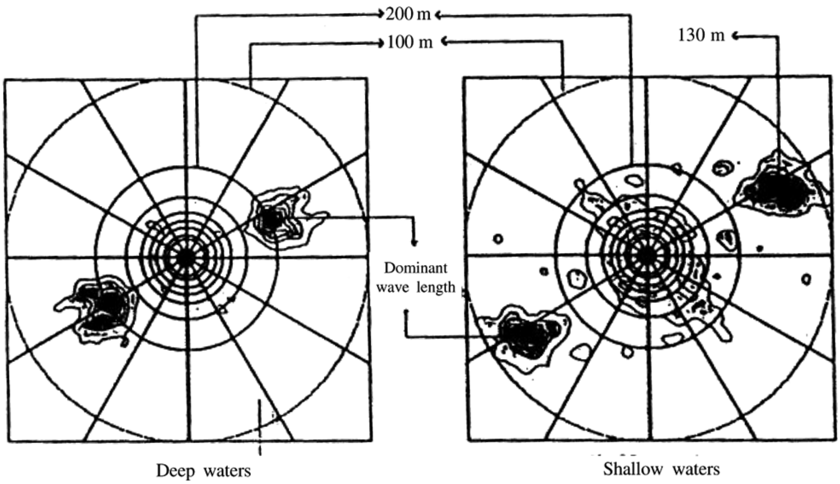

Fig. 2: Wave spectrum in deep and shallow waters.

Table 1: Comparison of depths (in metres) estimated from SAR on different dates with the charted values

Area	*Scene 1*	*Scene 2*	*Scene 3*	*Mean*	*Chart*
1	16	17	13	15.3	15
2	13	11	15	13.0	11
3	24	20	20	21.3	22
4	23	19	17	19.7	19
5	12	11	14	12.3	11
6	25	24	20	23.0	21
7	24	26	--	25.0	18
8	16	15	20	17.0	14
9	20	17	18	18.3	16
10	9	13	12	1.3	11
11	20	26	26	24.0	20
12	14	17	13	14.7	11
13	24	29	21	24.7	27
14	25	26	29	26.7	23
15	14	14	--	14.0	14
16	14	11	--	12.5	10
17	9	11	14	11.3	8
18	17	14	20	17.0	15
19	12	11	12	11.7	12
20	11	10	14	11.7	8

(Scene 1: 28/6/93; Scene 2: 30/6/93; Scene 3: 13/10/93)

charted values were found to be less than 15% (Table 1). For a few locations, the difference is found to be much larger than at other locations. This is considered encouraging in view of the assumptions of linear approximations for the gravity waves. Moreover, the effects of tides and currents on the SAR image have not been taken into account in this analysis. The technique may further be improved with the help of higher order ocean models for computing ocean wave lengths of the gravity wave field. The depths ranging from 5 m to 45 m have been estimated in this study. The difference in estimated coastal depths may also be attributed to accuracy in determining exact positions in two data sets. Since positions could not be located with very high accuracy, a few pixel error in location may lead to difference in estimation of wavelengths. Similarly, at the time of validation with hydrographic chart also, positions may be somewhat different than actually assumed. It may lead to error at locations, where changes in depths are quite rapid. The geocoding of the data sets with higher accuracy will lead to improved positional accuracy and better results in validation experiments. The methods described above are still not perfect, as the bathymetry data and bottom characteristics are not accurately known, and the deep water characteristics derived from SAR data are not properly validated because of non-availability of sea-truth data.

Wave Energy Potential along the Coastal Region by Integrating Altimeter Data and Models

In the model developed for the purpose to study wave transformation, Airy's, Stokes', Cnoidal and Solitary wave theories are used to calculate changes in wave length, wave height and wave speed at steps of 10 metres as the wave propagates towards the coast. In the model, waves are classified according to relative depth ratio (d/L) of depth (d) to wavelength (L). Depending upon the relative depth ratio, it is found (Lakhan, 1989) that Airy or linear theory is appropriate for deep water waves ($d/L > 0.5$) with small amplitude, Stokes' second order theory is appropriate for waves in transitional depth ($0.5 < d/L < 0.1$), Cnoidal theory is appropriate for waves in shallow water ($d/L < 0.1$), and Solitary theory is appropriate for describing shallow water wave characteristics close to the shore ($d/L < 0.1$). The changes in the wave height due to shoaling of the Stokes' waves are calculated with method described in the shore protection manual. The shoaling characteristics of Cnoidal waves are calculated with equations given by Svendsen and Hansen (1977) which involve energy transport of the Cnoidal waves from one depth to another. The change in the height of Solitary waves is calculated with Munk's method (1949).

The model used wave statistics available from satellite data (mainly altimeter and SAR). The deep water wave characteristics are provided to the model as input. The change in wave characteristics at each step is calculated using different wave theories in different ranges of depth to wave length ratio. The wave period is considered to be conserved throughout the wave transformation. The differentiation between Cnoidal wave and Solitary wave is made by the modulus (m) of elliptic integral involved. A value of 0.99 of *m* is used in the model to differentiate between Cnoidal and Solitary waves (Lakhan, 1989). It is difficult to find the value of *m* analytically. The model finds zero of a function, $F(m)$, which is defined as $F(m) = T - (L/C)$, where L is wave length, C is celerity and T is time period of the Cnoidal/Solitary wave. A very efficient subroutine Zeroin developed by Brent (1973) is used to find zero of the function $F(m)$. The wave breaking criterion as described above is used to check the wave breaking in each step. The model uses the bathymetry data for deep oceans as well as continental seas which is originally produced by the Defense Mapping Agency (USA). The files were obtained from NGDC (USA).

Few model runs have been made with different deep water wave characteristics. The results of a typical run are presented here. Table 2 gives initialized values and values of various constants. Table 3 shows the results of the model run. The variation of various wave parameters with depth and latitude and longitude is shown. Though the wave characteristics are calculated with progress of ray in steps of 10 metre, only few steps are presented in this table, which gives general idea of wave transformation. The domain of Airy theory where the wave does not undergo any change is shown as initial point and last point where it enters into Stokes regime. The changes in most of wave parameters are as expected. The variations of shoaling coefficient, refraction coefficient, bottom friction, percolation and viscous dissipation are also found as expected (Chandramohan et al., 1991; Mahadevan, 1983).

Table 2: Initial values and model constants for a deep water wave model

Mean Wave Height in Deep Water	0.60 meter
Mean Wave Length in Deep Water	60.00 meter
Direction of Propagation in Deep Water	60.00° from TOPEX pass (i.e. ~81° from East)
Value of Constants	
Distance between Grid Points (ds)	10.00 meter
Longitude of Initial Point	72.00° East
Latitude of Initial Point	12.00° North
K_D, permeability coefficient (for bottom percolation computation)	0.0005 m/s
μ, kinematic viscosity of sea water (for viscous dissipation computation)	0.000001945 m^2/s
f, bottom friction factor (for bottom friction computation)	0.02

The mathematical terms used for percolation, viscous dissipation and bottom friction needs a value of certain unavailable parameters along the ray for their accurate computation. For example, permeability coefficient is needed for computation of bottom percolation, kinematic viscosity of sea water is needed for computation of viscous dissipation, and bottom friction factor is needed for computation of bottom friction. The values of these parameters

Table 3: Model results of various wave parameters

Wave theory	*Longitude*	*Latitude*	*Depth (m)*	*Wave length (m)*	*Direction (°)**	*Height (m)*	*Celerity (m/s)*	*Wave power (KW/m)*
Airy	72.00	15.00	2253.00	60.00	60.00	0.60	9.68	2.04
Airy	..	..	..	..	..	..	..	..
Airy	72.54	18.38	30.18	60.00	60.00	0.60	9.68	2.04
Stokes	72.54	18.39	29.88	59.78	60.00	0.59	9.64	2.03
Stokes	72.55	18.49	24.34	59.31	59.65	0.59	9.57	2.00
Stokes	72.57	18.59	18.90	58.03	58.73	0.57	9.36	1.95
Stokes	72.59	18.68	13.60	54.90	56.58	0.55	8.85	1.88
Stokes	72.61	18.78	9.27	49.57	52.83	0.54	7.99	1.83
Stokes	72.65	18.87	6.90	44.86	47.17	0.53	7.23	1.80
Stokes	72.69	18.96	5.55	41.29	35.26	0.51	6.66	1.75
Cnoidal	72.75	19.02	3.34	33.55	13.36	1.47	5.41	5.00
Cnoidal	72.77	19.04	2.47	32.14	1.62	1.47	5.18	5.02
Solitary	72.80	19.04	1.60	23.49	–7.50	1.31	4.66	4.48
Solitary	72.81	19.05	1.28	15.91	–9.87	1.53	4.40	5.22

Surf Zone Wave Breaking Occurred (H/d > 1.20)
*Angle is from TOPEX pass which is about 21° inclined from north.

are not available, so their accurate computation is not possible. However, for testing the model with these terms, the values of these parameters for the Goa coast is given in the literature (Chandramohan et al., 1991).

In Wave Mode operation, the SAR measures the changes in the radar reflectivity of the sea surface due to surface waves in 10 km × 6 km 'imagettes' at intervals of 200 km along the track. These imagettes are transformed into spectra providing information about wavelength and direction of the wave system (ERS User Handbook). The method of obtaining wave spectrum from SAR is described by various researchers (Beal et al., 1983; Raj Kumar et al., 1995).

The ERS-1 Synthetic Aperture Radar (SAR) fast delivery product provided by European Space Agency gives the power spectrum for each SAR wave mode imagette. The spectrum is provided in 12 angular sectors each of 15° representing range 0° to 180°, and the power given is normalized from value 0 to 255 for 12 spatial wave length bins in range 100 m to 1000 m. The digital data set also provides maximum of UWA spectrum components before normalization. This can be used to obtain the actual SAR spectrum power for each bin before normalization.

The integration of various SAR wave imaging theories into procedure for converting SAR image spectra into estimation of ocean wave slope and height variance spectra has not been fully successful. We have taken a novel approach of using near-simultaneous and colocated TOPEX-altimeter derived significant wave height values to calibrate and then transforming image spectra into wave height spectra. This study is undertaken over an area of interest, between 65°E and 80°E and 5° N to 25°N. All available ERS-SWM spectrum and TOPEX-Altimeter SWH values over this region for 1993 and 1994 are extracted from Exabytes and CD-ROMs. The SAR image spectrum which is in the form of intensity from 0 to 255 is converted into power using maximum UWA information available in the data set. The Altimeter has a footprint of between 3 and 14 km diameter for different sea states whereas SAR has imagettes of 10 km × 6 km size. Thus one Altimeter observation is almost of same order as that of SWM data. The two dimensional ocean wave spectra from ERS-1 SAR wave mode data (SWM) is calibrated with near-simultaneous and colocated TOPEX-altimeter measured significant wave height (SWH) values. To observe the temporal coherence of SWH, we used four data sets collocated within 3 hrs, 6 hrs, 12 hrs and 24 hrs, whereas spatial difference is maintained at 0.25°. The regression between square root of the integrated highest one-third values from SWM 12 × 12 SAR spectral intensity bins and TOPEX-SWH is obtained for all four data sets. The regression equation obtained from data set collocated within 3 hrs is used as calibration equation for SAR image spectra. This regression equation is as follows:

$$I = 26.0205 \times \text{SWH} + 33.7799 \tag{6}$$

The SWH from calibration equation for a typical SWM wave spectrum is attributed to average of square root of the highest one-third intensities of the SWM wave spectrum bins. By distributing proportional wave height in each bin as per square root of spectral intensity in that bin, the directional spectra of wave height is generated.

The TOPEX altimeter derived significant wave height (SWH) values are converted into average wave height values in each 0.5° latitudinal intervals along the TOPEX pass (No. 66) for April 1993 and 1994 for comparison with model wave height values. The model wave heights are also averaged in 0.5° lateral intervals along the same TOPEX pass. The comparison of two wave heights is shown in Fig. 3. It can be observed that model and altimeter derived wave heights match reasonably well. In the near-coast region, there is significant increase in the wave height from both altimeter and model.

The wave power near Indian coast at 4 m depth has also been computed. The wave characteristics of deep-water waves as derived from wave height spectrum ERS-1 SWM data are used as input to wave transformation model. The all-available image spectrums over study region from SAR wave mode data for year 1993 and 1994 were transformed into directional wave height spectrum and interpolated in each 1°. The wave power at 4 m depth is averaged in about 0.5° (~55 km) lateral intervals in 32 segments along west coast of India (Fig. 4).

Figure 5 shows monthly variation of average wave power in each segment. The wave power is found to show strong seasonal variability near coast with about two-fold increase during S-W monsoon season. Though the spatial variation of wave power is small, more wave power is expected near Ratnagiri

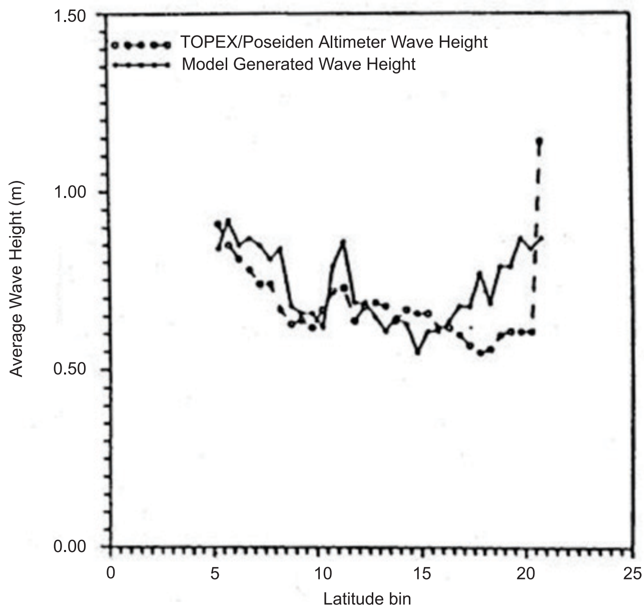

Fig. 3: Comparison of model derived wave height and TOPEX wave height.

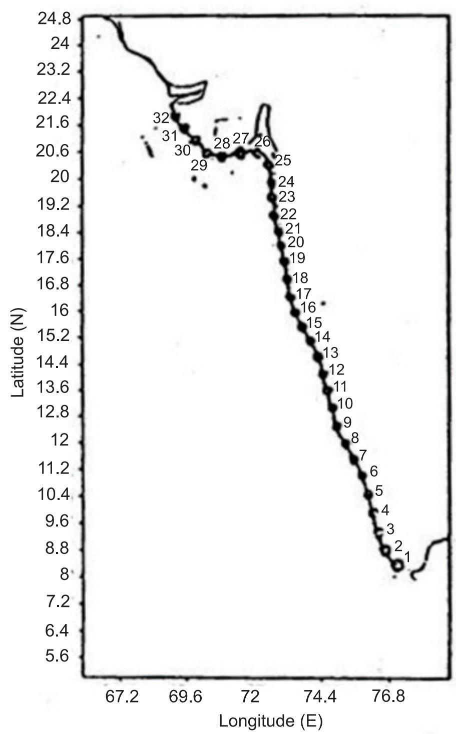

Fig. 4: Physical location of the centre of each segment along west coast of India.

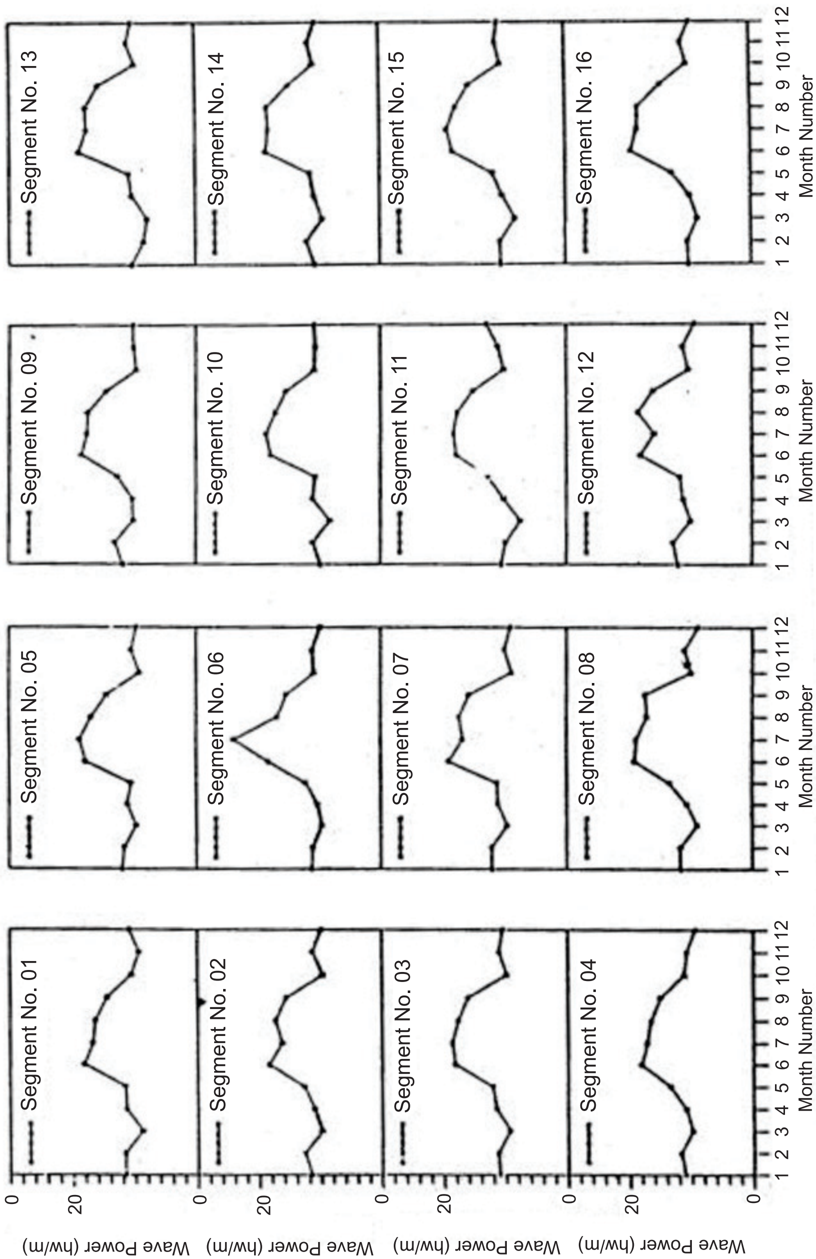

Fig. 5: Monthly average wave power distribution in each segment.

Coast and less near Veraval coast. The monthly variation of wave power as shown in Fig. 5 is as expected where the wave power increases significantly during S-W monsoon season. The minimum wave power is found during the month of March and maximum during the month of July.

The segment No. 1 covers coast between 8.1° and 8.6° latitude, which includes Trivandrum coast. In this segment, the wave power increases drastically in monsoon months when it varies from 15 to 18 kw/m; however for non-monsoon months it varies between 10 to 12 kw/m. The results compare well with the buoy measurements at 12 metre depth off Trivandrum coast at 8°29'N and 76°57'E (Fig. 6) (Pathak and Koola, 1996). From Fig. 6, it is evident that maximum wave power is during monsoon season and having value of 20.60 kw/m and 17.90 kw/m for 1991 and 1989, respectively. However, the minimum power is about 1.5 kw/m for both the years. Our results also match reasonably well with those of Thomas (1990). They have found that average power with five years (1980-1984) buoy data at 5.5 metre depth off Trivandrum coast is 15.5 kw/m for May to Oct. and 4.5 kw/m from November to April.

The monthly variation of wave power shows the expected trend. The wave power is high during S-W monsoon season from June to September. The wave power during these four months is about double that of non-monsoonal months. The variation in wave power all along the coast for different months is about 8 kw/m to 24 kw/m. There is not much variation along the coast. The maximum variation for any month between lowest and

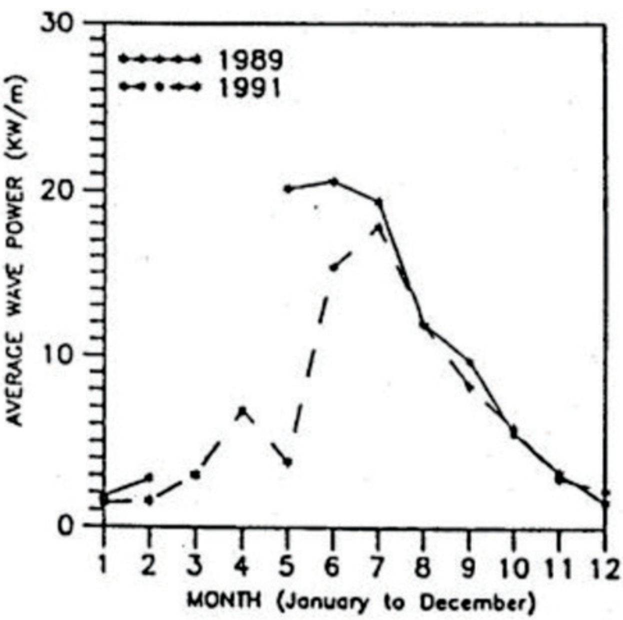

Fig. 6: Buoy measurement of monthly average wave power off Trivandrum coast.

highest power segment is about 25-30%. Though we have used a simple model for studying wave power potential along the coast, there is a good agreement between our results with sea truth data when validated near Trivandrum coast. The validation results show that our results are somewhat underestimated when wave power is high and over estimated when wave power is low. This may possibly be because our results are not only for different years and for different depths but also averaged over large lateral distances. Nevertheless, the trend of monthly variation of wave power is in good agreement with other studies.

SST from ATSR Data

European Remote Sensing Satellite ERS-1 was launched on July 17, 1991 with the onboard payloads as synthetic aperture radar, Altimeter and wind scatterometer and an instrument called Along Track Scanning Radiometer (ATSR) developed by Rutherford Appleton Laboratory, UK, CSIRO Australia and CNES, France. ATSR senses the terrestrial radiation in four bands centering around 1.6, 3.7, 11 and 12 μm with two look angles of near nadir and forward view at 55°. The primary objective of ATSR has been to improve upon the present SST retrieval accuracy by Multichannel SST algorithm of NOAA-AVHRR. In order to achieve this goal, there have been three major improvements in ATSR over AVHRR: (a) the scanning mechanism has been modified to include one more forward observation (at 55°) of the same target within a short time interval of less than two minutes for better atmospheric correction, (b) by improving upon the quantization level of the transmitting data to 12 bit and (c) by improving upon the cooling mechanism of the IR detector by employing special sterling coolers so that the NEΔT is reduced to 0.04 K as compared to 0.12 K in AVHRR. The capability of simultaneously (within two minutes) viewing the earth's surface from two different locations in space is an exciting feature of the ATSR. A conically scanning objective mirror gives a crosstrack scan passing through the nadir as well as a second scan forward of the subsatellite point. On the earth's surface these two scans are both curved and are separated by about 900 km. The instrument is equipped with hot and cold blackbodies to calibrate the sensor after each forward and nadir scan. ATSR scans nearly 554 and 370 pixels in nadir and the forward earth view, respectively.

As mentioned in the previous section, ATSR has the capability of viewing the same target from two angles i.e., 0° and 55° within a very short time. That means that the differential absorption due to different optical paths in thermal window channel can be attributed to the atmospheric water vapour (as differential absorption due to split window channels is proportional to the atmospheric correction) as explained by McMillin (1975). This argument can very well be supported by plotting the weighting functions of ATSR channels. The weighting functions are calculated for a typical tropical atmosphere i.e., SST and surface humidity being 302 K and 80% respectively. The normalized weighing functions are shown in Fig. 7. From Fig. 7, it is obvious that all the channels peak below 2 km where 90% of the total water vapour exists. Since the nadir viewing thermal window channels centering around 11 and 12 μm band have maximum contribution emanating from the ocean surface, the forward view of these channels will have the maximum contribution from very near to surface i.e., planetary boundary layer because of its optical path length being almost two times of that of nadir viewing. This fact can again be verified by Fig. 8. Figure 8 is drawn by assuming the simplest form of radiative transfer equation for a cloud-free, plane parallel atmosphere with local thermodynamic equilibrium, which gives the radiance reaching at the satellite height:

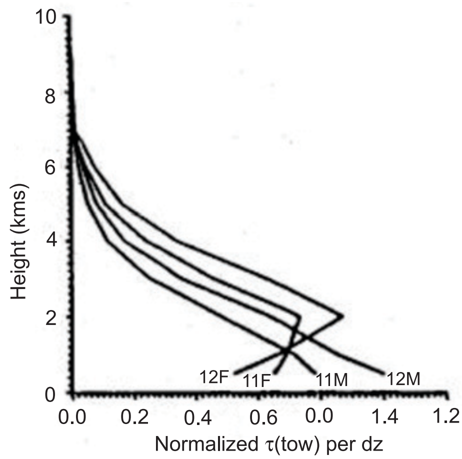

Fig. 7: Weighing functions for ATSR channels.

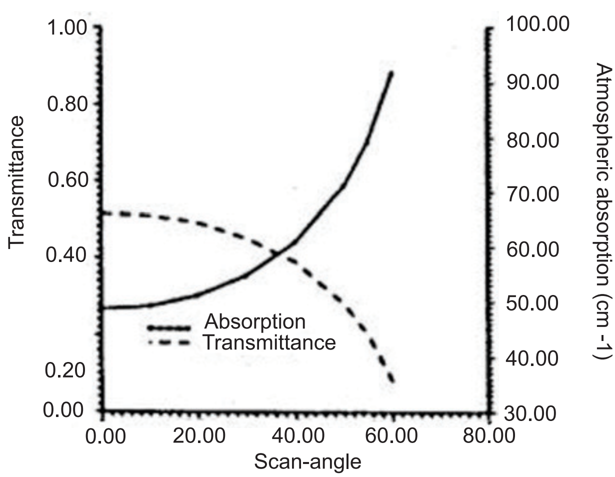

Fig. 8: Absorption and transmittance with respect to scan angle for ATSR channel (11 m).

$$I(\nu) = \tau(\nu, p_o, \theta)\, B(\nu, T_s) + B_a(\nu, T)[1 - \tau(\nu, p_o, \theta)] \quad (7)$$

where $I(\nu)$ is the radiance reaching the satellite sensor, τ is the total transmittance of that particular frequency (ν), $B(\nu, T_s)$ is the radiance contribution from the surface (at temperature T_s), $B_a(\nu)$ is the mean atmospheric radiance, p_o is the surface pressure, T is the mean atmospheric temperature, and θ is the zenith angle.

For all the window channels, the second term on R.H.S i.e., the atmospheric term is the minimum for nadir looking observations. Using radiative transfer simulations by LOWTRAN-7 package (Kneizyas et al., 1989), we have estimated the atmospheric absorption and transmittance at different look angles for a frequency band centering around 11 μm (defining the input surface parameters viz. SST as 300 K and relative humidity as 80%). From Fig. 8 one can infer that with the increase in look-angle from 0° to 60°, the atmospheric absorption increases and at a look-angle of 55° it increases by a factor of 2. Similarly the total transmittance decreases from 0.51 at 0° to 0.2 at 55°. Therefore, it is imperative to say that ATSR forward scan observations should have the information regarding the content and the distribution of water vapour which attenuates the IR signal and hence the near-nadir and forward angle observations could provide the key to the estimation of water vapour. Based upon the same principle, Mathur et al. (1996) have shown that near-surface level specific humidity can also be estimated from ATSR nadir and forward angle observations with an rms error of 3 gm/kg. In an earlier study by Gohil et al. (1994), the total water vapour content (TWC) has been taken as criterion for selection of different sets of SST retrieval coefficients for different TWC ranges. But the error of retrieval heavily depends upon the TWC estimation and a slight error in TWC would change the range of data set of coefficients for SST retrieval and thereby causing large errors. Here, in order to avoid such errors, we are not estimating the total water vapour content. Based upon this a multiple regression equation has been derived to estimate SST.

$$\mathrm{SST} = a_i + b_i(T11\mathrm{n}) + c_i(T12\mathrm{n}) + d_i(T11\mathrm{f}) + e_i(T12\mathrm{f}) \quad (8)$$

where suffix I = 1 to 5 depending upon the pixel position across track distance; *a*, *b*, *c*, *d* and *e* are the corresponding regression coefficients. T11 and T12 refer to ATSR channels centering around 11 and 12 μm and the suffix n and f refers to the nadir and forward scan observation respectively.

The rms error of SST retrieval algorithm was calculated by generating a different data set of EBBT using LOWTRAN-7 from an entirely new surface meteorological data set of 215 locations (not used in simulating the coefficients) obtained from ship cruises. From these, EBBT and then SST were computed using the corresponding derived coefficients. The difference between the derived SST and the ship SST yields an rms error of 0.2 K. Regression coefficients have been given in Table 4.

Table 4: Regression coefficients used to estimate SST

Set	*Across track distance (km)*	*a*	*b*	*c*	*d*	*e*
1	0-50	–7.3283	7.5337	–5.7105	4.5381	3.7396
2	51-100	–5.8402	7.0078	–5.4961	3.7695	3.2784
3	101-150	–6.4659	6.7292	–5.2795	3.4781	3.0512
4	151-200	–7.1492	6.6502	–5.2121	3.3928	2.9798
5	201-256	–6.5522	6.5350	–5.1330	3.2260	2.8872

The proposed SST retrieval technique was applied to an actual ATSR brightness temperature data set for March 3, 1992, April and May 1994, obtained from RAL, UK. Before applying the regression coefficients for retrieving SST, each set of image is subjected to cloud checks based upon the visible channel reflectance threshold, the difference in nadir and forward scan observations of 11 μm channel and the difference in nadir observations of 11 μm and 12 μm channel. Colocation of nadir and forward scan pixels has been performed by RAL, UK while processing 'ATSR.IBT' data product, so we have assumed that there is no earth location error. Based upon the climatology of Arabian Sea, Bay of Bengal and Indian Ocean SST, we have omitted the computed SST values which are greater than 308 K and lower than 295 K. The land part of the image was also masked before averaging the whole image of 512 × 512 by a window size of 8 × 8. The SST thus obtained is compared with near-simultaneous ship observations. Ship and satellite observations were assumed to be simultaneous if they are separated by not more than 1° in space and 6 hrs in time. Ship observations (Bucket temperature) taken during the cruises of research vessels SagarKanya, Gaveshani and Sagarsampada were provided by NIO, Goa while the ship observations for 3 March 1992 were provided by Royal Observatory, Hong Kong. The comparison between ATSR SST and ship SST shows that most of the time (44 out of 75) the difference lies between –0.5 to 0.2 K (Fig. 9). Table 5 shows the typical location and the ATSR derived SST, ship SST and the difference (ship SST – ATSR SST) alongwith the date of ATSR pass. Utilizing the available ATSR data, we have produced weekly composite SST contours for April and May 1994. The gaps are either due to persistent cloudiness or non-availability of data. These maps are produced by averaging the SST map 512 × 512 to a grid map of 1° × 1° and masking for the data over land.

A technique to estimate SST from ATSR nadir and forward scan observations has been developed on the basis of radiative transfer simulations and it has been validated for highly variable and moist conditions in Indian oceans. The average accuracy of retrieved SST is 0.5 K which improves the existing accuracy of 0.7 K by NOAA-AVHRR. Besides utility of such an accurate SST in climate change studies, it would also be useful for numerical weather prediction models as there is a strong connection between Arabian

Table 5: Location of ATSR and ship derived SST and their differences

Date	*Latitude*	*Longitude*	*SST*		*Difference*
ddmyy			*Ship*	*ATSR*	*S-A*
03392	8.25	108.75	300.40	301.00	-0.60
03392	9.75	109.25	300.20	300.40	-0.20
03392	9.25	109.25	299.80	299.70	0.10
03392	8.75	109.25	299.80	300.00	-0.20
26494	11.48	69.73	303.30	302.90	0.40
26494	12.08	70.02	303.10	302.90	0.20
26494	11.45	70.17	303.00	302.90	0.10
03594	16.07	63.80	304.00	304.70	-0.70
03594	18.09	64.10	302.40	302.80	-0.40
03594	18.50	64.25	302.30	302.80	-0.50
03594	19.05	64.08	302.20	302.80	-0.60
19594	11.41	84.52	303.40	303.60	-0.20
19594	12.50	82.50	303.20	303.80	-0.60
19594	12.50	82.94	303.50	302.70	0.80
19594	11.46	85.70	303.50	303.70	-0.20
19594	11.33	85.20	303.70	303.50	0.20
19594	11.21	86.01	303.60	302.80	0.80
19594	11.15	86.20	303.60	303.80	-0.20
19594	11.04	86.40	303.40	302.80	0.60
19594	10.05	89.40	302.50	302.10	0.40
19594	9.59	90.07	302.40	302.20	0.20

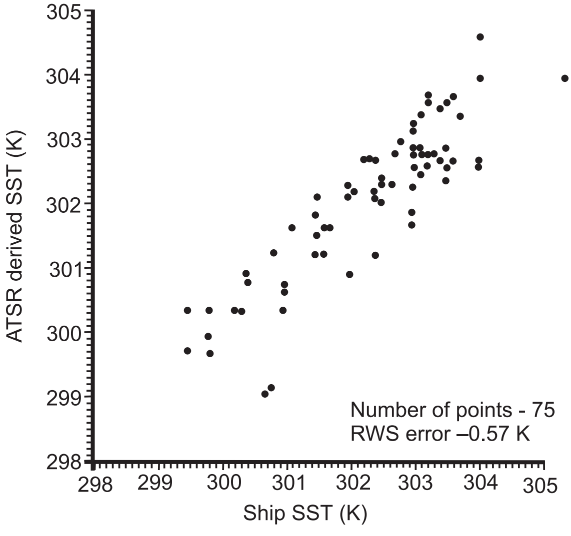

Fig. 9: Comparison between ATSR derived SST and ship SST.

Sea SST during premonsoon season and the monsoon intensity (Gohil et al., 1994). Latent heat flux, which is a very important parameter for understanding the oceanic boundary layer dynamics and evaporative processes, can be mapped over scantily observed Indian oceans by combining the present study and the wind speed by ERS-1 scatterometer with the study by Mathur et al. (1996) for calculation of near-surface humidity.

Chlorophyll Estimation Using Ocean Colour Data

The Coastal Zone Colour Scanner (CZCS- onboard Nimbus-7) data set for the first time provided an opportunity to view the global distribution in space and time of phytoplankton pigment concentration in the upper ocean layer. The processes that lead to nutrient enrichment play a key role in seasonality particularly in tropical regions. Recent concern about increased levels of atmospheric carbon dioxide and global warming has led to studies of ocean's role in Global Carbon Budget. Joint Global Ocean Flux Study is one such example.

The spatial and temporal distribution of phytoplankton pigment (with optimized and non-optimized sensors) in relation to physical oceanographic parameters is discussed below. CZCS was launched in 1978 and remained functional till 1986. Besides Landsat MSS, that was originally meant for land applications, could detect very high concentration of phytoplankton pigment i.e., algal bloom conditions (Ulbricht, 1983; Chaturvedi et al., 1986; Chaturvedi et al., 1998). Largely the data from CZCS (optimized marine applications sensor) has been used to determine chlorophyll concentration. Landsat TM data has also been used to determine chlorophyll concentration (Kim and Linebaugh, 1985; Dwivedi and Narain, 1987). Similarly the Indian Remote Sensing Satellite (IRS) is meant for land applications but due to presence of spectral band in blue region, the detection of pigment concentration above 1.0 mg m^{-3} and seasonal analysis for a part of Gujarat coast could be achieved (Chaturvedi et al., 1992). Besides understanding the interaction between biological and physical oceanographic parameters the processes leading to enhanced production, viz., internal wave phenomenon could also be studied. The characterization of initiation or maturation phase of internal waves in the Andaman Sea using IRS LISS-I data is one such example (Chaturvedi et al., 1985). Distributional pattern of phytoplankton pigment/temperature for northwest coast of India off Bombay and further south has been studied using CZCS data. The relationship between phytoplankton pigment and physical oceanographic parameters (temperature profile, mixed layer depth, wind speed etc.) were studied using processed CZCS data (DAAC, NASA) and climatological data, respectively, to evaluate and define requirement of biophysical coupled models (Chaturvedi et al., 1997).

The studies performed were towards mapping very high concentration of chlorophyll-a localized phenomenon, seasonal change of chlorophyll at the northwest coast of India besides interrelationships of biological along with physical oceanographic parameters. The chlorophyll concentration is reported to be of the order of 600 mg m^{-3} during the peak bloom conditions (Devassy et al., 1978). The occurrence of algal bloom has a significant contribution in acting as carbon dioxide sink. In addition, it plays an important role in the enrichment of water by fixing atmospheric nitrogen. The role played by the sudden appearance of bloom is significant from the point of view of biological productivity, carbon dioxide flux (acting as sink) and nutrient enrichment (nitrogen fixation). The mapping and monitoring can be done on a regular basis with the help of satellite data. The genesis of algal bloom phenomenon can be readily mapped and studied with the sensors having broad spectral bands.

The spatial and temporal pattern of phytoplankton pigment depends on several oceanographic parameters viz., temperature, wind current, mixed layer depth etc., which affect nutrient availability and direction of transport. Based on biomass/temperature relationship, the water masses can be classified into mixed/stratified/frontal waters (Sathyendranath et al., 1991). A single date CZCS image of northwest coast of India covering the area off Bombay and further south for March showed distinct patterns of pigment distribution. The single channel thermal data when density sliced shows close similarity of features as that seen on the pigment image particularly in the offshore waters. The satellite derived ocean colour information pertains to the value at one attenuation length, which may be from less than 1 m in high turbid (pigment rich) area to 25–30 m in low pigment (<0.1 mg m^{-3}) area (Smith and Baker, 1978). Therefore, the satellite derived pigment concentration cannot be directly compared with the satellite derived sea surface temperature unless one is sure as to how temperature is distributed at different depths.

At few locations in the near-shore and offshore waters in the Arabian Sea, the phytoplankton pigment value (CZCS processed data: DAAC, NASA) and surface/subsurface temperature, mixed layer depth, wind speed, when analyzed showed region specific relationship. At few lacerations reasonably good correlation is observed between phytoplankton pigment and subsurface temperature (r^2 = 0.56, 0.72) in the near-shore waters while no significant correlation was observed with surface temperature. Mixed layer depth and wind speed showed a positive correlation (r^2 = 0.63) in the offshore waters. In the near-shore waters the subsurface temperature and wind speed were found to be correlated (r^2 = 0.60). A locational difference in the relationship between different parameters is obvious.

Future Missions

There are currently over 45 missions operating and around 70 more missions are planned for operation during next 15 years for the Earth Observations

Table 6: An example of satellites carrying oceanographic sensors

Mission	*Launch*	*Sensor*	*Applications*
JERS	1992	SAR	Wave spectrum, bathymetry, Wave energy
TOPEX	1992	Altimeter	Wave height, wind speed
ERS-2	1995	Altimeter SAR	Wave height, wind speed Wave spectrum, bathymetry
RADARSAT	1995	SAR	Wave spectrum, bathymetry, Wave energy
IRS-P3	1996	MOS	Chlorophyll, suspended sediment, Aerosol
OrbView-2	1997	SeaWifs	Chlorophyll, suspended sediment, Aerosol
ADEOS	1997	OCTS	Ocean Colour, SST
IRS-P4	1998	OCM	Chlorophyll, suspended sediment, Aerosol
EOS-AM	1998	MODIS	Ocean colour, SST
ENVISAT	1999	ASAR AATSR	Wave spectrum, bathymetry, energy, SST, LST
RADARSAT-2	2001	SAR	Wave spectrum, bathymetry, Wave energy
NOAA-M	2001	AVHRR AMSU	SST Atmospheric sounding
OCEANSAT-2	2003	AltimeterScat	Wave Height, Wind Vector

(CEOS Yearbook, 1977). Out of these, many of them will be carrying sensors for coastal oceanographic use (Table 6). In view of this, ample opportunities will be available for observing coastal features. To monitor wave features such as wave height, wave spectrum, missions like TOPEX, ERS, ENVISAT will continue to monitor for long. As far as ocean colour remote sensing is concerned, data from US SeaWiFS (launched on August 1, 1997), the Indian Satellite System OCEANSAT I and II, MODIS and MERIS will be having new generation spectrometers. The colour sensors onboard these have large number of narrow spectral bands in the visible and infrared regions of electromagnetic spectrum for ocean colour retrieval in presence of coloured dissolved organic matter (CDOM) besides atmospheric corrections.

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Modelling of Coastal Marine Pollution

Coastal Transport and Dispersion Modelling

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INTRODUCTION

The coastal ocean, where land, air and sea meet, is a region of very high physical energy and biological diversity that is heavily exploited by man. Nearly 60% of the world's population live within 60 km from coastline and use the coastal resources directly or indirectly for their livelihood. The multifarious demands on the coastal zone has already resulted in over-exploitation of many marine resources and marked degradation of the quality of coastal habitats and environment. Industrial and urban pollution including sewage, solid waste and chemical discharges combined with unplanned construction activities, land reclamation and human manipulation of the hydrological cycle have resulted in appreciable and measurable changes to coastal environments in many countries. Such changes pose problems for environmental management in both developed and developing countries. Besides, natural calamities including floods, storms, and other episodic events affect society's use of the resources and complicate the management problem. In addition to the current problems of coastal pollution, habitat degradation, coastal erosion, harmful algal blooms and unplanned water management must now be added to the threat of global climatic change. Coastal pollution can have readily apparent and immediate impacts, such as oil spills, the closure of beaches, or fish kills due to toxic contaminants. This type of pollution can be very serious but it is usually short term. The effects of chronic pollution, such as excess nutrients and persistent toxic contaminants can be subtle, leading to long-term effects.

The difficulty of predicting the discharges into coastal waters often lead to either over or under-estimation of their impacts. Domestic or industrial sewage is quite buoyant in sea water and forms a turbulent plume. Coastal currents exist over a wide range of length and time scales such as tidal oscillations, wind-driven currents and large scale mean circulation. Although these spatial and temporal variations in coastal currents, especially their oscillatory behaviour, can result in a highly dispersive environment, these complexities often lead to worst case assumptions which lead to overly conservative predictions. Often currents parallel to the coast or moving from ocean into coastal waters are significant sources of nutrients. We need long-term records of these currents, salinity and temperature patterns, nutrient concentrations, and population of primary producers so that we can relate these variations to the effects of climatic variability and coastal pollution sources. We also need better models of coastal waters in order to synthesize our knowledge and test mechanisms and process controls.

Managing the North American Great Lakes system and shared boundary waters, is a mutual responsibility between Canada and the United States mandated through the bi-national International Joint Commission (Fig. 1a). Towards achieving this goal, models have been developed and applied to manage the resources in a sustainable way. A hierarchy of models is required to deal with such problems. Hydrodynamic models of large lakes predict the dynamics of the physical environment such as circulation, thermal structure, wave climatology and transport and dispersion. These models form the fundamental building blocks to develop reliable operational management tools.

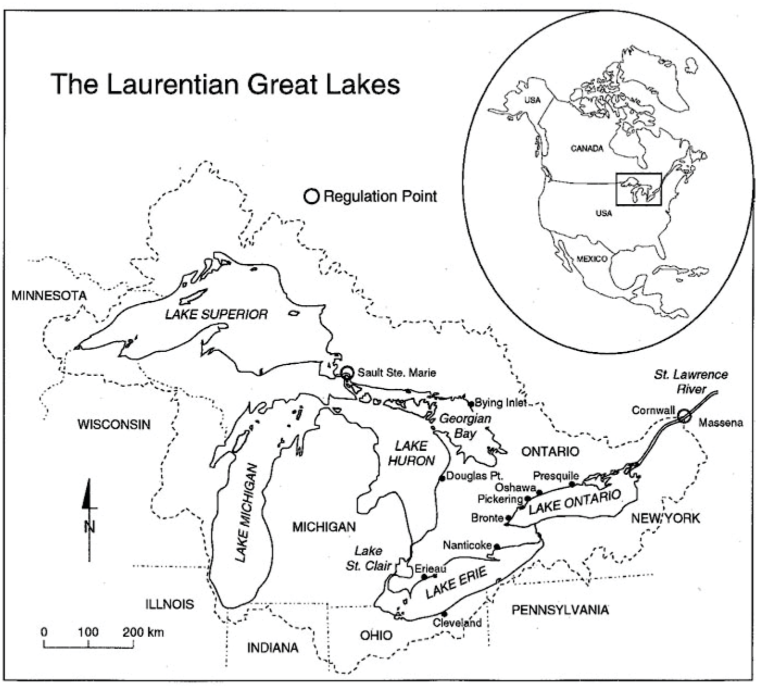

Fig. 1a: Map showing the geographic location of the North American Laurentian Lakes.

This paper will focus on the discussion of some of the coastal hydrodynamic and pollutant transport model studies for the following coastal environments: sewage outfall in the western Lake Ontario and Niagara River Plume in Lake Ontario.

COASTAL TRANSPORT MODELS IN WESTERN LAKE ONTARIO

In the western end of Lake Ontario an urban community of over five million residents turn to Lake Ontario almost exclusively for both water supply and wastewater disposal (Fig. 1b). Intakes and discharges alike are typically installed in a narrow band of the lake extending, at most, a few kilometres offshore. Improvements in water purification and sewage treatment technology

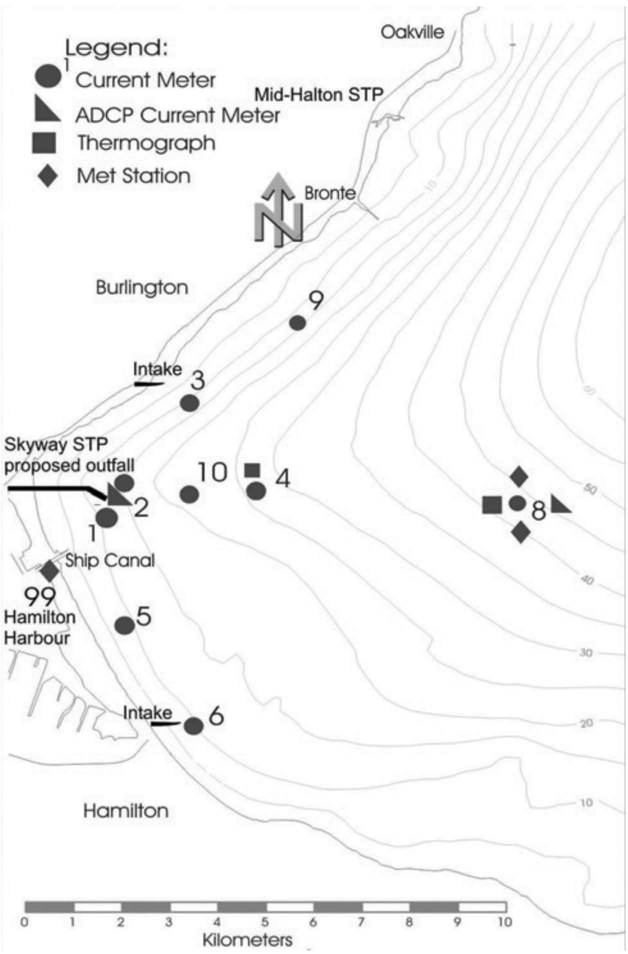

Fig. 1b: Map of western Lake Ontario showing 1996-97 measurement stations and the location of proposed outfall site.

have, to some degree, offset the deleterious effects of increased development. However, current treatment technology seems to be nearing its practical design limit, while the demand for clean water and the need for suitable waste disposal facilities continue to rise at an ever-increasing rate. Excessive loadings of phosphorus, ammonia, and suspended solids from sewage treatment plants, bacterial contamination from Combined Sewer Overflows (CSO) and storm runoffs contribute to the problems of nearshore water clarity and poor water quality. In addition, loadings of toxic substances continue to be a concern today. One factor that has helped to minimise the degradation of the western Lake Ontario waters has been that the sewage treatment plants (STP) of Burlington and Hamilton discharge into Hamilton Harbour. The Remedial Action Plan (HHRAP) guidelines call for further reductions in contaminant loading over time, while continued development in the region will require substantial expansion of wastewater treatment facilities to meet the additional demand. For facilities discharging into Hamilton Harbour it will likely be very difficult to meet RAP loadings targets and still keep up with future demands using foreseeable improvements in treatment technology. Soon, however, benefits are expected, such as improvements in beach quality due to CSO containment and water quality improvements due to progressive optimization of STPs (Charlton, 1997).

Current meter data include time-series of current speed and direction data plus water temperature. Where possible, nearby concurrent meteorological data are also included in the analysis. Locations of moored instruments in western Lake Ontario during 1996 and 1997 are shown in Fig. 1b. The data were hourly averaged for the analysis. In addition to data from moored current meters and meteorological stations, results of the analysis of trajectories of satellite-tracked drifting buoy released about a kilometre east of the proposed outfall site in 1997 are also included to estimate the circulation and horizontal exchange coefficients. Current profiles near the present location of the outfall in the Hamilton Harbour were obtained from a bottom mounted Acoustic Doppler Current Profiler (ADCP) deployed from May 31 to September 7, 2000. Figure 2 shows the stacked rose-plots of winds and currents from ADCP station during the summer stratified season. The currents show significant vertical structure; however the predominant direction seems to be oriented alongshore. In summer, stratification typically developed at 5-8 m depth then decayed in the fall until temperature profiles became isothermal and remained so over the winter. The complete details of the experimental work and historical results are presented in a comprehensive report (Miners et al., 2002) and are not the subject of this paper.

Near-Field Model

The primary goal of an outfall diffuser system is to accomplish a rapid initial mixing of the effluent with the receiving waters and thus minimize detrimental

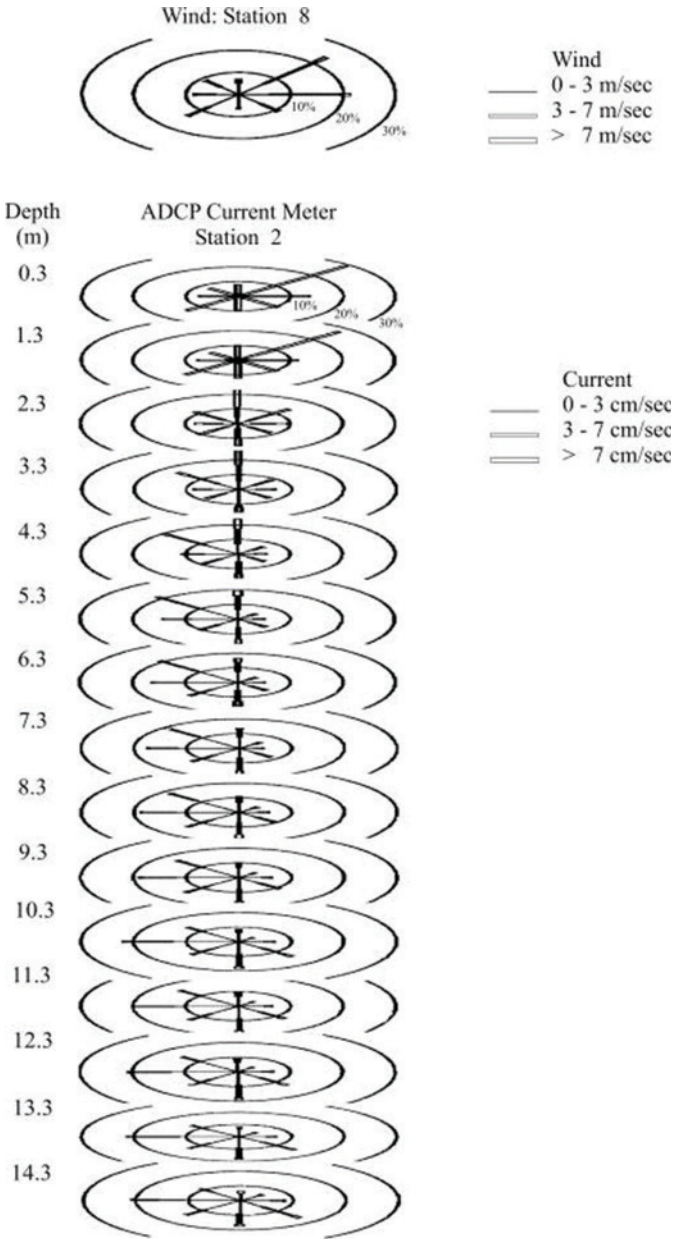

Fig. 2: Rose plot summaries of wind and ADCP current meter data at station 2 from May 1 to October 21, 1997.

effects of the effluent discharge on the environment. Hydrodynamic mixing processes of effluent discharge depend primarily on the discharge condition, diffuser length, and the ambient current and density conditions. Initial mixing occurs within about 100 m (near-field) and within a few minutes after release from the diffuser (Figure 3). A wastefield is established at the end of the initial mixing region (IMR), which drifts with the currents to be diffused by lake turbulence in the far-field. Mathematical mixing models have been developed to predict the near-field characteristics of effluent discharges. Some of the important wastefield parameters of submerged effluent discharges are the height to the top of the established wastefield, Z_e, the height of the level of maximum concentration (minimum dilution), Z_m, and the thickness, h_e (Roberts, 1996). The minimum dilution at the end of initial mixing region (x_i) is S_m, which is defined as the smallest value of the dilution observed in a vertical plane through the wastefield at the end of the IMR.

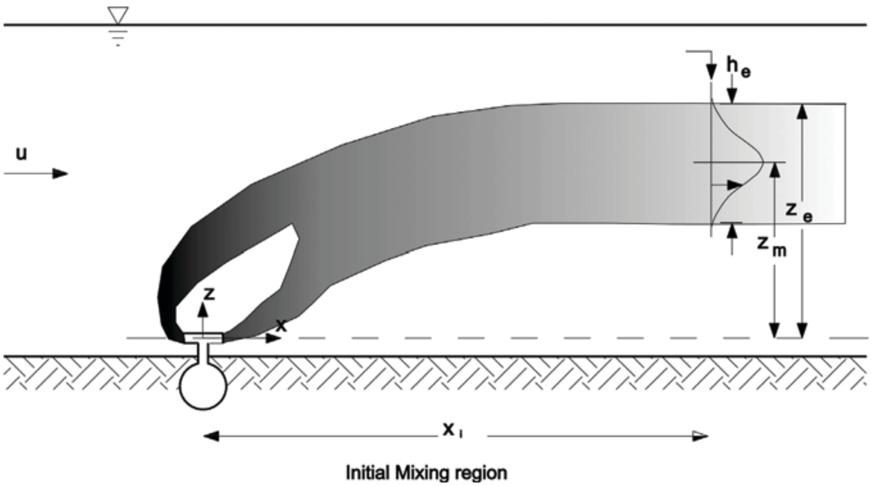

Fig. 3: Schematic of Initial Mixing Region and waste field characteristics of a diffuser system.

The PLUMES modelling suite consists of two initial dilution models RSB and UM3 for fresh water and marine applications (Frick et al., 2000). The RSB model can be broadly classified as an updated model of United State Environmental Protection Agency's (USEPA) earlier ULINE model. It also accommodates the effects of varying source momentum flux and port spacing. It is based on the experimental results for merging plumes in linearly stratified cross-flows. The RSB model assumes that the density profile is linearized up to the top of the plume, and so can be used with non-linear stratification also. Because RSB is based on experiments, it will, of course, provide reliable estimates of minimum dilution, rise height and other wastefield characteristics for these experiments. Independent comparisons of RSB predictions have been reported in several studies (Roberts and Wilson, 1990).

The RSB model was used to obtain near-field dilution characteristics for different flow conditions. For summer conditions we have taken the mean temperature profile obtained from thermistor chain data for August (station 2), and for winter simulations we assumed homogeneous condition with 4^{o}C as the mean temperature. For ambient flow velocities we considered three different cases with currents perpendicular to the diffuser. The simulated outfall was as described above. Tables 1 and 2 show the predicted results of waste field characteristics and dilution rates near the outfall for summer with present and future discharges.

Far-Field Model

In view of the limitations of Gaussian Plume model developed for the northshore of Lake Ontario (Kuehnel et al., 1981), and the inadequacy of the information regarding the flow field, a numerical model for transport and diffusion was developed for western Lake Ontario (Rao et al., 2003). For the present case, a two-dimensional (x, y) model is found to be adequate, if we assume that the effluents are contained and vertically mixed in the top few metres during summer stratification, and well-mixed during the winter season.

The two-dimensional transport equation for a moving patch of pollutant is given as

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} = K_x\left(\frac{\partial^2 c}{\partial x^2}\right) + K_y\left(\frac{\partial^2 c}{\partial y^2}\right) - kc + S_c\,, \qquad (1)$$

where c is the concentration, u and v are velocity components, K_x and K_y are eddy diffusivities, S_c is the pollutant source and k is a decay constant. The boundary conditions completing the model impose a no-flux condition at a solid boundary, and at open boundaries, the diffusive flux is assumed zero. At the pollutant source, the input concentrations are taken from the output of the near-field model. A central difference scheme is applied for the diffusion terms, and advection terms are solved by an upstream finite difference scheme. Thus, the distribution of an effluent can be obtained by solving equation (1) for a sufficiently long period.

In these numerical experiments the modelled area extends over a region of 10.5 km in the x-direction (east-west) and 11.4 km in y-direction (north-south) with a grid resolution of 300 × 300 m. For this grid interval a time step of 30 sec is found to be consistent with computational stability. The decay rate is taken as zero in the simulations, mainly because phosphorous is assumed to be conservative for the simulation period. The choice of horizontal diffusion coefficients is very important to the prediction of model concentrations. The horizontal diffusion coefficients varied significantly during episodic events compared to summer or winter conditions (Rao and Murthy, 2001). Horizontal eddy diffusivity values may also vary in space and time. However, in this study we use the average values of diffusion coefficients as K_x (0.48 m^2/s) and K_y (1.02 m^2/s) obtained from both Lagrangian and Eulerian experiments conducted in 1996 and 1997.

Two types of methods are used to provide currents to this transport model. In the first example, the lake-wide currents obtained from a three dimensional model (Great lakes Princeton Ocean Model, Schwab and Bedford, 1994) were downscaled to the transport model grid. Because of discrepancies in these predictions a different approach was finally used. In this approach following Lam et al. (1984) an objective analysis method was used to define the flow field from the observed Lagrangian and Eulerian currents. It consists of interpolation of currents by radii of influence around the observed points. The currents at all stations were first hourly averaged, and then interpolated to the grid points to generate u and v components.

Several numerical experiments are conducted with the current and future sewage discharge rates (Tables 1 and 2). For example, in an experiment for a discharge rate of 2 m^3/s the near-field mixing model yielded initial dilution of 17.6:1 for current speed of 5 cm/s which is equivalent to a concentration of 17.05 μgP/L. By introducing this input as a continuous source the model was run for a typical shore parallel episode occurring from August 1 to 5, 1997. Figures 4(a) and 4(b) show the concentration distributions on 1st and 5th August, respectively, with current vectors at the model grid points superimposed. The area affected by the effluent was confined to the region near the outfall. Far-field calculations show that for proposed outfall location and flow conditions concentrations would attain lake background levels (10 μgP/L) within 510 m from the diffuser for weak to moderate currents (5 to 10 cm/s). These results also suggest that, with a flow of 2 m^3/s, the pollutants may not extend beyond 4-5 sq km from the outfall. However, when the outfall capacity was increased to 6.94 m^3/s owing to the projected population growth in the region, it is expected that the concentrations be higher than 10 μgP/L near the beaches. In another numerical experiment the

Table 1: Wastefield characteristics during summer with discharge of 2 m^3/s (concentration 300 μg/l)

Current speed, cm/s	*IMR (m)*	*Ze (m)*	*He (m)*	*Zm*	*Initial dilution Sm*	*Dilution at 100 m*	*Distance of 10 μg/l (m)*
3	10.5	5.7	5.1	3.8	12.3	14.9	510 m
5	17.5	5.7	5.1	3.8	17.6	20.3	470 m
10	35.2	4.5	4.0	3.0	27.3	31.4	<100 m

Table 2: Wastefield characteristics during summer with 6.94 m^3/s (concentration 300 μg/l)

Current speed, cm/s	*IMR (m)*	*Ze (m)*	*He (m)*	*Zm*	*Initial dilution Sm*	*Dilution at 100 m*	*Distance of 10 μg/l (m)*
5	18.1	8.6	7.6	5.8	8.7	10	1150 m
10	37.2	7.9	7.0	5.3	13.9	15.2	1300 m
15	52.6	6.9	6.2	4.6	18.3	21.0	<1300 m

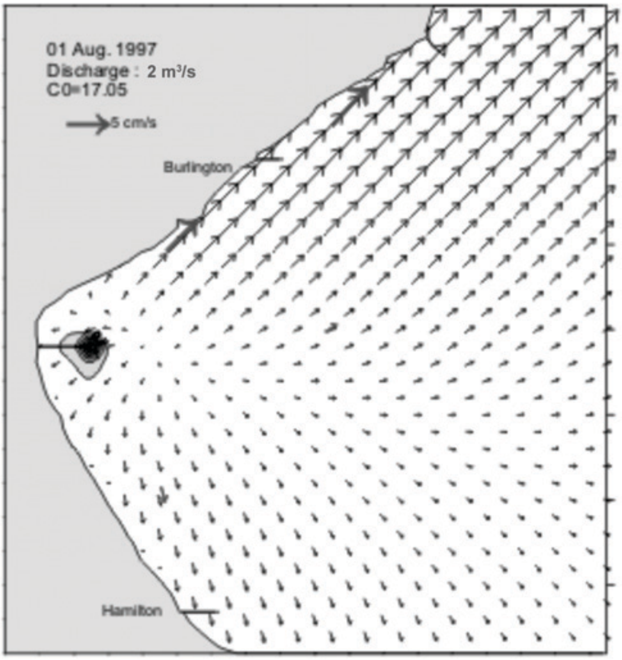

Fig. 4a: Simulated concentration field superimposed on circulation on 1 Aug 1997. (Thick grey arrows are from observations; thin arrows from model results).

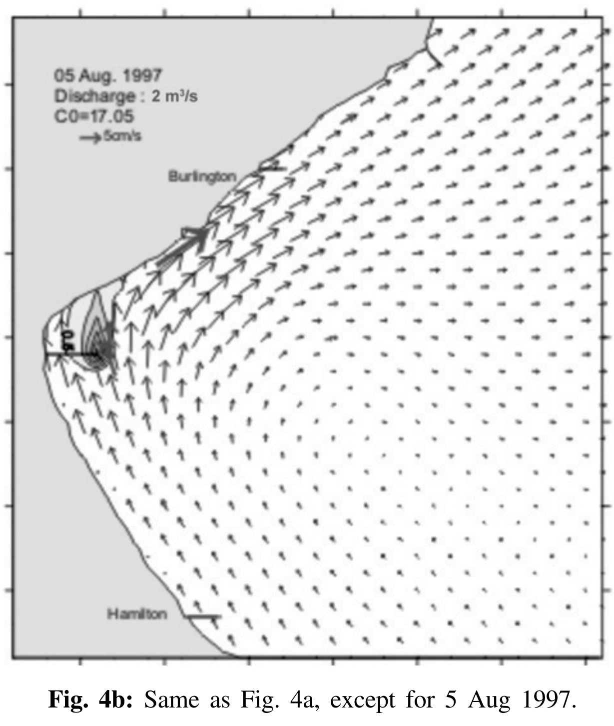

Fig. 4b: Same as Fig. 4a, except for 5 Aug 1997.

outfall was relocated to 2 km (20 m depth) from the shore. The results show that dilutions at 100 m and beyond improved considerably by relocating the discharge location to offshore (figures not shown).

RIVER PLUME MIXING MODEL

Discharge from rivers contains sediments, nutrient and pollutant loads that can have significant adverse impacts on water quality in the receiving lake. Horizontal mixing and dispersion of river plume in shallow receiving basins are key processes which affect the distribution and fate of water-borne material, especially for low buoyant plumes travelling in unstratified receiving waters. Understanding these mixing processes is critical for more effective environmental management to support the important biological resources heavily impacted by human activities.

The mixing between Niagara River and Lake Ontario has a critical impact on the coastal zone of Lake Ontario environment. The Niagara River provides the bulk of the materials that flow into the lake Ontario, including toxic contaminants. The Niagara River discharge forms a plume by strong horizontal gradients or fronts. Our current understanding of the Niagara River plume has been derived from a series of experiments conducted by National Water Research Institute between 1982 and 1985. These studies collected physical data to aid in the interpretation of chemical and biological data collected in and around the plume. A contaminant transport model was developed to simulate the transport and pathways of toxic contaminants from the Niagara River plume in Lake Ontario. Because of the strong river flow and lake circulation, the chemicals associated with Niagara River water remain in the Niagara bar area for only a few hours. Over such a short time frame, chemical processes such as biodegradation, bio-accumulation, and volatilization are relatively insignificant and can be neglected. In the model formulation it is more pertinent to consider the advection-diffusion, settling-resuspension and adsorption-desorption processes (Stephien et al., 1987).

It is assumed that sediment-water system is at near-equilibrium. The exact proportion of dissolved to adsorbed form at equilibrium is dependent on the properties of individual chemicals and characteristics of suspended particles, thus

$$C_{\mathrm{p}} = \frac{C_{\mathrm{ss}}\Pi}{1+\Pi C_{\mathrm{ss}}} C_{\mathrm{T}} \tag{2}$$

$$C_{\mathrm{d}} = \frac{1}{1+\Pi C_{\mathrm{ss}}} C_{\mathrm{T}} \tag{3}$$

where C_{T} is total concentration, C_{p} is particulate concentration, C_{d} is dissolved concentration, C_{ss} is suspended sediment concentration and Π is partition coefficient. In order to describe the temporal and spatial changes of suspended sediment concentration and total concentration we require two additional equations as

$$\frac{\partial hC_{ss}}{\partial t} + \nabla.\overline{U}C_{ss} = k\nabla.h\nabla C_{ss} - WC_{ss} \tag{4}$$

$$\frac{\partial hC_{T}}{\partial t} + \nabla.\overline{U}C_{T} = k\nabla.h\nabla C_{T} - W\frac{\Pi C_{ss}}{1+\Pi C_{ss}}C_{T} \tag{5}$$

where $\overline{U}$ is the two dimensional vertically integrated transport vector, h is the depth, ∇ is the two dimensional spatial gradient operator, k is turbulent diffusivity and W is the settling velocity.

The hydrodynamic model provides the computed currents for the advection of both the suspended sediments and chemicals (Murthy et al., 1986). Since the numerical calculations are concerned only with a very small portion of

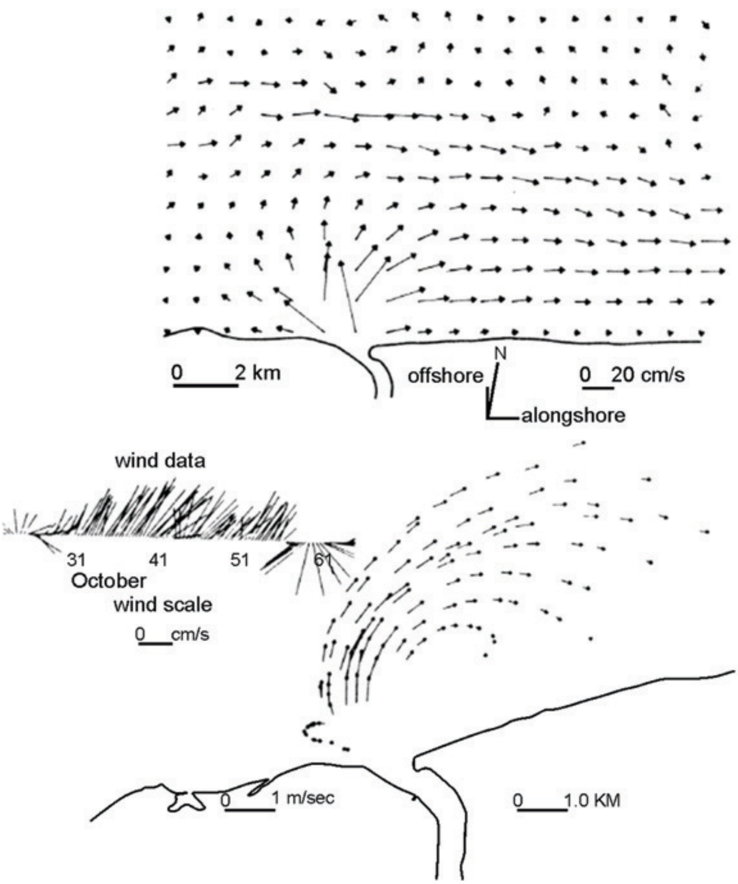

Fig. 5a: Vertically integrated currents from the model and drogue observations on 4 October, 1983; winds during this period are shown as stick plot.

Lake Ontario, nested system of models are used. As an example computed currents from the hydrodynamic model for 4 October, 1400 GMT are shown in Fig. 5a. In this figure the lower half shows the currents obtained from drifter trajectories, and the lower right portion shows the wind history before and during the drogue experiments. The easterly orientation of the Niagara River plume is a consequence of the prevailing wind direction and the semi-permanent easterly flowing currents along the south shore of Lake Ontario (Simons et al., 1985). Figure 5b shows the two dimensional distributions of simulated 1,2,3,4- TeCB concentration at 1700 GMT, 4 October 1983. The observed values are shown in circles for this period. Mean standard deviations between computed and observed data are well within the uncertainties of the observed data.

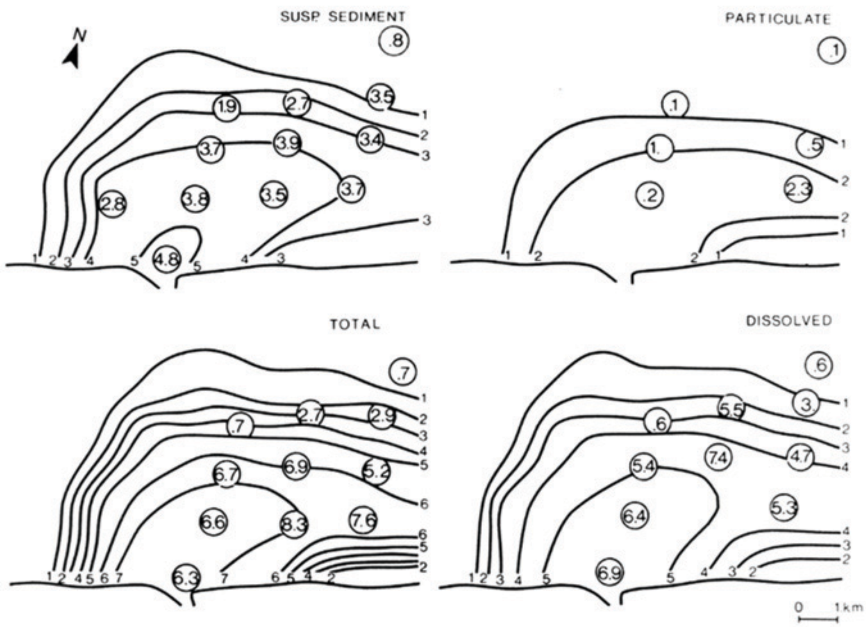

Fig. 5b: Total and fractional 1,2,3,4-TeCB concentration (ng/L) and suspended sediment concentration (mg/L). The model predicted values are shown as contours and circled values are observations on 4 October, 1983.

In another example, the direction and shape of the plume is controlled by an easterly wind during August 1983. Figure 6a shows horizontal velocity field produced by hydrodynamic model and drifter trajectories for 10 August 1983, 1400 GMT. As before, the quasi-synoptic observed values of another

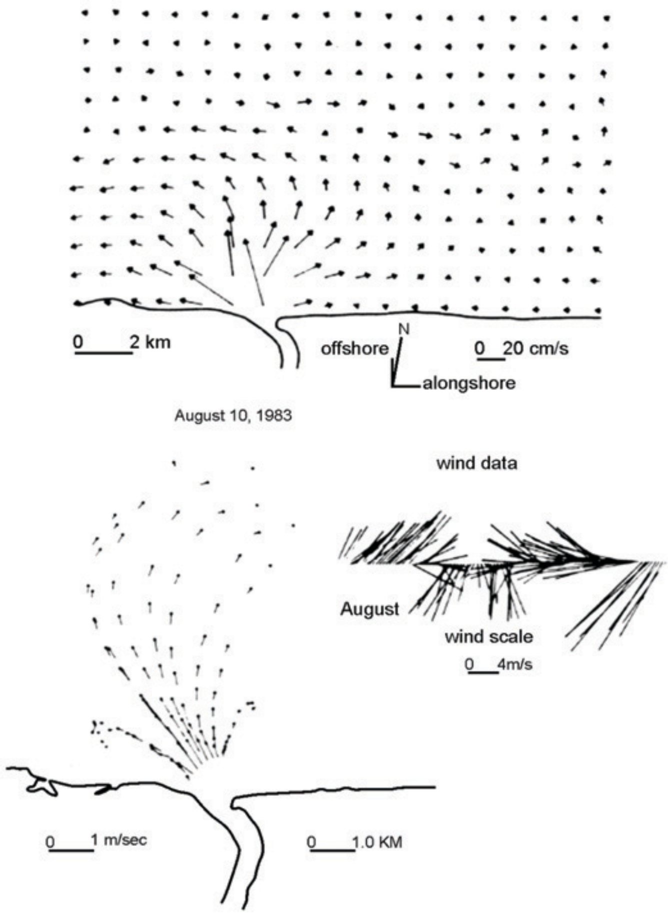

Fig. 6a: Same as Fig. 5a, except for 10 August 1983.

chlorinated benzene 1,2,4-TCB are shown in circles in Fig. 6b and corresponding computed values as contours. In this case only the partition coefficient has been changed. The observed decreasing concentration gradient is reflected in the computed values. The simulation also shows an eastward movement of the plume. It is difficult to quantify rigorously the accuracy of the model results because of limited number of observational points. For example, if we use the mean standard deviation between the computed and observed total concentrations as a measure of accuracy, the model calibration runs produced a value of 1.5 ng/L, whereas the confirmation runs showed values of 1.1 ng/L and 2.3 ng/L from Figs 5b and 6b. Thus the model seems to produce results of comparable accuracy to those from calibration runs, showing that the calibration parameters are accurate for the Niagara River plume.

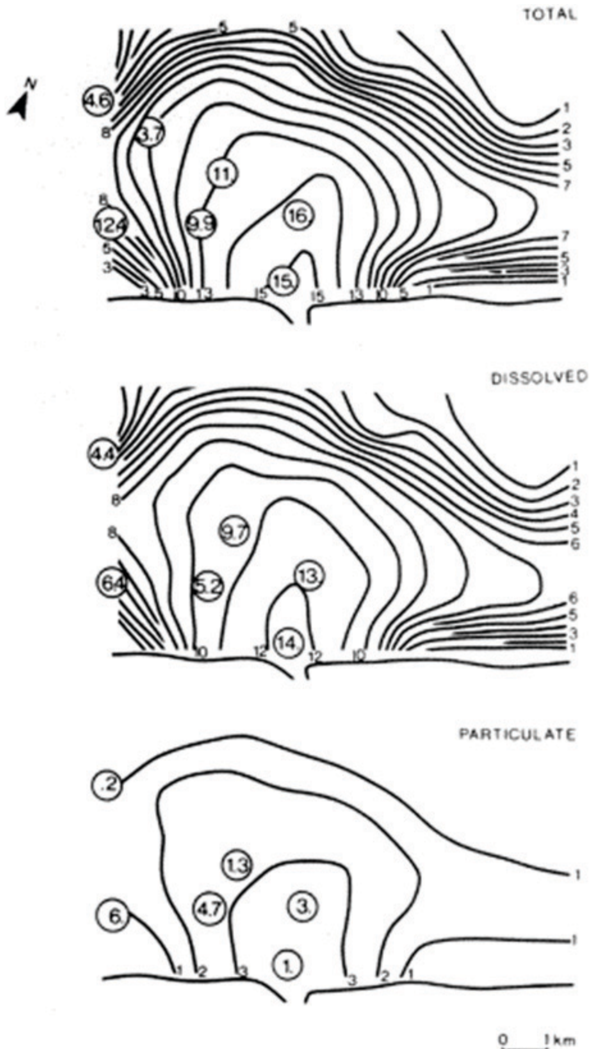

Fig. 6b: Total and fractional 1,2,4-TCB concentration (ng/L). The model predicted values are shown as contours and circled values are observations on 10 August, 1983.

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Modelling Circulation and Salinity in Estuaries

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INTRODUCTION

The region between the free flowing river and ocean forms a complex and diverse water system known as estuary. Estuaries are regions of the coastal ocean where salinity variations in space are so large that they strongly influence the circulation. Most estuaries are found at river mouths; they are thus long and narrow, resembling a channel. Compared to the flow in the direction of the estuary axis, cross-channel motion is very restricted, and the estuarine circulation is well described by a two-dimensional current structure. However, if the estuary has a vast water surface and complicated coastal geometry other influences due to Coriolis force and wind may become significant. The interaction between the dense saline water and fresh water gives rise to a wide spectrum of circulation pattern and estuarine mixing.

United Nations Educational, Scientific and Cultural Organization (UNESCO) defined estuary as “a semi-enclosed coastal body of water having free connection to the open sea and within which sea water is measurably diluted with fresh water deriving from land drainage”. This definition works well for estuaries in the temperate zone where estuaries are linked with river mouths but does not include bodies of anomalously high salinity such as lagoons, or coastal inlets which are connected to the ocean only occasionally. Many scientists have recently suggested another definition as “an estuary is a semi-enclosed coastal body of water having free connection to the open sea at least intermittently, and within which the salinity is measurably different from the salinity in the adjacent open sea”.

Estuaries can be grouped into classes, according to their circulation properties and the associated steady state salinity distribution. The balance of forces that establishes a steady state in various types involves advection of freshwater from a river and introduction of sea water through turbulent mixing. Mixing is achieved by tidal currents. The ratio of freshwater input to sea water mixed in by the tides determines the estuary type. One way of quantifying this is by comparing the volume of freshwater (*R*) that enters from the river during one tidal period, with the volume of water (*T*) brought into the estuary and removed over each tidal cycle. *R* is sometimes called the river volume, while *T* is known as the tidal volume. It is important to note that it is only the ratio *R*/*T* that determines the estuary type, not the absolute values of *R* or *T*. In other words, estuaries can be of widely different size and still belong to the same type.

Salt Wedge Estuary

River volume *R* is very large relative to the volume *T*, or there are no tides at all. The fresh water flows out over the sea water in a thin layer. All mixing is restricted to the thin transition layer between the fresh water at the top and the wedge of salt water underneath. Vertical salinity profiles therefore show zero salinity at the surface and oceanic salinity near the bottom all along the estuary. The depth of the interface decreases slowly as the outer end of the estuary is approached.

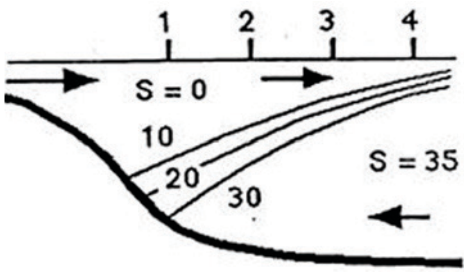

Fig. 1a: The flow and salinity distribution in salt-wedge estuary.

Highly Stratified Estuary

River volume *R* is moderate to strong relative to tidal volume *V*. Strong velocity shear at the interface produces internal wave motion at the transition between the two layers. The waves break and topple over in the upper layer, causing entrainment of salt water upward. Entrainment is a one-way process, so no fresh water is mixed downward. This results in a salinity increase for the upper layer, while the salinity in the lower layer remains unchanged, provided the lower layer volume is significantly larger than the river volume *R* and can sustain an unlimited supply of salt water. The upward mass flux of salt water leads to an increase of flow speed in the upper layer. This increase of mass transport in the upper layer can be quite significant, to the extent that the river output appears insignificant compared with the overall circulation. The surface velocity increases likewise, although not as dramatically, as the downstream increase in width of the estuary compensates for some of the increase in mass transport.

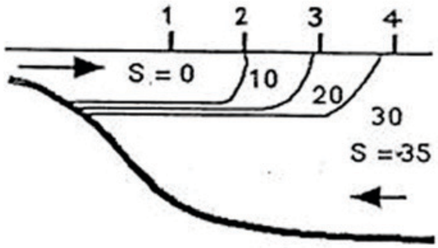

Fig. 1b: The flow and salinity distribution in highly stratified estuary.

Partially/Slightly Stratified Estuary

River volume *R* is small compared to tidal volume *T*. The tidal flow is turbulent through the entire water column (the turbulence induced mainly at the bottom). As a result, salt water is stirred into the upper layer and fresh water into the lower layer. Salinity therefore changes along the estuary axis not only in the upper layer as was the case in the highly stratified estuary, but in both layers. There is some increase in surface velocity and upper layer transport towards the sea, but not nearly as dramatic as in the highly stratified case.

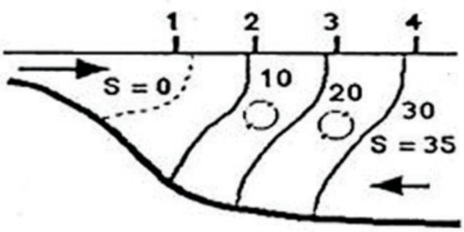

Fig. 1c: The flow and salinity distribution in partially stratified estuary.

Vertically Mixed Estuary

River volume *R* is insignificant compared to tidal volume *T*. Tidal mixing dominates the entire estuary. Locally it achieves complete mixing of the water column between surface and bottom, erasing all vertical stratification. As a result, vertical salinity profiles show uniform salinity but salinity increases in the horizontal from station to station as the outer end of the estuary is approached.

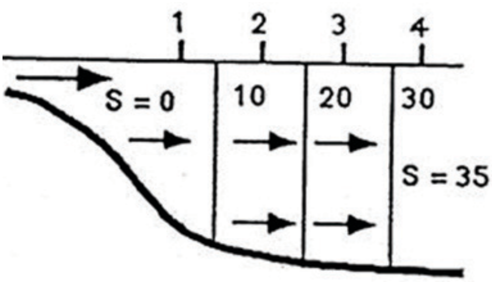

Fig. 1d: The flow and salinity distribution in well-mixed estuary.

Varying the ratio *R/T* produces a range of salinity distributions, which can be classified by the ratio of surface salinity S_s against bottom salinity S_b. The ratio S_s/S_b can therefore be used as a substitute for the ratio *R/V*. Estuaries can change type as a result of variations in rainfall and associated river flow. They may show different characteristics in different parts as a result of topographic restrictions on the propagation of the tide along the estuary, which affect the tidal volume. The classification diagram can be used to establish changes of estuary type in space and time.

Inverse Estuaries

These estuaries have no fresh water input from rivers and are in a region of high evaporation. Surface salinity does not decrease from the ocean to the inner estuary, but water loss from evaporation leads to a salinity increase as the inner end of the estuary is approached. This results in a density increase and sinking of high salinity water at the inner end. As a result, movement of water is directed inward at the surface and towards the sea at the bottom, with sinking at the inward end. Compared to the estuaries discussed above their circulation is reversed, which explains the name inverse estuary.

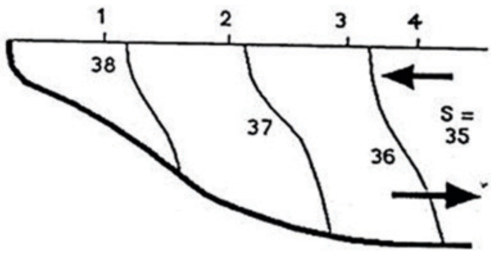

Fig. 1e: The flow and salinity distribution in an inverse estuary.

Intermittent Estuaries

Many estuaries change their classification because of highly variable rainfall over the catchment area of their river input. River input may be small, but as long as some fresh water enters the estuary, the estuarine character is maintained (in the form of a salt wedge estuary). If the river input dries up completely during the dry season, estuaries lose their identity and turn into oceanic embayments.

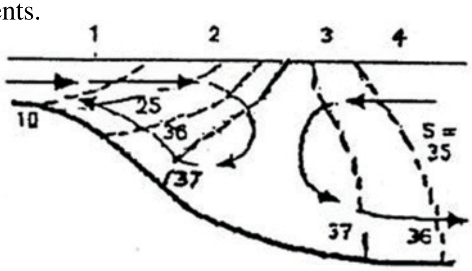

Fig. 1f: The flow and salinity distribution in intermittent estuary.

MODELLING STUDIES

In order to predict the transport of pollutants, thermal circulation, sedimentation, salinity intrusion etc., it is a prerequisite to have the knowledge of water movements. In general, three approaches have been used to model the abovesaid phenomena: physical/hydraulic modelling, electrical analogs and mathematical modelling. Reproduction of estuarine hydrodynamics by physical modelling is a very useful and wholesome investigation technique. But physical modelling of vast regions is expensive and it is difficult to achieve the scaling of certain parameters like friction coefficient, pollutant dispersion and Coriolis parameter. Besides physical modelling, electrical analogs have also been used to predict tidal heights throughout an estuary, but the cost of producing such kind of devices for tides, currents and pollutant transport is often enormous and hence not practical.

Stochastic Modelling

Some of the simplest types of models are empirical models that are developed from statistical fits of data using simple or multiple linear regression analysis to predict the response of one variable to changes in one or more variables. Other statistical models use a stochastic approach in which the model inputs and results are given as a range of possible realizations, which accounts for the natural randomness that can characterize estuarine processes. However, this type of model requires sufficient length of reliable data which is not always available.

Analytical Modelling

Analytical modelling of estuarine hydrodynamics has been attempted by many researchers all over the world. However, this involves simplifying assumptions such as steady state or ideal geometry, and hence lacks generality.

NUMERICAL MODELS

Numerical models offer certain advantages in coping with more realistic physical aspects. Simulation of coastal and estuarine processes may require detailed treatment of irregular coastal geometry, complicated bottom topography, tidal effects, sediment transport, chemical transformation, biological production etc. The translation of these complex processes into mathematical formulations is very complicated. Recent advances in computer technology have made it possible to use sophisticated numerical techniques to get accurate solutions with less computer time and cost. There are a number of fundamental principles that form the basis of numerical models, of which the conservation of mass, momentum and energy, the chemical equilibrium equations and population dynamics equation are some examples. Once the model formulation is ready, a number of solution procedures such as finite-differences, finite-volume, finite-element schemes can be used to obtain hydrodynamic or concentration fields.

In the formulation of the model, the sphericity of the earth's surface is ignored. A system of rectangular Cartesian coordinates is used in which the origin, O, is in the equilibrium level of the sea surface. Ox points towards the east, Oy points towards the north and Oz is directed vertically upwards. The displaced position of the free surface is given by $z = \zeta(x, y, t)$ and the position of the channel floor by $z = -h(x, y)$.

The basic hydrodynamic equations of continuity and momentum for dynamical processes in the estuary may be given by:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}-fv=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\Delta^2 u+\frac{1}{\rho}\frac{\partial \tau_x}{\partial z} \tag{2}$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}+fu=-\frac{1}{\rho}\frac{\partial P}{\partial y}+\nu\Delta^2 v+\frac{1}{\rho}\frac{\partial \tau_y}{\partial z} \tag{3}$$

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-g-\frac{1}{\rho}\frac{\partial P}{\partial z}+\nu\Delta^2 w \tag{4}$$

$$\frac{\partial s}{\partial t}+u\frac{\partial s}{\partial x}+v\frac{\partial s}{\partial y}+w\frac{\partial s}{\partial z}=K\Delta^2 s \tag{5}$$

where $\Delta^2 = \frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}+\frac{\partial^2}{\partial z^2}$ u, v, w: Reynold's averaged components of velocity in x, y and z directions, t: time, s: salinity, K: diffusion coefficient, P: pressure, f: Coriolis parameter, g: acceleration due to gravity, ν: kinematic eddy viscosity, and τ_x, τ_y: x and y components of Reynold's stress. The terms in τ_x and τ_y are included to model vertical turbulent diffusion.

One-Dimensional Models

One-dimensional (1-D) models can give an accurate description of waste concentration and movement in a well-mixed estuary. Usually, by neglecting non-linear advective terms and linearizing the resistance term, the equations are solved either by numerical schemes or analytical methods. Because of their simplicity and economy, a wide range of one-dimensional models are developed all over the world. These models are able to provide good estimates of tidal height and mean velocities and adequate estimates of pollutant transport. The one-dimensional approach assumes that the estuary is well mixed over every cross section.

By assuming the flow to be uni-directional, a one-dimensional model can be constructed as follows. Here we have not considered the baroclinic part of pressure gradient term. If $b(y)$ is the breadth at position y, the continuity, momentum and salt conservation equation can be written as

$$b\frac{\partial \zeta}{\partial t} + \frac{\partial (bHv)}{\partial y} = 0 \tag{6}$$

$$\frac{\partial (bHv)}{\partial t} + \frac{\partial (bHv^2)}{\partial y} = -g\,bH\frac{\partial \zeta}{\partial y} - \frac{gb}{C^2}v\,|\,v\,| \tag{7}$$

$$\frac{\partial (bHS)}{\partial t} + \frac{\partial (vbHS)}{\partial y} = \frac{\partial}{\partial y}\left(K_y bH\frac{\partial S}{\partial y}\right) \tag{8}$$

The upstream boundary conditions are usually specified as the discharge or water level. At the lateral boundaries, the transport normal to the coast line has been taken as zero. At the mouth of the estuary the elevations are prescribed. It is assumed that the diffusive salinity flux at the lateral boundaries vanishes. For various freshwater flow conditions, we can utilize salinity boundary conditions based on observations. In many estuarine environments, there are significant variations in the vertical and horizontal directions. To include these effects two-dimensional estuary models are required.

Two-Dimensional Models

If the estuary is wide, and experiences cross-channel variations or narrow but having significant variations in the vertical direction, then the two-dimensional depth-averaged or laterally-averaged models are required to simulate the flow.

Depth-Averaged Models

If the estuary is wide but shallow, it is appropriate to average all variables over the depth. Hence the continuity equation, momentum and salt conservation equations can be integrated over the depth and solved numerically to give the water level, depth-averaged currents and salinity. In the momentum equations of the two-dimensional depth-averaged model, the pressure gradient terms are expressed as the gradient of the surface elevation and density gradient. The hydrostatic equation is integrated to an arbitrary depth as

$$P(z) = g\rho(\zeta - z) + P_a \tag{9}$$

where P_a is the atmospheric pressure, hence

$$\frac{\partial P}{\partial x} = \rho g \frac{\partial \zeta}{\partial x} + \frac{\partial P_{\mathrm{a}}}{\partial x} + g(\zeta - z)\frac{\partial \rho}{\partial x} \tag{10}$$

$$\frac{\partial P}{\partial y} = \rho g \frac{\partial \zeta}{\partial y} + \frac{\partial P_{\mathrm{a}}}{\partial y} + g(\zeta - z)\frac{\partial \rho}{\partial y} \tag{11}$$

The variations of atmospheric pressure at the free surface are neglected in most coastal and estuarine studies. Now by assuming that the density is primarily a function of salinity in the estuary, an equation of state for the sea water can be written as

$$\rho = \frac{\rho_{\mathrm{o}}}{(1 - \beta S)} \tag{12}$$

By using equation (12), the vertically integrated momentum form of momentum equations can be written as

$$\frac{\partial (Hu)}{\partial t} + \frac{\partial (Hu^2)}{\partial x} + \frac{\partial (Huv)}{\partial y} \quad fHv$$
$$= \left(g\,H \frac{\partial \zeta}{\partial x} + \frac{1}{2}\beta g H^2 \frac{\partial S}{\partial x} \right) + \frac{F_{\mathrm{S}}}{\rho} \quad \frac{gu(u^2 + v^2)^{\frac{1}{2}}}{C^2} \tag{13}$$

$$\frac{\partial (Hv)}{\partial t} + \frac{\partial (Huv)}{\partial x} + \frac{\partial (Hv^2)}{\partial y} + fHu$$
$$= \left(g\,H \frac{\partial \zeta}{\partial y} + \frac{1}{2}\beta g H^2 \frac{\partial S}{\partial y} \right) + \frac{G_{\mathrm{S}}}{\rho} \quad \frac{gv(u^2 + v^2)^{\frac{1}{2}}}{C^2} \tag{14}$$

and the continuity and salinity equations

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (Hu)}{\partial x} + \frac{\partial (Hv)}{\partial y} = 0 \tag{15}$$

$$\frac{\partial (HS)}{\partial t} + \frac{\partial (uHS)}{\partial x} + \frac{\partial (vHS)}{\partial y} = \frac{\partial}{\partial x}\left(K_{\mathrm{x}} H \frac{\partial S}{\partial x} \right) + \frac{\partial}{\partial y}\left(K_{\mathrm{y}} H \frac{\partial S}{\partial y} \right) \tag{16}$$

Case Study 1

The circulation, salinity and pollutant transport in the Hooghly estuary have been studied by developing a two-dimensional depth-averaged model as described in the previous section. This model is applied to the lower part of the estuary where the flow is vertically well-mixed. This has been coupled with a one-dimensional model for the upper estuary, where the flow is assumed to be uni-directional and well-mixed over the depth and breadth.

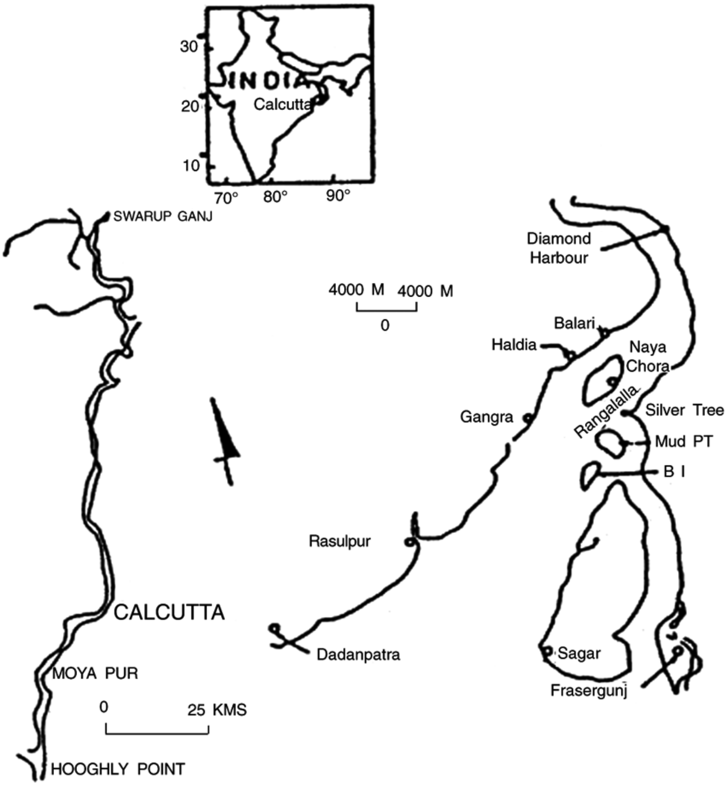

Fig. 2: The map of the Hooghly estuary.

The Hooghly river receives high freshwater discharge during the monsoon season (June- September), which will have profound influence on the salinity intrusion in the estuary. To study the circulation and salinity distribution in the lower estuary between Hooghly point and Bay of Bengal, we have considered all major islands. The coast line is made up of straight line segments parallel to the *x* and *y* axes. The bathymetry used in this model was taken from Calcutta Port Trust. The breadth of the one-dimensional model decreases from 1.5 km at the joining point to 500 m at the upstream end. The depth varies in this model smoothly, but realistically. The discharges are specified at the upper end; whereas semi-diurnal tidal amplitudes and phases are specified at the seaward end.

The computed elevations at four stations show good agreement with the observations. Some variations at the fourth station are found mainly because of its location in one-dimensional stretch, where depth and topography are idealized.

The model computed currents and salinity show reasonable agreement between observations and computations during dry season. However, significant deviations are noticed in wet season simulations, which may be mainly due to gravitational circulation.

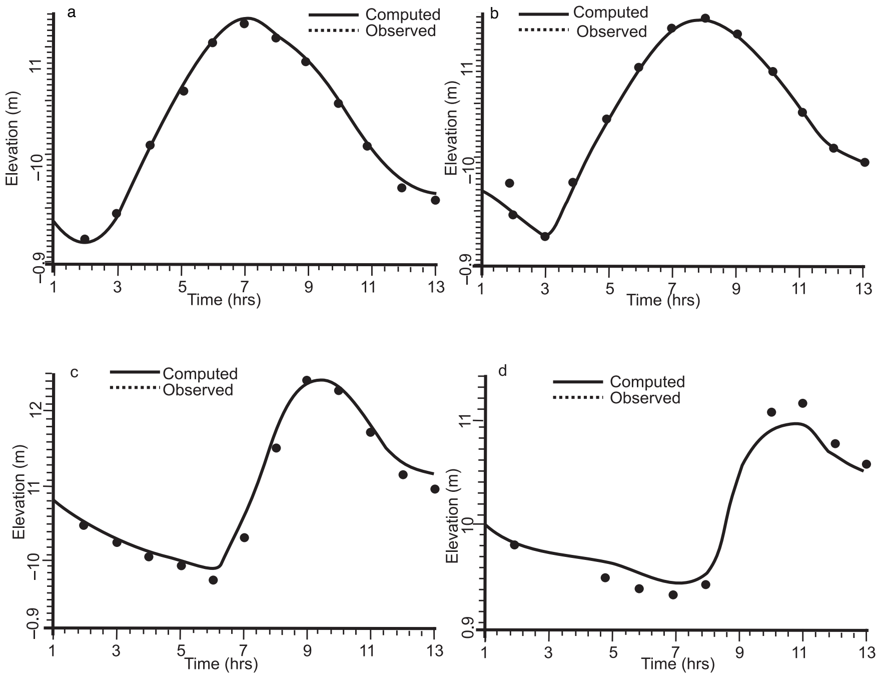

Fig. 3: Comparison of observed and computed elevations at (a) Gangra, (b) Haldia, (c) Moyapur and (d) Calcutta.

Laterally Averaged Models

The numerical modelling of hydrodynamics in partially-mixed estuaries is a complicated exercise. Partial stratification is evidence that density fields actually drive currents through gravitational forces. To simulate the vertical variations within the hydrodynamic model, a two-dimensional, laterally averaged estuarine model is required.

The landward end has been taken at $x = 0$ and the seaward end is denoted by $x = L$, where L is length of the estuary. The elevations of the free surface above its mean level is denoted by $z = \zeta(x, t)$ and the bottom topography by $z = -h(x)$. The breadth of the estuary at position x is denoted by $b(x)$. The Reynold's-averaged components of the fluid velocity and fluid density are denoted by (u, w) and ρ, respectively. By invoking Boussinesq and hydrostatic approximation, the breadth-averaged momentum equation can be written as

$$\frac{\partial}{\partial t}(bu) + \frac{\partial}{\partial x}(bu^2) + \frac{\partial}{\partial z}(buw) = -\,gb\frac{\partial \zeta}{\partial x} - \frac{b}{\rho_e}\int_z^{\zeta} \frac{\partial}{\partial x}(g\rho\,)dz$$

$$+\frac{\partial}{\partial z}\left(K_M \frac{\partial (bu)}{\partial z}\right) + \frac{\partial}{\partial x}\left(bN\frac{\partial u}{\partial x}\right) \tag{17}$$

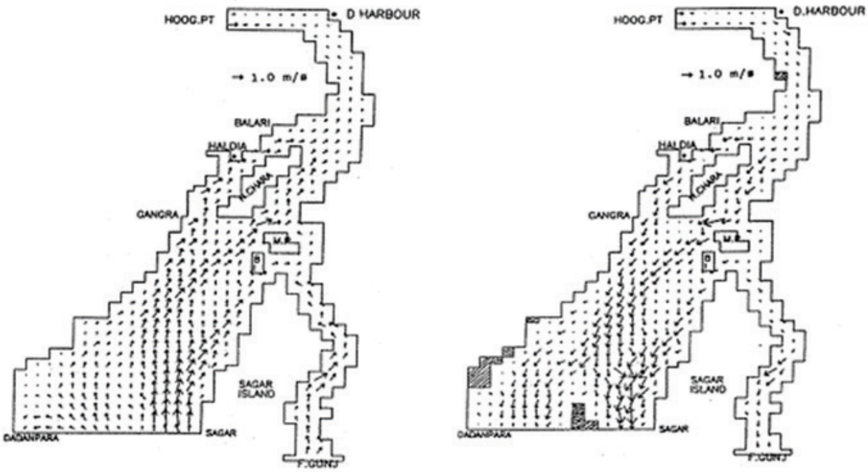

Fig. 4: Flood and ebb currents in Hooghly estuary (shaded areas denote exposed tidal flats).

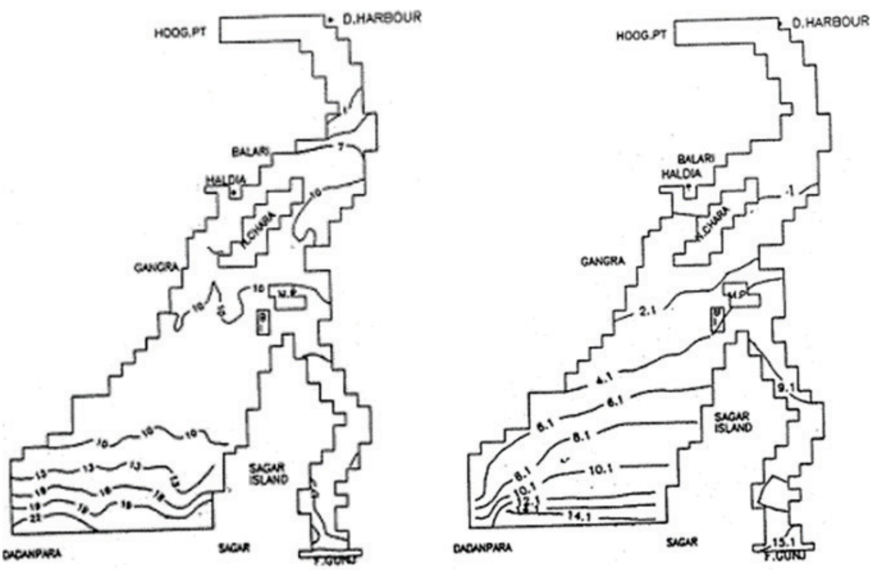

Fig. 5: Salinity distribution during dry and wet seasons.

The first term on the right hand side of equation (17) gives the barotropic contribution to the pressure gradient resulting from the slope of the free surface in the channel. The second term, in which ρ_o is the density of the fresh water, gives the baroclinic contribution to the pressure gradient. The third term represents the vertical transfer of momentum by turbulent motions and is expressed in terms of conventional gradient law involving a vertical coefficient of viscosity, K_M. The final term simulates the effect of horizontal momentum exchange by turbulent scale motions and N is the horizontal eddy transfer coefficient.

The equation of continuity is expressed either as

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0 \tag{18a}$$

or

$$\frac{\partial \zeta}{\partial t}+\frac{\partial}{\partial x}(H\bar{u})=0 \tag{18b}$$

where H is the total depth, $(z + h)$ and $\bar{u}$ is the depth-averaged velocity given by

$$\bar{u}=\frac{1}{H}\int_{-h}^{\zeta}u\,dz \tag{19}$$

The density ρ is related to the salinity, S, by an equation of state as

$$\rho=\rho_o(1+\gamma S) \tag{20}$$

where $\gamma = 7.5 \times 10^{-4}$/ppt and S is the salinity in the estuary.

The salinity is determined from a transport equation having the form

$$\frac{\partial}{\partial t}(bS)+\frac{\partial}{\partial x}(buS)+\frac{\partial}{\partial z}(bwS)=\frac{\partial}{\partial z}[K_s\frac{\partial}{\partial z}(bS)]+\frac{\partial}{\partial x}[bN\frac{\partial S}{\partial x}] \tag{21}$$

On the right hand side of equation (21), the vertical transfer of salinity by turbulent processes is represented in terms of gradient transfer law with an eddy coefficient, K_s. The second term simulates the effect of horizontal salinity flux by turbulent scale motions.

The parameterization of turbulent processes has been completed by using either simple first order or more complex higher order schemes.

A simple parameterization scheme based on a mixing length approach can be chosen which applies well to circumstances where the shallow water approximation is made as

$$K_M=l_m^{\,2}\left|\frac{\partial u}{\partial z}\right|f(R_i) \tag{22}$$

$$K_s=l_m^{\,2}\left|\frac{\partial u}{\partial z}\right|g(R_i) \tag{23}$$

where the mixing length, l_m is obtained by various formulations. The Richardson-number, R_i, which is a measure of stability is given by

$$R_i=\frac{-g\dfrac{\partial \rho}{\partial z}}{\rho_o\left(\dfrac{\partial u}{\partial z}\right)^2} \tag{24}$$

A more complex scheme based on turbulent energy density is given as

$$\frac{\partial}{\partial t}(bE)+\frac{\partial}{\partial x}(buE)+\frac{\partial}{\partial z}(bwE)=bK_{\mathrm{M}}\,(\frac{\partial u}{\partial z})^2+bN(\frac{\partial u}{\partial z})^2+\frac{g}{\rho_{\mathrm{o}}}bK_{\mathrm{S}}\frac{\partial \rho}{\partial z}$$

$$+\frac{\partial}{\partial z}[K_{\mathrm{E}}\frac{\partial}{\partial z}(bE)]+\frac{\partial}{\partial x}[bN\frac{\partial E}{\partial x}]-b\varepsilon \tag{25}$$

where K_{E} and K_{S} are the exchange coefficients for turbulence energy density and density, respectively. The first term on the right hand side of (25) represents the production of turbulence energy due to vertical shear in the Reynold's averaged flow. The second term represents the production of turbulence energy associated with the action of the normal eddy stress. The third term gives the positive or negative contribution of E depending upon the vertical density stratification. The fourth term represents the vertical diffusion of turbulence energy with an eddy coefficient, K_{E}. The fifth term represents the horizontal distribution of turbulence itself. The final term simulates the dissipation of turbulence energy. The various eddy coefficients appearing in the formulation are expressed in terms of the turbulence energy density.

Case Study 2

The breadth averaged model described earlier has been used to simulate the circulation and salinity in Hooghly estuary. To study the tidal flow and salinity profiles, we have chosen the lower portion of the estuary of 45 km from seaward end. The actual variations of breadth and depth are represented in the model. A vertical resolution of 0.5 m to 1 m is provided through sigma coordinates by taking 11 levels. Basically the model is forced by M2 tide and freshwater discharge and no wind influences are considered. Although the main aim of this study is to simulate the circulation during wet season, we also use this model to understand the vertical circulation during the dry season. The model is able to simulate many observed features during both wet and dry seasons.

The model is able to predict the tidal amplitudes and phases in reasonable limits i.e., within 4-8 cm for elevations and 5^{o}-15^{o} for phase.

The along channel plots of depth dependent salinity and currents during low discharge period shows well-mixed profiles in the major part of the estuary, with partial stratification near the head of the estuary. Partial stratification is noticed all along the estuary during high discharge periods. The currents varied from 0.7 m/s to 0.1 m/s from top to bottom. However, it was observed that bottom currents are under-estimated in these simulations. The models are also tested for spring neap variations for low and high discharge periods.

Three-Dimensional Models

The models described in the previous section may be useful to simulate the circulation if the estuary is well mixed in vertical or in lateral direction. However, this circulation need not give an indication of the actual flow in the estuary which is three-dimensional in nature. Although a complete description of the three-dimensional model is not in the scope of this article, we present important features of one of the models (Princeton Ocean Model).

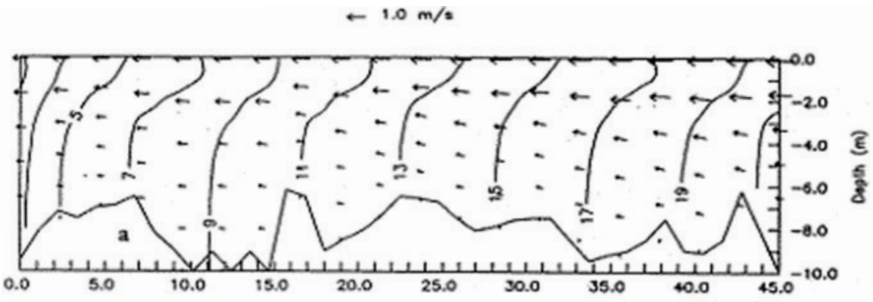

Fig. 6a: Salinity and velocity fields during flood for low discharge conditions.

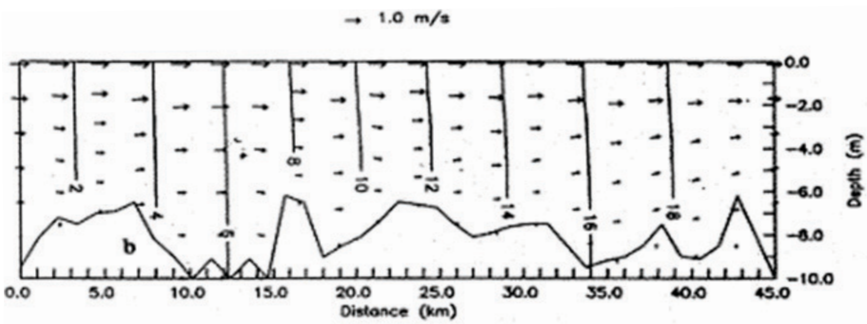

Fig. 6b: Salinity and velocity fields during ebb for low discharge conditions.

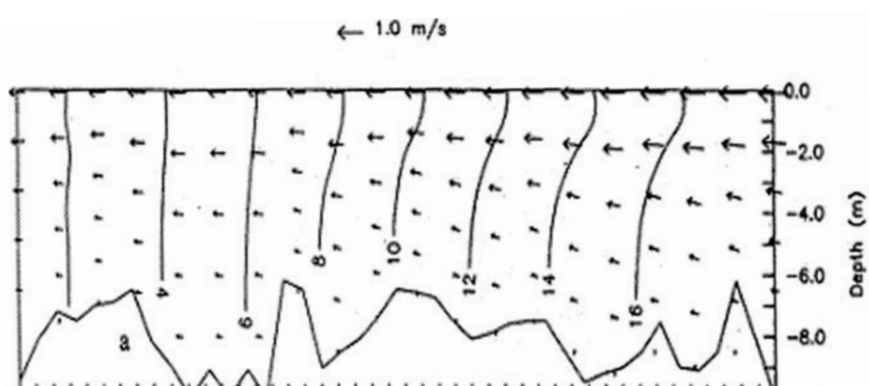

Fig. 7a: Salinity and velocity fields during flood for high discharge conditions.

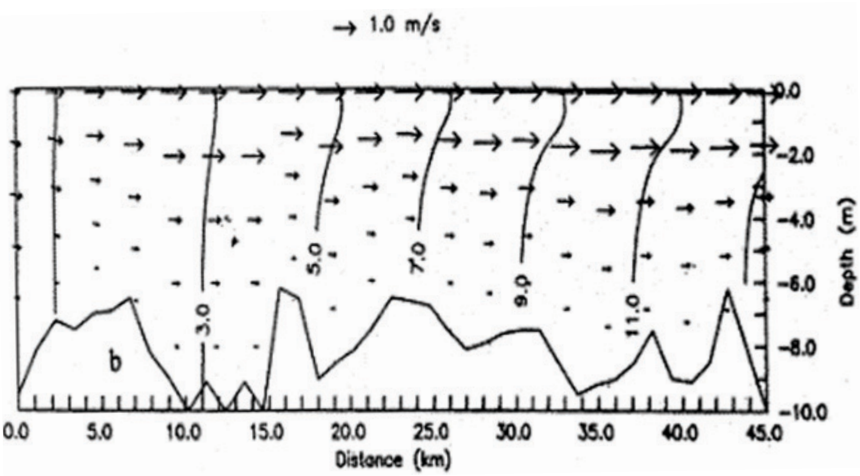

Fig. 7b: Salinity and velocity fields during ebb for high discharge conditions.

A three-dimensional model in principle should solve the basic hydrodynamic equations (1-5). The large scale motions of an estuary whose depth is relatively much less than horizontal dimensions, can be modelled by assuming a hydrostatic equilibrium. A sigma coordinate system is used so that a vertical coordinate is scaled on the water column depth. This is necessary to deal with significant topographical variations encountered in the estuary. The horizontal grid uses curvilinear orthogonal coordinates and an Arakawa-C differencing scheme. It contains imbedded second moment turbulence closure sub model to provide vertical mixing coefficients. The model has a free surface and a split time step. One of the important features of the model is that it has necessary thermodynamics with it. The model has been used for many estuarine and coastal flows with reasonable success.

With the progression from a one-dimensional model to a full three-dimensional model, it is apparent that the computational cost associated with the model will increase significantly. Also, the type and quantity of field data required to formulate, calibrate, and validate will increase. Since no model is perfect, each solution will contain some uncertainty. For each process within a model there is some uncertainty associated with it. The implication of these uncertainties, for accuracy of the model, is that there is little benefit in using a very complex model to model one process if another process, which is crucial to the overall accuracy of the model, can only be modelled in a simple manner with correspondingly high uncertainties. Hence, while choosing a model there should be a consistency in the degree of complexity used in each stage of the overall model.

Obtaining a model is done either by acquiring the code through public domain or proprietary sources, or by building, testing and implementing the code. A few steps for acquiring a model are (a) a review and evaluation of available codes based on selection criteria, (b) assessment of required computer resources and labour available for intended use and maintenance of the model and (c) an estimate of associated costs. In order to consider a model for a particular application, the following factors may be considered:

- Applicability of flow problems of interest
- Calibration and verification record
- Performance of selected benchmark cases or experimental data
- Efficiency of the model in comparison with other models
- Availability of documentation
- Pre- and Post-processing capabilities
- Technical assistance availability
- Compatibility of the model to various computer systems

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Modelling and Measurement of Sediment Transport in Lakes

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INTRODUCTION

The quantification of sediment transport has a great practical value for navigational and harbour construction purposes, silting in reservoirs and distribution of suspended solids washed from water sheds. Many important substances can be carried by the fine grained sediments. The attached substances can be pollutants like heavy metals or toxic compounds. From the particle bound substances, phosphorus is most important. The organic compounds carried by water in particle form have a great effect on the oxygen environment of waters.

In the following text, sediment transport phenomena, and sediment transport modelling are briefly discussed together with basic instrumentation.

The literature references are not given here since space is limited, and they are found in Huttula (1994).

Hydrodynamic Forcing in Sediment Transport

The hydrodynamic processes related to sediment transport are shown in Fig. 1 by Bedford and Abdelrhman (1987).

Wind generated surface oscillations (waves and seiches) and oscillations within the thermocline (internal waves) also have an effect on the transport of substances. The orbital movements in waves cause shear and small scale mixing. As the orbital movement reaches the lake floor it causes a shear and in shallow lakes, this shear is a dominant forcing factor in erosion. Internal waves have a long time scale and their role in sediment transport is limited. In narrow straits, the currents induced by internal waves can cause significant erosion (Hiltunen and Kansanen, 1986).

The waves in shallow lakes are mostly calculated with equations, which were first presented by Sverdrup and Munk (1947) and later modified by

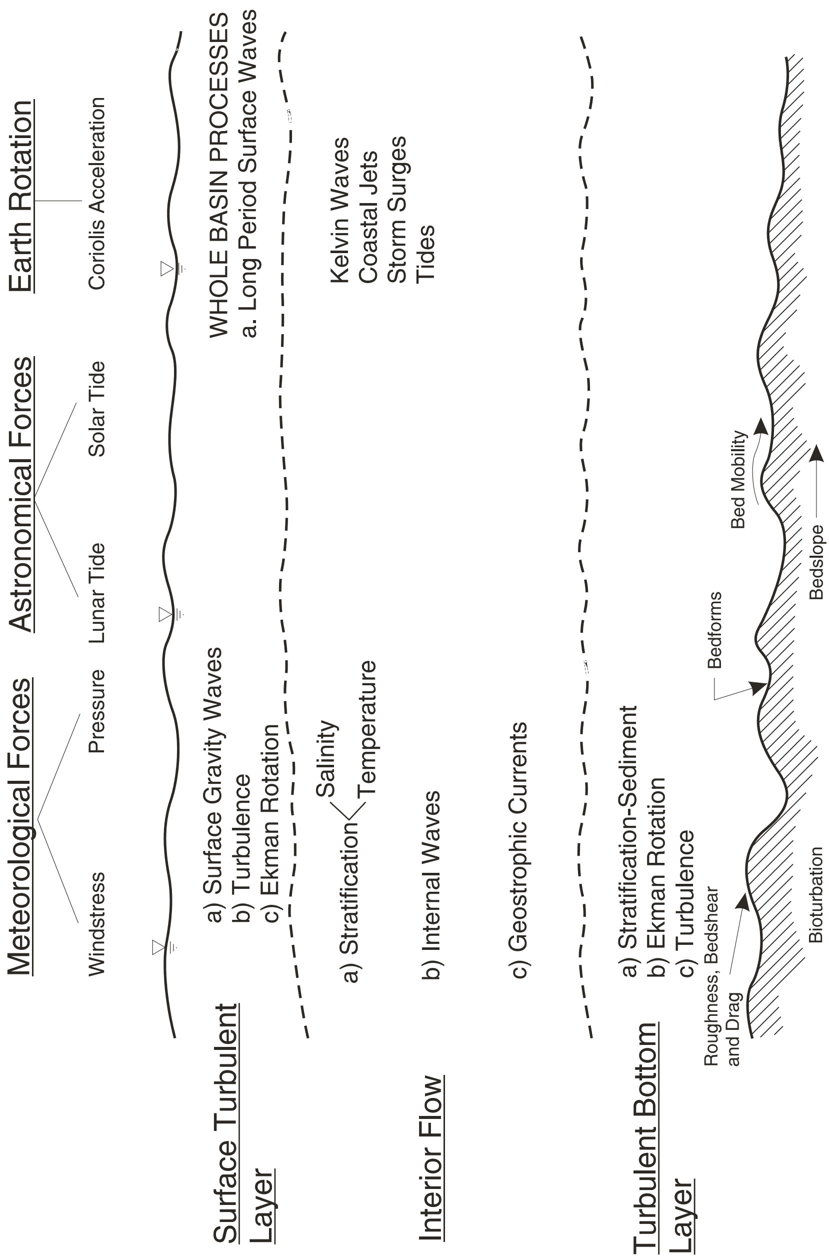

Fig. 1: Schematic of Benthic boundary layer (from Bedford and Abdelrhman, 1987).

Bretschneider (1958). Sverdrup and Munk's semi-empirical equations were first developed for sea conditions. Using these equations, the wave height and period is calculated using fetch, storm duration, and wind speed. Bretschneider (1958) improved these equations and later the method was named, in honour of its developers, the SMB-method and introduced, for example, in the U.S. Army Coastal Engineering Research Centre (1977 and 1984).

There are more sophisticated methods for waves but the SMB method has been widely used as it needs little data and has proven to be useful. The input for SMB equations are wind speed, duration, fetch and water depth. The equations give significant wave height, period and length.

The significant wave height, H_s is

$$H_s = A \tanh \alpha \tanh \frac{\gamma}{\tanh \alpha} \tag{1}$$

The wave period T_s, is

$$T_s = B \tanh \beta \tanh \frac{\delta}{\tanh \beta} \tag{2}$$

The following notations are used in equations (1) and (2):

$$\begin{aligned}
\alpha &= 0.53\left(\frac{gh}{W^2}\right)^{0.75} \\
\gamma &= 0.0125\left(\frac{gF}{W^2}\right)^{0.42} \\
A &= 0.283\left(\frac{W^2}{g}\right) \\
\beta &= 0.833\left(\frac{gh}{W^2}\right)^{0.375} \\
\delta &= 0.077\left(\frac{gF}{W^2}\right)^{0.25} \\
B &= 2\pi.\left(1.2\frac{W}{g}\right)
\end{aligned} \tag{3}$$

where W is the wind speed, h the water depth, F the effective fetch and g is the acceleration due to gravity.

The equations assume a bottom friction factor of 0.01. The effective fetch is the distance over the water in which the wind blows, corrected for modifications caused by adjacent land forms. Waves generated in long narrow basins are significantly smaller than in more open basins under the same wind conditions. The fetch can be corrected with a correction factor based upon the width to length ratio of the basin. Another method for correcting the effective fetch is to use the sum of radials between the wave station and the shoreline on both sides of wind direction.

Significant wave length (L) is calculated iteratively from the equation

$$L = \frac{gT_s^2}{2\pi} \tanh\left(\frac{2\pi h}{L}\right) \tag{4}$$

From the linear wave theory, the elliptical orbital motion on the bottom is calculated as follows (Komar et al., 1972):

$$d_o = \frac{H}{2\sinh\left(2\pi\frac{h}{L}\right)}$$

$$u_m = \frac{\pi H}{T_s \sinh\left(\frac{2\pi h}{L}\right)} \tag{5}$$

where d_o= displacement due to the waves on the bottom, u_m= maximum velocity on the bottom, and T = mean wave period (= T_s).
H denotes the mean wave period, which is 0.626 H_s (U.S. Army Coastal Eng. 1977).

The shear stress (t_w) caused by waves is

$$\tau_w = f_w \rho \frac{u_m^2}{2} \tag{6}$$

where f_w = friction factor caused by waves, and ρ = water density.

In very shallow fetch limited lakes, the friction factor is

$$f_w = \frac{2}{\sqrt{Re_w}}$$

$$Re_w = u_m \frac{d_o}{V} \tag{7}$$

where Re_w= Reynolds number for orbital motion on the bottom, and v = kinematic viscosity.

The parameter values in SMB-equations differ somewhat by different authors (see e.g. Aalderink, 1984; Bengtsson, 1986).

Critical shear stress (τ) and critical velocity ($u_{*c} = \sqrt{\tau/\rho}$) have been widely used as criteria for erosion. As the total shear exceeds the critical shear the erosion starts. The total shear on the bottom is the sum of the shear caused by waves and currents. There are several methods for calculating the current induced shear stress, where the stress is expressed in terms of drag and directly to the current speed, its square or even cubic formulation.

MATHEMATICAL FORMULATION OF SEDIMENT TRANSPORT

Advective Dispersive Equation

The mass balance or advective-dispersive equation in a three dimensional case has the form:

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial x}\left(\mu_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(\mu_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu_z \frac{\partial C}{\partial z}\right)$$

$$- \frac{\partial (u_x C)}{\partial x} - \frac{\partial (u_y C)}{\partial y} - \frac{\partial (u_z\text{-}w_s) C}{\partial z} + S(x, y, z, t) \tag{8}$$

where C = suspended sediment concentration, μ_x, μ_y, μ_z = eddy diffusivity, u_x, u_y, u_z = velocity components, w_s = settling speed of the particles, and S = source and sink term. S includes the effects of erosion and deposition.

The simplest numerical solution for the advective-dispersive equation is carried out in a box model (Fig. 2) (Somlyody, 1981; Kettunen and Stenmark, 1982; Varis, 1984; Aaldrink et al., 1984; Ambrose, 1986; Koncos, 1990; Somlyody and Koncos, 1991; Kristensen et al., 1992; Malve et al., 1994). Virtanen et al. (1982) used a three-box model to simulate an effluent sediment interaction.

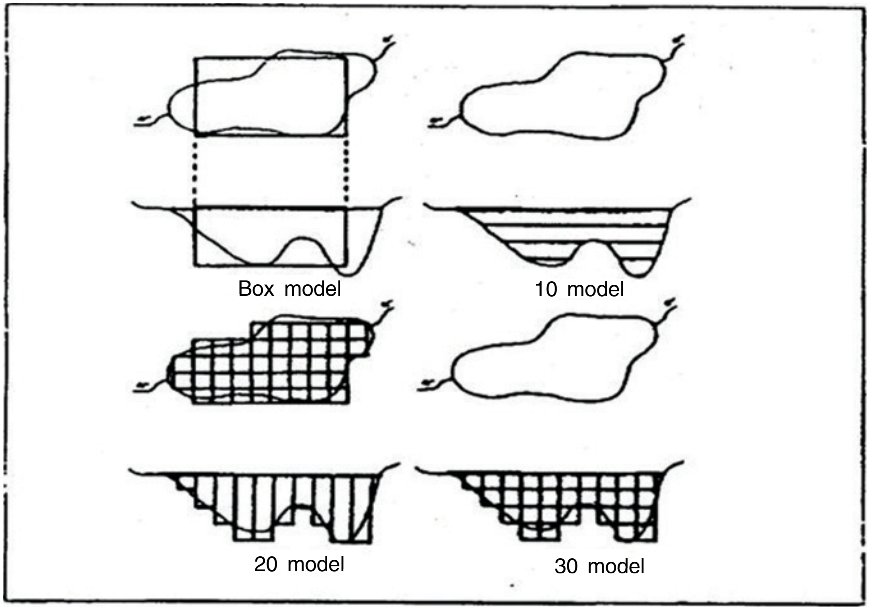

Fig. 2: Different grids in numerical model realizations.

In the simplest form of the box-model, the suspended sediment concentration is dependent on gravity and wind erosion directly connected to the wind speed. The effect of waves and currents in the box models is introduced by some sort of empirical equation. The source term in equation (8) can have different forms, where the erosion rate of surface sediment is dependent on rate coefficient and wind velocity. A threshold value for wind speed can be used to determine the initiation of resuspension.

Although including the effects of the current and waves make models better supported physically, the differences between the model results of different box-model versions are small. The box-models lack the vertical resolution, and the advective transport is not described in a horizontal direction. These types of models are most suitable in studying the effect of various processes on water quality. The time scale under consideration has to be selected carefully with regard to the aim of the study.

In one-dimensional (1-D) vertical models, the lake is assumed to be horizontally homogeneous. As the vertical dimension of the lake is described in the model, the settling and the decay of the wave power are better described than in the box models. The seasonal thermal stratification and development of water quality in the lakes has been calculated in several lakes in Finland (Eloranta et al., 1981; Huttula and Kinnunen, 1985; Malve et al., 1991; Huttula et al., 1992; Kallio, 1993; Bilaletdin et al., 1993). This model type is most suitable in lakes where the morphology is simple and the lake has only a few islands and the time scale of study is order of weeks and months (seasonal study).

In 2-D horizontal sediment transport models, the water is assumed to be homogenous in a vertical direction. These types of models have been widely applied to shallow lakes (Onishi, 1977; Jozsa et al., 1990; Podsetchine and Huttula, 1994; Huttula, 1996) and in Finland there are more than 60 applications of these types of flow and water quality models (Virtanen et al., 1979; Virtanen, 1984; Virtanen and Koponen, 1985).

2-D vertical models are laterally integrated. The depth and longitudinal dimensions are included in the grid (Van Rijn, 1980; Podsetchine and Huttula, 1994). The models are most applicable in rivers and narrow river-like water courses.

The numerical solution of a complete set of three-dimensional flow and sediment transport equations is carried out in unsteady conditions e.g., by Sheng and Butler (1982), Miller (1983), Van Rijn (1986), Van Rijn and Meijer (1986), Wang and Adeff (1986), Van Rijn and Meijer (1991) and Van Rijn et al. (1990). Koponen (1984) has made a great number of applications of a Simons-type 3-D flow model. These applications are reviewed by Virtanen et al. (1994). In the suspended sediment transport part of the model the settling of suspended solids is included, and the erosion has been formulated mostly by a critical velocity approach (see eq. Huttula et al., 1990).

Settling

The fall or settling velocity is a fundamental process present in all sediment transport problems. The concept is defined as the gravity caused by vertical motion of the particle. Although the definition of the process is clear, the modelling and calculation of it faces many problems.

A particle falling in a motionless fluid will reach a constant velocity when the drag equals the submerged weight of the particle. The drag is caused by the viscosity of the fluid.

When the particle falls slowly, the flow around is dominated by fluid viscosity. When the settling velocity is rapid the inertia dominates. A Reynolds number Re_s (= $w_s d/n$) is used as a measure of these effects where n is the kinematic viscosity (m/r) and d is the particle diameter. When $\mathrm{Re}_s < 1$, flow is laminar and falling particles develop no wake. Above this limit, the flow separates in the lee of the particle and vortices start to develop. Thus the boundary layer around the particle becomes turbulent. At Reynolds numbers < 1 the settling speed can be solved and the well-known Stokes equation expresses this:

$$w_s = \frac{d}{18}\left(\frac{\rho - \rho_s}{\mu}\right)g \tag{9}$$

where ρ and ρ_s are the grain and water densities respectively and μ is the molecular viscosity of the water.

The parameterization of this function for quartz particles is presented e.g. by Raudkivi (1990) and Dyer (1990). At Reynolds numbers > 1, the fall velocity cannot be theoretically predicted. Still, many experimental results exist. In Stokes' equation, the particles are assumed to be spherical whereas in nature the particles are very rarely spherical. The settling velocity of any natural particle is less than that for an equivalent sphere because particles spin and oscillate as they fall. Baba and Komar (1981) studied the true settling speed and the effect on this of particle shape. Their data suggests that $w_n = 0.761\ w_s$, where w_n is the settling velocity of natural grains and w_s is the settling velocity of spheres having the nominal diameter of grains.

Also rare is that in nature the particles would settle in a motionless fluid. Small particles will travel up and down with turbulent velocity fluctuations, but in a viscous regime they will be settling at a constant rate relative to the fluid. For coarser particles, the time response of the boundary layer around the particle becomes important. If there is asymmetry in up and down velocities, the drag exerted on the particle will be different and the particle may move in the direction where acceleration is greatest.

The effective falling velocity of a sediment mixture is defined by Raudkivi (1990) as a weighted mean of settling speeds of the size classes. This value can be one or two orders of magnitude higher than the settling speed based on median grain size of the sediment mixture. The usage of effective settling speed is not widespread in the modelling of sediment transport. In this study, the calculations are also made on the basis of medium grain size.

The concentration affects the settling speed in high concentrations. An exponential relationship has been used (e.g., Lang et al., 1989; Richardson and Zaki, 1954 and Maude and Whitmore, 1958). The effect of the concentration is anyhow insignificant in Finnish lake waters. It has significance near the bottom where the momentary Suspended Sediment (SS) concentrations can be high.

In our studies we are normally dealing with fine particles having a range from fine sand to very fine silt (from 250 mm to 4 mm). The effect of cohesion and aggregation is not modelled as such, although the processes are clearly present in the case studies; their effect comes out in the calibration of the settling speeds.

Deposition

The concepts of settling and deposition are used in sediment transport modelling. The deposition is by definition "the process, which governs the removal of sediment particles from the water column to the bottom" (Sheng et al., 1991). As compared to the settling, the deposition is a flux having a dimension such as $ML^{-2}T^{-1}$, whereas the settling is considered as a velocity with dimension of LT^{-1}. There are basically two approaches to describe deposition. One is that deposition is related to near-bottom concentration (Monin, 1959; Calder, 1961) with a proportional factor w_d having units of velocity. In the other approach, deposition is related to the settling speed of the particles. Several authors have supposed that erosion and deposition happen simultaneously and the flux to the water column is the sum of erosion and deposition (Partheanides, 1972; Sheng and Lick, 1979; Lick, 1982; Lavelle et al., 1984). This has been based on the observations made by Krone (1962). If we consider that erosion and deposition are local (no advection and diffusion in x- and y-directions) vertical processes, then the equation (1) will be simplified and the changes in time in SS concentration are:

$$\frac{\partial C}{\partial t} - w_s \frac{\partial C}{\partial z} - \frac{\partial}{\partial z}(\mu_z \frac{\partial C}{\partial z}) = 0 \qquad (10)$$

where t = time, z = vertical coordinate, positive upwards, and μ_z = eddy diffusivity.

The boundary conditions are:

$$-w_s C - \mu_z \frac{\partial C}{\partial z} = E - w_d C, \quad \text{when } z = z_o$$

$$C = 0, \quad \text{when } z = \infty \qquad (11)$$

where z_0 = bottom roughness length, and w_d = deposition speed.

Lick (1982b) suggested that w_d is proportional to w_s with a factor 1.0 for particles whose settling dominates the diffusion near the sediment water interface. Only for very small particles ($d < 1$ mm) w_d differs from w_s. For this reason we have taken $w_d = w_s$.

In our studies, deposition has been related to the gradient of near-bottom SS-concentration and settling speed as follows,

$$D = w_s \frac{\partial c}{\partial z} \tag{12}$$

As was seen from above, the definition of deposition is rather loose. The deposition as a term has more meaning for the practical modelling work than as a real physical process. It seems that physically the most relevant thing is to connect the deposition to the settling speed.

The sedimentation trap data has been used in our studies to describe the gross deposition. It has to be noted that the traps tend to over-estimate the deposition but the data can be used to calibrate and validate relative spatial and temporal distribution of simulated deposition.

Erosion

The concept of erosion is used in sediment transport modelling with two meanings. The first meaning is the soil erosion from the watershed. In this process particles are eroded from the soil matrix and are then transported away from their original position. In lake sediment transport modelling this, like many other concepts, was first adopted in river studies since the erosion of river beds is a similar process to erosion in watersheds. In both cases, water is moving particles away from their original position, although the initial cause of the particle movement may be very different. The effect of rain drops is of primary importance in a watershed, whereas the effect of critical shear stress caused is a dominant factor on the lake bottom.

When we are dealing with suspended sediment transport modelling in lakes, erosion is used in terms of particles losing contact with the bottom and being lifted either into suspension or to bottom transport. But as the forcing is by nature very different than that on watersheds and rivers, the particles may sink back to the same area after a fairly short period of time; or particles originating from some other location at the bottom may be transported to this erosion area. As a result the changes in bed morphology are quite small and only very high and exceptional forcing can cause significant changes in them.

The term resuspension is also widely used. It is defined as the redistribution into the water column of sediment particles, which have settled on the lake bottom at some earlier time (Bloesch, 1994). It seems that it is used more by limnologists and biologists than in the purely hydrodynamic literature. Mehta et al. (1982) suggest that the term redispersion describes the process of bringing very recently sedimented material, in a high storm, almost immediately back into suspension. It is used in the same sense by Bengtsson and Hellström (1992).

In hydrodynamically simple water quality models that describe the water body as a continuously stirred tank, the erosion and settling are directly dependent on wind or waves (Somlyody, 1981; Kettunen and Stenmark, 1982; Aaldrink et al., 1984; Varis, 1984; Koncos, 1990; Somlyody and Koncos, 1991; Kristensen et al., 1992). Usually the scales of processes in bottom boundary layers are smaller than the grid cell size in numerical models. This causes serious difficulties in choosing the right bottom boundary conditions. Critical shear stress (τ) and critical velocity $\left(u_{*_c}\sqrt{\tau/\rho}\right)$ have been widely used as criteria for erosion. The published values vary in the range of three orders of magnitude (Table 1). A classical formulation for critical velocity on sandy bottoms is the one by Hjulström (1935). For fine sediments, there is not such a widely used formulation for critical velocity. Reported critical velocities values vary according to the study material and the research approach. Lesht (1989) found for the Indiana Shoals sands in Lake Michigan two criteria: one for bedform migration (V_{crm}= 8.4 cm^{-1}) and one for resuspension V_{crs}= 17.8 cm^{-1}. Similar results were also reported by Chesters and Delfino (1978). The fine sediments were set in motion by orbital velocities of 5 cm^{-1} and all particles which were sands were resuspended by orbital velocities of 20 cm^{-1}. Gloor (1994) has shown that resuspension occurs in burst like currents having a speed of upto 7 cm^{-1} and a duration of 15 min. The resuspended material was 95% organic.

Lavelle et al. (1984) and Luettich et al. (1990) used an erosion formulation, where the erosion rate was directly dependent on bottom shear stress without any threshold value:

$$E = \alpha_{\tau}^{n} \tag{13}$$

where n = exponent and α = erosion rate constant.

Table 1: Values of critical shear stresses for different case studies

Authors	*Material*	*Case Study*	*Nm^{-2}*
Metha and Partheanides 1975	mud	laboratory experiments	0.18
Krone 1976	mud	laboratory experiments	0.06-0.08
Sheng and Lick 1979	sand, silt	Western Lake Erie	0.05
Huttula and Krogerus 1986	cellulose, fibres	Valkeakoski, Finland	0.008
Lang et al. 1989	fine silt	Weser Estuary, W.C.	0.5
Dyer 1989	mud	laboratory experiments	3.0
Luetich et al. 1990	fine silt	Balaton	0.05
Sheng et al. 1991	mud	Tampa Bay, Florida	0.001-1.0
Sheng et al. 1991	mud	Okeechobee, Florida	0.04
Pickens and Lick 1991	fine sand, clay	California Coast	0.1
Verkfræðistofan Vatnaskil 1993		Lake Myvatn	0.05-0.4

Lavelle et al. (1984) pointed out that in laboratory flume tests, very often slight but finite transport has been observed even when the stress has been small. Their statement that critical shear stress determination involves a lot of subjectivity on the part of the researcher is supported also on the basis of our studies on the erosion of cellulose fibres in the laboratory. Van Rijn (1990) also later made a comment on the critical shear stress concept and referred to Lavelle's and Graf's results. He stated that "Although a critical stage below which no single grain is moving does not really exist, a critical stage is necessary for practical design purposes". This has also been the main reason for using the critical shear stress approach in this study.

Another way to express the criteria for a particle to erode is to relate to the settling velocity and the turbulence. The sediment is maintained in suspension, against the gravitational fall velocity, by the turbulence diffusion from the bed. The root mean square value of a turbulent vertical velocity component is of the same order of magnitude as the shear velocity on the bottom. Thus for initiation of suspension, $u_*/w_s > 1$. By assuming a logarithmic velocity distribution, Dyer (l986) gave values for $u_* = 0.0374\ U_{100}$ for silt and sand bottoms, where U_{100} is the velocity measured 1 m above the lake bottom. This ratio U_{100}/u_* is quite evidently also a function of flow conditions, water depth and bottom roughness. Smith (1975) discussed the ratio of mean water velocity in a river to u_*. According to him, for shallow water (depth less than 5 m) both in the dynamically smooth and rough flow range, the ratio varies between less than 10 to nearly 30.

CASE STUDY: LAKE KARHIJÄRVI

Karhijärvi is a small shallow lake in the southwestern part of Finland. The length of the lake along its main axis is about 14 km, the width in the wide eastern part is up to 5 km, the mean depth is 2.2 m and the maximum depth is 8 m. The water quality of Lake Karhijärvi is eutrophic and turbid. The lake has recieved a lot of nutrients from agricultural activities. There has been two major water level arrangements in parts of Lake Karhijärvi and they together with increased load from farm lands have caused the decreasing of water quality. The sediment transport study is part of water quality model development for the lake. The data from this lake has been collected during summer 1992 and 1993. Several model applications have been done also in this lake. The first one was a two dimensional depth integrated (2DH) model by Jozsa (1990). The other two are a two dimensional horizontally integrated (2DV) model and three-dimensional (3D) sediment transport model by Podsetchine and Huttula (1994). In the 2DV models, the depth and longitudinal dimensions are included in the grid.

The model 2DH uses an implicit scheme in order to solve the momentum equations together with the continuity equation. The model has a refined grid system and it is possible to track buoyant particles transported by flow. In this way, it is possible to study the true retention time in various wind situations.

Figure 4 shows a flow pattern of Lake Karhijärvi in south westerly winds. The results are calculated with the Karhijärvi 2DH-model. It is seen that in the eastern part, two main gyres are developed with the converging zone situated in the middle of the lake. The same phenomenon is also to be observed in the middle basin. The calculated and observed currents in the strait in the middle of the lake have been in good agreement.

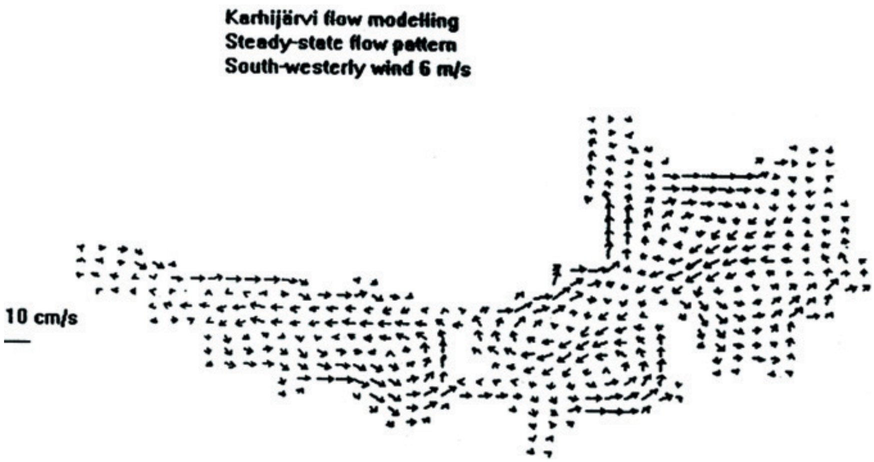

Fig. 4: Calculated circulation pattern in Karhijärvi.

Figure 5 is an example of the calculated path of buoyant particles which have been released from river Susikoski. In the easterly wind they are advected via Riihonlahti bay along the northern shore towards the middle basin. The limited exchange between the eastern and middle basins is obvious during southerly winds (Fig. 6). In this case, the particles were released from the small bay on the northern shore of the middle basin.

The variation of sediment transport and deposition in time and space are clearly seen in sediment trap results from summer 1992 (Fig. 7). In Karhijärvi, a high turbidity peak was observed in the middle of October 1992. The peak was observed by the turbidity sensor installed on recording current meter at site 2 (Fig. 7). The reason for this turbidity was quite likely the heavy rain during the previous three days (45.5 mm), which caused a flushing of SS from the watershed. This occasion was simulated using the three models. Firstly the travel path of buoyant particles was tracked with the 2-DH model. Several potential erosion areas along the north shore were tested. The 2-DH model, with a steady E wind of 6 m s^{-1}, gave a travel time from the Susikoski river mouth to the measuring site of about 40 hours (Fig. 5).

Fig. 5: Particle paths as calculated by the 2DH-J Karhijärvi model.

Fig. 6: Particle paths as calculated by the 2DH-J Karhijärvi model.

The 2DV model was applied on the same occasion on October 14, 1992 as the 2-DH model above. The settling speed, erosion criterion and rate constant were chosen on the basis of observed data. The volumetric grain size was determined by laser analyser from sediment trap deposits. The values for d_{50} varied from 9×10^{-6} to 18×10^{-6} m. Following Stokes law values for settling velocity w_s and similarly for deposition velocity w_d, a value of 10^{-5} ms^{-1} was chosen. For erosion rate coefficient with a value of 10^{-5} kgm^{-2}s^{-1} was obtained. This rate coefficient was parameterized using a cubic dependence on the bed shear stress. The 2DV model had 56 cross sections with 15 layers. Time step in calculations was 600 s.

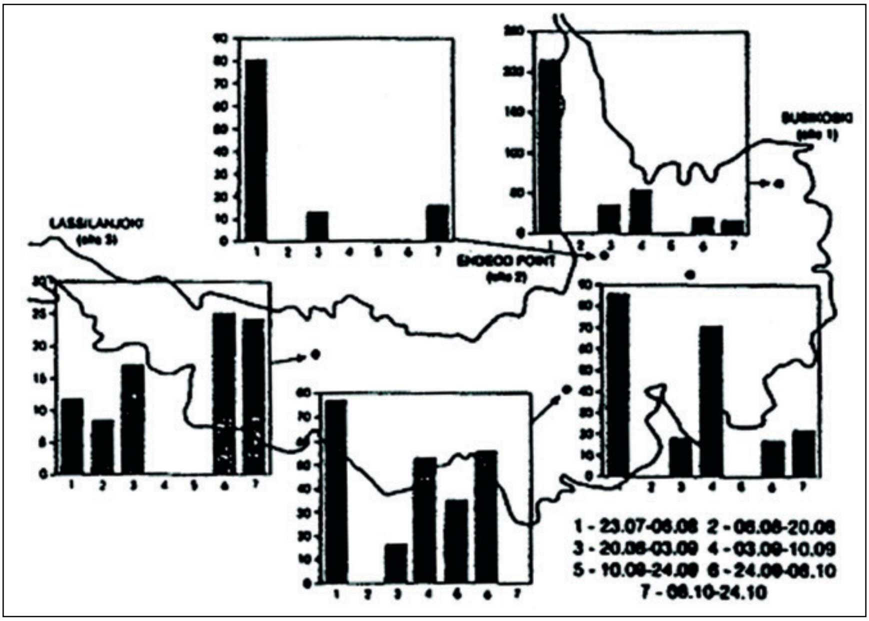

Fig. 7: Sedimentation trap results in Lake Karhijärvi (gm^{-2} day^{-1}) for summer and autumn 1992.

Wind data from Tampere airport was used to run the water flow. In the model applications the SS inflow was approximated with the basis of rain data from Tampere airport with a linear increase from 10 to 70 mgl^{-1} during the first half of the day of Oct 14 and with linear decrease of the same intensity of the second half of the day. This was approximated since no measured data was available from Susikoski. The model gave a travel time of five hours from the Susikoski river mouth to the turbidity measuring site (Fig. 8). This value was estimated to be too short when compared to observed currents and the distance from the river mouth to the measuring site.

Also a 3D model application was carried out. In this model, the flow field is first worked out with the 2-D horizontal model and then a logarithmic distribution of vertical velocity is applied. The 3D model was applied with the same set of parameters as the 2DV model. The model consisted of 1058 elements in ten layers. The calibration of flow was conducted against the observed currents. The computational time step was 300 s, Manning roughness coefficient 0.01 and the diffusion coefficients $\mu_x = \mu_y = 0.01$ m^2s^{-1}. Vertical diffusion coefficient was approximated with the linear-parabolic relation, suggested by Van Rijn (1990). Current direction was calculated well during strong winds. The magnitude of the calculated vertically integrated current was significantly less than the observed surface current, but the variation of current in time was calculated well. The calculated travel time of the inflow peak from Susikoski to measuring site was now about 30 hours (Fig. 9). This result is ten hours less than the travel time calculated with the 2DH model

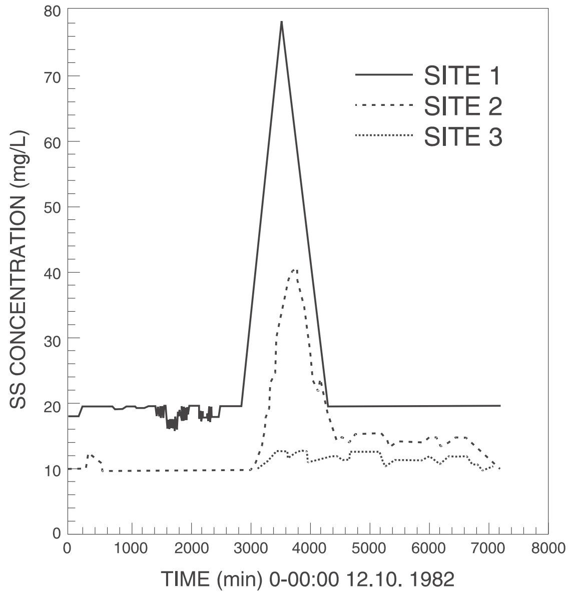

Fig. 8: Calculated near-bottom concentrations of SS (mgL^{-1}) at three sites of Lake Karhijärvi. 2-DV model, October 12 to 16, 1992. The output sites are shown in Fig. 7.

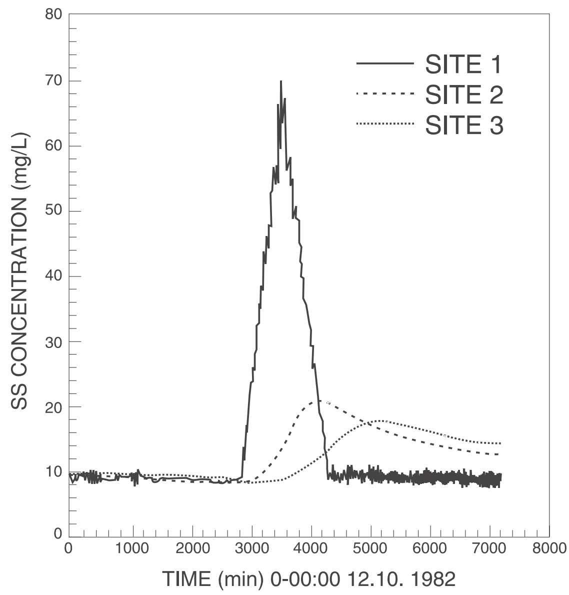

Fig. 9: Calculated near-bottom concentrations of SS (mgL^{-1}) at three sites of Lake Karhijärvi. 3-D model, October 12 to 16, 1992. The output sites are shown in Fig. 7.

and six times the value calculated by the 2DV model. The 3D model was also used to study the possibility of local resuspension as a cause of October 14, 1992 turbidity peak. The results clearly implied that the peak cannot be produced by any local erosion, but it must be caused by the heavy rain on October 11-13. The wave erosion during the October 14 was limited within areas having a depth of less than 1 m.

MEASUREMENT TECHNIQUES

Current Measurements

Current measurements are done by Eulerian (measurement in a fixed site) or Lagrangian (travelling with flow) method. Different types of commercial current meters are available. The mechanical ones are based on the counting of the rotor or propeller revolution. Acoustic meters have been available since the middle of eighties. Lagrangian methods are based on the following travel path and time of certain floating objects like flow cylinder, tracers or satellite buoys.

Drogues

A simple drogue has a form of cylinder (Fig. 10). A typical diameter is 60 cm and the height is 1 m. The cylinders are submerged to a desired depth

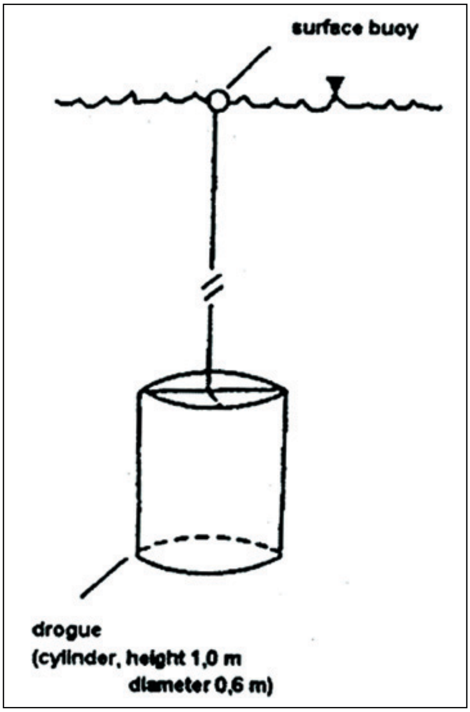

Fig. 10: Flow cylinder.

with a thin rope and a small buoy. The cylinder will travel with the water flow and from the movements of the buoy the flow is detected. The positioning of the buoy is normally done with Global Positioning System (GPS). It has a standard accuracy of 100 m, but with differential correction, an accuracy of few metres can be obtained. Since the method is very simple and not so expensive, it can be used for many purposes such as:

- to find the areas of strong currents
- to provide information about currents for installation of recording current meters in the future
- to determine the horizontal diffusion rate

Mechanical Current Meters

Two quite known mechanical current meter models are shown here. They both record the current speed on the basis of rotor revolutions. The Endeco uses a tethered current meter and whereas in Aanderaa Instruments a current meter is installed between a buoy and an anchor (Fig. 11).

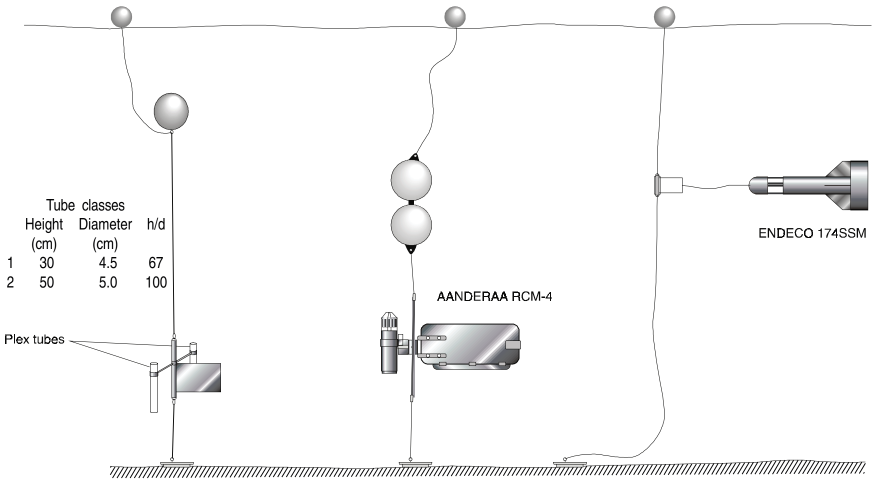

Fig. 11: Recording current meters and a sedimentation trap model used in effluent transport studies in Finland.

Endeco SSM174 current meter is relatively light and easy to handle. The depth of the instrument (relative to the water surface) is independent of water level changes. However, changes in water density (e.g. through cooling) cause changes in the depth of the meter when water speeds are low. For example, when the water is cooling the buoyancy force of the water increases and lifts the meter. The basic sensors are current direction and speed as well as water temperature. It is also possible to measure turbidity, conductivity and/or salinity depending on the type of the meter.

The Aanderaa RCM 7 (Recording Current Meter, model 7) is a self recording current meter intended to be moored for obtaining and recording vector averaged speed, direction and temperature of ocean currents. Figure 11 shows two typical ways of mooring the instruments in deep waters.

Both Aanderaa RCM7 and Endeco use a true vector averaging for recording the current speed and direction. Both the instruments have a threshold value (about 2 cm-s $^{-1}$) for current speed. The reading of these variables is taken with frequency of 1 Hz and the data is stored to the memory at user defined intervals.

The Endeco SSM174 has a memory unit (CMOS RAM). The maximum interval for SSM174 is two hours. The stored data is retrieved by a specially designed computer program. RCM 7 records data internally in a removable and reusable solid-state Data Storing Unit (DSU) 2990 with maximum interval of three hours.

Acoustic Current Meters

Doppler Meters

The Acoustic Doppler Current Profiler (ADCP) has four beams, which are oriented at an angle of 20° or 30°. The beams transmit short acoustic pulses to the water at a known, fixed frequency. The ADCP receives and processes the echoes from successive layers to determine how much the frequency is changed. The difference in frequency between transmitted and reflected sound is proportional to the relative velocity between the ADCP and the reflectors in the water. This frequency shift results from the Doppler Effect. The sound is reflected primarily by zooplankton and/or small particles (diameter order of magnitude of 1 mm) of suspended sediment. Reflections from fish are relatively infrequent and rarely affect the measurement. The ADCP is able to profile currents in 128 layers simultaneously. The ADCP can be used from a vessel in direct reading mode or as bottom mounted looking upwards. Also a buoy installation with downward looking configuration is possible. In direct reading mode the instrument can detect the movement of the vessel by bottom tracking and the true water velocity is measured by subtracting the vessel velocity from the ambient velocity.

Ultrasonic Meters

Measurement is based on differences of travel time of an ultrasonic wave as it passes the flowing water. This is determined by a precise measurement of the difference in transit time between an ultrasonic wave that is propagated along a defined distance through the water and an ultrasonic wave that is simultaneously transmitted in the opposite direction over the same distance. The transit time for a pulse along the one path is dependent upon the fluid velocity component along the same path. The difference in transit time for the two pulses transmitted simultaneously in opposite directions will, therefore, be a direct expression for the current speed resolved along the same axis.

The velocity of the acoustic pulse will vary with the water temperature, pressure (depth), and salinity. The current meter, however, automatically compensates for variations in the sound velocity by measuring the pulse transit time, deriving the actual sound velocity to the correct value.

Ultrasonic measurement provides a very accurate and quick measurement of a point velocity. It is used in Finland mainly for very slow velocity measurements (like advective currents under ice) and near bottom velocity measurements.

Sediment Measurement

The composition of sediments in lakes differs between shallow and deep parts of a lake or a water course. Distance from a source of suspended matter e.g. a river or waste water discharge also affects on the quality of the sediments. Fine cohesive materials generally dominate the open water areas, whereas coarser deposits (sand, gravel) dominate shallow regions where erosion and transportation of fine materials prevail.

The quality (e.g. water content, organic content) of the sediment differs according to the layer of the sediment both because the sedimenting material varies with time and because consolidation and decomposing processes are going on in the sediment layers. For this reason it is valuable to know the thickness of the active layer which takes a part in sedimentation/ resedimentation processes. Usually the surface layer is presumed to be a few centimetres thick though changes in sediment appear gradually.

Particle Size Analysis

Analyses of particle size distribution can be determined with sieving, aerometrically or optically. In lake and river water analysis the sieving method can be used together with optical or centrifugal analyzers. The samples are first filtered. 0.22 mm filters are used in Norwegian sediment transport programme for rivers (Bogen, 1986). We have used 0.125 m filters in analysing the size distribution of deposited material in the sediment traps. The finest fraction can be determined by laser optics or with Coulter Counters.

The first applications of Coulter Counters in water analysis started during 1960's (Hastings et al., 1962; Davidson and Keen, 1963; Sheldon and Parson, 1967; Ilmavirta, 1974). In Counters particles in electrolytic suspension are forced to flow through a small hole, which has electrodes on both sides. As a particle goes through the hole a short current pulse is produced. This pulse is related to the volumetric grain size.

Laser method is based on deflection of a laser beam when particles pass the beam in a capillar pipe. With the laser method, it is possible to study a wider fraction as with Coulter counters, which have a practical range from 0.6 mm to 60-70 mm. In Fritz laser analyzator, the measuring range can be selected from 0.16 mm to 1160 mm (Bernuth, 1988). The resolution within a selected measuring range covers two decades.

Hydrometric methods are based on the Stokes law. Hydrometer records the specific gravity of the sediment suspension. The method can be applied for particles, which have the range from 1 mm to 74 mm. The sediment sample is first dried in 105 °C temperature. Then it is mixed with peptisator mixture in order to burn away the organic compounds. After mixing and reaction time of 24 hours and mixing again the solution, the measurements with hydrometer is done with distinct time intervals. SediGraph is utilizing the penetration of X-ray beam through the suspension. As the particles settle the true settling speed is obtained by recording the amount of particles in different heights of the sedimentation liquid. The transparent cell containing the sedimentation liquid is moved vertically between the X-ray source and detector. The distribution of particle mass at various points in the cell affects the number of X-ray pulses reaching the detector. The pulse count is used to derive the particle diameter distribution and percent mass at given particle diameters.

Turbidity Sensors

The turbidity measurement technique has been used in water research for about fifty years (Grassy, 1943; Benedict, 1945). The turbidity meters are based either on the transmission of light or the scattering of light. The absorption is a change of light energy into other forms of energy. In scattering, the direction of light beam is changed as it hits the particles in water. In pure absorbing medium, the loss of light intensity is exponential following the form

$$I = I_0 e^{az} \tag{14}$$

where z = distance, a = absorption constant and I_0 = emitted light intensity.

The light scattering from a single particle depends on its shape, size and internal index of refraction distribution. These all and the concentration of particles also vary in natural waters very much. Thus the relation between optical and particle variables varies also. The turbidity meters have been used successfully in a laboratory to speed up the determination of suspended solids concentration in fine silts and coarse clay from a river water samples (Ward and Chikwanha, 1980). Allen (1979) reported results from extensive simultaneous suspended solids and turbidity measurements in two rivers during two years. In his measurements turbidity responded little to larger sediment sizes. The best response between turbidity and suspended solids concentration was in the size classes less than 10 mm.

Sedimentation Traps

Many types and shapes of traps have been introduced but the trap technique has been limited by the lack of investigations of in situ physics of catching and retaining the particles. At the turn of the 1980's Lau (1979), Hargrave and Burns (1979), Bloesch and Burns (1979) and Blomqvist and Håkanson (1981) contributed significantly to the standardization of the traps technique. And it is widely accepted that a plexi glass cylinder with a height/diameter ratio > 10 with minimum diameter of 5 cm is the best trap (Fig. 11). This type of trap catches the settling material so that the sample represents the settling flux around the trap, with no resuspension within the trap by currents and waves.

In the sediment transport studies, the time of exposure should be kept as short as possible. This is especially important when the fluxes of organic matter are studied, the exchange time of the traps should not exceed three weeks (Bloesh and Burns, 1979). The results may be distorted by the bacterial mineralization, attracted zooplankton and benthic organisms caught by traps. In practice, traps have been exchanged biweekly, but shorter collection times have also been used (Huttula and Krogerus, 1982; Harsch and Rea, 1982). Bengtsson and Hellström (1990) recommended that, in order to study the relationship between winds and resuspension, the traps should be exchanged daily.

The mooring of traps is done with subsurface buoys. Pennington (1974) found significant material losses (about 70-98 %) from traps by motion caused by waves being transferred down the mooring line to the traps. Vibratory movement of sediment trap fixtures in strong currents can be diminished by attaching a fin to the sediment trap and allowing it to rotate around the cable. Several traps can be used in the same mooring line in order to calculate the resuspension as a difference between the catches at different levels.

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Coastal Marine Hazards

Storm Surges: Worst Coastal Marine Hazard

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INTRODUCTION

Storm surges associated with severe tropical cyclones constitute the world's worst coastal marine hazard. Storm surge disasters cause heavy loss of life and property, damage to the coastal structures and the losses of agriculture which lead to annual economic losses in affected countries. Death and destruction arise directly from the intense winds characteristic of tropical cyclones blowing over a large surface of water, which is bounded by a shallow basin. As a result of these winds the massive piling of the sea water occurs at the coast leading to the sudden inundation and flooding of coastal regions.

About 300,000 lives were lost in one of the most severe cyclone that hit Bangladesh (then East Pakistan) in November 1970. The Andhra Cyclone devastated the eastern coast of India, killing about 10,000 persons in November 1977. These two and most of the world's greatest human disasters associated with the tropical cyclones have been directly attributed to storm surges.

Storm Surges in India and Neighbourhood

India and its neighbours are threatened by the possibility of storm surge floods whenever a tropical cyclone approaches. Storm surges are extremely serious hazards along the east coast of India, Bangladesh, Myanmar and Sri Lanka. Typically, Sri Lanka is affected only occasionally by the storm surge; however, tropical cyclones of November 1964, November 1978 and the recent cyclone of November 1992 have caused extensive loss of life and property in the region. Storm surges affecting Myanmar are also to much less extent in comparison with Bangladesh and India. Notable storm surges which have affected Myanmar have been during May 1967, May 1968, May 1970, and May 1975, of which May 1975 was the worst cyclone. The storm surge due to the May 1975 event penetrated at least 100 km into the Irrawaddy river system and caused serious inland flooding.

A detailed review of the problem of storm surges in the Bay of Bengal is given by Murty (1984), Murty et al. (1986) and Dube et al. (1997). Of all the countries surrounding the Bay of Bengal, Bangladesh suffers most from storm surges. The main factors contributing to disastrous surges in Bangladesh may be summarized as (Ali, 1980):

(a) Shallow coastal water,
(b) Convergence of the bay,
(c) High astronomical tides,
(d) Thickly populated low-lying islands,
(e) Favourable cyclone track, and
(f) Innumerable number of inlets including world's largest river system (Ganga-Brahmaputra-Meghna).

Although the frequency of storms and storm surges is less in Arabian Sea than in the Bay of Bengal, major destructive surges can still occur occasionally.

Destruction Potential

Although the frequency of tropical cyclones in the Bay of Bengal and the Arabian Sea is not too high, the coastal regions of India, Bangladesh and Myanmar still suffer most in terms of loss of life and property caused by the surges. The reasons, besides the inadequate accurate prediction, are the low lands all along the coasts and considerably low-lying huge deltas, such as, Gangetic delta and Irrawaddy delta. Table 1 lists the number of deaths associated with several deadly cyclone disasters where death tolls were in excess of 5000 lives. These major surges usually occurred unexpectedly.

There can be little doubt that the number of casualties would have been considerably lower if the surge could have been predicted, say, 24 hours in advance allowing effective warnings in the threatened area. The prediction must, of course, be accurate enough so that one can distinguish between the dangerous surges and the surges that cause little harm, as people cannot be evacuated from exposed areas for every approaching storm. Some success has been achieved in predicting storm surges by computer oriented numerical models. The purpose of the present paper is to give a review of recent developments in predicting the storm surges in the Bay of Bengal and Arabian Sea. A real time storm surge prediction system is also proposed here for disaster management (Dube et al., 1994).

Table 1: Deaths in tropical cyclones

Year	*Countries*	*Deaths*
1970	Bangladesh	300,000
1737	India	300,000
1886	China	300,000
1923	Japan	250,000
1876	Bangladesh	200,000
1897	Bangladesh	175,000
1991	Bangladesh	140,000
1833	India	50,000
1864	India	50,000
1822	Bangladesh	40,000
1780	Antiles (W.Indies)	22,000
1965	Bangladesh	19,279
1963	Bangladesh	11,520
1961	Bangladesh	11,466
1985	Bangladesh	11,069
1971	India	10,000
1977	India	10,000
1963	Cuba	7,196
1900	USA	6,000
1960	Bangladesh	5,149
1960	Japan	5,000
1973	India	5,000

DATA INPUT FOR SURGE PREDICTION MODELS

In order to achieve greater confidence in surge prediction in the Indian seas, one should have sufficient knowledge of the input parameters for the model. These parameters include the oceanographic parameters, meteorological parameters (including storm characteristics), hydrological input, basin characteristics and coastal geometry, wind stress and sea bed friction and information about the astronomical tides. It has been seen that in many cases these input parameters strongly influence the surge development. A brief account of these data input is given below.

Meteorological Input

This is mainly concerned with the characteristics of the tropical storm. The main characteristics required are

(a) The pressure drop (difference between ambient pressure surrounding the storm and the central pressure),
(b) Vector motion of the storm,
(c) Point of landfall,

(d) Duration of the storm,
(e) Maximum sustained winds and
(f) The radius of maximum wind.

These parameters of tropical cyclone are needed for the computation of wind field in a cyclone which is the foremost requirement for the computation of surges.

Oceanographic Data

Data on oceanography are concerned with
(a) Bathymetry
(b) Astronomical tides, and
(c) Inshore currents in closed regions.

Most of the northern Bay of Bengal is very shallow and is characterized by sharp changes in sea bed contours. The shallowness of water may considerably modify the surge heights in this region. Therefore, accurate bathymetry maps are needed for improved surge prediction.

Astronomical tides and the inshore currents also influence the surges through nonlinear interaction in shallow water. Experiments have been made to study the tide-surge interaction with the help of numerical models (Johns et al., 1985, Sinha et al., 1996).

Basin Characteristics and Coastal Geometry

The location of the highest surge depends predominantly on the coastal geometry of the basin. Experiments suggest that the curving coasts not only shift the peak surge position but also affect its height (Dube et al., 1982). Some recent modelling experiments show that the surge is sensitive to the way of coastline representation. It is seen that conventional method of coastline representation by orthogonal straight line segments tend to over-reflect the wind driven water (Johns et al., 1981).

Surface and Bottom Stress

The surface stress and sea-bed friction is usually parameterized by conventional quadratic law. Wind is the main generating mechanism of the surge, the height of the wave depends on the strength of the wind. Special care should be taken while computing the surface winds associated with a tropical cyclone.

Hydrological Input

The main hydrological information needed is

(a) river discharge in the sea, and
(b) rainfall distribution.

The results of river-ocean coupled mathematical models show that the discharge of fresh water carried by the rivers may modify the surge situation, especially in the northern Bay of Bengal where one of the world's largest river systems, Ganga-Brahmaputra-Meghna, join the sea. Another dynamic effect of these inlets and estuaries is the potentially deep inland penetration of surge originating in the sea.

The impact of heavy precipitation, associated with tropical cyclone, on surge height has not been considered in the models for the Indian seas. However, it is expected to influence the surge amplitude.

For the development of any forecasting storm surge model for the Indian seas one must take the above factors into consideration as far as possible.

Operational Storm Surge Prediction

In India, the study of the numerical storm surge prediction was pioneered by Das (1972). Subsequently several workers attempted the prediction of storm surges in the Bay of Bengal and Arabian Sea (Das et al., 1974; Ghosh, 1977; John and Ali, 1980; Johns et al., 1981; Murty and Henry, 1983; Dube et al., 1985, etc.)

Operational numerical storm surge prediction models have been developed and are being routinely used for several coastal regions of the world such as North Sea, the Gulf of Mexico and Atlantic coast, Hong Kong, China etc.

Most of the operational models require large computing power. Therefore for routine forecasting of storm surges, especially providing multiple forecast scenarios, the models cannot be used in the absence of access to sufficient computing facility. To overcome this difficulty, most of the forecasting offices use the nomogram methods of Jelesnianski (1972) for prediction of storm surges associated with tropical cyclones. The nomograms have been developed from modelling studies of a large number of bathymetries and approach angles.

The second WMO International Workshop on Tropical Cyclones (WMO, 1990) recommended the use of personal computers by the developing countries in order to adopt the stand-alone storm-surge forecasting system. Recent advent of powerful personal computers (PC) has opened up the possibility of running dynamical models in real time on PC-based work stations in an operational office. In fact, a PC-based work station (the Automated Tropical Cyclone Forecasting System, ATCF) is already in operation at the Joint Typhoon Warning Centre, Guam for the past many years. The Australian Bureau of Meteorology Research Centre, together with their Bureau Severe Weather Programme Office has also developed an Australian work station for storm surge forecasting. In India, efforts have been made towards adaptation of the IIT Delhi Surge Model (Dube et al., 1994) on the Personal Computers for its use as an operational system. The first version of this storm surge prediction system has been implemented at India Meteorological Department. The operational feasibility test of the system is currently ongoing.

BASIC FEATURES OF THE MODEL

In this section we will briefly describe some of the basic features of the model proposed to be used as a real time storm surge prediction system (Dube et al., 1994).

Dynamic Storm Model

In the above predictive system the surge is generated by a cyclone, tracking across the analysis area. In view of the strong associated winds and consequently high values of wind stress, the forcing due to barometric changes have been neglected. Thus, the surface wind field associated with tropical cyclone is the primary requirement for modelling storm surges. The wind field at the sea surface is derived by using a dynamic storm model developed by Jelesnianski and Taylor (1973). This storm model uses as input the radius of maximum wind and the pressure drop. The main portion of the storm model is a trajectory model and a wind speed profile approximation scheme. The trajectory model represents a balance between pressure gradient, centrifugal, coriolis and surface frictional forces for a stationary storm.

Storm Surge Model

Vertically integrated numerical storm surge prediction models of IIT Delhi have been adopted for the surge prediction. These models can be used as a menu-driven stand-alone system. The details of the models and the numerical solution procedure are described in Das et al. (1983) and Dube et al. (1985). Only a brief description of specific features will be presented here.

The model is fully non-linear and is forced by wind stress and by quadratic bottom friction. It is found that the non-linear advection terms have significant effect on the final results, especially in the shallow coastal waters of the head Bay of Bengal. Therefore, for operational applications, the non-linear terms cannot be left out. The treatment of the coastal boundaries in the model involves a procedure leading to a realistic curvilinear representation of both the western and the eastern sides of the Bay of Bengal. This coastal representation has another added advantage of taking automatically into account the finer resolutions in the shallow regions of the Northern Bay. A desirable feature of storm surge simulation scheme is the ability to incorporate increased resolution adjacent to the coastline. This has been achieved by using a variable grid which leads to a substantial refinement of resolution near the coastline and a coarser resolution in the deeper waters. This type of grid assists in the incorporation of a more detailed bathymetric specification in the important coastal region. With the specification of east-west grid points, the first off-shore grid points at which the elevation is computed is on an average about 5 km from the coastline.

Integration Procedure

A conditionally stable semi-explicit finite difference scheme with staggered grid is used for the numerical solution of the model equations. The staggered grid consists of three distinct types of computational points on which the sea surface elevations and the zonal and meridional components of depth-averaged currents are computed (Johns et al., 1981).

Bottom Stress

The bottom stress is computed from the depth integrated current using conventional quadratic law with a constant coefficient of 0.0026.

Boundary and Initial Conditions

The coastal boundaries are taken as vertical side walls across which the normal transport vanishes. The model has also option to take continuously deforming shoreline; however it is not included in the present operationalization system due to unavailability of detailed onshore topography data. The normal currents across the open sea boundaries are prescribed by a radiation type of condition. As usual it is assumed that the motion in the sea is generated from an initial state of rest.

Bathymetry

The bathymetry for the model is derived from the Naval Hydrographic Charts and is interpolated at the model grid points by using cubic spline interpolation scheme. With this procedure sufficiently accurate and realistic bathymetry is generated over the continental shelf.

VALIDATION EXPERIMENTS

In order to validate the model, several simulation experiments have been performed by using the data of severe cyclonic storms hitting the coastal regions in the Bay of Bengal and Arabian Sea. In the present paper an attempt has been made to compare the simulated sea surface elevations with observations from local tide gauges wherever possible or with post-storm survey estimates of Meteorological Departments of India, Bangladesh, Myanmar and Sri Lanka.

East Coast Of India: Andhra Cyclone (November 1977)

A severe cyclonic storm with a core of hurricane winds hit the Andhra Coast of India on November 19, 1977. The genesis area of the cyclone was in

Malaysia region from where it moved westward as a low pressure area becoming concentrated into a deep depression with its centre near 6 N, 92 E on the morning of 14th November. Whilst continuing to move generally westward, the system rapidly intensified and on the morning of 16th, lay near 7 N, 85.5 E with a well-developed core of winds exceeding 30 m/s. On the evening of November 16th, the storm changed its course towards a more northerly track and continued to follow this until landfall at the Andhra coast. The history of the storm just before the landfall is shown in Fig. 1. Satellite reports indicated that the storm attained its peak intensity on 18th and maintained this on 19th. The maximum wind speed associated with the storm during this period was estimated to be about 70 m/s at a distance from the Centre of about 40 km. A pressure drop of 80 hpa was estimated at the centre of the cyclone. A major part of the destructive effect of the cyclone was felt along the main coast south of Masulipatnam in Andhra Pradesh. This resulted from the surge-induced sea-surface elevations which caused widespread flooding in the low-lying region, claiming a heavy toll of human life. The sea-surface elevations of five metres above mean-sea level was estimated at Divi Island on the basis of floating debris which had become entangled in trees.

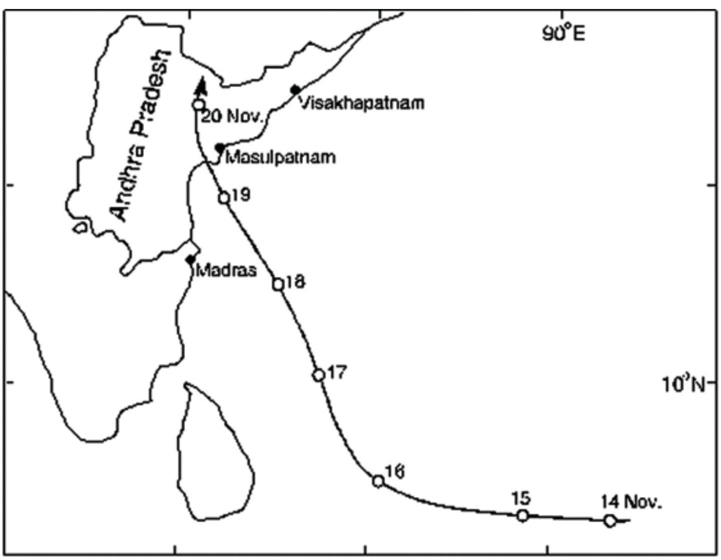

Fig. 1: Track of 1977 Andhra cyclone.

A two-day simulation of the surge generated by the cyclone was commenced at 1200 UTC on November 17. Model computed peak surge values associated with the storm are shown in Fig. 2. It may be seen that the maximum model simulated surge of five metres occurs at a grid point closest to Divi Island. This is in very good agreement with the post-storm survey estimated sea level of about five metres in that region.

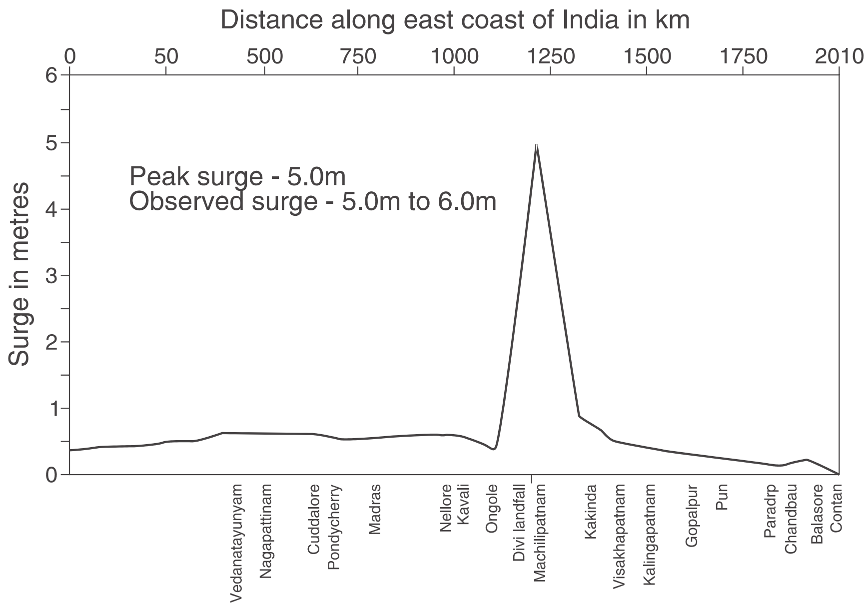

Fig. 2: Predicted peak surge along the east coast of India (Andhra cyclone 1977).

Bangladesh: Chittagong Cyclone (November 1970)

This cyclone ranks as one of the most deadly, if not the deadliest, storm having ever devastated Bangladesh. The origin of this cyclone can be traced back to the remnant of a tropical storm that moved westward across Malaya on November 5th. The system appeared as a depression over the south central Bay of Bengal on November 8. While attaining storm intensity on November 9, it moved very slowly northward. Sustained winds reached hurricane intensity as it moved inland on November 11. The cyclone made a landfall about 80 km to the north of Chittagong on the morning of November 13 (0520 hrs Bangladesh standard time). The track of the cyclone is shown in Fig. 3. The observed range of maximum surge at Chittagong and neighbourhood was reported to be between 4.2-7.2 m. This is in good agreement with model computed peak surge (Fig. 4).

Sri Lanka: Rameswaram Cyclone (December 1964)

A severe cyclonic storm crossed the Sri Lanka coast about 50 km to the north of Trincomalee on 22nd December at about 0600 UTC. Moving northwestward it crossed Sri Lanka and struck the Indian coast about 30 km to the south of Tondi on December 23 at 0600 UTC. This was one of the severest storm that have occurred in Indian seas and probably the most severe storm which affected Sri Lanka and extreme south of the Indian

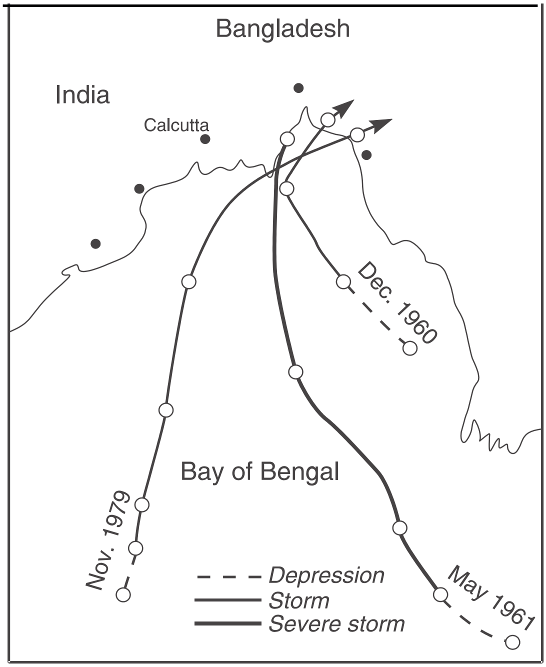

Fig. 3: Track of Bangladesh cyclones (Dube et al., 1985).

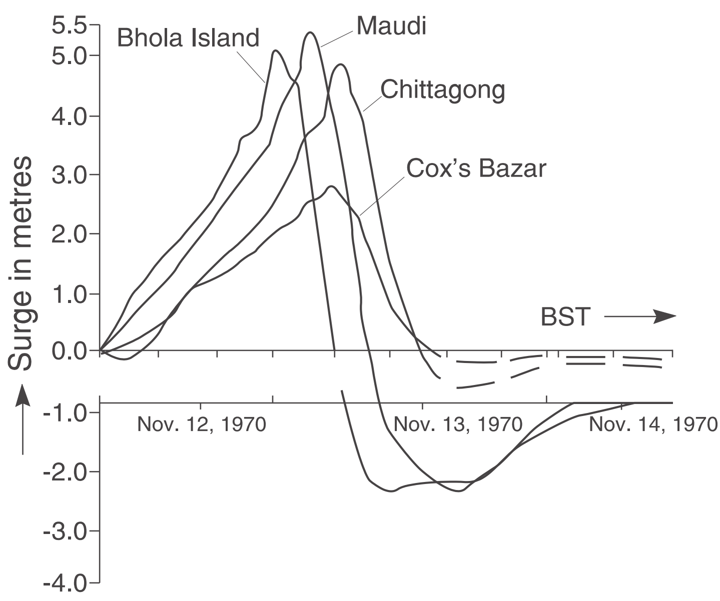

Fig. 4: Time variation of the predicted sea-surface elevation at coastal stations of Bangladesh (Dube et al., 1985).

peninsula. The track of the cyclone is shown in Fig. 5. Computed maximum sea surface elevations for the landfall of the cyclone in Sri Lanka and later in India are shown in Fig. 6 (Rao et al., 1994).

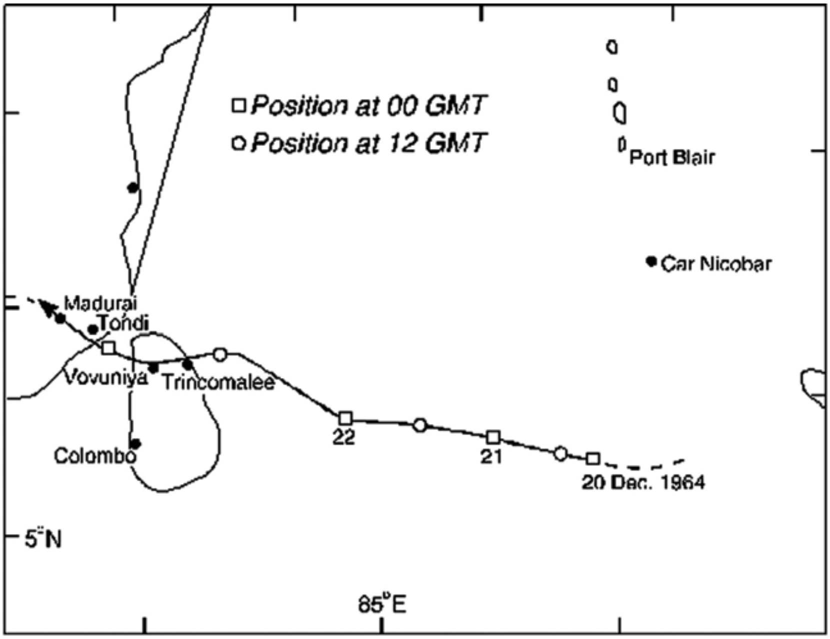

Fig. 5: Track of 1964 Rameshwaram cyclone.

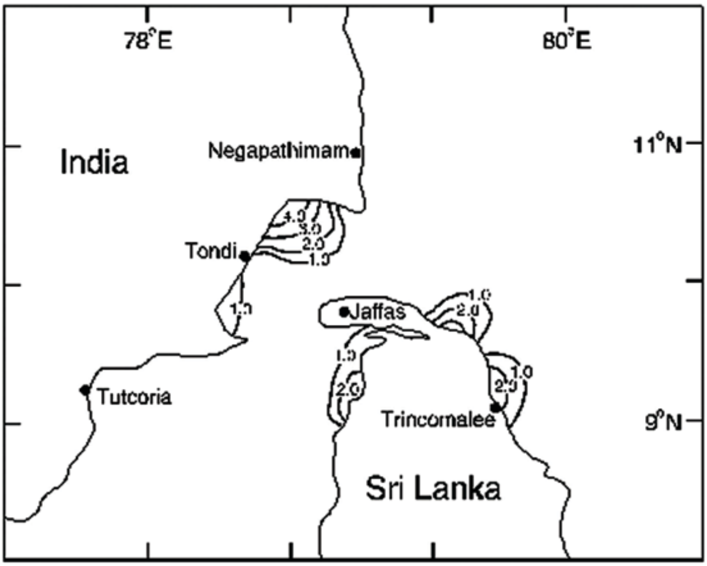

Fig. 6: Predicted peak surge along Sri Lanka and southern part of India (Rao et al., 1994).

A peak surge of 3.7 m is predicted at about 50 km north of Trincomalee while near Tondi (India) a peak surge of 5.6 m is predicted. This is in agreement with the reported flooding and surge in the region.

Arabian Sea: Porbandar Cyclone, West Coast of India (October 1975)

A severe cyclonic storm crossed Gujarat coast near Porbandar on the afternoon of 22 October 1975, causing large scale damage in the northern parts of Gujarat state. The cyclone formed over the central and southern Bay of Bengal on the morning of 15 October and intensified into a depression, moved west-northwest and lay centered 50 km east-southeast of Ongole at 0300 UTC, 18 October. At this time a low pressure area formed over east central Arabian Sea with its centre near 14 N 73 E.

The depression in the Bay of Bengal crossed the Andhra coast near Ongole on the afternoon of 18 October, weakened into a low pressure area and moved into the Arabian Sea between Harnai and Ratnagiri. The system over the Arabian Sea also moved north-westward. Finally, the two systems merged and concentrated into a deep depression by the evening of 19 October, centered near 17 N 73.5 E. The subsequent history of storm is shown in Fig. 7. While continuing to move north-westward, the system intensified into a deep depression and then into a cyclonic storm with its centre near 19

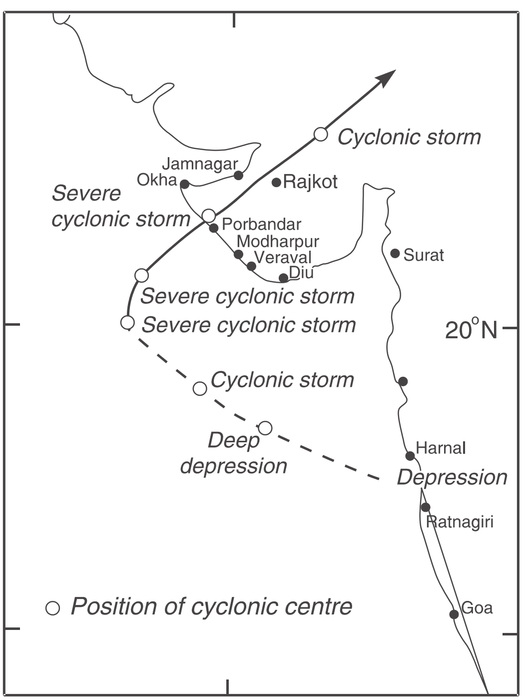

Fig. 7: Track of 1975 Porbandar cyclone (west coast of India).

N 69.5 E on the evening of 20 October. On the morning of 21 October, the storm started to deviate towards the north and then moved north-northeast and by that evening it had concentrated into a severe cyclonic storm. The system further intensified and, on the morning of the 22nd, lay near 20.8 N 69 E with a core of hurricane winds. The reported maximum wind speed associated with the storm during this period was 115 knot. The distribution of the predicted maximum sea-surface elevations, observed surge and the time of occurrence along the Gujarat coast are given in Fig. 8 (Dube et al., 1985).

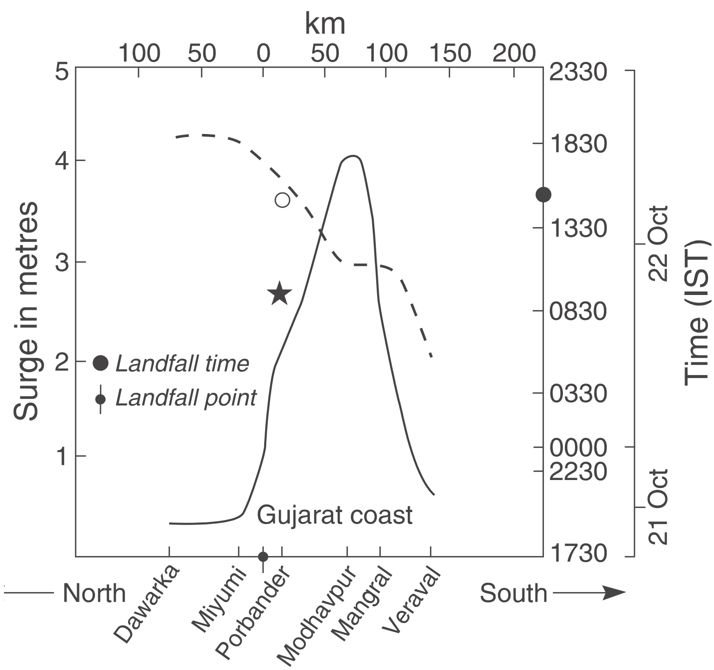

Fig. 8: Predicted peak surge along Gujarat coast of India (Dube et al., 1985).

SEA LEVEL RISE AND STORM SURGE

The issue of the sea level rise as a consequence of climatic warming and the greenhouse effect is of extremely grave concern for Bangladesh. The projected worldwide rise of sea level during the next 100 years will be particularly hard-felt in the low-lying regions of West Bengal in India and Bangladesh. These regions have been created as a result of sediment washing down the major rivers Ganga, Brahmaputra and Meghna.

The rise in the sea-level would inundate low lying areas, destroy coastal marshes and swamps, erode shoreline and cause coastal flooding and increase salinity of rivers, bays and aquifers. Mangroves and other vegetation will migrate landward with rising sea-level, but such migration will be inhibited by manmade developments. Thus the protective buffering effects of coral reefs and mangroves against cyclones will be reduced as a result of sea level rise and increased temperatures (Broadus, 1993).

Rising air temperature resulting from the greenhouse warming may increase SST. An increase in the surface water area of warmer SST for cyclone generation is expected to increase frequency and intensity of tropical cyclones and also the duration of the cyclone season (Raper, 1993). Storm surges caused by rising water resulting from landward movement of these huge storms would also be more frequent, more severe and last longer. With increasing population densities in the future, through the combined effects of natural population increase and loss of coastal zone due to sea-level rise, the exposure to severe storm surges will only increase.

Broadus et al. (1986) and Broadus (1993) have made a detailed study on the potential consequences of sea-level rise in the deltaic regions of the Nile River in Egypt and the complex Ganga-Brahmaputra-Meghna river system in Bangladesh. In the case of Bangladesh the authors have presented different transgression scenarios as a result of the projected rise in the sea level. They have also discussed the problem of exposure of population to storm surges as a result of sea-level rise. Economic considerations vis-à-vis sea level rise are also detailed in the study.

Dube and Rao (1991) used a continuously deforming shoreline model to determine the effect of sea-level rise on storm surges affecting the east coast of India. Their model uses an idealized onshore topography to compute the inland inundation associated with sea-level rise and storm surges. Flather and Khandker (1993) used numerical model to determine the effect of an increase in mean sea level on tidal storm surge and combined tide and storm surge levels for Bangladesh, while Brammer (1993) made an impact assessment of sea-level rise and geographical complexities for the Ganga-Brahmaputra-Meghna delta of Bangladesh. In a recent paper Sinha et al. (1996) studied the impact of sea level rise on the tidal circulation in the Hooghly estuary.

CONCLUSIONS

The recent developments in the storm surge forecasting for the Bay of Bengal and Arabian Sea is described. A real time storm surge prediction system is proposed, which can be run in a few minutes on a personal computer. The forecasting system is based on the vertically integrated numerical storm surge model of Dube et al. (1985). A dynamic storm model developed by Jelesnianski and Taylor (1973) is used for computation of surface winds associated with cyclonic storms. The only meteorological inputs required for the model are positions of the cyclone, pressure drop and radii of maximum winds at any fixed interval of times. The system is operated via a terminal menu and the output consists of the 2-D and 3-D views of peak sea surface elevations with the facility of zooming in on the region of interest. The system can handle multiple forecast scenarios.

The model results reported for several case studies are in very good agreement with the available observations and estimates of the surge. The model has extensively been tested with severe cyclonic storms of the last three decades which have affected the coastal regions in the Bay of Bengal and Arabian Sea.

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Deterministic Methods for Prediction of Tropical Cyclone Tracks

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INTRODUCTION

Prediction of the tracks of tropical cyclones is one of the most difficult and challenging problems of current international tropical cyclone research. The focal point of this research is to minimize the forecast errors to the extent that the forecast can be used effectively for issuing appropriate warnings for disaster management purposes. The level of importance is reflected in the large number of forecast techniques that have been developed using wide range of approaches, from empirical through statistical and dynamical. However, due to complexities of the problem, no single technique has proven to have outstanding performance relative to the others. Figure 1 is a good example of the performance of eight different operational track prediction models for hurricane 'Elena' of August, 1985. All the eight predicted tracks are in different directions, but the hurricane moved unexpectedly in yet another direction far apart from all the above tracks.

Strong winds, heavy and torrential rains and worst of all, the cumulative effect of storm surges and astronomical tides are the three major elements of tropical cyclone disaster. In the Indian region, the storm surge is the most devastating element. Much of this is contributed by extremely shallow coastal bathymetry of certain segments of the east coast of India and Bangladesh. The track prediction of tropical cyclones in this region is therefore crucial especially for the purpose of storm surge forecasting as a minor deviation of the landfall point may generate altogether different peak surge height. Storm surge prediction is intimately related to the intensity of the cyclone in terms of maximum sustained surface winds and minimum sea level pressure. Fortunately, there has been good progress towards the development of storm surge prediction models in the Indian region. Das (1972) did the pioneering

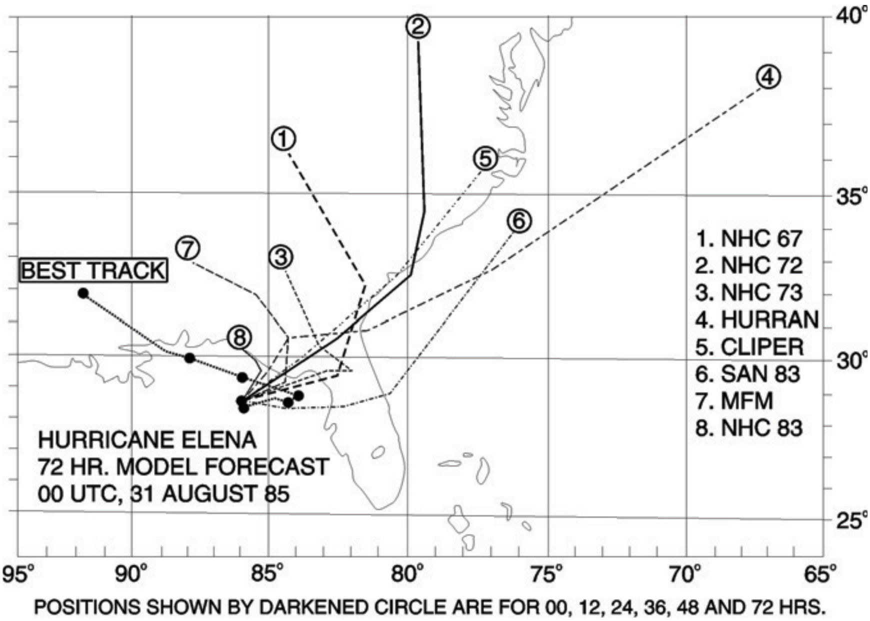

Fig. 1: Best track prediction for Hurricane Elena.

work in this field. Subsequently, there were a large number of such studies in the region (Ghosh, 1977; Das, 1981; Johns et al., 1981 & 1982; Das et al., 1983).

Recent analysis of the error statistics reveal that technique development together with observing methods in some basins had resulted in a slow, but steady decrease of forecast errors of approximately 1% per year (Neumann,1981). There has been significant increase in basic research on tropical cyclone motion aspects in recent years. Moreover, a large number of field experiments on cyclone probing have been conducted in Pacific and Atlantic regions during past few years. At the same time the resolution and initialization of tropical cyclones in numerical models have been considerably improved in recent years. Much more improvement is still possible and it is expected to happen in the years to come.

This article provides a brief description on the deterministic methods used in India and abroad for cyclone track forecasting. For the sake of completeness, a brief description of forces (internal as well as external) responsible for the cyclone motion is also presented.

BASIC PRINCIPLES OF CYCLONE MOTION

The most important factors which cause a tropical cyclone to move are best represented by the use of barotropic vorticity equation in the form:

$$\partial\zeta/\partial t = \underbrace{-V.\ \nabla\zeta}_{A} - \underbrace{V_n\beta}_{B} - \underbrace{(\zeta + f)\ \nabla.V}_{C} \qquad (1)$$

where ζ is the vertical component of relative vorticity, V is the horizontal wind vector, Vn is the meridional wind component (positive towards north), β is the meridional gradient of earth vorticity, and f is the Coriolis parameter or the vertical component of earth vorticity. The tilting, solenoidal and frictional effects have been neglected.

As a first approximation, the cyclonic vorticity is assumed maximum at the centre and decreases with increasing radius. Hence, if the cyclone is moving in a given direction the local rate of change of cyclonic vorticity given by left hand side term of the eqn. 1 must also increase in the same direction. This vorticity change can only be achieved by processes implicit in the terms on right hand side of eqn. 1. In eqn. 1, the term 'A' represents advection of relative vorticity, the term 'B' the advection of earth vorticity and the term 'C' the vorticity change from divergence or convergence.

Environmental Steering

The tropical cyclones generally respond like a protected symmetric vortex in a uniform non-interacting fluid flow. This motion is governed by the term 'A' of eqn. 1 and is considered as an external force responsible for the motion of the cyclones. The flow simply advects the vortex along and, as a result, the environmental flow is referred to as a steering current. Details of steering current method are discussed in the section Dynamical Models.

The Beta Effect

The so-called beta effect was first introduced by Rossby (1948) to explain the propensity for cyclones to drift poleward with time, a phenomenon which is commonly referred to as the Rossby drift in his honour. Rossby used a beta plane approximation and considered a symmetric wind field superimposed on a symmetric pressure field. Since the Coriolis force is larger on the poleward side than on the equatorward side, a poleward directed force is exerted on the cyclone. This force will be greater for larger cyclones than for smaller ones, so the former will drift poleward faster. Rossby reasoning was, however, incorrect in that even if we could superimpose a symmetric wind and pressure field, geostrophic adjustment processes would rapidly bring the two into balance and thus remove the unbalanced poleward force. Though, the Rossby drift theory was a failure, it led to an alternative hypothesis described in the section Poleward Rossby Drift hereafter.

The correct beta effect can be readily seen in term 'B' of eqn. 1. This indicates that only meridional flow will advect earth vorticity. A cyclonic vortex has equatorward flow on its western side and poleward flow on its eastern side. Since the earth vorticity increases cyclonically towards the poles, this will produce a differential advection of vorticity with a maximum increase of cyclonic vorticity to the west, and of anticyclonic to the east of the vortex centre. If there is no superimposed environmental flow, the vortex will then propagate to the west in a direct analogy to the higher latitude Rossby waves. This was shown in more rigorous treatments by Kasahara (1957) and Holland (1983). Holland showed that the inclusion of vortex scale convergence change the propagation to a direction of slightly poleward of west.

The Combined Steering Plus Beta Effect Propagation

Kasahara (1957), Kasahara and Platzman (1963), and Holland (1983) have shown that cyclones embedded in a uniform flow will deviate to the west (or slightly poleward of west if typical large-scale values of convergence are used) because of the above described beta effect propagation. Holland's method was to specify a vortex and uniform flow and derive analytic solution for linear cyclone from eqn. 1. The propagation speed is determined by the size of the envelope of 'effective radius', which in turn is determined by the size and outer wind strength of the cyclone. This shows that the tropical cyclone motion is quite sensitive to size or outer core wind strength changes, but is almost independent of the core region intensity. A small cyclone will have almost negligible westward propagation speed, whereas a large cyclone could be propagating towards the west at a relatively much higher speed. This clearly shows that a large cyclone will move more independent of the environmental flow than will a small cyclone. These results are in good agreement with observations and have been confirmed by numerical modelling experiments (DeMaria, 1983).

The Poleward Rossby Drift

Anthes (1982) proposed that the observed tendency for tropical cyclones to drift polewards was due to a second order, non-linear adjustment of the basic current to the outer region distortion detailed below. This can be described by considering a symmetric, non-divergent cyclone on a northern-hemispheric beta plane with no basic current. Then the instantaneous time rate of change of relative vorticity given by term 'B' in eqn. 1 is shown in Fig 2. In addition to propagating the vortex to the west, these vorticity changes will produce a vortex distortion with an accumulation of cyclonic vorticity to the west and anticyclonic vorticity to the east. This distortion produces two opposing secondary circulations, counterclockwise to the west and clockwise to the east, as shown by the dashed lines in Fig. 2. The resulting southerly flow over the vortex will advect it poleward. Introducing convergence into the cyclone will rotate the field in Fig. 2 in a clockwise direction, so that the generated steering current will be from more southwesterly direction. Thus the poleward Rossby drift may be explained by non-linear development of an induced poleward steering current.

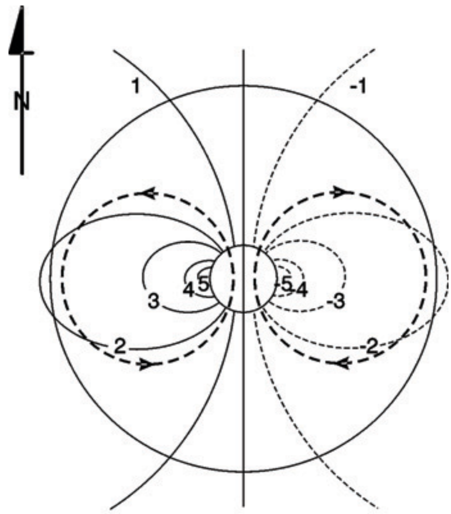

Fig. 2: Instantaneous time rate of change of relative vorticity.

Surface Frictional Effects

The effects of surface friction on cyclone motion have been studied analytically by Rao (1970) and Kuo (1969) and in a numerical, *f*-plane simulation by Jones (1977). Since a northern-hemispheric cyclone embedded in an environmental flow over the open ocean has stronger winds on the right, it will experience a greater frictional dissipation in the right, compared to the left semicircle. Both Kuo and Jones found that this produce a small motion deviation (around 5 deg.) to the right. Rao also found that a pseudo land surface represented by a greater frictional drag on one side compared to the other side of a cyclone like vortex would cause a deviation towards the side with increased friction.

TRACK PREDICTION TECHNIQUES

The tropical cyclone track prediction techniques are grouped into the following two categories: Subjective and Deterministic. Synoptic, Satellite, and Radar methods are examples of Subjective techniques. Statistical and dynamical methods are broadly categorized as objective or Deterministic techniques. Figure 3 shows different methods of track prediction under each of these categories. In this paper we shall confine our discussions to only deterministic methods. Table 1 gives a list of some of the important work carried out on different aspects of track prediction techniques in India and abroad.

Statistical Methods

Statistical models are widely used to provide the objective guidance on the storm track forecast at various forecast centres. The basic approach of these

Table 1: Different methods/techniques/models of tropical cyclone track prediction

Type of Method	*Method*	*Technique/ Model*	*References*
Statistical	Statistical-Climatological	Climatology	Lourensz, 1981; Crutcher and Hoxit,1974; Martin, 1974
		Analogue	Hope and Neumann, 1971; Jarrell and Somervell, 1970; Jarrell et al., 1975; Annette, 1978; Leslie, 1992
		Cliper	Bell,1963; Chin, 1970; Neumann, 1972; Leftwich and Neumann, 1977; Neumann and Mandal, 1978; Kivganov and Mohanty, 1979(a); Aoki, 1979; Xu and Neumann, 1985; Leslie et al., 1990, Morrison et al., 1992.
	Statistical-physical	NHC-67, NHC-72, TOPEND, USTCYC 7075, Stepwise Screening.	Viegas and Miller (1958); Miller et al., 1968; Kivgnav and Mohanty, 1978; Mohanty, 1979; Mohanty, 1980; Neumann et al., 1972; Keenan and Woodcock, 1981; Kuuse, 1979; Keenan, 1984; Chen, 1985.
	Statistical-dynamical	NHC-73, NHC-83, NHC-90	Neumann and Lawrence, 1975; Matsumoto (1984); Neumann, 1988; Neumann and McAdie, 1991; Wu and Xu, 1980; Chen, 1985; JTWC (1992).
Dynamical	External Force	Steering Current Method	Kasahara,1959; Chin, 1970; Chin, 1972; George and Gray, 1976; Neumann, 1979; Kivganov and Mohanty, 1979(b); Keenan, 1982; Chan and Gray, 1982, Holland, 1984; Pike, 1985; Elsberry, 1988; Fiorino and Elsberry, 1989; Marks, 1989; Ueno, 1989; Shapiro and Ooyama, 1990; Smith et al., 1990; Evans et al., 1991; Elsberry and Bohner, 1993; Wang and Holland, 1993.

(contd.)

Integral Method	Barotropic Model	Kasahara, 1957; Das and Bose, 1958; Dutta and Pradhan, 1968; Sanders and Burpee (1968); Renard (1968); Sikka, 1975; Singh and Saha, 1976, 1978; Ramanathan and Bansal, 1977; Goldenberg et al., 1985; DeMaria et al., 1992; Holland et al., 1991; Lord and Franklin, 1987; Franklin, 1990.
	Baroclinic Model	**Regional Models** Harrison, 1969; Elsberry and Harrison, 1972; Miller, 1969; Miller et al., 1972; Harrison, 1973; Hinsman, 1977; Ookochi, 1978; Hodur and Burk, 1978; Harrison and Fiorino, 1982; Mathur, 1974; Hovermale and Livezey, 1977; Elsberry and Peak, 1986; Prasad, 1990; Prasad et al., 1992; Iwasaki et al., 1987; Mathur, 1991; Puri et al., 1992; Chen et al., 1995; Kurihara et al., 1993, Stinikov, 1991; Zhu, 1992.
		Global Models Manabe et al., 1970; Bengtsson et al., 1982; Miller, 1993; Andersson and Hollingsworth, 1988; Mathur, 1991; Mathur and Shapiro, 1992; Ueno and Ohnogi, 1992; Fiorino et al., 1993; Krishnamurti et al., 1989, 1993; Goerss and Jeffries, 1994; Redford et al., 1995.

statistical techniques is to use historical data to formulate some sort of prediction algorithm by which the tropical cyclone motion (predictand) over some future time interval is found to be statistically related to some current parameters (predictors), environmental or otherwise. The sources of predictors are from one or more of the four original informations: climatology, persistence, environmental data and numerically forecast fields data.

The relative importance of three predictive sources (climatology, persistence and environmental fields) in reducing the variance of storm motion varies from basin to basin (Neumann and Hope, 1972; Neumann, 1975; Keenan, 1985; Pike, 1985). These studies on the relative predictive potential of three sources suggest that the Australian basin is statistically most difficult amongst

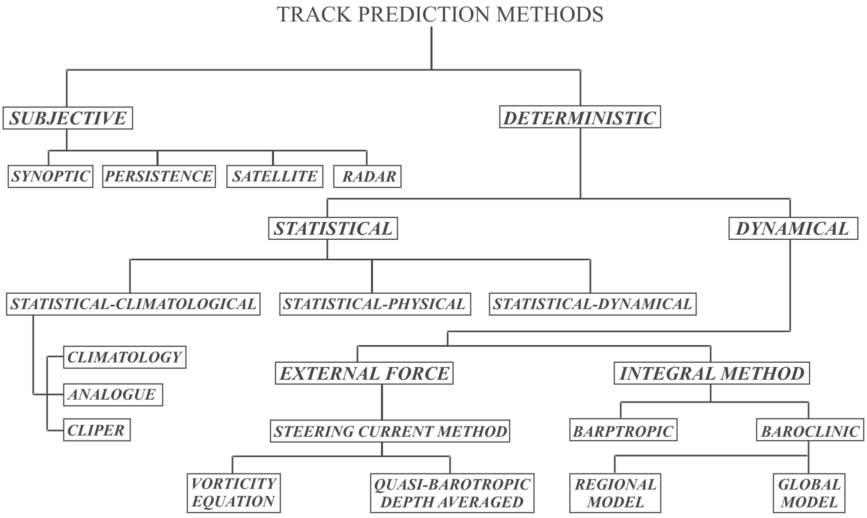

Fig. 3: Different methods of track prediction.

all basins. On the other hand, the North Indian Ocean (the Bay of Bengal and Arabian Sea) are the easiest of all.

The statistical methods are broadly categorized into three groups: statistical-climatological, statistical-physical/synoptic and statistical-dynamical.

Statistical-Climatological Methods

Observations that tropical cyclones in certain regions and seasons move along similar tracks have given rise to a range of climatological techniques for forecasting motion. These techniques may be grouped into four categories: climatological mean motion, analogue, Markov chain method and combined persistence and climatology techniques.

a. Climatological Technique

The simplest approach is to calculate the mean motion of all tropical cyclones in a few degrees latitude/longitude square (Marsden square) for a specified time period. One method is to use means and standard deviations of meridional and zonal motion for five Marsden squares by the calendar month; the standard deviations give an indicator of the uncertainty in the climatological forecast. A variation on this method is to develop histograms for specified direction and speed ranges and to present these as cyclone roses on charts for display in the forecast office (Lourensz, 1981).

The climatological tracks can be used to calculate the probability of a tropical cyclone being in a specified area at each of the standard forecast time periods (Crutcher and Hoxit, 1974). A very effective variation on this method is to generate a scatter plot of the 12, 24, 48 and 72 hour positions of cyclones that moved through the current storm location (Martin, 1989). This plot may contain all tropical cyclones or some subset, such as those within a certain time or motion window for the current storm. Such plots effectively indicate potential bifurcation regions where storms have a tendency to move in one of two (or more) preferred directions. This knowledge is useful for identifying potential for large forecast errors and for interpreting other techniques, such as Cliper.

b. Analogue Technique

The analogue technique is based on the assumption that a given cyclone is expected to move with the mean speed and direction of all storms that have occurred in that region within some time interval close to the current day. This is another type of climatological prediction. Although, an experienced forecaster keeps a note of such information in his mind in his day-to-day work, objective method of selecting such analogues was required. These techniques were developed for the Atlantic by Hope and Neumann (1970), for western North Pacific by Jarrell and Somervell (1970), for the eastern North Pacific by Jarrell et al. (1975), and for the Australian region by Annette (1978).

The important aspect of such technique is the specification of analogues in terms of tolerance in space and time. Depending on the data set and accuracy required, these limits of tolerance can be relaxed. The complication arises when more than one family of storms is associated with a given area and time of the year. In such situation, a simple mean of both the tracks is taken.

Analogue method consists of searching for all tropical cyclones in the historical record that occurred within a preset spatial, seasonal and translational velocity range of the cyclone to be forecasted (Hope and Neumann, 1971). The forecast track is derived as the mean of all cyclones. The scatter in analogue track provides an objective indicator of the uncertainty in the forecast.

For Indian region, Gupta and Datta, (1971) used an analogue technique for prediction of tropical cyclone tracks which was put in operational use in India until 1975 for issuing storm advisories. In 1975, Datta and Gupta further modified this scheme. After selecting the analogues, a predicted velocity was arrived at for each analogue by giving time-dependent weighting to the velocities of analogue and existing storms. From the different forecast positions probability ellipses were drawn for different probabilities for each of the forecast hours. The scheme also incorporates a programme to calculate the probability of existing storm striking a particular coastal area. Datta, Bansal and Bindra (1981) published the results of the performance of the scheme for the storms of the period 1971 to 1975. This scheme is currently in use in India for issuing advisories during the storm situations.

c. Markov Chain Method

The Markov chain approach provides transition probabilities between speed and direction ranges, known as "bins", based on the climatological characteristics of previous cyclones in the region and time of the year (Leslie et al., 1992). The selection of bins is constrained in that each must contain a similar proportion of cyclones with sufficient number to allow a stable prediction. The Markov chain technique provides useful indications of the likelihood of changes in speed and direction and thus the degree of consideration given to persistence. Though, this is a new concept, yet it is not found to be of much use for prediction of tropical cyclone tracks.

A variation on this approach, used by JTWC (J. Martin, 1990), is to keep all cyclone tracks in a database on a personal computer, then to search for the analogue by any criteria specified by the forecaster. This method provides a degree of flexibility in the analogue selection criteria and provides a ready, objective answer to the types of climatological questions that often arise in forecast discussion.

d. Combined Persistence and Climatology

A combination of persistence and climatology provides the best basic forecast technique and the basis for comparing forecasts from different regions. The first such technique was to combine persistence and climatology with equal weights, the $1/2(P + C)$ method developed at the Royal Observatory, Hong Kong (Bell, 1963; Chin, 1970). This is still used in a number of forecast offices (WMO, 1987) and is designated HPAC at JTWC. Operational analogue techniques also use persistence with decreasing weight over the first 36 hours.

In recent years the CLIPER technique (CLImatology and PERsistence, Neumann, 1972) has gained widespread acceptance (Leftwich and Neumann, 1977; Aoki, 1979; Xu and Neumann, 1985; WMO, 1987; Leslie et al., 1990). Cliper consists of regression equations to predict the zonal and meridional displacement of a tropical cyclone for set time periods, usually 12, 24, 36, 48 and 72 hours. The equations are developed by some form of stepwise regression with the set of predictors including current and past position, intensity, motion, and Julian date of climatological days. Generally with these limited number of predictors, polynomial equations up to 3rd order are used. The selection criteria are based on the amount of variance explained from the climatological cyclone record and additional methods are used to further stabilize and enhance the final result (Neumann, 1972). As a general outcome, persistence predictors are given the highest weighting for the first 24 hours or so, and climatology dominates at longer time periods.

For Indian seas, Sikka and Suryanarayana (1966) developed a scheme of prediction of tropical storms based on climatology and persistence. The authors found higher errors in position and/or direction of movement vector when the storm is in the recurvature stage or when it shows sudden acceleration or deceleration. Mandal and Neumann (1978) developed a set of regression equations using the same elements as predictors that are typically used for selecting storms in analogue methods, namely, the day number, initial latitude and longitude, average meridional speed during past 12 and 24 hr, average zonal speed, past 12 and 24 hr. The predictands were: latitudinal and longitudinal displacements at 12 hourly steps up to 72 hours. Probability ellipses are also produced in this scheme. The major difference from the analogue method was while the analogue method uses the clusters of predicted positions obtained from the different analogue storms; this method used the prediction errors to construct the probability ellipses. The scheme was superior to the analogue method because of its computational simplicity and also because this method will always produce a forecast whereas it is quite likely that the analogue method may produce no forecast due to non-availability of matching pattern. Kivganov and Mohanty (1979a) developed a method based on empirical predictors only (i.e., climatology and persistence) which was similar to Cliper technique. The method was developed based on the climatological information for the period and tested for cyclones of subsequent years. The results are discussed in the Section on Statistical-Dynamical Model.

It has been widely accepted by all forecast offices in the world to use Cliper as their basic forecast tool. Although a large computer is needed to develop the original equations, the forecasts can be made on any computing system, in essentially no time. Cliper also provides a convenient and consistent benchmark for indicating the skill of other forecast techniques.

Neumann (1981) introduced the concept of forecast difficulty level (FDL) to assess forecast improvements over the North Atlantic basins. The concept is based on the use of residual errors of Cliper to provide a threshold skill level and a basis for determining forecast difficulty. The value of FDL is proportional to operational forecast errors. The idea behind development of this parameter is to normalise all forecasts by the Cliper errors to provide homogeneous indication of forecast skill. Pike and Neumann (1987) presented FDLs for all the tropical cyclone basins in the world (Table 2). It may be seen that maximum values of FDL are observed for Australian/southeast Indian and southwest Pacific regions. The North Indian Ocean has the lowest magnitudes of the FDL. This implies that under similar circumstances the cyclones are easiest to predict in the North Indian Ocean compared to any other basins in the world. However, it may be noted that the FDL relates to only the intrinsic nature of the cyclone tracks. The operational factors such as accuracy of fixing the cyclone centres will affect the persistence forecasts. This is particularly important for cyclones of North Indian Ocean which are relatively weak and therefore the accurate fixing of their centres is difficult.

In recent years, there have been considerable advancements in the development of advanced statistical techniques using physical and dynamical parameters as inputs to the statistical models. These techniques generated a

Table 2: Forecast Difficulty Level (FDL) in Km in six different ocean basins of the world

Basin	*Mean Storm Latitude*	*24 hr FCST*	*48 hr FCST*	*72 hr FCST*
SW Pacific (Australian)	20.1° S	241	503	728
North Atlantic	27.6° N	210	463	680
North West Pacific	20.4° N	184	416	632
SW Indian	18.4° S	161	339	500
North East Pacific	17.9° N	144	295	431
North Indian	15.7° N	117	230	328
Mean of all Basins		176	374	550

* After Pike and Neumann (1987)

lot of interest among cyclone forecasters as some of them are found to have skills much better than climatological or analogue techniques.

Statistical-Physical Models

In this approach, the physical factors responsible for the movement of tropical cyclones are taken into account through synoptic observations in and around the storm's field. The contribution of environmental field relative to climatology and persistence in explaining the variance of cyclone motion varies in different regions. Significant differences occur between the zonal and meridional components. Climatology is found to be almost insignificant as a predictor of meridional motion in the Atlantic, but is good predictor for zonal motion. Although the persistence is a good predictor for short range prediction, it contributes considerably less at 72 hr. The synoptic information, by contrast, contributes more at longer time intervals for Atlantic region. Synoptic information is also found important for Australian region, but the contribution decreases with time.

The earliest Statistical-Synoptic model is the NHC-67 model (Miller et al., 1968). Regression equations were developed using data from 1945 to 1965. Apart from past 12 hr movement, the predictors included 1000, 700 and 500 hPa heights and 24 hr height changes, as well as 700-500 and 1000-700 thickness, at 120 grid points centred on the storm. Additional predictors, evaluated at only selected grid points, included the geostrophic wind components and vorticity at 1000, 700 and 500 hPa, thermal winds based on the 700-500 and 1000-700 hPa thickness, and average height changes at the three levels.

Kumar and Prasad (1973) developed two regression equations with the 24 hr displacements in longitudinal and latitudinal directions as predictands. The difference of 700 hPa contour heights at grid points located 71/2 deg. to the N,S,E and W of the storm centre along with persistence of the storm motion were the predictors. The scheme was developed based on six years data and tested on storms occurring in the following year. The average vector error was found to be 80 nm, the range being 5 to 163 nm.

Bansal and Datta (1974) developed two sets of two regression equations each. The predictors for both the sets were latitude, longitude and central pressure of the storm and surface pressure values at grid points 5 deg. apart on 20 deg. square area centred at the storm centre at corresponding synoptic hour. The predictands were latitude and longitude of the storm centres: one set for 12 hr forecast period, the other for 24 hr forecast period. A screening procedure was applied to reduce the number of variable entering the equations. The scheme was developed using eight years data and was tested on the storms of following year.

Mohanty (1979) used synoptic predictors such as sea level pressure fields, geopotential fields at 700 and 500 hPa and the 1000 to 700 hPa and 700 to 500 hPa thickness computed over a 5 deg. lat./long. moving coordinate to obtain prediction for the cyclones of the Bay of Bengal. Other parameters taken are geostrophic steering currents at 700 and 500 hPa surfaces and the preceding 12 hour track of the storm. Kivganov and Mohanty (1978) developed a physical statistical method of forecasting post-monsoon storms in the Bay of Bengal. They used coefficients of empirical orthogonal functions of meteorological fields and the past 12 hr storm movement as predictors. A minimum number of predictors with maximum amount of prediction information were selected by stepwise regression technique. Another method based on empirical predictors only (i.e., climatology and persistence) was developed by Kivganov and Mohanty (1979a) which was similar to Cliper technique developed for other regions. Mohanty (1980) developed a scheme in which three independent forecasts derived from the above three methods are obtained and then used as basic predictors to derive a new set of prediction equations. In order to consider the non-linear effects, a third-order polynomial with three basic predictors and 16 additional predictors are generated. A stepwise screening regression procedure is used to eliminate the predictors which fail to provide the prescribed minimum incremental reductions of variance (0.1%). Mohanty (1994) summarizes the performance of different objective methods discussed above in predicting the tracks of the post-monsoon cyclones. It is found that the method using combination of three independent forecasts from three different models provides the best forecast.

Some of the statistical-synoptic techniques used by different forecast offices in the world are: NHC-72 (Neumann, et al., 1972); Topend (Keenan and Woodcock, 1981), AUSTCYC 7075 (Kuuse, 1979) and other statistical techniques (Keenan, 1984) for use in Australia; and Stepwise Screening Method at the Shanghai Typhoon Institute (Chen, 1985).

Statistical-Dynamical Model

These models use numerical outputs from a numerical model in addition to the predictors used by the Statistical-Synoptic Models. One of the earliest models of this kind was NHC-73 model developed by Neumann and Lawrence

(1975). The predictors used as input to this model were: Output from Cliper model, current 1000, 700 and 500 hPa height fields and 24, 36 and 46 hr height predictions from NMC, Washington numerical prediction model. The above model uses an overlapping aerial stratification of the dependent data set into 52 zones across the tropical Atlantic.

While the performance of such models is better than other statistical models, there are certain limitations of these techniques. Inclusion of numerical products as input to the model makes it very complicated. Moreover, the prediction from these models cannot be made until the output from numerical model is available for a large number of tropical cyclones from past records. This demands operational run of the same NWP model for a longer time. Further, the success depends on the quality of objective analysis and subsequent forecast of tropical cyclone environment with NWP model. This delay may be six hours or longer. The accuracy of the numerical models for tropics is questionable. While developing the model, actual analysis fields from numerical model are used. However, in an operational mode, serious problems can crop up from errors and biases in the numerical output.

NHC-73 model was insufficiently robust to withstand changes in the numerical model packages which provided input. With the lessons learned from the above model, NHC-83 was designed with sufficient robustness to withstand reasonable changes in the statistical characteristics of the large scale numerical model (Neumann, 1988). Nevertheless, changes to the large scale model have caused some problems with NHC-83 model also. The model, which was introduced operationally for the 1983 hurricane season, outperformed other models in use at NHC by a rather wide margin until 1988. Nevertheless, long-term operational use of the model has disclosed certain design weaknesses.

Two approaches to potential improvement are suggested (Neumann and McAdie, 1991). The first involves maintaining the basic integrity of the NHC-83 model but using deep-layer mean winds rather than deep-layer mean geopotential heights as the main source of predictive information. The second method involves retaining the geopotential heights as predictors but revising the model based upon an evaluation of NHC-83 error patterns. NHC-90 is based on the second approach. Early results of the performance of the model suggest that it is likely to outperform NHC-83.

WU and XU (1980) describe a statistical-dynamical model developed at the Shanghai Typhoon Institute. The horizontal equations of motion are integrated for a homogenous Rankine vortex on a *β-plane with environmental forcing estimated each six hours by a statistical stepwise screening method. This forecast tracks to 60 hours and is then related to predictors similar to those in the statistical*-synoptic model (Chen, 1985).

The statistical-dynamical models, though very successful in predicting the tracks of the tropical cyclones, are less popular amongst developing countries in the tropics affected by the tropical cyclones due to excessive demand of computer resources and for want of requisite NWP data for development of these models.

Dynamical Models

Numerical tropical cyclone track prediction models have recently proven to be successful in the operational prediction of tropical cyclone motion. The forecast errors of large-scale motions with global models have also improved considerably in recent years (Lange and Hellsten, 1984). Much of this success is contributed by increase in computer power, developments in numerical techniques, improved understanding of physical processes and improvements in observing systems and objective analysis and initialization. While the improvements in predictions in mid-latitudes have been quite dramatic, the numerical forecast improvements in tropics have been more modest. Perhaps, the most important factor is the relatively poor data coverage in the tropics compared to mid-latitudes. Moreover, the horizontal gradients of meteorological properties such as temperature and geopotential heights in the tropics are of the same order as the measurement inaccuracies. Inadequate understanding of the dynamics and thermodynamics of tropical circulations, especially about physical processes involved in the release of latent heat energy and its contribution to large-scale dynamics are some of the important factors contributing to problems of numerical forecast for tropics. It also follows that moisture measurements are more important in the tropics than in mid-latitudes, and yet the rawinsonde moisture observation may be representative of only a small area around the station. Convective-scale processes have been typically parameterized in terms of large-scale circulations. However, it is not clear whether the basic assumption of parameterizability is applicable for the smaller scale tropical circulations or not.

In spite of the above stated limitations, the use of NWO models for prediction of tropical cyclone tracks has a long history of more than four decades. Just after the first attempt of NWP model development, work has been carried out in Japan and USA to use NWP models for tropical cyclones. The numerical prediction of tropical cyclone tracks are broadly divided into two categories: Steering concept (external forcing) and Integral concept (both external and internal forcings).

Steering Current Method

Techniques to estimate the “steering current” in which a tropical cyclone is embedded has arisen from the notion that tropical cyclones are equivalent to corks in the stream, and that an accurate determination of stream flow will provide excellent forecasts. Research over the past several decades has shown that this simplistic picture is inaccurate and that interaction between the tropical cyclone and its environment has a marked impact on motion (e.g., Fiorino and Elsberry, 1989b; Shapiro and Ooyama, 1990; Smith et al., 1990; Wang and Holland, 1993). Nevertheless, up to 80% of the variance of tropical cyclone motion can be explained by the large scale environmental flow (Neumann, 1979; Keenan, 1982) and its estimation provides valuable support for track prediction. Operational techniques for determining an appropriate steering flow include space mean approaches, such as MUSIC technique (MUltilevel Steering by Integrated Current) used in several Asian countries (WMO, 1987), and the Control Point method of Chin (1970). The major difficulties arise from removal of the cyclone circulation and in determining the appropriate level or layer mean.

George and Gray (1976), Chan and Gray (1982) and Holland (1984a) examined the relationship between tropical cyclone motion and the environmental flow using composite cyclones. They estimated the basic current by averaging over a 1-7° latitude radial band surrounding the cyclone and found significant and consistent track deviations, which agreed with those from composites of operational analysis by Brand et al. (1981). In the mean, cyclones tend to move polewards and westwards of this basic current; for example, low latitude westward-tracking cyclones move faster and slightly poleward of the basic current; those moving to the northeast move slower and to the west. These findings are in qualitative agreement with the theoretical studies discussed above. The theoretical studies also support the forecaster experience that very large cyclones tend to move more independently of the environmental flow than do small systems.

Geopotential heights have been used in some studies to estimate the environmental flow (Chin, 1972 and George and Gray, 1976). Although, these produced similar results to direct wind observations, height fields are quite smooth and unreliable in the deep tropics (Neumann, 1979) and modern wind analysis methods are becoming quite accurate.

Kivganov and Mohanty (1979b) proposed a hydro-dynamical method of prediction of tropical cyclone tracks in the Bay of Bengal. In this method, the cyclonic storm is represented by a constant circular vortex stream described in terms of the maximum sustained wind and the radius of the storm's eye. A depth averaged barotropic flow is assumed. The vortex representing tropical cyclone is eliminated from the initial stream function analysis leaving only a steering wind field in the region of the cyclone. The cyclonic vortex motion is estimated by the steering current which is determined by a numerical model using quasi-solenoidal approach.

Removal of a symmetric cyclone is not recommended for operational applications, as this does not always provide a good indicator of the environmental flow. The cyclone may be asymmetric and non-linear asymmetries in the environment will be partially removed, as has been shown by the idealised studies of Evans et al. (1991) and Smith et al. (1990). A better approach is to use an appropriate filter to remove the cyclone scales, preferably only in the vicinity of the cyclone. A Fourier filter has been used with success by Marks (1989) and Ueno (1989), and Elsberry and Bohner (1993) have suggested a method of filtering consistent with known theoretical studies of tropical motion.

The appropriate level or layer mean to be used to indicate the steering current has been debated widely (Elsberry, 1988). The most consistent observational result is that the 700 or 500 hPa level provides the closest approximation (George and Gray, 1976; Neumann, 1979; Pike, 1985). This is supported by the theoretical studies of Wang and Holland (1993) and Holland and Wang (1993). A more consistent and stable relationship is found for layer means, however. Holland (1984) argued against the inclusion of outflow and inflow layers and recommended the layer from 850-300 hPa. The layer from 900- 500 hPa was found to be the best by Wang and Holland (1993) and Holland and Wang (1993). This agreed with the barotropic forecast studies of Velden and Leslie (1991) and Velden (1993), who also found a distinct relationship between intensity and depth of the optimum layer mean. Many forecast offices consider that deeper layer-mean, e.g., 850-200 hPa, are best for forecasting. This apparent conflict with observational and theoretical results probably arises from the lack of good mid-level observations in the vicinity of most of the tropical cyclones. In these cases, the inclusion of 200 hPa analyses, with their observations from satellite cloud drift winds and commercial aircraft may provide a more stable analysis.

Integral Method

In this method, the tropical cyclone vortex is considered as inseparable part of the large scale flow and thus free interaction of the cyclonic storm with its outer environment is allowed. Although, these techniques were in use in most of the countries affected by the cyclones for the past four decades, with the availability of advanced computer resources in recent years, there has been a greater emphasis to employ complex NWP models to predict the tropical cyclone tracks. Considerable advances have been achieved in the prediction of midlatitude circulation systems with numerical models during past one decade. On the other hand, the advances in accuracy of the prediction of tropical systems have been relatively much slower due to various reasons. Nevertheless, a good progress has been achieved in understanding the structure and dynamics of movement of tropical cyclones. These advances provide a basis for improved track predictions with dynamical models.

The barotropic models, which were first developed in the beginning of NWP era, are still in use at several tropical cyclone forecasting centres. The regional baroclinic models continue to be the primary dynamical track prediction tool. Due to considerable improvement in the horizontal resolution and the availability of supercomputing facility at most of the NWP centres, the global models are becoming popular these days for tropical cyclone track prediction.

(a) Barotropic Models

Barotropic models are useful for tropical cyclone prediction because of their simplicity in nature, less computational requirement and easy to have higher resolution to resolve the storm structure and the interaction between the vortex and its environment. However, the environment also evolves due to baroclinic processes, especially during recurvature in association with mid-latitude trough. Thus, a barotropic model can be useful for situations in which the lower tropospheric flow in tropics is more barotropic, and for limited periods of times before baroclinic processes significantly influence the environmental circulation.

Riehl and Haggard (1953), Sasaki and Miyakodo (1954) and Kasahara (1957) were some of the earliest studies on tropical cyclone track prediction using barotropic models. In these studies, the prediction for steering flow is obtained by separating the vortex field from the total flow. By solving the equation which includes interaction terms between the hurricane and the steering flow, the prediction of movement of the vortex is obtained.

In India, the first study on the prediction of movement of low pressure systems by dynamical methods was by Das and Bose (1958). Authors computed 24 hr forecast of two monsoon depressions on the basis of barotropic model of Charney and Estoque's baroclinic model. Dutta and Pradhan (1968) used dynamical methods to predict the tropical storm movement. Sikka (1975) used a barotropic vorticity equation applied to the non-divergent part of the wind flow at 500 hPa to predict tropical cyclone movement. He used the wind flow over a large area as he found it difficult to define the vortex field and to remove it from the total field because of the paucity of data over the Indian sea area. The study shows that the storm's displacement is better predicted than its direction of movement. Recurvature is predicted generally 24 hr after its occurrence. Singh and Saha (1976) performed numerical experiments with a primitive equation barotropic model for prediction of a depression and a storm. The basic input was the observed wind from which the stream function was obtained and from the computed stream function field, the values of two horizontal components of wind vector were derived. These wind components were used as inputs to the balance equation to obtain the height fields. Ramanathan and Bansal (1977) used a primitive equation barotropic model to predict storm tracks. They treated the vortex in three different ways. The first method was to treat it as an integral part of the total flow which was integrated. They found a westward bias in the predicted tracks. The vortex was taken as symmetric one in this method. In the second method, the total field was subjected to double Fourier analysis and residual was taken as the basic field. Though the method provided good forecasts, in many cases the difficulty arose when the basic flow became so weak that the vortex advection was practically nil. In the third method, the basic flow was obtained similar to the second method, but the vortex was assigned certain characteristic with a wind maximum symmetrically around a centre. This had further improved the performance, but the vortex movement remained generally slower than actual. Singh and Saha (1978) repeated their earlier experiment on the same set of tropical storm and monsoon depression but used an improved quasi-Lagrangian advection scheme. This led to some improvement in 48 hr forecast but rapid deterioration was noticed beyond this period.

Hurricane Research Division (HRD), USA model (DeMaria et al., 1992) and BMRC, Australia model (Holland et al., 1991) are the two recent barotropic models which have shown good results. The HRD model (called VICBAR) utilizes a nested grid with high resolution near the centre and coarser grid at greater distances. In the operational version, the inner grid resolution is 50 km. The model uses the cubic spline approach for analyses on nested grid (Lord and Franklin, 1987; Franklin, 1990). In this operational case, the analysis is of layer average (850-200 hPa) winds and heights using the prior 12 hours global forecast fields as background. A crucial part of the analysis is the specification of the fields near the storm where inadequate observations exist to specify the steering and the storm structure.

The Vicbar model is run whenever a named tropical cyclone (Vmax> 33 kt) exist in the Atlantic region. It has been noticed that the performance of Vicbar model matches closely with the advance statistical-dynamical models, e.g., NHC-83 and NHC-90. In addition, this barotropic model is superior to the limited area baroclinic model (Quasi-Lagrangian Model - QLM) up to 36 hours, and is comparable beyond 36 hours. In general, the model performance diminishes beyond 72 hours.

The BMRC barotropic model (BARO) was aimed for cyclone track prediction on a workstation and can be integrated so quickly that it is feasible to do multiple integration. Thus the forecaster can use the model interactively to test various scenarios that might apply in particular situations. The basic advantage of using a barotropic model is to have multiple integration of the model in a given period compared to a single integration of a more complex baroclinic model.

(b) Baroclinic Models

Baroclinic Models are expected to improve predictions of the steering flow, especially beyond 36 hours when baroclinic effects become more evident. The vertical shear effects in the tropical cyclone structure and in the environment will be represented better. However, the real key to the success of these baroclinic models is the specification of the initial conditions to represent the location, structure, initial motion of the tropical cyclones and parameterization of physical processes in the model.

The baroclinic models are mainly of two types: (i) Limited-area/regional models (LAM) for specific region with a capability to integrate over a shorter time period (1-2 days), and (ii) General circulation models (GCM) for the entire globe with capability to integrate for a longer time period as they are not influenced by artificial lateral boundary conditions such as those imposed in LAM.

(i) Regional Models: Some of the earliest work on baroclinic models was by Harrison (1969), Elsberry and Harrison (1972), Miller (1969) and Miller et al. (1972). These research groups developed multi-layer, primitive equation models with a parameterization of number of important physical processes. It was demonstrated that tropical NWP models were not only computationally and numerically feasible, but that some tropical cyclone features could even be predicted. After these initial attempts at real data forecasting, the future efforts split into two aspects: the synoptic-scale or steering aspects on the motion problem and other concentrating on the tropical cyclone scale. The studies on synoptic-scale aspect include Harrison (1973), Hinsman (1977), Ookochi (1978), Hodur and Burk (1978), and Harrison and Fiorino (1982). The work of Mathur (1974) and Hovermale and Livezey (1977) are good examples from the approach emphasizing the tropical cyclone simulation. The advantage of synoptic approach is that the computational savings achieved through a simple treatment of the tropical cyclone allowed a greater number of cases to be run which can be useful for operational purposes.

The earliest baroclinic models which were made operational for tropical cyclone track forecasts include Moving Nested Grid (MNG) model for Japan by the Japan Meteorological Agency (JMA), the One-way influence Tropical Cyclone Model (OTCM) and the Nested Tropical Cyclone Model (NTCM) by the U.S. Navy Fleet Numerical Oceanography Centre (FNOC) and a Movable fine-mesh Model (MFM) for tropical cyclones threatening U.S. coastal areas by the National Meteorological Centre (NMC). Elsberry and Peak (1986) summarize the development of these models.

In India, there has been good progress in recent years towards the use of limited area model for the prediction of tropical cyclones in the Indian seas. Prasad (1990) proposed a scheme for generating synthetic observations in tropical cyclone field for initializing a limited area primitive equation model and tested on a coarse resolution ($2° \times 2°$) forecast model (Prasad et al., 1992). Mohanty et al. (1989) used a multi-layer primitive equation limited area model appropriate to a meso-scale quasi-hydrostatic baroclinic system to predict the track of monsoon depression. He found that there is a significant improvement of the predicted track by this model compared to a barotropic primitive equation model.

The single objective of the earlier dynamical models was to predict the future positions. The development of new models was intended to improve cyclone-related precipitation forecast as a secondary objective. Moreover, intensity predictions are also expected to improve with the development of these high resolution baroclinic models, although the resolution is still not adequate enough to represent the details of inner core wind distribution.

Some of the other recent baroclinic models for prediction of tropical cyclone tracks are: Typhoon Model (TYM) for western North Pacific (Iwasaski et al., 1987), Quasi Lagrangian Model (QLM) for U.S. (Mathur, 1991), BMRC model for Australia (Puri et al., 1992), Taiwan Model (Chen et al., 1995) and Geophysical Fluid Dynamics Laboratory (GFDL) model (Kurihara et al., 1993).The development and testing of baroclinic models are underway in several other countries. Stinikov (1991) and Zhu (1992) give review of the developments in this direction in former USSR and People's Republic of China respectively.

(ii) Global Baroclinic Models: One of the serious demerits of LAM is their poor prediction of large scale features due to unrealistic lateral boundary conditions. This is particularly important for tropical cyclone track prediction since large scale steering current is one of the most essential mechanisms that determines movement of the cyclone. The main advantage of the global baroclinic models relative to the limited-region baroclinic models is that it does not require lateral boundary conditions that eventually limit the useful forecast interval. However, until recently the most serious problem associated with global models was the specification of initial cyclone field. It has been first noted by Manabe et al. (1970) that tropical cyclone like vortices do form in coarse resolution global circulation model. They simulated tropical disturbances in their model with a horizontal resolution of 400 km and have shown that increase of horizontal resolution from 400 km to 200 km grid made the structures of the disturbances more realistic. Bengtsson et al. (1982) examined tropical cyclone vortices in the operational forecasts performed at the European Centre for Medium Range Weather Forecast (ECMWF).

The most important problem associated with the large scale models in predicting the tropical cyclone is the discrepancies of the detailed structures of tropical cyclones between the predicted and the observed, due to coarse horizontal resolutions. Tropical cyclone models are characterized by the very fine resolution of the order 10 to 50 km which is too fine to be attainable in the large scale models due to computer power limitations.

Recent developments towards the improvement of global models have yielded improved tropical cyclone forecasts. These efforts were mainly in two directions: to increase the resolution of the models and to include appropriate and more accurate parameterization schemes of the physical processes available. Miller (1993) indicates substantial reduction of systematic errors in the ECMWF model due to finer resolution and inclusion of more realistic parameterization schemes for physical processes.

Another important problem in connection with tropical cyclone forecast by global models is the representation of initial cyclone fields. The ECMWF researchers, Andersson and Hollingsworth (1988), were one of the first groups to study methods of inserting synthetic observations into a global model to represent tropical cyclones. The ECMWF, however, does not use such observations in their operational model. The JMA was one of the first to introduce synthetic observations into an operational global model (Ueno and Ohnogi, 1992). The Fleet Numerical Meteorology and Oceanography Centre (FNMOC) began inserting synthetic observations in their global model during 1990 (Fiorino et al., 1993; Goerss and Jeffries, 1994). The United Kingdom Meteorological Office (UKMO) has also introduced bogussing procedures in their global model (Redford et al., 1995). Lord (1991) described the bogussing system for the U.S. NMC global model which uses the position and structure information transmitted from the tropical cyclone warning centres. The procedure is based on the scheme proposed by Mathur (1991) and Mathur and Shapiro (1992). In summary, all the important global model centres except ECMWF insert synthetic observations to atleast define the position of the tropical cyclone. All these centres insert the synthetic observations during the analysis, which blends these observations with actual observations in and around the tropical cyclone to provide the initial conditions for the global model.

Krishnamurti et al. (1993) summarize the improvements related to the tropical cyclone life cycle and track forecast through the physically-based initialization system that has been developed to make use of the diverse data sources, especially the satellite-based rainfall rates. The FSU global model is typically integrated with T170 horizontal resolution, which is surpassed only by the ECMWF T213 model. Krishnamurti et al. (1989) have tested the effect of horizontal resolution for tropical cyclone prediction with T21, T31, T42, T63, and T106 spectral models. Systematic improvements in the formation and motion of the storms are achieved for several case studies when the horizontal resolution is improved and an additional vertical level within the surface layer is utilized to improve the surface flux calculations.

There has been considerable improvement of track prediction forecasting by these global models mainly through the improvement in the resolution, improvement of the accuracy of parameterization schemes for physical processes and the use of synthetic observations. These advances in the global model suggest that useful track forecasts up to 5-day can be achieved in certain cases with advanced global models. However, more complete and systematic evaluation of these models for tropical cyclone forecasting is needed.

Expert Systems

Besides statistical and dynamical models as described above in operational set up, another objective approach in use for making final operational forecast is the Expert System. This system is used for integrating various methods of forecast available to the forecaster. The traditional check list used in different forecast centres to suggest logical steps to be followed in the event of a tropical cyclone is a rudimentary form of an expert system. More complex decision trees also have been developed for interactive use on workstation or personal computer (Hanstrum and Foley, 1988). The Joint Typhoon Warning Centre (JTWC) has a technique called TAPT (Typhoon Acceleration Prediction Technique) which uses surrounding wind fields to estimate the potential for rapid or delayed acceleration associated with poleward oriented or recurving tropical cyclones. Guidelines are provided for duration of acceleration, maximum acceleration and typhoon path.

One area of considerable potential for meteorological applications is the use of visualization techniques. Specific patterns such as satellite imagery could be recognized objectively and entered into decision trees. A sequence of satellite imagery and cyclone track could be used to develop new motion forecast algorithms.

Greater complexities can be achieved by the use of high order expert systems, such as neural networks. These accept a set of input data and results from historical events, such as past tropical cyclone tracks, then iteratively calculate the potential paths via a series of cases and branch points. They require massive computing facilities to develop, however, and have not been shown to be better than standard statistical and dynamical techniques.

CONCLUDING REMARKS AND FUTURE PROSPECTS

Track prediction has been the focal point of the tropical cyclone research all over the world. Accurate prediction of cyclone motion is extremely crucial for cyclone forecasting and warning work. Availability of a large number of subjective and objective techniques reflects the level of importance and concern of the cyclone forecasters.

There has been considerable progress in recent years towards the development of track prediction models. There are two important areas where significant progress has been achieved in the past one decade. These were: improvement in the global circulation models in terms of its resolution, improvement of the accuracy of parameterization schemes for physical processes and use of synthetic and non-conventional data in the data assimilation schemes and improvement in the statistical-dynamical techniques.

Further improvements in the track prediction will come from several areas, including research, improved observations, numerical models and statistical techniques. Continued research is required to develop proper understanding of the processes involved in the cyclone motion. Improvement in observations is essential for building appropriate knowledge of the structure and anomalous behaviour of the cyclones. Improvement in numerical models will provide further improvements in forecast skill.

With the advent of advanced super-computing techniques, much more improvement in the resolution of global model is expected in the years to come. This is quite evident from the improved performance of ECMWF's high resolution T-213 model. Parameterization of physical processes appropriate to intense tropical convection in the global model is yet another area where considerable improvement is needed. Other areas where improvement is required are the extensive data coverage over the data void regions through non-conventional observations and synthetic cyclonic vortex data generation, use of nudging technique for initial matching of analysed cyclone centres with the corresponding observations and physical initialization of input data. Expert systems using neural network technique is another area through which a lot of improvement is also expected. Better assimilation of the cyclone and its environment and the use of coupled atmosphere-ocean models can bring in substantial improvement in the model performance. Coupling numerical model and statistical forecast can also provide further improvements. A significant improvement of performance is expected from a new approach known as Ensemble technique. This technique combines some estimates of the forecast skill with different forecasts. This is done by a method known as the Monte-Carlo method of integrating a numerical model many times whilst introducing slight changes in the initial analyses. Alternatively, the forecast from several centres can be combined in a manner which indicates the degree of forecast uncertainty and overall improvement of the prediction of the tracks of tropical cyclones.

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Risk Analysis for Oil Spillage in Marine Environment

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INTRODUCTION

Recent major oil spillage intentionally made in Gulf war as well as past accidental releases prove that the oil spillage can cause severe adverse effects on water, air and social environment by damaging fishes, plankton and other organisms, sea birds, tourist beaches and shorelines etc. It is, therefore, important to know the nature of oil spill spread on the shore and the time available for deployment of contingent measures for combating oil pollution.

The oil spills during the Gulf war was more than the Exxon Valdez spill which took place into Alaskan waters (Bugle et al., 1991). As a result, 15 million barrels (2.5 million tons) of oil spillage was sighted in the Gulf. With the help of Sagar Sampada, National Institute of Oceanography investigated its impact on the ecology of India's marine environment. Table 1 gives an account of major oil spillage in India and their impacts on environment which are much less in magnitudes than the above mentioned major spillages in the world.

The extent of damage caused by an oil spill depends upon the quantity of oil spilled, type of oil involved in the spillage and the oceanographic and meteorological conditions prevailing in location where the spill has occurred. When the oil spills in large quantity, it temporarily affects the air-sea interaction, thus preventing the entry of oxygen from atmosphere. The first sets of organisms to be affected are the primary producers like phytoplankton, which is the basis of marine food chain. The others are free-swimming organisms.

The objective of the risk analysis is to estimate quantitatively the probabilities of accidental as well as chronic oil releases from different segments of offshore operations and to calculate the possible consequences

Table 1: Major oil spillages in India

Incident	*Quantity Spilled*	*Impact on Environment*
Cosmos Poineer's grounding off Gujarat (1973)	3000 tons	No report available
Transhuron accident in Lakshadweep Sea (1974)	5000 tons of furnace oil	Extensive damage to coral reefs around Kilton Island; tar balls along West Coast
Disappearance of a Greek tanker off the Gulf of Kutch (1974)	Patches of oil off Gulf of Kutch	No report available
Grounding of Sea Leaf Mediterranean in Bay of Bengal (1979)	Not known	No report available
Blow out Sagar Vikas (1982)	Nil	Nil
Major oil spill in Arabian Gulf as a result of damage to Iranian oil rigs during attack by Iraqi Aircraft (1983)	Film of oil on surface noted	Damage to planktonic organisms
Major fire on board SCI ship Lajpat Rai in Bombay Harbour (1984)	Less than one ton	Unaesthetic appearance of beach in Bombay
Maltese tanker AMT Puppy@ in June 1989	5500 tons beyond EEZ off Bombay and two tons in Bombay Port	Oil sank into the sea beyond western EEZ bottom and no surface appearance. However spilled oil in Bombay deposited on beach rocks giving unaesthetic appearance.
Accident of A Santa Mohan @, 29 July, 1989 in Bombay Harbour	Trace amount	No significant damage to environment
Oil spilled by merchant vessel off Tarapore on 4 August, 1989.	Trace amount	No significant damage to environment
Oil spilled by merchant ship off Saurashtra coast on 29 August, 1989.	Trace amount	No significant damage to environment
Oil spilled by merchant ship 65 NM off Cochin on 22nd March, 1982.	Trace amount	No significant damage to environment
Kerosene spill in Madras Port in August 1982	1000 tons	Localised effect; low oxygen led to death of planktonic organisms. No other adverse impact.

(*contd.*)

Table 1 (*contd.*)

Oil slick off Nicobar Islands due to oil spill caused by Danish super tanker Maersk Navigater in January 1993	Not known. Estimates indicate 3000 tons	Few oil patches off Nicobar Island caused extensive mortality of planktonic organisms
Rupture ONGC offshore pipeline in May 1993	3000-6000 tons	Mortality of planktonic organisms; 3 km long Murud beach contaminated with deposits of 1000 tons oil, leading to mortality of intertidal fauna.
Grounding of M.V. Sea transporter off Singuerim, Goa in June, 1994	Trace amount	Unaesthetic appearance of beach due to oil deposition. Mortality of planktonic organisms around the grounded area.

of such spillages. However, risk analysis is not deterministic in nature. It is, rather a probabilistic approach to estimate the extent and the associated probability of the occurrence of adverse impacts due to the concerned oil spillage episode.

ENVIRONMENT AND ECOSYSTEM IMPACTS

Impact on environment and ecosystem due to oil spillage depends upon various factors such as quantity, type of oil discharged, prevailing environmental conditions, and geographical location especially coastline topography and fragility of coastal-ecosystem. The effect is less when spill is in a relatively open area or rocky coastline due to natural dispersion and evaporation. Sheltered coastlines are more fragile and can retain oil for many years within beach sediments which is released in winters. In coastal zones, the effect can be summarized as below:

(i) *Effect on phytoplankton:* Its sensitivity varies in a wide range. Green algae are more sensitive than diatoms, blue green algae and flagellates. Biological effects vary among groups and even species.

(ii) *Effect on zooplankton:* Zooplankton and newston (fish, egg, fish larvae, etc.) are more vulnerable due to exposure of lighter concentration of water soluble constituents leaching from floating oil. The effect is less in open sea and even in coastline due to higher reproduction ability.

(iii) *Effect on benthos:* The most severe effect in shallow water is on benthos. These move slow or remain stationary at the bottom and may remain in oil-polluted environment for years causing detrimental behaviour and mortality.

(iv) *Effect on fish:* Fish have an enzyme system, which reduces the effect of petroleum hydrocarbon. Therefore, mortality is negligible. However, it makes the habitat unsuitable for eating. The effect reduces in long run. The greatest danger is to benthic fish, spawning and breeding grounds of fish, their eggs, and larvae and shellfish grounds.

(v) *Effect on birds:* Aquatic birds are vulnerable since oil soaks their plumage and destroys water proofing, buoyancy as well as insulating properties. Large mortality of such birds may occur depending upon the location of spillage and species of birds involved.

(vi) *Effect on intertidal habitats:* Oil trapped in tide pools on falling tides can saturate small volumes of water into dissolved organics. Oil stranded on beaches due to felling tides tend to percolate into sediments and gets transported to estuaries and inlets. When oil contacts tissues directly, epifauna are damaged while salt marshes, mangrove swams, etc. are the damaged flora.

(vii) *Effect on human health:* It is hazardous to human health due to consumption of contaminated, bioaccumulation and retention of carcinogenic compounds like benzopyrene which is of serious concern.

METHODS OF CONTROL OF OIL SPILL

Oil slick is controlled by several methods depending upon the local environmental conditions, the significance of the areas as a natural resource and how fast the slick is required to be removed. These may be categorized broadly in the following way:

Mechanical Methods

It involves use of booms, skimmers or scoops and spray of cement. These are more effective in thicker (1 mm) and more than 500 cst viscous oil slicks. A variety of floating oil retention barriers called booms is used to stop the spread of oil slick. The method has its limitations due to underflow caused by currents/waves splash, mechanical failure of member joints, anchoring problems etc. Skimmers also work best on thick slicks floating on quiescent waters. Wind, waves, currents and high viscosity are however detrimental to its use. For example the waves reduce the mobility of skimmers as well as currents and can sweep oil under the skimmer. However, different skimmers are used depending upon viscosity of oil to increase its performance.

Chemical Methods

Absorbents such as saw dust, cotton, polyurethane foam, ureaformaldehyde, etc. and dispersants such as hydrocarbon solvents are categorized as chemical methods. The absorbents are used to absorb the crude oil and reduce its negative effect while dispersants breakup the oil film into droplets, which remain suspended in the water column due to reduction in the surface tension at oil water interface. Conventional hydrocarbon solvents containing 5-10 percent surfactant, odourless kerosene and concentrate dispersants containing

30 percent surfactant in glycol type solvent are principally used. These are more effective in early stages of oil spills and become less effective for higher viscosity and thickening of layer. Chemical agents are classified as water based, solvent based and concentration having minimum dilutant.

Biological Methods

Biological methods are characterized by biodegradation of hydrocarbons by micro-organisms such as bacteria, yeast and fungi. Over 200 such organisms are known. But the duration required may be two to six months or even longer for biodegradation. Most of these micro organisms are aerobic, and need low temperature conditions, as well as nutrients for oxidizing the hydrocarbons. There exist naturally occurring bacteria known as hydrocarbonoclastic (HCC) microbes. These convert oil into carbon dioxide and other harmless products. The common species of these microbes are:

(i) Pseudomonas putida
(ii) Bacillous Substilils
(iii) Bacillous megaterium, etc.

Burning

This is the last resort to contain the adverse effect of oil spillage, since it involves release of toxic gases and degradation of ecosystem as well as ambient air quality.

Combatant Methodology

Chemical and mechanical methods are predominantly used for combating oil slicks. Besides natural weathering, processes such as spreading, evaporation, emulsification, photooxidation, dispersion, sinking resurfacing, tarball formation, and biodegradation simultaneously occur and reduce its impact. The kinetics of these reactions depends upon the sea conditions and meteorological conditions. Among externally employed methodologies, chemical dispersion is most effective. The crude is most unlikely to form film over sea-surface. Therefore contact of sprayed chemical too is restricted. The evaporation process depends upon spreading of oil on sea surface. Those spreading slowly are difficult to combat by natural, chemical or bacterial methods. In this case, physical means such as double layered net cloth may be used.

PROCESSES FOR TRANSPORT AND FATE OF SPILLAGE

The fate and transport of oil spilled in water are governed by complex, interrelated, physicochemical processes that depend on oil properties, hydrodynamic conditions, and environmental conditions. Physicochemical and biological processes that affect transport and fate of spilled oil include advection, turbulent diffusion, surface spreading, evaporation, dissolution, emulsification, vertical mechanical dispersion, photo-oxidation, biodegradation and sedimentation. Figure 1 shows the physical and chemical processes affecting an oil slick after a spill. As biodegradation and sedimentation are slow processes these can be neglected while predicting the fate of oil spill within a week after the spill. The mechanisms involved in evaporation, emulsification and vertical mechanical dispersion process are still not well understood and thus models accounting for these processes contain high degree of empiricism. Dissolution is expected to account for 1 to 10 percent of the mass of oil spill. The effect of all these processes is dilution or removal of oil from the oil slick. It would thus not be inappropriate to consider only spreading and evaporation to predict worst case impact on the coast line in the event of an oil spill.

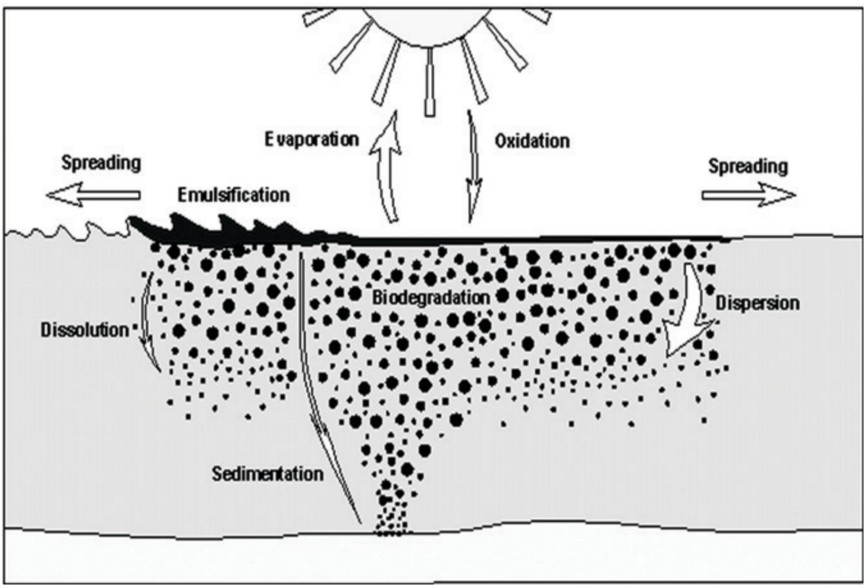

Fig. 1: Physical and Chemical processes affecting an oil slick after a spill.

Transport of Oil Slick on Water

Spreading is the horizontal expansion of an oil slick due to mechanical forces such as gravity, inertia, and viscous and interfacial tension. During spreading phase, the shape and direction of movement of the oil slick depends upon the wind, surface currents, waves and Langmuir cell circulation. As a very rough first approximation, the velocity, V_o of the centre of mass of oil move as the vector sum of the surface currents V_c and a fraction of the wind velocity W. The fraction f is the wind factor, whereas the wind induced drift f_w is known as leeway.

$$V_o = V_c + f_w$$

Dispersion of the Slick

Dispersion is one of the processes removing oil from the water surface, besides evaporation and dilution. Dispersion of surface oil is defined as the breakup of the coherent oil slick into small droplets and the spread of the diffusion of the droplets in the water column. When oil is spilled, its rate of dispersion is a function of air-sea dynamics, chemical and physical properties of the oil and the quantity of the spill. Meteorological factors control two major effects: the motion of oil over the sea and its evaporation. Oil discharged into the sea spreads out on the surface into a large slick. A semi-empirical Blokker model can be used for assessing the spread of an oil spill (Blokker, 1964). The model gives the oil slick radius (r) as a function of time

$$r = \{(3/\pi).\ k_b.(p_w - p_o)\ (p_o/p_w)\ \mathrm{v.t})^{1/3}$$

and oil film thickness (h) as

$$h = [(v/\pi)^{1/3}.\ (p_w/(3p_o\ (p_w - p_o).\ \mathrm{k_b})^{2/3}.\ t^{-2/3}$$

It is assumed that oil slick spreads in the form of a circle. Here, the symbols in the above equations are:

r = oil slick radius, h = oil film thickness, v = volume of oil spilled, t = spreading time, p_w = density of water, p_o = density of oil, and k_b = Blokker constant.

The Blokker constant is an oil specific parameter and an estimate is made from actual observation of rate of spreading of the oil on water surface.

Evaporation of the Oil Slick

A significant factor in the evaporation process is the thickness of the slick. Aravamudan et al. (1979), Audunsan et al. (1980) and Huang (1983) in their models have all assumed that slick thickness is constant over the spill area and varies with time. The model developed by Mackay et al. (1980) allows for variation in thickness. The rate of evaporation of oil from a surface of slick is given by:

$$F = (1/C)\ \{\ln p_o + \ln\ (Km.\ A.\ V.\ T.\ C/RTV) + (1/p)\}$$

where F = Fraction evaporated, V = Spill volume C = Constant dependent on temperature, A = Area of spill (thick part), R = Gas constant, T = Environment temperature, V = Molar volume, T = time, Km = Mass transfer coefficient proportional to $U^{0.78}$, where U is wind speed, p_o = Liquid vapour pressure, T_o = Boiling point temperature, and p = Surface pressure.

Emulsification

Emulsification is the process of the formation of water-in-oil emulsions often called "chocolate mousse" among oil spill workers. The formation of emulsions changes the properties and characteristics of oil to a large degree. Stable emulsions contain between 50% and 80% water representing an expansion in volume of spilled material from two to five times of the original volume. The specific gravity of the resulting emulsion can reach 1.03, compared to an original value of 0.80. Most significantly, the viscosity of the oil typically increases by an order of 1000. This viscosity increase changes a liquid product to a heavy semi-solid material that shows non-Newtonian character. As a result of emulsification, evaporation slows by an order of magnitude, spreading slows by similar rates, and the emulsified oil rides lower in the water column.

Oil-Spill Models

Several oil spill models have been developed to simulate the fate and transport of oil spills. Many of them simulate only the surface advection of oil and are called trajectory models. Some of the trajectory models include the shoreline deposition processes but not the other oil spill processes. Since the understanding of the physics of many processes is rather poor, the accuracy of the simulations must be viewed with some reservation. An extensive list of available oil spill models and oil spill processes is discussed in several publications (e.g. Lee et al., 1990). These publications also include some implementation details about each model.

METHODOLOGY OF RISK ANALYSIS: AN OVERVIEW

For systematically evaluating the potential oil outflow into the marine environment and its effect, the risk analysis is conducted in the following five parts (Mudan et al., 1989)

- Development of a spill event tree
- Assessment of oil release probability
- Evaluation of spill size distributions
- Quantification of spill consequences
- Development of risk profiles

Each of these parts can be summarized as follows (Mudan et al., 1989):

As a first step the particular broad events are identified diagrammatically (viz. event tree). These events are those which could result in a release of oil. Once it is completed, it forms the basis for the remainder of the analysis.

The probabilities of individual components identified in the event tree are determined on the basis of reliability data (when available) and statistical analysis of historical data. These component probabilities are combined to yield the probability of occurrence of the top event in the event tree.

There are no deterministic methods currently available for predicting exactly when any spill will occur, in what size, and what the precise nature of the outcome will be. So, in general, the approach to quantifying the distribution of spill sizes is statistical, relying on the historical data as a basis for the estimates.

Despite these reservations about predictability, the spill distribution phenomenon is not completely chaotic. The basic approach to spill size estimation is through the use of lognormal distribution assumption.

Once the probability and volume of oil spills associated with various segments of an offshore operation are determined, a consequence analysis can be conducted. The consequence analysis consists of two parts. The first part is deterministic and deals with spread and evaporation of oil slicks, their interaction with rough seas and their eventual break-up. The second part deals with the trajectory of the oil slicks and the determination of probable shoreline impact.

A slick of oil floating on the ocean water moves by the forces exerted by the wind and current actions. In addition, the surface area of the slick increases due to the spreading phenomenon which is caused initially by gravity and later by surface tension. The high vapour-pressure fraction of crude oil and petroleum products tend to evaporate relatively quickly (one to two days), leaving behind the heavier fractions. A part of the spilled oil may dissolve in sea water and a part of the heavier fractions may even sink because of increased density. In addition, when the oil slick thickness becomes very small after the slick has spread for a long time, the oil may form an emulsion with water (mousse). Finally, when the thickness becomes sufficiently small, the sea-slick interaction may take place leading to break up of an initially coherent oil slick. The oil that is moved by wind and the current may have impact on long shoreline.

Upon successful completion of above tasks, the expected probability of oil spilled and the consequences in terms of slick size and shoreline impact are quantified. This combined information is displayed graphically in terms of risk profiles viz. event tree or fault tree. These risk profiles graphically represent the probability of an event leading to an oil spill and the associated severity of the event.

Spill Event Tree

A simple event tree depicting events leading to an oil spill in the marine environment can be developed in the conventional way. The total spill probability is the sum of the probabilities of different initiating events, however, and may vary widely.

Assessment of Oil Release Probability

In principle, it is possible to estimate the probability occurrence of the top event by combining the probability of individual components through AND and OR gates. A detailed knowledge of the reliability of the individual components is required to compute their failure rates. In the absence of detailed information regarding reliability of offshore drilling and production systems, one uses the historical data to determine the probability of top events.

Quantification of Spill Consequences

Once the volume of the oil spilled is known, we can quantify the spill consequences using suitable mathematical models. A few of them have already been described. As stated earlier, the oil spill consequence model has both a deterministic and a probabilistic component. The deterministic component deals with the physical processes that follow an oil spill. The probability component couples the result of the deterministic model with wind and current data to evaluate the trajectories of the oil slick and predict shoreline impact.

Oil spilled in large quantities and in a very short duration of time (instantaneous spill) initially spreads rapidly on water. Oils that contain significant fractions of highly volatile components, such as light crude, undergo simultaneous evaporation and spreading. The rate of total mass loss by evaporation increases initially because of the increasing surface area, but decreases as the remaining amount of volatiles decreases. The oil is also subjected, simultaneously, to the action of waves on the ocean, particularly to the breaking wave action in rough seas. The waves breaking within the oil slick produce oil droplets of varying sizes, which are projected into the water column. Large droplets tend to rise up and attach themselves to the surface slick whereas the small droplets remain in suspension for a long time. Oceanic turbulence also tends to maintain a spatial distribution of oil drops. Submerged drops represent the non-recoverable portion of oil. The mass fraction of oil submerged in the water column increases with time.

The evaporation of light component and weathering of oil on the water surface brings changes in the physical properties of the oil, specially the value of spreading coefficient. Spreading coefficient ultimately reaches a value of zero, which results in the maximum surface area of oil spread. This stage is generally reached when the oil thickness is very small. In rough seas, because of breaking wave action and surface turbulence, the oil slick is likely to be broken into a relatively large number of patches. These patches tend to drift apart, aided by large-scale surface eddies, thereby creating a polluted area that is substantially greater than the area of the coherent oil slick.

Risk Assessment by the Development of Risk Profiles

This task utilizes the results of previous four tasks to develop a variety of risk profiles for a present or proposed offshore operation. The oil spill probabilities, spill size distributions, consequence analysis, oil slick trajectories and land fall probabilities are combined to provide a series of graphical displays depicting the risk associated with the offshore oil development.

Other similar risk profiles for evaporation of lighter fractions and sinking of heavier fractions can be developed. The actual evaporative release of lighter hydrocarbons occurs for several days over the increasing surface area of the oil slick. Once the quantity of hydrocarbons released to the atmosphere is known, dispersion models can be used to determine the impact of oil spills on air quality. Risk profiles of sinking of heavier hydrocarbons into the water column can be used for determining the impact of oil spills on water quality and marine life.

CONCLUSION

In summary, risk analysis provides a sound method for assessing the impact of oil spills resulting from offshore operations. There is increasing concern about such risks on the part of authorities, environmental groups, the general public, and last but not least, the companies involved in these operations. The concern applies equally to the expansion of existing offshore oil and gas facilities or to completely new developments. The probabilistic and deterministic approaches discussed here can be applied successfully to determine the environmental and economic impact of oil spills and their relationship to the expansion of offshore oil and gas development.

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Coastal Marine Policy/ Management

National Legislations and International Conventions for Regulation of Coastal Zone Activities

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INTRODUCTION

One of the major tools for control of marine pollution is legislation. A number of legislations at the national and international level are enacted to ensure control of marine pollution arising due to various sources from land- and sea-based activities. A number of legislations have been enacted in India to tackle the pollution problems. Besides India is also a party to many international conventions relating to pollution. Brief details about the Maritime Zones Act describing various zones, various national legislations dealing with pollution problems and international conventions concerning marine environment are discussed below.

NATIONAL LEGISLATIONS

Territorial Waters, Continental Shelf, Exclusive Economic Zone and Other Maritime Zones Act, 1976

This Act delineates the limits of each zone in the Indian waters, in consonance with the respective provisions of the Law of the Sea Convention. The definitions for each zone and regulations prescribed under the Act are as under:

Territorial Waters: It extends from the baseline up to 12 nautical miles in the sea. A few important regulations applicable in the territorial waters are described below:

(1) Without prejudice to the provisions of any other law for the time being in force, all foreign ships (other than warships including submarines and other underwater vehicles) shall enjoy the right of innocent passage through the territorial waters.

(2) Foreign warships including submarines and other underwater vehicles may enter or pass through the territorial waters after giving prior notice to the Central Government provided that submarines and other underwater vehicles shall navigate on the surface and show their flag while passing through such waters.

Contiguous Zone: The Contiguous Zone is an area beyond and adjacent to the Territorial Waters and the limit of the Contiguous Zone is the line, every point of which is at a distance of 24 nautical miles from the nearest point of the baseline. The regulations applicable to territorial waters are applicable to contiguous zone also.

Exclusive Economic Zone: The Exclusive Economic Zone (EEZ) is defined as a sea area up to a distance of 200 nautical miles from the baseline.

Continental Shelf: The Continental Shelf comprises the seabed and sub-soil of the submarine areas that extend beyond the limit of its Territorial Waters throughout the natural prolongation of its land territory to the outer edge of the continental margin or to a distance of 200 nautical miles from the baseline.

Both in the EEZ and Continental Shelf, India has, and always had, full and exclusive sovereign rights (a) for the purposes of exploration, exploitation, conservation and management of all resources; (b) exclusive rights and jurisdiction for the construction, maintenance or operation of artificial islands, offshore terminals, installations and other structures and devices necessary for the exploration and exploitation of the resources of the continental shelf or for the convenience of shipping or for any other purpose; (c) exclusive jurisdiction to authorize, regulate and control scientific research; and (d) exclusive jurisdiction to preserve and protect the marine environment and to prevent and control marine pollution.

Further, no person (including a foreign Government) shall, except under, and in accordance with, the terms of a licence or a letter of authority granted by the Central Government, explore or exploit its resources or carry out any search or excavation or conduct any research or drill therein or construct, maintain or operate any artificial island, offshore terminal, installation or other structure or device therein for any purpose whatsoever.

Most of the legislations dealing with marine pollution have a jurisdiction upto the territorial waters. Attempts are being made to extend certain provisions of acts dealing with environmental aspects to the other zones prescribed in the maritime zones act.

NATIONAL LEGISLATIONS DEALING WITH POLLUTION PROBLEMS

1. Environment Protection Act (1986)

This is the most comprehensive legislation which encompasses all the legislations relating to pollution in the country. A number of rules have been framed under The Environment (Protection) Act, to deal with various aspects like handling, transport and disposal of hazardous substances, regulation of activities in the land part of the coastal areas and also for prescribing the waste disposal standards for various types of industries, as well as for the municipal sewage system. So far disposal standards have been set for 61 types of industries and 434 substances have been classified as hazardous and toxic. General standards given for discharge of effluents in the coastal waters are given in Annexure I. The details on Coastal zone regulation rules are given in Annexure II. The offences committed under the Act are either punishable through this Act or through the Water and Air Pollution Act. The act has a jurisdiction upto the territorial waters.

2. The Water (Prevention and Control of Pollution) Act, 1974 as Amended upto 1988

The act deals with all basic aspects, means and mechanisms to deal with the control of water pollution. Jurisdiction of the act has been restricted up to 5 km in the sea. Constitutions of Central and State Pollution Control Boards, their composition, functions and powers are dealt under this act. The Central Pollution Control Board which is the apex body is entrusted with the functions on advising the central government on matters relating to control of pollution and co-ordinate the activities among the State Boards. The State Boards which shoulder the major responsibilities in dealing with pollution problems have been entrusted with the following functions:

(a) to plan a comprehensive programme for the prevention, control or abatement of pollution of streams and wells in the State and to secure the execution thereof;
(b) to advise the State Government on any matter concerning the prevention, control or abatement of water pollution;
(c) to collect and disseminate information relating to water pollution and the prevention, control or abatement thereof;
(d) to encourage, conduct and participate in investigations and research relating to problems of water pollution and prevention, control or abatement of water pollution;
(e) to collaborate with the Central Board in organising the training of persons engaged or to be engaged in programmes relating to prevention, control or abatement of water pollution and to organise mass education programmes relating thereto;
(f) to inspect sewage or trade effluents, works and plants for the treatment of sewage and trade effluents and to review plans, specifications or other data relating to plans set up for the treatment of water, works for the purification thereof and the system for the disposal of sewage or trade effluents or in connection with the grant of any consent as required by this Act;

(g) lay down, modify or annul effluent standards for the sewage and trade effluents and for the quality of receiving waters (not being water in an inter-State stream) resulting from the discharge of effluents and to classify waters of the State;
(h) to evolve economical and reliable methods of treatment of sewage and trade effluents, having regard to the peculiar conditions of soils, climate and water resources of different regions and more especially the prevailing flow characteristics of water in streams and wells which render it impossible to attain even the minimum degree of dilution;
(i) to evolve methods of utilisation of sewage and suitable trade effluents in agriculture;
(j) to evolve efficient methods of disposal of sewage and trade effluents on land, as are necessary on account of the predominant conditions of scant stream flows that do not provide for major part of the year the minimum degree of dilution;
(k) to lay down standards of treatment of sewage and trade effluents to be discharged into any particular stream taking into account the minimum fair weather dilution available in that stream and the tolerance limits of pollution permissible in the water of the stream, after the discharge of such effluents;
(l) to make, vary or revoke any order—
    (i) for the prevention, control or abatement of discharges of waste into streams or wells;
    (ii) requiring any persons concerned to construct new systems for the disposal of sewage and trade effluents or to modify, alter or extend any such existing system or to adopt such remedial measures as are necessary to prevent control or abate water pollution;
(m) to lay down effluent standards to be complied with by persons while causing discharge of sewage or sullage or both and to lay down, modify or annul effluent standards for the sewage and trade effluents;
(n) to advise the State Government with respect to the location of any industry the carrying on of which is likely to pollute a stream or well;
(o) to perform such other functions as may be prescribed or as may, from time to time, be entrusted to it by the Central Board or the State Government.

Penalties

Penalties are levied for several offences under the Water Act. A few are described below:

Failure to Give Information on Quantity of Water Discharged

Any deviation from the quantities of water being discharged in contravention with the directions given by the Pollution Control Boards will attract a penalty with imprisonment for a term, which may extend to three months or with fine which may extend to Rs.10,000/- or with both and in case the failure continues, an additional fine, which may extend to Rs.5,000/- for every day is levied from the date of first failure.

Failure for Preventing Action to Mitigate Pollution

In case the Pollution Control Boards find that any noxious, poisonous or polluting matter is present the polluter will take necessary action for removing the matter or remedying or mitigating the pollution and also stopping the discharge. In case of failing to do so, the offender will be punishable with imprisonment for a term which shall not be less than one year and six months, but may be extended up to six years with fine. The fine may extend to Rs. 5,000/- for every day during which such failure continues from the first date of committing the offence.

For Destruction of Board's Property

Any property belonging to the Board which is either at its own operational place or at its field, the act is punishable with an imprisonment for a term of three months or with fine up to Rs.10,000/- or with both.

Disposal of Poisonous or Noxious Waste

The offence of disposal of poisonous as well as noxious waste is punishable with an imprisonment for a term from 1-1/2 years to six years and with a fine.

3. Indian Ports Act, 1908

The operative section of the Indian Ports Act 1908 is section 21(1) and (2) which reads as follows:

"No ballast or rubbish and no other thing likely to form a bank or shoal or to be detrimental to navigation, shall without lawful excuse, be cast or thrown into any such port or into or upon any place on shore. Also no oil or oily mixture may be discharged into the port waters. In case of violence of this provision, the master of the ship or tanker shall be punishable with fine which may extend to five hundred rupees and shall pay any reasonable expenses which may be incurred in removing the same". It is understood that the fine amount is proposed to be increased to Rs. 5000/- at present.

4. Merchant Shipping Act, 1958

Certain provisions of the Act (part XI A) deal with pollution problems caused by the discharge of oil or oily wastes from ships into the sea. The initial enactments made during 1974 were comprehensively amended to incorporate higher standards for control of oil pollution from ships. They came into force from 5 January, 1985. Accordingly to this part of the Act, i.e. part XIA,

(a) Discharge of oil or oily mixture from tankers/ships/offshore oil exploration installation and pipelines is prohibited except under certain circumstances. These wastes from tankers are not to be discharged within 50 miles of land and discharges are severely restricted in the rest of the sea all over the world (not exceeding 60 lit/mile when the ship is en route). Discharge of such wastes is totally prohibited in specially protected areas.
(b) No sludge is permissible.
(c) Oily bilge pumped over board not to contain more than 100 ppm of oil and that too beyond 12 miles from land.
(d) The slops and dirty ballasts must be discharged in the reception facilities to be made available by ports.
(e) Oil record book be maintained strictly.

Heavy penalties have been proposed for illegal dumping of oil or oily wastes in contravention of the provisions of the act. For such violations the master of the ship/tanker is charged with a fine upto Rs. 10 lakhs (previously Rs. 5000/-) or with an imprisonment of six months to the master of the vessel.

Besides anti-pollution provisions, the Act also governs civil liability compensation for oil pollution damage by ships and to levy oil pollution cess on the basis of every tonne of oil imported/shipped.

5. Coast Guard Act, 1978

As described in the Coast Guard Act 1978, the Coast Guards are responsible for "taking such measures as are necessary to preserve and protect the maritime environment to prevent and control marine pollution". Even though the Coast Guard Act does not mention the jurisdiction of Coast Guards in this function and also any specific activity, the Act elicits that the CG may carry out their tasks in close liaison with Union agencies, institutions and authorities to avoid duplication of effort. Adopting the latter, the Coast Guard Organisation performs only task of combating of oil pollution beyond 5 km in the seas around India and surveillance against intentional dumping of oil or other wastes by ships/tankers visiting/passing our waters. A national contingency plan to combat oil spill disasters approved by the Government is also coordinated by the Coast Guards.

INTERNATIONAL CONVENTIONS

Several multilateral conventions have been concluded before and after the conclusion of the "Law of the Sea Convention" with regard to specific aspects of pollution. The International Maritime Organisation (IMO) has set up an institutional framework of expert inter-government groups such as Marine Environment Protection Committee, Maritime Safety Committee etc. which address a wide range of technical, legal and scientific problems related to the protection of the marine environment from pollution from ships, disposal of wastes at sea and liability and compensation for pollution damage. As the prevention of pollution from ships is inextricably linked to the maritime safety measures regarding design construction, equipment, navigational procedures, communications and crew standards etc. have also been established under different Conventions. Under the Law of the Sea Convention it is mandatory for the parties to take all necessary measures to prevent and control marine pollution. The Convention entered into force in Nov. 1996.

The International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto referred as MARPOL 73/78 is the most comprehensive treaty covering marine pollution arising from ships and offshore platforms. In 1973, the International Conference on Marine Pollution adopted the International Convention for the Prevention of Pollution from ships, 1973 (MARPOL 73) to replace OILPOL 54/69. MARPOL 73 was further modified by the Protocol of 1978 relating thereto adopted by the International Conference on Tanker Safety and Pollution Prevention 1978. The 1978 MARPOL Protocol incorporates and merges with the 1973 MARPOL Convention and the 1973 Convention and the 1978 Protocol are treated as a single instrument which is generally referred to as MARPOL 73/78. India is party to the convention.

MARPOL 73/78 consists of Articles, two Protocols dealing respectively with the reports on incidents involving harmful substances and arbitration, and five Annexes which contain regulations for the prevention of pollution by:

1. oil (Annex I);
2. noxious liquid substances carried in bulk (Annex II);
3. harmful substances carried in package form (Annex III);
4. sewage from ships (Annex IV);
5. garbage from ships (Annex V).

Annexes I and II are mandatory, and States ratifying or acceding to MARPOL 73/78 must give effect to the provisions of these Annexes. On the other hand, Annexes III, IV and V are optional, and States may get out of any of these Annexes. MARPOL 73/78 entered into force on 2 October 1983 in respect of Annex I. Annex II is presently scheduled to enter into force three years later, i.e. 2 October 1986. Optional Annexes have not yet received a sufficient number of acceptances and their entry into force dates are not yet known. Annex I shows the status of each Annex of MARPOL 73/78. The main features of the technical provisions of MARPOL 73/78 which relate to the control of operational discharge are briefly summarized in the following paragraphs.

Prevention of Pollution by Oil

Annex I of MARPOL 73/78 maintains substantially similar discharge criteria to those specified in OILPOL 54/69 but also contains several provisions to strengthen the OILPOL requirements. These are summarized in the following:

1. "Oil" is defined as petroleum in any form including crude oil, fuel oil, sludge, oil refuse and refined products (other than petrochemicals).
2. The discharge criteria are substantially the same as those prescribed in OILPOL 54/69 (the total quantity of oil which a tanker may discharge in any ballast voyage whilst under way must not exceed 1/15000 of the total cargo carrying capacity of the vessel) except that for new tankers, the total quantity of oil which may be discharged into the sea must not exceed 1/30,000 of the total quantity of the cargo carried in the previous voyage.
3. The rate at which oil may be discharged must not exceed 60 litres per mile travelled by the ship and no discharge of any oil whatsoever must be made within 50 NM of the nearest land.
4. When discharging oil, tankers and other ships must have in operation an oil discharge monitoring and control system and oily-water separating or filtering equipment.
5. Certain regions, including the Mediterranean Sea, the Black Sea, and the Baltic Sea, have been designated as "Special areas" in which any discharge of oil or oily mixture into the sea is prohibited except segregated or clean ballast.

In addition, MARPOL 73/78 introduces certain requirements for the construction and equipment of ships with respect to the prevention of operational discharge of oil and the mitigation of uncontrolled release of oil should accidents to tankers occur. The following is a summary of such requirements relating to operational discharges of oil:

1. Oil tankers must be fitted with oil discharge and monitoring equipment, with a recording device to provide a continuous record of the discharge.
2. Any ship of 400 tons gross tonnage and above must be fitted with oily-water separating or filtering equipment.
3. Oil tankers must be provided with suitable slop tank arrangements with the capacity necessary to retain the slops generated by tank washing, oil residues and dirty ballast residues.
4. New crude oil tankers of 20,000 dwt and above and new products carriers of 30,000 dwt and above must be provided with segregated ballast tank (SBT) of sufficient capacity to enable them to operate safely on ballast voyage without recourse to the use of oil tanks for water ballast except in very severe weather conditions. In addition, new crude oil tankers must be provided with a crude oil washing system (COW).
5. Existing crude oil tankers of 40,000 dwt and above must be provided with SBT, dedicated clean ballast tanks (CBT) or COW. Existing product carriers of 40,000 dwt and above must be provided with SBT or CBT.

The main features of the above-mentioned constructional requirements are briefly explained in the following:

1. Segregated Ballast Tanks (SBT) are tanks which are reserved exclusively for the carriage of ballast water. Since they are not used for the carriage of cargo oil and have separate pumping and piping arrangements, there is no oil/water mixture resulting from ballasting cargo tanks and hence the risk of operational pollution is decreased.
2. Dedicated Clean Ballast Tanks (CBT): On existing ships certain cargo tanks can be reserved solely for the carriage of water ballast. Since the same pumping and piping arrangements are used for both cargo oil and ballast water, this is not regarded as true segregation and the system is only a temporary solution.
3. Crude Oil Washing (COW): It is a system whereby crude oil, instead of water, is used to wash the residues left clinging to the tanks walls after the discharge of cargo oil. It is more effective than water cleaning and also virtually eliminates the accumulation of sludge.

Control of Pollution by Noxious Liquid Substances (Annex I)

The convention sets out detailed requirements for the discharge criteria and measures for control of pollution by noxious liquid substances carried in bulk. For this purpose noxious liquid substances are divided into Categories A, B, C and D depending upon their hazard to marine resources, human health, amenities and other legitimate uses of the sea. Prior to the 1973 MARPOL Conference, some 250 substances were evaluated for this purpose and those falling under the above four categories are included in the list appended to the Convention. The discharge criteria for noxious liquid substances are determined in relation to the categories of substances.

Prevention of Pollution by Harmful Substances Carried in Packaged form or in Freight Containers or Portable Tanks or Road and Rail Wagons (Annex II)

The Convention contains general requirements relating to the prevention of pollution by harmful substances carried by sea in packaged form or in freight containers, portable tanks or road and rail tank wagons. Detailed requirements on packaging, marking and labelling, documentation, stowage, quantity, limitations and other aspects aimed at preventing or minimizing pollution of the marine environment by such substances will be developed within the framework of the International Maritime Dangerous Goods Code or in other appropriate form.

Prevention of Pollution by Sewage and Garbage (Annexes III and IV)

Ships will not be permitted to discharge sewage within four miles from the nearest land unless they have in operation an approved treatment plant;

between four and twelve miles from land, sewage must be comminuted and disinfected before discharge. As regards garbage, specific minimum distances from land have been set for the disposal of all the principal kinds of garbage. The disposal of all plastics is prohibited. In special areas, stricter restrictions are applied for the discharge of garbage.

The Convention is implemented by State through the promulgation of national legislation and regulation which affect ships which fly their flags and use their ports and coastal waters.

The Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal, adopted in 1989, prohibit the export of hazardous wastes from the country to another unless certain conditions are met including the availability of adequate disposal facilities and the environmentally sound management of such waste and avoidance of pollution. India is a party to the Convention.

Disposal of wastes in all marine waters seawards beyond the baselines is governed by the London Dumping Convention of 1972. In addition, this Convention controls the incineration at sea of land generated wastes and sets out criteria for the selection of dumping and incineration sites at sea. Guidelines and recommendations adopted by the consultative meetings of contracting parties to the London Dumping Convention deal with the disposal of radioactive wastes and other radioactive matter at sea. India is not a party to this Convention.

In response to the economic impact of a major oil spill, the Civil Liability Convention was adopted in 1969. This Convention establishes strict liability for pollution damage for owner of a sea-going vessel actually carrying oil in bulk as cargo. The owner is exempted from this liability only in exceptional cases, i.e. if he proves that the damage resulted from an act of war, or a natural disaster or was caused by sabotage by a third party, or by negligence of authorities exercising their function of maintaining navigational aids. India has ratified this convention. In 1971 the Liability Convention was supplemented by the establishment of the *International Oil Pollution Compensation Fund* which provides for compensation to the persons who sustain pollution damage as a result of an escape or discharge of persistent oil and who cannot receive full compensation under the Civil Liability Convention. It also relieves the ship owner to some extent, of the burden imposed on him by the Civil Liability Convention. The maximum compensation for any one incident under the Fund Convention is 80 million US $. India has acceded to this Convention.

Further the International Convention for the Regulation of Whaling (1946), the Convention on the Conservation of Migratory Species of Wild Animals (1979), the International Plant Protection Convention (1951), deal with the protection of marine species. India is a party to these Conventions.

Enforcement

The Ministry of Environment and Forests is the Administrative Ministry for all legislations relating to the control of land-based sources of marine pollution. The acts administered include Environment Protection Act and the Water Act. Anti-pollution measures under the acts are enforced by the Central and State Pollution Control Boards. In case of other acts like Merchant Shipping Act and the Indian Ports Act, they are administered by the Ministry of Surface Transport and they are enforced by the Directorate General of Shipping and the Major Ports respectively.

AGENDA 21

The United Nations Conference on Environmental Development (1992) formulated Agenda 21 in order to ensure coordinated efforts for the protection of environment and sustainable development of all terrestrial and aquatic ecosystems. The Chapter 17 of Agenda 21 deals with the protection of oceans, all kinds of seas including enclosed and semi-enclosed areas, coastal waters and the protection, rational use and development of their living resources. The aspects covered under Chapter 17 provide the international basis to the States for pursuing protection and sustainable development of marine and coastal areas, at the national, sub-regional, regional and global levels. The Chapter has identified the following programme areas with respect to coastal areas and the oceans.

(a) Integrated management and sustainable development of coastal areas, including exclusive economic zones;
(b) Marine environmental protection;
(c) Sustainable use and conservation of marine living resources of the high seas;
(d) Sustainable use and conservation of marine living resources under national jurisdiction;
(e) Addressing critical uncertainties for the management of the marine environment and climate change;
(f) Strengthening international, including regional, cooperation and coordination;
(g) Sustainable development of small islands.

Each programme area has been described in detail to indicate its objectives, activities that are needed to be undertaken and the means of implementation. The aspects that are stipulated include policy making, planning, collection of data and information, regional and international cooperation, application of science and technology, human resource development and the capacity building. A copy of the Chapter 17 giving in detail the programme areas and other related activities is placed in the Annexure III.

Annexure 1

COASTAL AREA CLASSIFICATION AND DEVELOPMENT REGULATIONS

Classification of Coastal Regulation Zone

The entire coastal stretch has been divided into zones from lowest low tide to highest high tide line which is a no development zone for all purposes and the coastal stretches within 500 metres from the High Tide Line on the landward side. The latter is classified into four categories, namely:

Category I (CRZ-I)

(i) Areas that are ecologically sensitive and important, such as national parks/marine parks, sanctuaries, reserve forests, wildlife habitats, mangroves, corals/coral reefs, areas close to breeding and spawning grounds of fish and other marine life, areas of outstanding natural beauty/historically/heritage areas, areas rich in genetic diversity, areas likely to be inundated due to rise in sea level consequent upon global warming and such other areas as may be declared by the Central Government or the concerned authorities at the State/Union Territory level from time to time.

Category II (CRZ-II)

The areas that have already been developed up to or close to the shore-line. For this purpose, “developed area” is referred to as that area within the municipal limits or in other legally designated urban areas which is already substantially built up and which has been provided with drainage and approach roads and other infrastructural facilities, such as water supply and sewage mains.

Category III (CRZ-III)

Areas that are relatively undisturbed and those which do not belong to either Category I or II. These will include coastal zone in the rural areas (developed and undeveloped) and also areas within Municipal limits or in other legally designated urban areas which are not substantially built up.

Category IV (CRZ-IV)

Coastal stretches in the Andaman & Nicobar, Lakshadweep and small islands, except those designated as CRZ-I, CRZ-II or CRZ-III.

Norms for Regulation of Activities

The development or construction activities in different categories of CRZ area shall be regulated by the concerned authorities at the State/Union Territory level, in accordance with the following norms:

CRZ-I

No new construction shall be permitted within 500 metres of the High Tide Line. No construction activity, except as listed under 2(xii), will be permitted between the Low Tide Line and the High Tide Line.

CRZ-II

(i) Buildings shall be permitted neither on the seaward side of the existing road (or roads proposed in the approved Coastal Zone Management Plan of the area) nor on seaward side of existing authorised structures. Buildings permitted on the landward side of the existing and proposed road/existing authorised structures shall be subject to the existing local Town and Country Planning Regulations including the existing norms of FSI/FAR.

(ii) Reconstruction of the authorised buildings to be permitted subject to the existing FSI/FAR norms and without change in the existing use.

(iii) The design and construction of buildings shall be consistent with the surrounding landscape and local architectural style.

CRZ-III

(i) The area up to 200 metres from the High Tide Line is to be earmarked as 'No Development Zone'. No construction shall be permitted within this zone except for repairs of existing authorised structures not exceeding existing FSI, existing plinth area and existing density. However, the following uses may be permissible in this zone—agriculture, horticulture, gardens, pastures, parks, play fields, forestry and salt manufacture from sea water.

(ii) Development of vacant plots between 200 and 500 metres of High Tide Line in designated areas of CRZ-III with prior approval of Ministry of Environment and Forests (MEF) permitted for construction of hotels/beach resorts for temporary occupation of tourists/visitors subject to the conditions as stipulated in the guidelines at Appendix I.

(iii) Construction/reconstruction of dwelling units between 20 and 500 metres of the High Tide Line permitted so long it is within the ambit of traditional rights and customary uses such as existing fishing villages and gothans. Building permission for such construction/reconstruction will be subject to the conditions that the total number of dwelling units shall not be more than twice the number of existing units; total covered area on all floors shall not exceed 33 per cent of the plot size;

the overall height of construction shall not exceed 0 metres and construction shall not be more than two floors (ground floor plus one floor)

(iv) Reconstruction/alterations of an existing authorised building permitted subject to (i) and (iii) above.

CRZ-IV

Andaman & Nicobar Islands

(i) No new construction of buildings shall be permitted within 200 metres of the HTL;

(ii) The buildings between 200 and 500 metres from the High Tide Line shall not have more than two floors (ground floor and first floor), the total covered area on all floors shall not be more than 50 per cent of the plot size and the total height of construction shall not exceed nine metres;

(iii) The design and construction of buildings shall be consistent with the surrounding landscape and local architectural style;

(iv) Corals and sand from the beaches and coastal waters shall not be used for construction and other purpose;

(v) Dredging and underwater blasting in and around coral formations shall not be permitted; and

(vi) However, in some of the islands, coastal stretches may also be classified into categories CRZ I or II or III with the prior approval of Ministry of Environment and Forests and in such designated stretches, the appropriate regulations given for respective categories shall apply.

Lakshadweep and Small Islands

(i) For permitting construction of buildings the distance from the High Tide Line shall be decided depending on the size of the islands. This shall be laid down for each island, in consultation with the experts and with approval of the Ministry of Environment & Forests, keeping in view the land use requirements for specific purposes vis-à-vis local conditions including hydrological aspects erosion and ecological sensitivity;

(ii) The buildings within 500 metres from the HTL shall not have more than two floors (ground floor and 1st floor), the total covered area on all floors shall not be more than 50 per cent of the plot size and the total height of construction shall not exceed nine metres;

(iii) The design and construction of buildings shall be consistent with the surrounding landscape and local architectural style;

(iv) Corals and sand from the beaches and coastal waters shall not be used for construction and other purposes;

(v) Dredging and underwater blasting in and around coral formations shall not be permitted; and

(vi) However, in some of the islands, coastal stretches may also be classified into categories CRZ I or II or III, with the prior approval of Ministry of Environment & Forests and in such designated stretches, the appropriate regulations given for respective categories shall apply.

Appendix I

Guidelines for Development of Beach Resorts/Hotels in the Designated Areas of CRZ-III for Temporary Occupation of Tourist/Visitors, with Prior Approval of the Ministry of Environment & Forests

7(1) Construction of beach resorts/hotels with prior approval of MEF in the designated areas of CRZ-III for temporary occupation of tourists/visitors shall be subject to the following conditions:

(i) The project proponents shall not undertake any construction (including temporary constructions and fencing or such other barriers) within 200 metres (in the landward side) from the High Tide Line and within the area between the Low Tide and High Tide Lines;

(ii) The total plot size shall not be less than 0.4 hectares and the total covered area on all floors shall not exceed 33 per cent of the plot size i.e. the FSI shall not exceed 0.33. The open area shall be suitably landscaped with appropriate vegetal cover.

(iii) The construction shall be consistent with the surrounding landscape and local architectural style.

(iv) The overall height of construction up to highest ridge of the roof, shall not exceed nine metres and the construction shall not be more than two floors (ground floor plus one upper floor);

(v) Ground water shall not be tapped within 200 m of the HTL; within the 200–500 metre zone it can be tapped only with the concurrence of the Central/State Ground Water Board;

(vi) Extraction of sand, levelling or digging of sandy stretches except for structural foundation of building swimming pool shall not be permitted within 500 metres of the High Tide Line;

(vii) The quality of treated effluents, solid wastes, emissions and noise levels etc. from the project area must conform to the standards laid down by the competent authorities including the Central/ State Pollution Control Board and under the Environment (Protection) Act, 1986;

(viii) Necessary arrangements for the treatment of the effluents and solid wastes must be made. It must be ensured that the untreated effluents and solid wastes are not discharged onto the water or on the beach; and no effluent/solid waste shall be discharged on the beach;

(ix) To allow public access to the beach, at least a gap of 20 metres width shall be provided between any two hotels/beach resorts; and in no case shall gaps be less than 500 metres apart; and

(x) If the project involves diversion of forest land for non-forest purposes, clearance as required under the Forest (Conservation) Act, 1980 shall be obtained. The requirements of other Central and State laws as applicable to the project shall be met with.

(xi) Approval of the State/Union Territory Tourism Department shall be obtained.

7(2) In ecologically sensitive areas (such as marine parks, mangroves, coral reefs, breeding and spawning grounds of fish, wildlife habitats and such other areas as may be notified by the Central/State Government/Union Territories) construction of beach resorts/hotels shall not be permitted.

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Central Considerations in Initiating and Operating Programmes in Integrated Coastal Management

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FUNDAMENTAL CONCEPTS

What Is Integrated Coastal Management?

Integrated coastal management can be defined as a continuous and dynamic process by which decisions are made for the sustainable use, development, and protection of coastal and marine areas and resources. First and foremost, the process is designed to overcome the fragmentation inherent in both the sectoral management approach and the splits in jurisdiction among levels of government at the land-water interface. This is done by ensuring that the decisions of all sectors (e.g., fisheries, oil and gas production, water quality) and all levels of government are harmonized and consistent with the coastal policies of the nation in question. A key part of ICM is the design of institutional processes to accomplish this harmonization in a politically acceptable manner.

Integrated coastal management is a process that recognizes the distinctive character of the coastal area—itself a valuable resource—and the importance of conserving it for current and future generations. The coastal area, be it continental or island based, is a special area where land and sea meet that includes various characteristics:

- The coastal area is characterized by dynamic and frequently changing physical features (e.g., changes in beaches and barrier islands due to the force of winds and waves).
- Valuable ecosystems of great productivity and biodiversity are present, such as mangrove forests, sea grass beds, other wetlands, and coral reefs—all of which provide crucial nursery habitat for many marine species.

- Coastal features such as coral reefs, mangrove forests, and beach and dune systems that serve as critical natural defenses against storms, flooding, and erosion.
- The area is generally of great value to human populations as they seek to settle in, use, and enjoy coastal marine resources and space.
- The coastal area provides the base for all human activities in the ocean—from marine recreation and fishing to marine transportation and offshore mineral development. Many of these activities represent significant economic benefits—both actual, for those resources already under exploitation, and potential for resources yet to be exploited. All such activities depend, to various extents, on the coastal area for their operation.
- Because the coastal area is often highly desired by various users and populations, coastal space is a finite resource over which there are often conflicts.
- Management of the two sides of the coastal area—land and sea—poses difficult challenges and complexities based, in part, on the public character of the ocean area and the generally mixed public and private character of the land area. Typically, the presence of "general-purpose" government authorities for land and "single-purpose" authorities for the ocean further complicates the governance issue.

Islands, unique in being surrounded and enclosed by the sea, represent the maximum coastal condition and thus require a high degree of integrated coastal management. For small islands, the coastal zone and ocean may be the only potentially developable assets. Consequently, planning and management for these resources require great care if a long-term pattern of sustainable development is to be achieved.

KEY FEATURES OF ICM: A SUMMARY

We believe that it is possible to pinpoint four key features which are central to the ICM approach. These are:

1. The use of a set of principles based on the special character of the coasts and oceans to guide ICM decision making.
2. The need to ultimately work at ICM from both directions—bottom up (involving the local community level) and top-down (involving the national government).
3. The need to have a coordinating mechanism or mechanisms to bring together coastal and ocean sectors, different levels of government, users, and the public in the ICM process.
4. The need to have good (relevant) science available on a timely basis to inform the ICM decision-making process.

The need for ICM is directly tied to the rapidly increasing pressures being imposed on the world's shorelines and coastal areas. Populations are burgeoning in these areas as more and more people are drawn to the coasts for both economic and recreational purposes. Furthermore, pressures for development of coastal and ocean resources (offshore oil and gas, ocean minerals, fisheries, aquaculture, etc.) often compete with the need to protect and conserve particularly sensitive coastal areas, such as those with valuable and diverse habitats. Similarly, growing human settlements in the coastal zone places additional stress on natural systems as pollution and sewage loadings increase. Clearly, the best hope for dealing with these multiple and interconnected problems is an integrated approach that brings all coastal sectors, levels of government, and coastal users into a rational goal-setting and decision-making framework such as ICM.

We stress the need to tailor the ICM approach to fit the unique circumstances of each country undertaking such a programme. Countries differ a great deal in their resource bases, levels of economic development, systems of government, cultures and traditions, needs and expectations, and approaches to government regulation and resource management. A successful ICM programme will incorporate these distinctions into its structure and, to the maximum extent possible, will build on existing organizations and arrangements, adding new institutions or procedures only to the extent necessary to fill gaps or meet new requirements—for example, to coordinate and harmonize coastal activities.

A PRACTICAL GUIDE TO ICM PROGRAMMES

Here we provide a summary of options and possible choices faced during three major phases of the ICM process: initiating an ICM effort, formulating an ICM programme and getting it adopted, and implementing and operating the programme.

Initiating an ICM Effort

Major issues faced by coastal policy makers as they begin an ICM effort are summarized in this section, as are possible strategies for addressing such issues.

Tailoring ICM to a Particular Country's Context

- It is imperative to tailor ICM to fit the physical, socioeconomic, and political context of a particular country.
- A study of physical and socioeconomic variables establishes which problems and opportunities are present in a coastal or ocean area, why ICM is needed, and what its goals and objectives should be. An understanding of the country's political system is crucial to determining how best ICM can proceed and by whom it should be carried out, and answers such questions as, who needs to be convinced to establish ICM? Who will design, implement, monitor, and enforce ICM? And whose behaviour needs to change to make ICM effective?

- In understanding a political system for ICM purposes, two questions are central: (1) What is the degree of concentration of power and authority among national-level institutions? (2) What is the division of authority between national and subnational (provincial, local) levels of government?
- It may be useful for nations to draw lessons from similar ICM efforts in other countries. Care should be taken, however, to draw lessons from the countries most similar in coastal context, socioeconomic makeup, and political system characteristics. Whereas nations once outright copied and emulated other countries' programmes and institutions, today a more common approach is for decision makers to engage in 'synthesis" and "inspiration" methods of lesson drawing, shaping unique ICM programmes that correspond to their countries' particular circumstances.

Getting Started

- Political will at the national and local levels is essential to establishing ICM. Recognition of the need for an ICM programme can develop in many different places—the national government, the local community, the NGO community, a donor agency—but wherever it first emerges, it must find its way to and ultimately be accepted by both the national and local or community levels of government since both generally play important roles in ICM implementation.
- To enhance its political acceptability, ICM should be described not as supplanting sectoral programmes but supplementing and strengthening them.
- ICM need not be presented as an elaborate, complex methodology that will require simultaneous full-scale implementation in all coastal areas and for the full range of coastal issues. Rather it should be made clear that ICM can be fashioned in such a way as to be implemented incrementally, beginning in locations most in need of integrated management or with issues of highest priority.
- Visible support for ICM by the constituencies most affected by coastal management measures—users of coastal resources and the concerned public—is important for generating the necessary political will.
- A well-written and well-reasoned document on the need for ICM generally needs to be prepared, showing: (1) clear evidence of problems with existing sectoral approaches, such as escalation of conflicts; (2) new management needs, such as protecting biodiversity or addressing the effects of climate change; and (3) new economic opportunities that would benefit from a more integrated approach.
- Such a document should describe the ICM concept and outline the benefits that would be derived from its adoption, as well as how ICM would function in the government setting in question and steps needed to develop an ICM plan and put it into practice, including a timetable, an estimate of costs, and professional staff requirements.

- It is usually best to reserve politically sensitive decisions, such as questions regarding establishment of a lead agency, for later, when the scope and objectives of the programme are better known.
- ICM advocates can expect to encounter, and must overcome, a number of barriers to ICM initiation, such as bureaucratic inertia, ideological opposition, and opposition from economic interests tied to the status quo.
- Support of coastal users, NGOs, and the public is crucial to ICM initiation. In this regard, it is useful to create a coastal users' group ("users" is broadly defined) that: (1) includes representatives from all groups likely to be affected by ICM, (2) fully informs members about the ICM process, (3) is structured so members perceive that their suggestions and input are fully considered (i.e., are not a "rubber stamp" for already agreed-to government actions) and can actually affect the way the ICM programme is defined and ultimately implemented.
- It is important to gain broad political support for ICM at the national level of government. Some conditions that facilitate this are formulation of the ICM effort by a high-level interagency group that has been named and is led by the highest level of government (e.g., the prime minister's office); is bureaucratically higher than the sectoral agencies; operates with written terms of reference and a timetable; has good representation from the relevant ministries and from provinces, local governments and communities, and NGOs; is run in a transparent manner; and is required to present its findings in a public forum.
- Although the length of time required to initiate and implement ICM will vary greatly from country to country, in our view, the initial work in deciding how to begin ICM (not the creation of an ICM plan or programme itself) can take place in about a six-month period. ICM plan formulation, including assessment studies, could take a year or two. Tangible results from ICM should be seen by the end of a five-year period. If the process extends over too long a period without tangible results, momentum for ICM may well be lost.

Structuring A Phased Approach

- ICM need not be implemented all at once and for a country's entire coastal zone. In many cases a phased approach may be more appropriate—for example, if urgent problems exist more in one part of the nation's coastal zone and less so in others; if one coastal area is institutionally, technologically, or politically ready for ICM and others are not; if funding and staff limitations dictate an incremental approach; or if it is desirable to conduct an ICM or pilot approach in a specific coastal area before applying it generally.
- If a phased approach is chosen, it should be structured carefully so that later increments can benefit from the first effort. Even though the area covered by the initial effort may be small, care should be taken to ensure

that the intergovernmental and intersectoral coordinating mechanisms are adequately comprehensive. The institutional, technical and political changes made as part of the pilot effort can be scaled up to ultimately handle the country's entire coastal zone, but tests to judge the success of the pilot effort must be built in as part of the process.

- If human and financial resources are limited, ICM programmes can be simplified to include only the following components: (1) harmonization of sectoral policies and goals; (2) cross-sectoral enforcement mechanism; (3) a coordination office; and (4) permit approval and Environmental Impact Assessment (EIA) procedures (FAO, 1991).

Addressing Intergovernmental Issues: National- and Local-Level Involvement

- Responsibility for the management of coastal and ocean resources rarely falls on one level of government. In most countries, national, provincial, and local governments have some form of jurisdiction or management control over coastal lands and waters. Therefore, it is essential to reach an understanding of the relative roles of national, provincial, and local authorities in ICM.
- National and local governments may sometimes be in conflict over ICM because they have different responsibilities, legal authorities, and priorities and respond to different constituencies. In a cross-national survey of 29 nations we conducted in conjunction with the ICM book, 41 percent of respondents indicated that the nature of the intergovernmental relationship (positive or negative) varied according to the issue, whereas 20 percent of respondents reported a competitive or "hands off" relationship. Among developing country respondents, 30 percent reported that national-level institutions had little to do with or were generally competitive with state- and local-level institutions.
- Local government resistance to ICM can be expected if a national government's proposal is viewed as shifting power or authority away from the local level, reducing the amount of discretion available to the local government, or imposing additional costs or other burdens on the local government without providing commensurate benefits.
- National government resistance to an ICM proposal that originated at the local level may be expected if the local plan was developed in isolation from the national level or if national concerns were ignored.
- Each level of government, however, brings unique expertise and perspective to the ICM process. The local level can contribute the most detailed understanding of the local coastal zone and its problems, constraints and limitations that will affect the choice of solutions, data and information on the local coastal zone, and support of coastal user groups and the community. The national government, in turn, can contribute specialized data and expertise on various sectors of coastal activity (fisheries, wetlands,

etc.), capacity to harmonize sectoral activities through a coordinating mechanism, funding assistance (in some cases), and ties to relevant global and regional coastal and ocean programmes.

- Fruitful intergovernmental partnerships may be built through the following means: (1) identification and pursuit of common interests, such as reducing loss of life and property due to coastal hazards, rather than focusing on questions of ownership and control; (2) identification and use of unique expertise, talent, and data that exist at the two levels; (3) deferral of difficult issues, such as those involving jurisdiction and division of management responsibilities and revenues, until a history of working together has been established; and (4) use of respected outside expertise for difficult issues.
- In one model for an intergovernmental partnership in ICM, the national government, with advice from local governments and affected stakeholders, formulates and legislates broad coastal policies and goals for the nation, and the local government develops plans and actions for their coastal zones that are consistent with and incorporate these national coastal policies. The local government then operates a regulatory system consistent with its coastal plan.

Addressing Intersectoral Issues

- The problem of achieving intersectoral coordination was the integration challenge cited most often by respondents to our cross-national survey. In three-fourths of the cases, ocean management and coastal management are not administered by the same organizational unit.
- Although the problems associated with lack of intersectoral integration are generally serious, they should not be exaggerated; not every interaction among sectors is problematic and in need of management. Moreover, the costs of achieving integration should be kept in mind, and it should be recalled that integrated management generally does not replace sectoral management but instead supplements it.
- Integration should be viewed as a continuum rather than an absolute. The goal is to move away from a situation in which agencies don't talk to one another and towards a situation in which a forum for coordinating and harmonizing policies exists and is used frequently and effectively.
- Incentives are needed to bring about continued collaboration among sectoral agencies. Some factors that may enhance the likelihood of cooperation among agencies include financial incentives, legal mandates, perception of a shared problem, shared professional values, perception of political advantage, desire to reduce uncertainty, and availability of a forum for cooperation.
- Some options for achieving intersectoral coordination include creation of a special interministerial coastal coordinating council or commission, assignment to an existing high-level planning, budget, or coordination

office (provided it is at a level above that of the line ministries or agencies); and formal designation of an existing line ministry to act as lead ministry for the ICM programme. About one-half of the countries in our cross-national survey had an interagency or interministerial commission as the national-level coordinating mechanism, and in almost half of these cases, a lead agency for ICM had been named. Fifty-eight percent of respondents also reported that creation of an ICM coordinating mechanism was highly or somewhat related to Agenda 21 recommendations, with middle developing countries (78 percent) being most influenced by the results of the United Nations Conference on Environment and Development.

- Three factors tend to enhance the effectiveness of an integrated coastal management process: (1) the coastal management entity and process should be at a higher bureaucratic level than the sectoral agencies, to give it the necessary power to harmonize sectoral actions; (2) the effort should be adequately financed and staffed with its own people; and (3) the planning aspect of integrated coastal management should be integrated into national development planning (where such planning is taking place).
- Various government entities generally have legal authority over various aspects of management of coastal lands and waters. Legal analysis is needed to ascertain whether existing legal authorities in use by sectoral agencies are adequate to be used for broader coastal management purposes as well. To the extent that the existing legal framework is found to be deficient, new legal authority may have to be sought to fill specifically identified gaps.

Obtaining and Utilizing Scientific Data and Information

- One of the strengths of the ICM process is its reliance on accurate information and data. ICM must be based on sound scientific information; otherwise, ICM decisions will not stand up to political challenges raised by, for example, economic interests whose development activities may be affected by the ICM process.
- Different types of information are needed at different stages in the ICM process. For example, during the formal adoption, implementation, and operation stages of ICM, it is useful to have information on the costs and benefits of ICM, regulatory and management measures, conflict resolution techniques, and relevant analytical methods.
- The coastal zone and adjacent ocean constitute a complex and dynamic environment in which a number of physical, biological, geological, and chemical processes take place. Coexisting in the coastal zone are large number of people joined together in a wide variety of social institutions which themselves are made up of social processes and behaviour. Much has yet to be learned regarding the behaviour of both the physical and social systems making up the coastal zones. Therefore, one of the important challenges of ICM is the design of a decision-making system that can function in the presence of gaps in information and understanding.

- Some rules for making ICM decisions in the presence of scientific uncertainty include the following: (1) do not make decisions that have irreversible consequences; (2) do not make decisions that seriously threaten the resource base over the long term; and (3) do not make decisions that could reduce the options of future generations for utilizing coastal and ocean resources.
- The precautionary principle should be followed regarding proposed new activities. In the absence of convincing evidence to the contrary, a conservative regulatory and management approach should be taken. In such cases, the burden of proving that no adverse environmental effects will occur should fall on the developer. The government, acting on behalf of the public interest, should not have to demonstrate that harm will occur in order to regulate.
- Another strategy for coping with sparse data on the impacts of a proposed coastal or ocean development activity is to require that the needed data be collected as a condition of approval of the initial development activity. Where adverse environmental effects are a concern, it may be possible to design a monitoring programme to detect any such effects before serious degradation takes place. The development activity could then be scaled back or terminated, depending on the circumstances.
- A continuing challenge in the management of natural resources generally centres on the science-policy interface. Improvements in resource management usually depend on improvements in understanding of the processes involved, yet obtaining these gains in scientific understanding has proven to be difficult and slow. Managers and policy makers seem to have difficulty motivating the scientific community to carry out the needed research because it is perceived as “too applied”. Similarly, researchers complain that they do not get clear messages from policy makers as to what is needed and that managers and policy makers do not use much of the information scientists have already provided.
- Although environmental impact assessment (EIA) should undoubtedly be a part of an ICM process, it cannot by itself substitute for ICM. Environmental impact assessment tends to operate on a project-by-project basis and hence is not a good tool for comprehensive area-wide planning. Moreover, preparation of an EIA by no means guarantees that the developer will take the least environmentally adverse alternative. It merely requires that he or she follow the process and prepare an accurate and complete assessment of potential impacts.

Formulating an ICM Programme and Getting it Adopted

Major challenges faced by coastal decision makers as they formulate an ICM programme and get it approved are summarized here. Possible strategies to address such challenges are also discussed.

Formulating an ICM Programme

- An ICM plan is best formulated by an interagency team formed for this purpose. All key agencies involved in coastal or ocean activities should be represented on the ICM programme formulation team. A range of disciplines should also be represented (or available), including planners, resource managers, coastal scientists (geologists, marine biologists, physical oceanographers), and social scientists (experts in legal and institutional issues, economists, cultural anthropologists).
- If possible, the team should work on a full-time basis over a specific period (about a year) to produce an ICM plan. Team members could be seconded from other agencies for this period.
- Some steps the team will have to take in the programme formulation process include: (1) identifying initial problems, issues, and opportunities to be addressed in the ICM programme and setting priorities among these; and (2) setting the programmatic scope of the initial ICM effort: what bundle of issues should be included? ICM programmes might include the following:
    - Protection and management of coastal resources such as beaches, dunes, and coral reefs.
    - Protection of important coastal habitats such as wetlands, mangrove forests, sea grass beds, and mud flats.
    - Protection of coastal water quality.
    - Promotion of a coast-dependent economic use (e.g., tourism, aquaculture).
    - Improvement of public access for recreational purposes.
    - Reduction of loss of life and property due to coastal hazards such as storms.
    - Management of beach erosion.
    - Management of the use of coastal space, including restoration of urban waterfronts.
- A major initial decision in the ICM process concerns the geographical scope of the ICM programme: should the programme cover the country's entire coastal zone or be limited to a pilot project in a smaller area?
- Formulation of goals, objectives, and strategies is clearly an important aspect of ICM. The goals and objectives of ICM must be set carefully to reflect the real problems and opportunities present in the coastal zone. Setting measurable goals will make evaluating the programme's performance much easier.
- Another important early decision in the ICM process involves the setting of boundaries (landward and seaward) for the management area. The area must be sufficiently large to encompass the uses and resources that need management, on both the land side and the ocean side.

- Appropriate design of the intersectoral/intergovernmental coordinating mechanism is a key decision in the ICM process. Functions of the mechanism include strengthening interagency and intersectoral collaboration, reducing rivalry and conflict, providing a forum for conflict resolution among sectors and ocean uses, and monitoring and evaluating the progress of the ICM programme.
- An ICM plan will most likely include the following:
  - A clear description of the coastal area to be managed.
  - A clear description of the problems to be addressed and the goals and objectives to be sought.
  - A clear description of the policies and principles that will guide the programme.
  - A statement of the initial management actions to be taken.
  - A description of the proposed institutional arrangements, including assignment of responsibility for various parts of the programme, such as the interagency coordinating mechanism and supervision and support of the overall ICM programme.
  - Funding and staffing requirements for the programme.
  - A listing of the formal actions needed for official adoption of the plan and suggested timetable for those actions.

Getting Approval for the ICM Programme

Timely government approval of an ICM plan will be aided by the following:

- The ICM programme being proposed is succinctly described in clear and understandable terms (What is it? Why do we need it? What will it do?).
- The benefits (economic, environmental, and social) that will flow from the ICM programme are described in tangible and understandable terms.
- The proposed programme is clearly and visibly endorsed by users of the coast, by the public, and by interested NGOs.
- Key legislative and government leaders have been kept informed of the progress of the ICM plan formulation effort from its inception and have received periodic progress reports.
- The costs (political, financial, and administrative) of implementing and operating the ICM programme are clearly spelled out and sustainable ways to cover such costs are suggested.

Implementing and Operating an ICM Programme

Issues faced during the ICM implementation and operation stages are summarized in this section.

Resolving Issues in ICM Implementation

- Implementation refers to the actions that must be taken to put the ICM programme into operation: start-up activities such as enactment or amendment of legislation, preparation of new or revised regulations and procedures, formal establishment of new institutions or interagency mechanisms, securing of additional personnel, and the like. Decision makers may face a number of problems at this stage. For example, securing necessary legislative and legal changes and obtaining needed resources may be difficult; policy gaps may have to be identified and filled satisfactorily; if an undue length of time has elapsed since the plan was formulated, changes may have occurred that invalidate part of the proposal; or institutional changes may be difficult to put in place because of bureaucratic inertia and resistance to change.
- With regard to the interagency coordinating mechanism (such as a coastal council), the following attributes are usually important: the council is composed of directors of the coastal and ocean agencies or their high-level alternates; the council is chaired by an appointee of the chief executive and is of higher rank than the members themselves; the council has sufficient resources to hire its own staff and technical support (creation of an operating arm of the council or a technical secretariat is important to implement the decisions of the council and carry out the day-to-day work of coastal management; the council is formally established by the usual legal or legislative procedures used in the nation (e.g., legislation, presidential order, decision by local community leaders, etc.).
- Symptoms of problems in the operation of an interagency council are the following: key coastal and ocean decisions begin to be made outside the council's deliberations; council members lose interest in attending meetings and send low-level representatives in their place; the chief executive loses confidence in the council; the council is unable to obtain adequate staffing and financial resources.
- The major functions of an ICM office (created as a technical secretariat for the interagency council or as a separate office in a lead ocean or coastal agency) are to establish and oversee new zonation schemes and other management programmes that do not fit within the mission of existing line agencies; oversee environmental impact assessment processes; coordinate the planning activities of the various line agencies; supervise the performance monitoring and programme assessment functions; engage in training and human resources development; develop an active public participation programme; and address transnational and transboundary issues.
- From the outset, attention should be given to finding ways and means of making the ICM programme financially self-sustaining through, for example, the assessment of fees for the use of ocean and coastal resources and space.

- It is imperative that affected interests be involved in the ICM process from the outset, to better inform the ICM process as well as garner support for it.

Resolving Issues in the ICM Operational Stage

- The emphasis of the ICM programme in its operation phase (once new or altered ICM processes have been put in place) will be on such areas as coordination, harmonization, conflict resolution, coastal and ocean policy integration, management gaps, and monitoring and assessment of performance.
- A wide variety of management tools and techniques are available to the ICM programme in the operation phase; which are used will depend on the extent to which they are authorized under legislation, their technical suitability, and the public acceptance of the approach. Examples include zonation; establishment of set-back lines and exclusionary zones; establishment of protected areas; special area planning; acquisition, easements, and development rights; mitigation and restoration; and issuance of coastal permits.
- An essential function of an ICM programme during its operation phase is the resolution of conflicts among coastal and ocean users and agencies. For an ICM programme to be effective in addressing conflicts, the following elements are important: efforts to understand the roots, causes, and consequences of coastal and marine conflicts through conflict-mapping studies; the existence of an established and transparent process for making decisions about the conflicts; and the capability to adopt and implement measures to remedy injuries or damage to particular coastal and ocean users arising from coastal development or from the actions of other coastal and ocean users.
- Transparency in decision making and public participation are essential for the success of an ICM programme. A process that is seen as fully open, based on reliable information and good science, and accessible to all interested parties stands a much better chance of long-term success than does one that is difficult to gain access to, that does not encourage participation, and decision making goes on behind closed doors.
- Some strategies for ensuring public participation and building consensus include disseminating information on the ICM programme to the public through media coverage and public fora, meetings, and discussions in the local language(s); providing visible mechanisms for public participation in the ICM process; having proper feedback mechanisms to ensure that the outputs of public consultations are incorporated into revised ICM plans; and having a transparent approval process for pen-nits, environmental impact assessments, and the like.
- A strong public education programme that includes an active outreach effort to all educational levels and to the general public is essential in

obtaining and maintaining public understanding of the special character of ocean and coastal areas and the need for special ICM management.

- Evaluations and assessments are essential in measuring the success of an ICM programme and modifying them in view of the results. Unfortunately, of all the various phases of the ICM process, evaluation is the least developed, in terms of both methods and practice. This is one of the areas in which ICM practice most needs to be improved in the next decade.

A REALITY CHECK REGARDING ICM

Finally, we think it is useful to pause for a reality check. As mentioned earlier, the ICM concept has been widely adopted as the management framework of choice, both internationally and nationally. Is this justified? To explore this question, we pose and respond to five questions:

1. *Is ICM a planning and management methodology likely to meet the needs of most coastal countries?* We believe that ICM is a methodology sufficiently flexible to meet the different needs of most, if not all, coastal countries. It is a logical framework that contains the elements most experts agree are centrally important to sustainable use of the coastal zone and its resources. It is not geared to any particular political system or type of coastal zone. Nearly three decades of experience suggest that ICM is a workable methodology and it probably is the most appropriate framework for achieving long-term sustainable use of a country's coastal zone.
2. *In response to the call for ICM at the global level, are countries initiating ICM programmes?* Extrapolating the results of our cross-national survey, most coastal countries report that they are undertaking ICM programmes of one type or another or are planning to do so in the near future. The extent to which countries pursue full-scale ICM programmes will undoubtedly depend on such factors as the following:
   a. The perceived seriousness of existing coastal problems or opportunities (i.e., erosion, resource depletion, ecosystem degradation, new economic activities, etc.).
   b. An awareness within the government structure of ICM and its benefits and the presence of user groups, local communities interested in initiating ICM.
   c. Availability of necessary resources (trained staff, coastal information and data, finances).
   d. The existence of political will within the government to take the necessary steps to initiate and put in place an effective ICM programme.
3. *Is the emergence of ICM as the planning and management framework of choice for many international programmes a reasonable and logical*

development? It is clear that the specific goals of international agreements such as the Framework Convention on Climate Change and the Convention on Biological Diversity cannot be met in isolation. Similarly, achieving the goals of the Global Programme of Action on Protection of the Marine Environment from Land-Based Activities requires the comprehensive, intersectoral approach called for in the ICM framework. In our judgement, it is appropriate and necessary that these new global initiatives specify ICM as the preferred framework within which to pursue their goals and objectives. Indeed, in most situations there will be a coincidence between a coastal country's own goals and those to which it is committed under various international agreements.

4. *Is appropriate guidance on ICM methodology being provided by the international programmes that have designated ICM as the framework within which to meet some or all of their goals?* Only now are the secretariats and other institutions (e.g., expert groups such as the Subsidiary Body on Scientific, Technical, and Technological Advice to the Convention on Biological Diversity) created by the new international agreements beginning to focus on the ICM issue. It seems likely that under at least three of these agreements (the Framework Convention on Climate Change, the Convention on Biological Diversity, and the Global Programme of Action), guidance on ICM will be needed. In February 1997, an International Workshop on Climate Change and ICM produced a set of guidelines for an ICM framework to address such climate change issues as sea-level rise, increased erosion, saltwater intrusion, and increased storm frequency (Cicin-Sain et al., 1997). ICM guidelines may also be developed as part of the implementation of the Jakarta Mandate dealing with the protection of coastal and marine biodiversity under the Convention on Biological Diversity. The challenge will be to ensure that the various sets of ICM guidelines produced under these international agreements are generally consistent with one another and that they all share a common view of the ICM framework.
5. *Does a consensus exist on what ICM is and how to carry it out?* We believe the evidence demonstrates the existence of a consensus regarding the main features of the ICM methodology. There is general agreement among the ICM guidelines produced so far by IUCN, UNEP, the OECD, and the World Bank (Cicin-Sain et al., 1995). Some differences do exist, especially in areas of emphasis. But on the whole, the guidelines deal with such important issues as intersectoral and intergovernmental coordination and inland and seaward management boundaries in very similar ways. We expect that as use and application of ICM increase, a tendency toward even greater commonality will be manifested.

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Geographic Information Systems for Integrated Coastal Resource Management

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INTRODUCTION

In the modern day environment of improved decision making, there is an ever-increasing demand for the storage, analysis and display of complex and voluminous data in different fields of interest. This has led to the use of computers for data handling and the creation of sophisticated information systems. Geographic Information Systems (GIS) are the forerunners in the domain of information systems. There have been many attempts to define GIS, but no consensus has been reached at yet. Some of the GIS definitions from Maguire et al. (ed.) (1991: 10) are given below. Most of the material in this paper has been adapted from sources mentioned on the reference list.

- A system for capturing, storing, checking, manipulating, analyzing and displaying data which are spatially referenced to the Earth.
- Any manual or computer based set of procedures used to store and manipulate geographically referenced data.
- An institutional entity, reflecting an organizational structure that integrates technology with a database, expertise and continuing financial support over time.
- An information technology, which stores, analyses, and displays both spatial and non-spatial data.
- A special case of information systems where the database consists of observations on spatially distributed features, activities or events, which are definable in space as points, lines, or areas. A GIS manipulates data about these points, lines, and areas to retrieve data for adhoc query and analyses.

- A database system in which most of the data are spatially indexed, and upon which a set of procedures operated in order to answer queries about spatial entities in the database.
- An automated set of functions that provides professionals with advanced capabilities for the storage, retrieval, manipulation, and display of geographically located data.
- A powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world.
- A decision support system involving the integration of spatially referenced data in a problem-solving environment.
- A system with advanced geo-modelling capabilities.
- A form of MIS (Management Information System) that allows map display of the general information.

APPLICABILITY

GIS has found application in multifaceted forms and multifarious activities. It has proved itself useful as analytical tools, decision support tool and has been found immensely potential in natural resources management and planning. GIS is used as an analytical tool in the following manners:

- Increasingly, mathematical models can be run from within GIS.
- Models draw upon data in the GIS database.
- Models allow users to study systems of interest and explore different scenarios.
- Modeling employs a broad range of mathematical methods, often involving manipulation of large arrays where subscripts relate to locations as in spatial interaction models in resource planning, dynamic models in catchment hydrology and hill slope erosion and sediment yield models etc.

GIS is used to assist decision-makers by indicating various alternatives in development and conservation planning and modelling the potential outcome of a series of scenarios. It provides planners with a readily accessible source of objective for earth science related facts, and an inexpensive, rapid and flexible tool for combining these facts with various products to create decision alternatives.

GEOGRAPHIC DATABASE

The database in GIS consists of geometric and non-geometric entities. The geometric data describe the location, shape, size and dimension of points, lines, polygon and surface features, while the non-geometric data describe the characteristics of these features.

Geographic data has three major components: its geographic position, attributes or properties, and time or dynamics.

Position

Position refers to the location of the feature concerned, which is specified in a unique way. The location can be: (a) absolute such as coordinate position in a coordinate system like Cartesian (x, y) or global geographic (latitude, longitude); row/column position describing a position on a grid; position within some abstract framework such as street addresses, or (b) relative i.e. with reference to some other object described as “adjacent to”, “intersects with”, or “is contained in”.

Attributes

An attribute is a characteristic of an entity. Attributes are non-spatial, not having permanent locations with respect to other entities and are invariant to changes in scale and projection. Attribute value is the actual measurement that is stored in the database. Attribute data can be categorized as follows:

- Nominal: values that establish identity
- Attributes are described by name with no specific order (maize, wheat)
- Ordinal: These values establish an inherent order or ranking (First, second)
- Interval: Attributes with a natural sequence and equal intervals on a scale with an arbitrary zero point
- Ration: Attributes with same characteristics as interval but with a natural zero or starting point (0, 100, 200 tons/ha.)

Time

Time is an important aspect since geographic information is referenced to a point in time or period of time. Temporal data can be described in terms of:

- Time duration: Time span of the current database
- Temporal resolution: The discrete time interval for which data sets are collected and aggregated per unit of time. Daily or monthly data on water availability for crops and yield predictions can be cited as examples
- Temporal frequency: The frequency over time or the rate at which observations are collected, e.g. monitoring temperature and other climatic factors to determine the frequency of frost conditions for selected time intervals

Database Structure

Geographic information systems have three main data models: the hierarchical, network and relational. The data model, on which a database system is based, represents the organization, description and manipulation of the database.

Hierarchical Structure

The data are organized in a hierarchy or tree structure. The root is the top of the hierarchy, which is related to one or more lower elements, which in turn, may also have one or more elements subordinated to them. The elements lower in hierarchy are termed as children. Linkages are possible only vertically and not horizontally or diagonally. Hence, there is no connection between elements at the same level, hierarchical structure provide high speed of access to large inherent hierarchy, such as census data can be adequately represented by a hierarchical model.

Network Structure

This model overcomes some of the problems encountered in the hierarchical model. Entities can have multiple parents as well as children and no root is required. Network models have greater flexibility and less redundancy than hierarchical models. They also provide high-speed retrievals and include methods for building and reestablishing new links. The major drawback with this model is that all relations must be known beforehand for its implementation.

Hierarchical and network data structures are called navigational structures, because, the relations are built up by links, such as pointers, and users can navigate through the database using these links.

Relational Structure

This model is represented by a set of normalized relations (entities). A normalized relation may be viewed as a two-dimensional table where each row of the table, known as tuple, corresponds to one element of the relation. Association between tuples is represented by data values in attribute with values that uniquely identify the entries (tuples) in that entity table. This attribute is known as the primary key. A primary key is not restricted to a certain single attribute; it can also be a combination of several attributes, which together have the unique identification property.

Data Structure

There are four primitive types of geometric entities, which represent the spatial data: points, lines, polygons and continuous surfaces. The non-spatial data or the sets of attributes describing the properties of the entities are stored usually in relational database information systems.

The spatial distribution of points, line, areas and surfaces is represented in digital form by two basic types of spatial models: tessellation or raster and vector models. Each data model has its strengths and drawbacks and none appears to fulfill all perceived needs of users. Hence, several new GIS software include facilities for handling all these types of data models, thereby increasing functionality and flexibility in handling data from different sources and broadening the range of application of GIS.

Vector Model

In the vector model objects are represented by the points and lines that define their boundaries. The line is taken as the basic logical unit in a geographical context. This is represented by a label or attribute and a list of x,y coordinates to show its location in some coordinate system; points are recorded as lines of zero length, areas or polygons constitute lines with common beginning and ending points.

The most common vector models are the whole polygon structure and the topologic model. In the whole polygon structure or spaghetti model each polygon is encoded in the database as one logical record while in the topological model, the spatial relationship among entities is explicitly recorded. Topological data structures are considered to be essential for automated geographic and cartographic analyses such as automatic error detection and updating.

Raster Model

One of the simplest data structures is a raster or cellular organization of spatial data. Raster (tessellation) models have as the basic data unit, a cell or pixel. Each cell is assigned only one value, different attributes being stored as separate data files. It illustrates the structure of the raster model. The map space is arbitrarily divided into an array of pixels, the shape and size of which determines the basic resolution of GIS. Operations on multiple raster files involve the retrieval and processing of the data from corresponding cell positions in the different data files or layers. The overlay is done by stacking the layers (two-dimensional arrays) and then analyzing each cell location.

Comparison between Data Structures

Vector and raster models have both advantages and disadvantages. Raster models are generally well suited when the spatial variability of a phenomenon is analyzed while network analysis is best suited for vector models.

Advantages of Raster Model

- Simple data structure
- Overlay and combination of mapped data with remotely sensed data is easy, since remotely sensed data is stored in raster mode
- Various kinds of spatial analyses are easy
- Simulation is easy because each spatial unit has the same shape and size
- Technology is cheap and it is being energetically developed
- Same set of grid cells are used for several variables
- Simpler when doing one's own programming

Disadvantages of Raster Model

- Wasteful use of computer storage for spatially sparse data
- Basic logical unit is pixel which is often too coarse for detailed work
- Errors in estimating perimeter and shape
- Network linkages are difficult to establish
- Projection transformations are time consuming
- Difficult to convert raster to vector data models and get results of acceptable accuracy and cartographic quality
- Use of large cells to reduce data volumes can lead to serious loss of information
- Crude raster maps are usually less beautiful and accurate

Advantages of Vector Model

- Easy to transform vector data
- Can represent location with infinite accuracy
- Relatively efficient way of storing geographic data and linking attributes to locations
- Produces high quality cartographic maps and capable of representing surfaces in 3-D e.g. digital elevation models
- Good for network analysis in GIS
- Compact data structure
- Accurate graphics
- Retrieval, updating and generalization of graphics and attributes possible
- Widely used to describe administrative zones because of its accuracy

Disadvantages of Vector Model

- Complex data structure
- Simulation is difficult because each unit has different topological form
- Overlaying of several polygon maps or polygon and raster maps is difficult
- Difficult to generalize vector data
- Because of the need to handle large volumes of vector data, GIS based on vector data model tend to be slow and cumbersome
- Technology is expensive
- Spatial variability is not implicitly represented

Data Analysis

The most important characteristic of geographic information system is the capability for spatial analysis functions using the spatial and non-spatial attributes in the database. The database in a geographic information system is a model of the real world that can be used to simulate certain aspects of reality. A model may be expressed in words, in mathematical equations or as a set of spatial relationships displayed as a map.

The analysis functions have been divided into four categories: retrieval/ reclassification/measurement, overlay, distance and connectivity, and neighbourhood (Arnoff, 1989).

Retrieval, Re-classification and Measurement Functions

In these functions only the attribute data are modified. No changes are made in the location of spatial elements nor any new spatial element created.

Retrieval Operations

These involve the selective search, manipulation and output of data without modifying the geographic location of features or creating new spatial entities. Retrieval operations include:

- retrieval of data using geometric classifications, specifying the spatial domain of a geometrical entity (point, line or area), retrieval of all spatial entities and non-spatial attributes contained in the entire or in portion of that spatial domain,
- retrieval of data using a name or code of an attribute, for example, retrieving effective depth and dominant texture of a given soil type, and
- retrieval of data using conditional and logical statements.

Reclassification

Reclassification involves operations that reassign thematic values to the categories of an existing map as a function of the initial value, the position, size or shape of easy category. It can be performed in single data layers as well as in multiple data layers as part of an overlay operation. This process aims at locating the particular attribute/attributes and regrouping the units into assigned classes. For example, the desirable area for recreational purposes can be clubbed as undulated forest area with well-drained soils and non-agricultural zone.

Reclassification procedures sometimes combine the detailed classes into less detailed composites. This process is known as 'generalization'. In vector systems, using a topological model, boundaries are eliminated and it is then known as 'map dissolve'.

Measurement Functions

These incorporate the calculation of distances between points, lengths of lines, area and perimeter of polygons and volumes.

Overlay Operations

Overlaying of maps leads to the creation of a new map wherein the values assigned to every location on that map are computed as a function of independent values associated with that location on two or more existing maps. New polygon maps have multiple attributes i.e., the attributes which were given to each separate layer before the composition occurred.

Arithmetical and logical overlay operations are commonly in use. Arithmetical overlay includes operations such as addition, subtraction, division and multiplication of each value in a data layer by the value in the corresponding location in the second data layer. Logical overlay involves the selection of an area where a set of conditions is satisfied.

Neighbourhood Operations

The neighbourhood operations evaluate characteristics of an area surrounding specified target location/locations. The typical neighbourhood operations in most GIS are search functions, topographic functions and interpolation.

Search Functions

They determine the value of each target feature according to some characteristic of its neighbourhood. The search area is usually square, rectangular or circular; the size being determined by the analyst.

These functions are of two kinds, those operating with numerical data and the other ones operating with nominal and ordinal data. Typical functions on numerical data are the total, average, maximum, minimum and statistics such as standard deviation or variance. Functions on nominal and ordinal data can be enumerating the number of different classes and frequencies. Examples of search functions are the identification and enumeration of all farms with electricity in a given political region alongside a principal road.

Topographic Functions

The topography of a surface can be represented in a digital elevation model (DEM). A DEM represents a topographic surface in terms of a set of elevation values measured at a finite number of prints. Topographic functions are used to calculate values that describe the topography of an area such as shape, aspect and gradient.

Interpolation

Interpolation is the procedure of estimating unknown values at unsampled sites using the known values of existing observations at neighbouring locations. Point based interpretation estimates values at predetermined locations using points of known locations and values e.g., meteorological stations, spot heights, and porosity measurements. Aerial interpolation estimates the values in target zones using the known values from a source zone e.g., given population counts for census tracts, or estimating the population for electoral zones. The interpolation assumes that observations close together in space and more likely to have similar values than observations farther apart.

Connectivity Functions

Connectivity operations estimate values by accumulating them over the area that is being traversed. The values can be qualitative or quantitative. Connectivity functions are grouped into contiguity, proximity, network and spread operations.

- **Contiguity:** A contiguous area is formed by a group of spatial units that have one or more common characteristics and constitute a unit. Common operations under contiguity functions involve the determination of size of the contiguous area and the shortest and longest straight-line distance across the area.
- **Proximity:** Proximity undertakes the measurement of the distance between features. The measurement unit can be distance in length or travel distance in time or other units. For calculating proximity, the features or objects whether point, line or polygon, the units of measure; the function to calculate an example of proximity (Euclidean distance); and the area of interest should be specified, analysis is creating a buffer zone around the area selected as a forest reserve. Another example is the identification of areas within 400 km of potential sites for office building and more than 1500 m from proposed housing and conservation locations.
- **Network:** Network functions are used in analyses that require movement from one location to another. In network analysis, three components are usually considered: a set of resources (e.g., sediments transported by water); one or more locations where the resources are located (e.g., a fluvial system); a destination (e.g., outlet of the watershed). Examples of network analysis include scheduling the urban transportation service. The analysis includes optimization of the route to service as many persons as possible in a determined zone.
- **Spread:** Spread functions have characteristics of the proximity and network functions. It evaluates phenomena that accumulate with distance. These functions are used to calculate transportation time or cost over a complex surface.

Modelling

A model is a simplified representation of reality that presents significant features or relationships in a generalized form, i.e., it is a selective approximation of reality. There are three main categories of models:

Descriptive models—characterizing or describing the real world (for example a map).

Predictive models—these are concerned with estimating the phenomena which might occur under certain conditions. A well-known predictive model is the Universal Soil Loss Equation (USLE) soil erosion model.
Decision models—these are used to suggest certain courses of action to be followed in response to certain circumstances. Decision models may be considered as structured recommendations used in conjunction with descriptive and predictive models. A good example is the forecasting of fire danger using parameters such as slope, elevation, vegetation type and biomass and meteorological data.

In cartographic modelling, the problem to be solved can be broken down into sub-models that can be solved separately. The model is constructed in such a way that the solution of the individual sub-models can be combined to yield solutions to the original model. One should develop a clear, logical conceptual model with well defined spatial operations that can be linked together that forces the user to think clearly about the steps needed to solve the problem and to make his/her methodology open to examination (Burrough, 1986). There are some general steps involved during the decision making process as given below:

- Identifying the objective through a thorough analysis of needs and requirements, collecting the necessary data available and defining the data gathering procedure for non-available data
- Defining the problem rigorously in details, outlining clearly the objectives, assumptions, limitations and constraints
- If there is more than one objective, defining the relations between objectives in commensurate terms
- Finding the appropriate solution procedure and method
- Finding the solution to obtain the optimal answer to the problem

Errors in GIS

Geographic Information System provides spatial information to decision makers, planner and resource managers. Hence the products of GIS analysis and modelling operations should be reliable enough. Two types of errors are common with the GIS, the error in measurement and observation of data, which form the input to the GIS database, and the errors introduced by the GIS operations.

Errors can arise at every stage of using a geographic information system—from the collection of the original data to the output and use of the resulting information (Table 1).

Table 1: Sources of error in Geographic Information Systems

1. Errors in the source data
   - geometric (positional) and semantic (classification) errors in the compilation of source maps
   - geometric and classification errors in remotely sensed data
   - errors in other source data, e.g., from field sampling
   - inaccuracies due to the vague (fuzzy) character of natural boundaries, e.g., of vegetation and soil types
   - errors due to the source of data being out of date
2. Errors occurring during data input
   - digitizing errors due to operator mistakes and limited precision of the digitizer
   - errors in attribute data entry (typing errors)
3. Errors in data storage
   - errors due to the limited precision with which coordinates and other numerical data are stored
   - errors arising from vector to raster conservation
4. Errors in data analysis and manipulation
   - propagation of errors during map overlay
   - errors due to incorrect use of formula (misuse of logic etc.)
   - errors arising from interpolation, e.g., for the determination of terrain shape from digitized contours
5. Errors in data output and application
   - cartographic errors due to the limitations of output devices
   - incorrect or inappropriate application of GIS products

APPLICATION OF GIS IN THE COASTAL ZONE

While GIS have the potential to contribute to coastal management in a great variety of ways, a number of broad generic categories of application may be recognized as given below (Martin, 1993).

Inventory

Many early applications of GIS to coastal matters focused on the ability of computer systems to store data, and to permit selective retrieval of records on the basis of adhoc inquiries. Sometimes known as transaction-based processing, typical examples have included the RAMS inventory database which was developed to monitor developments along the shores of Chesapeake Bay, and more recently, the Northern Ireland sub-littoral survey which examined the distribution of marine benthic organisms.

In such applications, GIS can aid the sorting and rapid retrieval of data on the basis of location and other spatial relationships. Most proprietary systems nowadays, including IDRISI (GIS software), provide the means for performing such links: IDRISI, for example, includes the DBIDRIS module, which enables data sets held in dBASE to be accessed for analysis and display.

Coastal Change Analysis

The use of GIS for time series and change analysis has been comprehensively discussed in GIS application literature. It is useful to note, however, that GIS is increasingly being used, often in tandem with remote sensing and image processing techniques, in order to monitor changes in coastal systems. In particular, wetlands have been extensively studied using such techniques which have also been applied to the analysis of erosion and shoreline changes.

The dynamic nature of the coastal environment is one of its most important characteristics. The coast provides the setting for complex flow of matter, energy, organisms and information. These flows move in all directions and at a variety of spatial and temporal scales. The primary driving forces that power these exchanges are the short-term weather and long-term climate, secular changes in sea level and gravity-driven tides.

Coastal erosion, flooding, silt deposition in harbours, and oil spillage are but some examples of how human affairs are intimately related to the dynamics of the coast. The processes encountered, and thus requiring analysis, can operate according to time scales ranging from less than a second to those measured in millennia or more. They may be progressive, cyclic (i.e., they ultimately return to the same starting point), chaotic, ordered, or completely random, and they may operate semi-independently of other phenomena or else may be intimately associated with, and dependent on, other components of the coastal system. In spatial terms as well, these dynamic processes can operate over a wide range of scales, from those measured in millimetres less to ones extending over tens or even hundreds of kilometres.

Partly because of this high degree of mobility the coastal zone provides the setting for many important natural environment processes (e.g., erosion and deposition). Many important transfers of energy also take place at the shore, particularly in the transmission of heat from the oceans via the atmosphere to the land. Equally important, many marine organisms, and whole ecosystems, depend on the characteristics of the coast for their survival. The waters of the coastal zone, especially in estuarine and in-shore areas, are some of the most biologically productive areas of the earth, and underpin many aquatic and terrestrial tropic chains. Thus, for these and other reasons, the coastal scientist or manager increasingly requires access to technologies that can take account of the dynamics of the coastal system. Simulation of coastal processes by computer opens up important possibilities for clearer understanding of the shore, and of the likely impacts of management decisions.

The development and testing of dynamic process models and simulations of different abstractions of reality is one of the cornerstones of modern GIS. Besides allowing the impact of proposed developments to be assessed without risk of damage to the real-world, coastal system computer simulation also offers other benefits. In particular, development of a successful computer simulation depends on the creation of a robust data model for representing the system variables within the GIS, and this in turn requires a meaningful conceptualization of the phenomena under study. Thus, the process of setting up the simulation can, itself, promote greater awareness of the constituent elements and relationships at work within the coastal system.

Once the data model has been created, subsets of variables and processes may be isolated for particular attention. Thus the analyst may simplify the complexity of the system and selectively isolate key parameters of concern for more detailed examination. Additionally, simulation modelling also allows compression of temporal and spatial scales to more manageable dimensions and, where appropriate, allows a time-series to be run "backwards," so that the starting point of some dynamic process may be derived from the observed end results.

Traditional simulation modelling of coastal phenomena has tended to focus on specific, discrete aspects of the coastal system such as sediment, contaminant plume behaviour, or wave mechanics. However, within a GIS context, modelling may also refer to the merging, synthesis and analysis of spatial patterns in order to obtain answers to specific questions.

However, GIS can also allow mathematical process models to be used in conjunction with spatial data models (as represented by matrices of raster data or topological vector data), in order to obtain the best of each. Bartlett (1989), for example, demonstrated that a linear wave energy reflection model written in the Fortran programing language could successfully be merged with a proprietary vector GIS package (ARC/INFO) allowing digital maps of wave energy distribution to be generated and related to the distributions of sediment size, beach morphology, and other coastal phenomena of interest.

Decision-making and policy formulation is clearly linked to the above. By combining rapid data retrieval with analytical functions GIS has the ability to respond rapidly and flexibly to adhoc "what if" type questions. A well-designed coastal zone information system could, therefore, be a significant technological contribution to development of integrated and sustainable coastal management.

Coastal Resource Survey and Management

We have already seen that a growing human population is making demands on the shore for living space, leisure and recreation, and a host of other purposes. At the same time, the oceans and coastal waters of the world are important source of fish and other food resources, as well as oil, natural gas, aggregates, manganese and a variety of other minerals. Within the leisure and recreation sectors, several examples exist where GIS has been used to good effect in the assessment, development and management of coastal resources.

GIS is also a major technology within the mining and oil exploration industries where it is harnessed to assist in the discovery, assessment and exploitation of new mineral wealth. Unfortunately, many of these applications remain relatively undocumented for reasons of commercial confidentiality, but examples do appear in the literature from time to time. Other potential applications of GIS in the broad sector of resources exploration and management include the siting of landfalls for oil and gas pipelines, the analysis of seabed topography and geological structures to assess dredging/mining viability, etc.

IMPEDIMENTS TO THE USE OF GIS ON THE COAST

The foregoing section has focused on real and potential ways in which GIS can be used within the coastal zone. However, it is axiomatic that decision-makers should be aware of the limitations and shortcomings of the techniques they are using, as well as knowing about the areas of potential success. Nowhere is this more relevant than when considering the application of the technology to the coastal zone. Although the use of Coastal Zone Information System (CZIS) is increasing rapidly, and the analytical powers of such systems are continually being extended, it must be emphasized that the unique character of the coastal zone presents certain inherent problems for database creation and analysis. Broadly speaking, these limitations arise due to problems of data availability, the geometry and physical characteristics of the coastal system, and the dynamic nature of the coastal environment.

CONCLUSION

Irrespective of the basic data structure adopted, the coastal zone is an inherently difficult system to model because many coastal phenomena have very poorly defined boundaries. Sediment types, for example, can often grade imperceptibly over space from one category to another with no obvious point of transition. The dynamics of the coastal system, referred to above, are equally important in this context: to take a seemingly trivial example, how does one represent the position of the land/sea interface on a map if the line in question is constantly moving?

In practice, many applications of GIS will adopt a similar approach to that used by more traditional cartographers whereby the position of the shore is determined according to some arbitrary criterion (e.g., selection of mean sea level, or some other position of the tides, as a standard datum level). Other phenomena, however, may be less easy to model, and it may sometimes be appropriate to seek solutions based on fuzzy logic or probabilities of occurrence rather than on "absolute", or Boolean, logic.

With growing pressure on the shore and increasing environmental concerns being voiced an increasing number of coastal-oriented GIS applications are emerging. Most of these are based on the use of proprietary GIS packages. However, as has been outlined in this article, the coast has unique attributes and properties, and it is questionable whether currently available commercial GIS products are optimally configured to handle coastal data. While there is no doubt that such systems are being, and will continue to be, adapted to coastal data (or, more dangerously, coastal data are being "shoe-horned" to fit the requirements of the technology), in the longer term successful implementation of coastal GIS requires new concepts and approaches to be developed.

Because of the growing importance of sound integrated coastal management and the attendant need for efficient means of handling large quantities of spatially-referenced coastal data, in 1990 a working group of the International Geographical Union's Commission on the Coastal Environment (superseded since August 1992 by the IGU Commission on Coastal Systems) was established specifically to promote the optimum use of GIS for the coast. Much work in this area remains to be done; however, coastal GIS still offers many exciting challenges. Given the fundamental nature of some of the issues concerned, it appears that overcoming the hurdles will often require a return to first principles and re-examination of certain key paradigms of spatial science and GIS.

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Integrated Coastal Area Management: The Case of India

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INTRODUCTION

Littoral states have both distinct advantages and disadvantages caused by having the sea by the side. Developing maritime countries have to face the dual problem of mobilising resources to make use of the advantages, and also to combat the disadvantages.

Typical developing nations like India have accelerated activities in the field of industries, shipping, ports, fishing, mining, urbanisation and tourism. All these affect the coastal areas. Coastal zone takes the brunt of industrial pressure, environmental degradation, marine life depletion, socio-economic conflicts and security threats, and faces several technological challenges to mitigate them in the future.

Globalisation of economy invites multinational investments. Novel industries find place at unusual sites. Industries concentrate on the coastal zone because of the opportunity for cheap transport of building materials, raw materials and finished products by the sea, and the availability of an unlimited source for water and of a dynamic sink for wastes. Moreover, hazardous industries will have half of their danger circle (sterile zone) over uninhabited sea.

More and more coastal structures including marine outfalls are built. There is drastic reduction in the free-land adjoining the sea. Hinterland development dictates the fate of development of the coastal zone. Rural coastal areas are urbanised and urban areas get supersaturated into megacities. Coastal planning becomes totally industry-oriented.

Environmental degradation originates as a local problem, assuming regional and global scales later. Aesthetic values get affected first. Marine life depletes affecting the sustainable fish catch and the marine food chain. Socio-economic conflicts between the industry-oriented society and the marine/agrarian society lead to new legal tangles and ethnic upheavals. Security threats assume new dimensions owing to changed defence perceptions, and to stockpiling of hazardous materials. Novel technological skills will be needed to face rapidly changing technological challenges to the environment.

Sensitive ecosystems like islands, estuaries, mangroves, bays and creeks pose additional problems (Swamy, 1987). Briefly, the important elements that are to be reckoned in effective management of the coastal areas are (Swamy and Desai, 1993):

- Dynamics of the land-sea boundary
- Geological changes
- Man-made changes
- Natural hazards
- Extent of industrialisation
- Pollutant transport potential
- Corrosive and fouling properties of seawater
- Baseline water quality
- Sensitivity of the ecosystem
- Buffer nature of the sea
- Socio-economic aspects including maritime traditions
- Changing definitions of the coastal zone

We will discuss these briefly with reference to the case of India.

COASTAL ZONE OF INDIA

India has a long coastline of approximately 7500 km, along with two large island groups called Lakshadweep in the Arabian Sea, and Andaman and Nicobar in the Bay of Bengal. This sustains an exclusive economic zone of over two million sq. km, which is equivalent to 61% of the Indian land area. India is one of the wettest countries in the world, with an annual rainfall of about 1000 km^3. Fourteen major, 44 medium and 162 small rivers with a total annual runoff of 1645 km^3 empty into the sea through our coastline. About 500 million tonnes of sediments are discharged into the sea each year. The backwaters of the southern parts of the west coast of India are unique in their physical extent parallel to the coastline and their significance in local transport and fish spawning. Out of more than one billion people of India, about 200 million live in the coastal area. Three of our four metropolitan cities are on the coast.

The coastal zone accounts for almost one-third of the biological production in the adjoining seas, and three quarters of the organic matter burial. The coastal zone acts as a trap for most of the river-borne suspended material and almost all the biologically active and reactive elements of terrestrial origin (including pollutants). Ninety percent of the fish catch of the country is from the coastal waters.

The Indian agricultural economy is dependent on monsoons. The ocean supplies the moisture necessary for such large rainfalls. Another role of the ocean is that it provides food and occupation for millions of people. Some aspects of the east coast and the west coast are summarised in Swamy (1991 a & b). With our long coastline, wide coastal areas and vast exclusive economic zone, we have great promise, but we cannot neglect that we also have great challenges.

GENERAL OCEANOGRAPHIC SET-UP

Geologically, the coastline of India has seen both submergence and emergence. Some parts of the coast have registered rise in sea level and some other parts a drop over the century for which records are available. Large tidal oscillations influence the northern parts of the Indian coastal zone, the tidal intensity reducing southwards progressively. This, in combination with the southward tapering continental shelf, gives rise to very wide tidal flats towards the north and narrow intertidal zone towards the south. Especially the northern parts of our coastline are dotted with vast mud flats.

Reversing monsoon wind system over the north Indian Ocean causes systematic variability in the oceanographic conditions. While the west coast experiences the south-west monsoon (June-September) predominantly, the north-east monsoon (November-January) is more prominent along the east coast, and the southern parts of the west coast experience both. Cyclonic storms are acute in the Bay of Bengal during the period of north-east monsoon. The southwest and the northeast monsoons induce large-scale variabilities over the entire Indian waters. There are seasonal reversals of wind-driven currents. The timing of reversal of these currents and their turning points are still an enigma (Antony et al., 1992, and Antony and Shenoi, 1993).

Waves follow the pattern of winds (NIO, 1982). Surges associated with storms are more intense along the east coast than along the west coast. Littoral transport due to differential refraction of waves in shallow waters creates, depending on the local morphology and sediment type, alternate bands of accretion and erosion (Chandramohan et al., 1989). Erosion tendency is widespread along the central and southern parts of the coasts. Longshore currents tend to reverse in tidal and seasonal cycles.

Seasonal fresh-water discharges are known to cause silting of river mouths and breaching of sand bars selectively. Flash floods and deltaic inundation are frequent. Currents in shallow waters respond to tidal, wind, and other forcings of oceanic origin. Local bathymetry and geomorphology modify circulation patterns. There are a few waterways with active tidal bores. Seawater properties too vary seasonally. Significant variations in seawater temperature and nutrient content are noticed following upwelling episodes. Occasionally blooms of specific algae occur. Indian seas support diverse biological populations (neritic, pelagic and benthic) typical of tropical marine waters. Fish catches fluctuate notoriously.

Because of vast differences in the oceanographic and geologic set-up of different parts of the coastline, beach characteristics (in terms of width, elevation, composition, stability and biota) differ from place to place. Mangroves, coral formations, creeks, bays, lagoons, backwaters and island seas have distinct ecology. Their delicate ecosystems are maintained by preserving them as marine bioreserves.

COASTAL PROBLEMS OF INDIA

The largest problem is related to the health of the coastal sea. Due to the buffer nature of the sea, the marine environmental impacts will not be perceptible until the situation becomes irreversible. Dispersion of pollutants along the Indian coastal waters is characterised by site-specificity, as a result of seasonal and physiographic variabilities (Swamy, 1994). North Gujarat is typically a large-tide regime with occasional cyclonic activity. The Gulf of Kachchh has no appreciable freshwater input. The Saurashtra coast has an east-west tilt along the general north-south alignment of the west coast. The Gulf of Khambhat (Cambay) is influenced by large river systems. The North Maharashtra coast has a large inter-tidal zone with extensive rock outcrops. Both tide and wind dominate the regime, leading to well-mixed conditions almost throughout the year. While the Konkan coast is characterised by moderate tides and systematic winds and currents, the adjoining creeks and promontories have a definite influence on these characteristics. Water temperature variations too are pronounced; the atmospheric temperature has shown intricate variabilities. Presence of large rivers, estuaries and backwaters add multiple dimensions to the problems of waste disposal on the Karnataka and Kerala coasts, because of the sensitivity of the freshwater systems. Furthermore, the sandy stretches pose many other difficulties for the construction of sea outfalls. Northern parts of the east coast of India are prone to severe cyclonic activity. They are also influenced by very large river discharges, unlike in the west coast.

Despite moderate tides, currents and other oceanographic processes, the coastal problems are multiplied by excessive sand transport especially along, and possibly across, the shores of Tamilnadu. Vertical gradient of water temperature is strong and the bathymetry is such that deep waters are encountered at a short distance from the shore.

The Tuticorin coast may be similar to the Madras coast except for the typical climatic features associated with higher temperature, lower humidity, meagre precipitation, etc. Oyster beds, which are extensive on this coast, are very susceptible to thermal changes.

Kanyakumari coast has an east-west setting and is close to marine bioreserves. It is subject to the oceanographic influences of both the Bay of Bengal and the Arabian Sea. Tides being negligible, winds dominate the coastal currents. Winds being strong and erratic, waves and currents are consequently prominent and unpredictable. Water temperature exhibits abrupt variations presumed to be the result of large-scale mass exchange between the Bay of Bengal and the Arabian Sea.

Indian coastal waters with all these complexities are used for domestic and industrial waste disposal at an alarming scale in recent years. All three coastal metropolitan cities discharge sewage into the coastal waters. A variety of industries directly use the sea as a source and/or sink all along the Indian coastline. They include, among others:

- Salt industries along the Gulf of Kachchh
- Soda ash factories in Saurashtra coast
- Petrochemical complex in South Gujarat
- Multiple chemical factories (Maharashtra-Gujarat belt)
- Beach tourism in Goa
- Chemical industries along the south Konkan coast.
- Fertiliser, chemicals and ore industries in Mangalore coast
- Assorted chemical units along the Cochin coast
- Coconut rutting all along the Malabar coast
- Titanium factory in Thiruvananthapuram
- Chemical plants at Tuticorin and along the Madras coast
- Paper pulp and other industries along Pondicherry coast
- Aquaculture farms all along the east and west coasts
- Marine chemical industries along Andhra coast
- Mixed industries in the Bengal coast

In addition, there are two atomic power stations on the seashore—at Tarapur and Kalpakkam. Both Tarapur and Kalpakkam will soon have additional units. Mumbai has an atomic research reactor. The Kanyakumari region is considered for another nuclear power project. Jaitapur near Ratnagiri is yet another site for potential nuclear power installation in future. A nuclear fuel complex is also expected near Tuticorin. A rare-earth processing unit is operational in the southern part of the Kerala coast. There are a few thermal power stations along the Indian coastline. Ennore, Tuticorin and Mumbai each have one. Mangalore and Kayamkulam are going to have super thermal power stations, while Kakinada too is considered for another thermal power plant. The Malabar coast is likely to have gas-based industries. Mangalore is already set for large-scale petrochemical industries. The central part of the east coast has seen sea-water aquaculture boom. The future scenario of man-made pollution is formidable. Equally important are the natural problems related to the erosion of beaches, siltation of river mouths and ports, storms and surges, and the fluctuations in marine productivity. Technological complications are induced into natural systems during constructional activities for developmental works and navigation. Lack of proper master plans for coastal area utilisation by the states, and their incorporation in a national template are the primary environmental hurdles faced by the country for effective management of the coastal zone. In addition, rampant industrialisation is dictated by the facilities offered by the sea alone, without much forethought of pollution/contamination posed by them. The priority goes to engineering feasibility rather than to the environmental compatibility. Aesthetic considerations rank last in the priority of coastal industries. This has resulted in industrial giants overlooking recreational spots, spoiling the beauty of the sea front, if not the quality of the waters.

There has been total disregard for traditional values of the coastal community. This has led to several social conflicts. While on one hand, industries bring about socio-economic benefits, on the other hand cultural values are flayed. Many policies related to socio-economic, cultural, conservational, executional, and legal matters are contradictory and are subject to frequent revisions.

COASTAL OCEAN STUDIES IN INDIA

Considering the site-specificity and the coastal ocean utilisation plan of the industries, the National Institute of Oceanography has carried out studies at over one hundred locations along the Indian coastline. A coordinated coastal monitoring programme is operational at the initiative of the Department of Ocean Development. To obtain long-term data on the coastal and ocean parameters, several data buoys have been moored off the east and west coasts of India. More than 10,000 trajectories of flow are now available through the deployment of drifter buoys all over the Bay of Bengal and the Arabian Sea. Long-term monitoring of the upper-ocean thermal structure is carried out systematically in the seas around India, particularly through remote-sensing. All these will form a substantial basis for the proposed GOOS (Global Ocean Observing System) in the Indian Ocean region, and particularly the coastal module of it (Swamy et al., 1996).

Predictive modelling has been attempted by several agencies with limited success; these are mostly for large tidal systems like the Gulf of Kachchh, Gulf of Khambhat, Thane Creek, Hooghly estuary, etc., and for initial and near-field dilution at specific marine outfalls. The studies related to Tarapur Atomic Power Station have incorporated field monitoring, physical modelling and numerical modelling with great success. The case of Kalpakkam, nuclear power installation added one more dimension to the risk analysis-transient beach erosion (Krishnakumar et al., 1994). The corrosive nature of the sea and the fouling characteristics of tropical marine organisms have attracted extensive attention of the marine community.

PROBLEMS OF MODELLING POLLUTANT DISPERSION IN COASTAL WATERS

Dispersion is the combined action of turbulent diffusion of a contaminant and its advection in the receiving body of water. It is basically a scale-dependent process. This means that in order to find out its various attributes, one has to obtain the field data on the relevant parameters that constitute the process, at various scales in the space-time domain. It is not practical to make field observations below and above certain space scale and time scale in shallow waters.

Physical scale-models have innate scale distortion. Geometric physical models are neither practical nor free from model-induced variabilities. Numerical models have to handle a variety of assumptions and sub-problems having physical and mathematical uncertainties when applied to dispersion phenomena in shallow seas. Even where the models have been formulated, they are far from a hundred percent realistic. The models need to be validated. No field data can be generated satisfying fully the spatial and temporal and accuracy requisites of a numerical model. The skill lies in making use of the available field data that are collected within practical limitations.

There are two approaches to dispersion studies—Lagrangian and Eulerian. Lagrangian field (that is, the flow of a marked particle over space at different times) and the Eulerian field (that is, the flow of particles at a point over time) have some information in common. Each has certain exclusive information imbedded within and not obtainable from the other. Transformation of these fields is yet another problem.

Vertical shear (of flow) and its variabilities over space and time are most prevalent in coastal waters having tidal reversals. Horizontal diffusion induced by vertical shear is very dominant. There is no easy way either to measure shear diffusion or to predict it. Many times, a pollutant patch has a tendency to break away from the main patch and behave in somewhat erratic manner. Often such break-away patches would hug the shore and propagate on a shore-parallel course increasing the land-fall risk. These are to be handled on an adhoc basis.

Seasonal variabilities are another problem. Most of the time, values for the coastal oceanographic parameters are valid for a very brief time interval. Separating crucial episodes from insignificant ones is often arbitrary and subjective. In certain cases there are physical limits to sampling crucial distributions of the dynamic parameters. For instance, the flow in the breaker zone, water levels over muddy patches, propagation of tidal bores, currents during stormy weather, etc.

Perverse currents do prevail at coastal sites. There are two possibilities. One, they are captured during an observational sequence and are highlighted out of proportion. Two, they are missed during the field observations and are ignored totally. Both are serious issues in pollution monitoring and modelling in coastal waters.

All these give rise to site-specificity to the dispersion process in Indian waters. No single method or model can efficiently handle all the problems all the times.

In summary, the problems of handling dispersion process in shallow coastal waters are:

(i) Space-time description of field parameters
(ii) Limitations of physical models
(iii) Limitations of numerical formulations
(iv) Eulerian-Lagrangian transformations
(v) Shear-induced diffusion
(vi) Breaking of pollutant patch and its shore-hugging
(vii) Seasonal variabilities
(viii) Physical limitations of sampling
(ix) Perverse episodes
(x) Site-specificity of Indian waters

Unless the field research and model development take cognisance of these issues, the monitoring and modelling exercises will be on weak grounds. A logical approach will be:

(i) Examine the problems of each site specifically.
(ii) Make use of a combination of field data, physical models and numerical models.
(iii) Conduct, side by side, dedicated experiments to examine the dispersion process as a whole, incorporating all relevant parameters in an integrated manner, at typical coastal marine sites in India.

COASTAL ZONE MANAGEMENT STRATEGY IN INDIA

In India, the rate of growth of developmental activities that affect the coastal areas had been faster than the development of coastal zone management strategy. This resulted in certain degree of mismatch between developmental concepts and environmental concepts. However, the past decade witnessed a sea change in the approach of both the government and the public towards coastal zone management issues. Though the management policies lagged behind the management issues in the yesteryears, the government has caught up with coastal zone protection measures. It is a multi-pronged approach, namely: (i) Conservational, (ii) Developmental, (iii) Social, (iv) Regulatory, (v) Legislatory, and (vi) Voluntary.

(i) Conservational

In this approach, the environmental interests supersede the industries' interests. The stringent Environmental Protection Act has been enacted by the government, by which polluting industries have to conform to set standards as regards to the usage of land, air and water (including the sea). Many sites have been declared as marine bioreserves. Mechanisms have been devised to monitor the activities of the industries and the state of the environment regularly.

(ii) Developmental

To enable sustainable growth, infrastructural development is permitted with stipulations on environmental conformation during the construction and operational phases of projects such as ports/harbours, marine outfalls, sea defence structures, etc., at designated developmental sites. Reversible damages are tolerated to a certain extent, as a one-time consequence under this approach.

(iii) Social

In this approach, social implications assume priority. Some activities (although technically non-lethal) are shelved owing to public pressure, and certain industrial activities are allowed to continue to gain some more time for environmental compliance.

(iv) Regulatory

The regulatory approach allows certain activities on an experimental basis where the environmental and social consequences are not easily perceivable. These are mostly case-by-case decisions.

(v) Legislatory

Once the regulatory approach has confirmed the necessity of legislatory measures, and once the causes and effects of specific environmental problems are well-known, definitive legislatory measures are enacted for strict compliance, as in the case of shallow-water fishing, land reclamation, maintenance dredging, etc.

(vi) Voluntary

All the industries are encouraged to resort to environment-friendly processes, and are given incentives to go beyond the stipulated minimum standards. Many industries take up social welfare measures to demonstrate their commitment to the cause of clean environment. Several non-governmental organisations play a very important role in educating the public on environmental issues.

COASTAL ZONE REGULATIONS IN INDIA

Coastal zone regulation and environmental pollution control are in the 'concurrent list' of the Central and State governments in as much that the Centre's policies will be mostly generic in nature, whereas the states' policies will be specific to the concerned region, and both the Centre and the states will work together for their implementation. There are certain exclusive items under the Centre's purview (shipping, and industries having investments beyond a stipulated limit, for instance). Urban and local area development are in the purview of the states. In this context, it is noteworthy that coastal zone regulations were initiated by the Centre and the states were asked to demarcate the coastal zone under various categories.

Practical problems of demarcating the high tide line and the respective set-back distances for the long coastline belonging to nearly ten different states delayed full implementation of the Coastal Regulation Zone (CRZ) act. Several states were unable to meet the CRZ stipulations within the prescribed time limit, and litigation by interested stake-holders made the implementation all the more difficult. The problems arose because CRZ was a geometric approach towards a dynamic regime, what with shifting waterline due to both natural and artificial activities. Further, CRZ has not taken the elevation of a given site into consideration and tried to apply the rule only over the horizontal plane. As one would recognise, Indian coastal areas have a variety of configurations and elevations above the mean sea level, and different types of population densities and occupational traditions. CRZ is also silent on the seaward limit of the coastal activities.

LESSONS LEARNT

The following are the lessons learnt during the evolution of coastal area management regulations in India:

- Environmental laws and developmental concepts should evolve in tandem, not in isolation.
- Environmental laws should not be adhoc, and should integrate all interests.
- Environmental laws should have more teeth.
- Dynamic approach rather than geometric approach should have been more appropriate to tackle the dynamic sea environment.
- Quantum of pollutants, not concentration alone, needs to be considered for long-term planning.
- Socio-economic aspects should form the basis for developmental activities as well as for environmental controls.
- Political awareness and will are the first steps of any good regulations.
- Central and State policies should not be at variance, and should complement one another.
- Public/popular/community support will be obtained before formulating the regulatory laws. Ethnic/cultural/heritage aspects should not be lost sight of.
- Long-term and global vision is necessary in implementing environmental laws.
- Ground truth has to be researched before legislation; frequent revisions erode credibility of even good legislations.
- Bottom to top, rather than top to bottom, should be the sequence of environment-management conceptualisation.
- Environmental audit and environmental courts are very vital.

- The concept of 'Environmental Cess'—a small price to be paid now to avoid paying a huge price later—is yet to pick up. Then clean-up operations can be undertaken at governmental level rather than at the individual levels of erring agencies.
- Scientists are to be the part of the 'environmental brigade' of the environmentalists, local people and the government officials.
- Interpretation of the definitions of the coastal zone and of the environmental regulations varies from party to party (scientists, environmentalists, government, judiciary, stake-holders, users, general public), like in the story of the blind-men and the elephant. There has to be a legally unambiguous and scientifically correct definition of the coastal zone and interpretation of the regulations under dispute.

ACTIONS ON THE ANVIL

A lot of effort is made to evolve meaningful definitions, and realistic demarcation of the coastal zone based on scientific facts. Environmental strategies are being formed to match industrial development against environmental health. A grand network for the assessment of the conditions of the coastal zone and the adjoining seas is in the process of implementation. Permanent observing stations are being established, and remote-sensing and modelling techniques are being used widely. Side-by-side, public education and awareness campaigns are organised. It is expected that the feed-back will pave the way for an integrated management strategy for our coastal areas, with strong scientific, legislatory and popular support.

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