1 INTRODUCTION

1.1 Numerical modelling - a tool for sustainable development?

India's economic growth in recent years has accelerated the pace of industrial development in the coastal zones in a very rapid manner. The coastal regions of Mumbai, Ennore, Visakhapatnam, Paradip, Kochi, Gulf of Kachchh and Gulf of Cambay etc, have witnessed commissioning of industries such as oil refineries, fertilizer and cement plants, offshore platforms and major ports. The coastal zones have great potential for bioactive molecules from coral reefs, mangroves and sea-grass, provide proteins through fish and facilitate ports, harbours recreation, tourism, transport and facilities for industries. However, the developmental activities and the subsequent human settlement in the coastal regions could be hazardous when events such as tsunami, storm surge and tropical cyclones occur. Also, haphazard industrial development and urbanization in the coastal regions can lead to increased pollution levels, water quality deterioration and fish mortality. In order to make use of the coastal marine environment in a sustainable way, it is necessary that industrialization is balanced through an integrated approach that can keep the coastal environment healthy. Numerical modelling has become an essential and cost-effective tool in this context primarily because (i) it allows a better understanding of various components of the problem (ii) it can be used for accurate prediction of physical characteristics of coastal waters and (iii) it provides solutions well before investment decisions are made or even any costly field studies are taken up. Because of these advantages, significant development has taken place in recent years in the field of numerical modelling of physical and environmental aspects of coastal seas (Hoppensteadt, 1982; Jorgensen, 2001; Gertsev and Gertseva, 2004) and it has been evolved as an effective decision making tool for quantitative environmental impact assessment and for tackling environmental issues.

Knowledge about the hydrodynamics is a pre-requisite to model coastal processes or water quality of a water body as physical drivers such as tides and currents control these processes significantly. Biological and chemical processes can then be modelled based on a clear understanding of the physics of the water body. Recently, a number of modelling studies have been carried out in India to understand some of the basic issues related to water quality deterioration caused by the disposal of urban sewage and industrial effluents (Tyagi, et al., 1999; Gupta, et al., 2003; Vethamony, et
al., 2005; Desa, et al., 2005, Babu et al., 2005). The advantage of numerical modelling is that the required parameters can be simulated at each grid point of the model domain over a sufficiently longer period of time. This kind of spatial or temporal coverage is not practically possible in the case of field measurements. Advanced techniques such as finite element mesh, curvilinear or body fitted contours have made modelling of irregular coastline or bathymetry comparatively easier and decreased the complexities involved while formulating the numerical equations. However, the choice of numerical system, its accuracy and the quality of the measured data used to prescribe initial-boundary conditions to the model can lower the model accuracy to certain extent.

**1.2 Modelling currents in the marine environment**

In classical fluid dynamics, circulation of a fluid, \( C \) is defined as the instantaneous line integral of the velocity \( V \) of the fluid particle around a closed contour of its motion i.e. 
\[
C = \oint V \cdot dr
\]
where \( dr \) is a small line segment along the path of motion. In other words, velocity of the fluid is a pre-requisite to derive the circulation. When the system to be examined is of laboratory scale, the measurement of the fluid flow is quite simple. On the other hand, for systems with larger spatial scales like the oceanic currents, such measurements become difficult. However, flow measuring equipment such as current meters and drifters are being used extensively to determine the circulation pattern. Numerical simulation of currents using hydrodynamic model is commonly used as an alternative to measurements.

As oceanic motions exhibit variability in space from millimeters to thousands of kilometers and in time from a few seconds to centuries, the measurement of velocity field and accuracy with which it is carried out depends largely on the desired space and time scales of the water body. Different time scales are associated with physical phenomena like tides, waves and currents, which need due consideration while describing oceanic motion.

Our present understanding of circulation of the oceans is still incomplete in many aspects because of the difficulties involved in obtaining adequate and accurate measurements of oceanic currents. However, the technological advancements in field measurements (drifting buoys, deep sea current meter moorings, etc) coupled with satellite remote sensing and numerical modelling have enabled us to meet the required accuracies and to obtain a realistic picture of the prevailing current systems and their climatological variability. The evolution of different numerical models has laid the foundation for the study of ocean circulation, which influences the climate and global
distribution of chemical and biological productivity of the seas. The knowledge obtained through numerical modelling of ocean circulation could help in rational management of the planetary environment and its resources in a sustainable manner.

The pattern of flow throughout the water body, broadly expressed as the general circulation, is defined as the long time average global-scale flow that occurs in an oceanic environment. The motion depends on external forcing by wind, gravitational attraction of celestial bodies or density field - related to temperature and salinity of the waters. Now, the problem is to determine the flow field due to the combined forcing of winds, tides and density gradients either through direct measurements or numerical modelling.

Direct current measurements are carried out in the coastal seas using current meters. However, indirect methods are applied to study the currents in the open ocean where direct measurements are difficult to make. In general, in the open ocean, the pressure gradients resulting from density differences between two locations are computed from the measurements of temperature and salinity with depth. The pressure gradient constitutes the main driving force in most of the current systems. The resulting circulation is geostrophic in nature since the pressure gradient force balances the Coriolis force - the deflecting force due to earth's rotation. Most of the studies on open ocean currents are made using this method. But, in this method, acceleration and frictional forces are neglected. The fact that friction is not totally absent, energy must be supplied to the ocean to maintain the currents. This energy supply occurs through heating and cooling or wind-stress exerted over the sea by prevailing winds. Thus, wind forcing and solar heating over the surface and density gradients within the water body constitute the main forcing factors for the deep ocean circulation. However, in the coastal seas, gulfs and bays where water depth is relatively shallow (0-100m); the acceleration due to frictional and tidal forces becomes more important than the density gradients. In the shallow waters, the pressure gradient generated by the tidal forcing is much higher than the density induced pressure gradient. Also, the wind stress acting at the surface induces a frictional drag in the upper layers. This results in the Ekman transport which is confined to a depth of 10-100m. Similar Ekman layer is formed at the seabed layer due to the bottom friction. Further, tidal ranges and currents increase in the shallow regions of gulfs and bays due to amplification caused by resonance or funneling effect. Thus, wind and tide forcing are prominent in driving the currents near the coast, estuary or along the bank of a river connected to the sea.

Information regarding time of occurrence of high and low tides, tidal ranges and extent of ebb and flood currents (tidal excursions) are very important and have a variety
of practical applications in environmental perspective. The manifestation of tide is very visible at coastal locations and it affects activities of coastal inhabitants. Tide charts are essential for navigation in coastal waterways, bays and harbours, dredging of navigational channels, works related to harbour engineering projects such as construction of breakwaters, bridges jetties, docks and single point moorings (SPM). Also, the establishment of standard chart datum for hydrographs and demarcation of the seaward/landward extension of shoreline, property boundaries and coastal regulatory zones (CRZ) depend on the tide information. Information on tides is also important for water sports, boating, surfing and for fishing.

1.3 Physical characteristics of tides in coastal environment

Tides are astronomically induced periodic vertical oscillation of the sea surface, which have coherent amplitude and phase relationship to geophysical forces. Tidal currents refer to the accompanying horizontal movement of waters in phase with the tide, both near the coast and offshore, but distinct from the continuous stream flow of ocean current (Wood, 1986). Newton was the first to explain that tides are generated due to the gravitational attraction of the sun, the moon and the other planets. He derived the mathematical estimates for the forces of attraction (Cartwright, 1999). Laplace derived mathematical formulations for computing tidal forcing. Most of the coastal regions experience the rise and fall of water level twice in a day. This is the principal tidal component known as the lunar semidiurnal or $M_2$ tide. It has the frequency of $2\Omega_j$ and period $\pi/\Omega_j = 12.4$ hr, $2\pi/\Omega_j$ being the lunar day. A secondary variation is due to the revolution of the moon in its orbit during a lunar month ($2\pi/\Omega_m = 27.32$ days).

The geometry of a natural estuary is irregular in all spatial directions - longitudinal, transverse and vertical - due to the presence of bathymetric or geomorphological features such as shoals, groins, pinnacles and islands that locally affect the flow pattern. Such irregular bottom topography along with non-linear wind stress complicates the propagation of long waves in the coastal/estuarine region and deriving accurate analytical solutions to such problems is rather difficult. Numerical methods, therefore, are very useful in obtaining solutions in such situations. The problem is three-dimensional when the propagation velocity varies in x, y and z directions with time. However, such problems can be simplified into two dimensional if the velocity is vertically averaged as is the case for tidal propagation in wide estuaries, and further simplified to a one dimensional problem for the narrow river upstream of a wide estuary.
One-dimensional flow can be described with the help of mathematical equations for a regular gulf or channel, and for such a treatment, the irregular natural channel is transformed into regular hydraulically equivalent channel. The propagation of long waves can be mathematically represented by two partial differential equations for a one-dimensional problem. They are derived from the principle of conservation of mass and momentum (Dronkers, 1964) and can be represented by the equation of continuity and the equation of motion respectively. If \( Q(x,t) \) is the discharge through a cross section of area \( A(x,t) \) and \( h(x,t) \) is the elevation of the water surface, then the equation of continuity is

\[
\frac{\partial Q}{\partial x} + b \frac{\partial h}{\partial t} = 0
\]

Where, \( b \) is the surface width of the cross section. Eqn. 1.1 expresses the fact that the difference in discharge between cross sections \( x \) and \( x+\Delta x \) must be balanced by an increase or decrease of water level between these sections. An important aspect of long wave propagation in shallow waters is the channel bed that acts differently during flood and ebb tides thus satisfying the hydraulic functions. In terms of, the mean velocity \( u(x,t) \) across a section, the equation of motion is written as

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + g \frac{\partial h}{\partial x} + \frac{g u |u|}{C^2 R} = 0
\]

where, \( R \) = hydraulic mean depth of the function, \( C \) the Chezys coefficient and \( g \) the acceleration due to gravity. The frictional term is expressed as \( u |u| \) instead of \( u^2 \) for maintaining the flow direction during flood and ebb.

For computational purpose, Eqn. 1.2 is usually written in terms of discharge \( Q \) across the cross section area \( A \).

i.e \( Q = A u = b_s(a_0+h)u \)

Where, \( b_s \) is the stream width at the point of 'measurement' of the actual water level and \( a_0+h \) is critical depth.

Applying above relation in Eqn. 1.2, it can be expressed as

\[
\frac{\partial h}{\partial x} + \frac{1}{gA} \frac{\partial Q}{\partial t} \left[ \frac{b_s + b}{gA^2} \right] Q \frac{\partial h}{\partial t} + \frac{Q |Q|}{C^2 A^2 R} = 0
\]

The four terms in Eqn. 1.3 represent the pressure gradient, temporal acceleration, non-linear advection and friction respectively, and the contribution of each term must be calculated when examining the momentum balance in the model.
These equations are used to model the flow across a river when considering it as a one-dimensional problem. However it is prudent to use a two dimensional (2D) model for areas such as the Gulf of Kachchh (GoK) for the following reasons:

The highly irregular lateral boundaries of the Gulf can be easily accommodated, thus the field conditions are incorporated in the model more realistically.

Non-linear and eddy viscosity terms along with a realistic bathymetry, as is true for GoK, can be accommodated.

Geomorphologic features such as shoals, islands and swamps, and their tidal drying and wetting can be included.

Variable bottom friction and wind friction terms also can be included in a 2D model.

Because of these advantages, modelling studies are carried out to investigate the physical characteristics of GoK such as water level variation, currents temperature, salinity, density and circulation.

1.4 Objectives

The Gulf of Kachchh, is a highly energetic, macrotidal water body opening to the Northern Arabian Sea, where spring tides reach up to 7.2m in the upper areas. Such large tidal ranges play a key role in determining the hydrodynamics of the GoK as they induce a strong, semi diurnal current system. In order to adequately model these currents, wind forcing and bottom resistance need to be given special attention. Though the predominant component of the GoK circulation is tide-driven, other factors such as temperature and salinity distributions and the density gradient also need to be considered.

Taking into account the above factors, the present study focuses on the following objectives:

(i) to setup and run hydrodynamic model to simulate the tide driven currents in the Gulf of Kachchh

(ii) to simulate currents using different wind conditions and analyse the effect of wind on GoK circulation during three different periods: northeast monsoon (winter), pre-monsoon, and southwest monsoon, and compare with in-situ measurements to validate the model.
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(iii) to simulate temperature and salinity fields and compare with in-situ measurements and estimate the contribution of density in driving the currents.

(iv) to estimate the usefulness of modelling physical characteristics of the GoK in evolving a planning strategy for sustainable development of the GoK.

The thesis has been divided into eight chapters.

Chapter 1 deals with the advantages of numerical modelling of GoK in 2D, the factors influencing the dynamics of GoK and the need to include the effects of bottom topography, frictional forces, wind-stress, and density gradients arising from variations in the temperature and salinity fields. Chapter 2 discusses the geomorphic features of the Gulf of Kachchh. Chapter 3 reviews earlier studies available in the published literature as well as important project documents. Importance of modelling as a tool for studying the tide-driven circulation in GoK is addressed. Chapter 4 deals with the field measurement of tides, currents, temperature, salinity and meteorological parameters during phase I and II. Chapter 5 describes the governing equations used in the model, modelling parameters, model setup, boundary conditions and sediment characteristics used for estimating bottom friction. Formulation of the depth averaged momentum equations for shallow water free surface flow in a 2D regime is explained along with the scheme adopted for obtaining the solution. Calibration of the model and validation of the model results are also included in the Chapter. Chapter 6 presents the model results on tides and currents and analyse the effect of winds on currents in GoK for two periods: April and November 2002. Currents measured during winter, pre-monsoon and southwest monsoon are used to verify the simulated currents for each season. The residual currents obtained from the model results are also explained in the chapter. Chapter 7 deals with the temperature—salinity aspects of GoK based on the data collected during different field measurement programmes and model results. Chapter 8 summarizes the work brings together all the inferences obtained from this study. The usefulness of modelling as a tool in planning the sustainable use of the GoK, whilst preserving its special ecosystems, is explained. The effect of residual currents, residence period and flushing characteristics of the GoK are explained in the light of the results. The results obtained from the study are discussed and conclusions are included. A list of publications referenced in the study is also included.