Study of Sediment Transportation in the Gulf of Kachchh using 3D Hydro-dynamic Model Simulation and Satellite Data

August 2003

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三次元水理モデルの数値実験と人工衛星データを用いた
コチ湾の堆積物輸送の研究

2003年8月

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Abstract

A 3D hydrodynamic model 'COSMOS' is applied to the Gulf of Kachchh to predict tidal variation, ocean currents, residual tidal current, sea surface temperature distribution etc. The model is based on the hydrostatic and Boussinesq approximations and uses a vertical double sigma co-ordinate with a step-like grid. In addition to the momentum and continuity equations, the model solves two-transport equations for salinity and temperature and an equation of state to include the baroclinic effects. The other objectives are to quantitatively assess suspended sediments by digitally analyzing SeaWiFS data using SeaDAS software and to monitor suspended sediment movement by image processing of ocean color monitor data and finally establish relations between residual tidal currents and sediment transport.

The Gulf of the Kachcha (GoK) lies approximately between latitudes 22° to 23° N and between longitudes 69°00’E to 70°45’ E. The GoK presents a complex macro-tidal region. The model is set up for the GoK, and is validated using remotely sensed data. Sea surface temperature, Salinity, river input, meteorological parameters and five components of tide are utilized in COSMOS model. Five boundary conditions, such as land-ocean boundary, air-sea boundary, sea bottom friction boundary, discharge from river boundary and Gulf-open ocean (open) boundary are defined and used. Programs constituting the COSMOS model were executed along with initial input cards to simulate the model using an Alpher mini-computer system at the CERes, for November and December months of 1999. While modeling, the water column is divided into five layers and at each layer the distribution of current velocity and direction, pressure water temperature, salinity and turbulent energy were computed. Comparing the simulated results with the measured data available for those locations has validated the model.
The model results showed that the dominant current system is controlled by tidal variation. The tidal and residual tidal currents simulated by the model are similar to the results obtained by previous researchers. Surface current distribution slightly changes if wind stress is applied to the model. The subsurface layers and bottom layer display almost similar current distribution patterns. However, current speed reduces from the surface towards the bottom. Residual current velocity distribution displays an anti-cyclonic eddy. Several divergence and convergence areas were located in the center of the GoK. The current velocity decreased from 50 to 20 cm/s and the eddy pattern vanishes under uniform depth, which concludes that bottom topography plays an important role in determining the distribution of residual current velocity. The model results of sea surface temperature showed good agreement with temperature structure and pattern obtained form NOAA/AVHRR Data.

From sediment plume pattern studies using Sea WiFS and OCM images, it was concluded that the sediments are transported to the Gulf from the north as well as the south and are seasonally dependent. The residual current velocity distribution map for Dec-99 matches well with the map showing gross geomorphic subdivisions of the Gulf of Kachchh. Whereas, sediment distribution boundaries roughly match with those boundaries defined by current velocity distribution. A properly validated hydrodynamic model and sediment transport study of the Gulf would be of interest for coastal defense, management and economic purpose.
要旨

インド大西洋西部におけるコチ湾は、海洋学的および地質学的にも大変興味ある内湾である。その理由は、ナイジェリア・フェラナリから流出する大量の堆積物を含む河川水がインド大西洋西部を流れる湾海によって遮られ、湾内に流入されるからである。ここでは、コチ湾の堆積物の海流によって流れる結果、湾内とどのように分布されるかを三次元流動モデルによる数値実験と人工衛星観測結果を核合せて、その過程を解釈した。

3次元流動モデルとして COSMOS を採用し、コチ湾における表層流、海流、著微流、酸素酸化分布等を推定するモデルにより、水温と塩分の2つの輸送方程式を計算し、もう一つの目的は、堆積物の湾内への輸送過程を解析するために、人工衛星・SeaWiFS 海色データを使用した。最終的に、湾内の堆積物密度と堆積物の相関関係を明らかにすることができた。

コチ湾は、緯度22～25度、経度69～70度に位置し、複雑な堆積物が混在する内湾である。COSMOS の流動モデルを数値計算するにあたり、海面流速、塩分、河川からの流量、気象変化の気圧変動量等の5つの要素が用いられた。また、大気・海、大気・海、海、海・河川、河川からの流速、河川の流速分布等が設定された。COSMOS による数値計算は、1999年10月と12月のデータを用いて、深度方向に5層に分け含氷における流速、流速方向、水温、塩分、変流エネルギー、レイノルズエネルギーを計算した。そして、現地の実測値との比較を行った。その結果、モデルの有用性が示された。

モデル計算の結果を見てみると、支配的な流れは堆積物の変動によるものであることが分かり、本研究による堆積物密度の計算の結果、以前に行われた研究結果よりも空間分解能と計算プロファイルにおいても精度良い結果が得られた。湾内の堆積物密度の変動流速分布は、堆積物密度の変動を示すが、中層と底層を異なりしたパターンを示した。この事実は、N workshopの流速水温分布とほぼ一致する。また、流速は、中層から下層に向きに向かって、中心部の傾向を示し、最終的にそれらの低下は、ある一定の深さまで観察された。このことは、堆積物の流速の分布は、海面地形に対し堆積物の輸送に対し重要な役割をもっている事を示している。

衛星データ（SeaWiFS と OCM）より観測した海色センサ資料の解析は、堆積物の輸送分布において、北部から湾内及び南部に流入している事は示し、その変動を変形に推移していることが分かった。1999年1月と2月の流速流速分布は、大小な湾内流の変動を示した。つまり、湾内の堆積物の分布は、湾内の流速分布より間違った結果とほぼ一致していることを示した。

これらの結果、コチ湾の海洋流動モデルによる数値実験と人工衛星・海色センサの解析による比較検討実験は、より精度の高い堆積物輸送過程を示し、その湾内の堆積物輸送過程を正確に示す事が分かった。この研究結果は、将来係の沿岸保護、沿岸管理等に役立つものと思われる。
Acknowledgements

I wish to express my deepest and most sincere gratitude to my thesis supervisor Prof. (Dr.) Yasuhiro Sugimori, Center for Environmental Remote Sensing (CEReS), Chiba University, Japan for inspiring guidance, encouragement, and constructive criticism through course of this work. I am deeply grateful to my Indian supervisor Dr. B.G. Wagle for providing me guidance, support and valuable suggestions. I am grateful to Dr. E. Desa, Director, National Institute of Oceanography, Goa for permitting me to use the oceanographic data and for providing all kind of help. I gratefully acknowledge Japan Society for Promotion of Science (JSPS) for awarding me RONPAKU Fellowship, under which this work has been carried out.

My special thanks to Prof. Chao-fang Zhao and Mr. Osawa for extending me help from time to time. I am thankful to all students and the staff of Prof. Sugimori’s Laboratory for their kind assistance. Mr. Sarupria and other colleagues at Data Centre, NIO are acknowledged for their support. OCM data used for this work is procured under COMAPS Project. Sea WiFS data has been acquired from Goddard Space Flight Center. Oceanographic data became available from National Institute of Oceanography, Goa, India.

Last, but most of all, a very special thanks are extended to my wife Priya and my son Yash for their many sacrifices, their endless hours of patience, their understanding and for constant encouragement.

This thesis work is dedicated to my loving parents, Late Dinkar and Usha Kunte, for their cherished wishes and dreams.
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Chapter 1 – Introduction
Chapter 1

Introduction

Human population and activities in the world are generally concentrated near the coast. Over sixty percent of the human population lies in the coastal zone and about two third of the world’s large cities are located along the coast. The pattern of runoff and the delivery of nutrients and sediments to coastal waters are modified through human activities in catchments. Coastal development leads to modification of foreshore, loss of key habitats such as mangroves and sea grasses, changes to flushing rate, resuspension of sediments, and direct inputs of nutrients and toxicants through outfall. Coastal waters are also a major resource for human life as they contribute ninety percent of world fish catch. Human recreational activities and tourism are concentrated in coastal waters. As a result of this collision of impacts and uses, managing coastal zone is a high priority for all coastal nations.

The interaction of multidimensional and strongly interdependent processes or entities in the coastal environment makes it necessary to consider the coast as a system, to be examined as a whole by quantitatively analyzing and describing actions and relationships between its parts. Coast has to be viewed as a complex, dynamic large-scale system with an integrated arrangement of separate component systems, which vary in morphological form, pattern and configuration and cannot be fully comprehended with conventional time-limited studies. Since this complex systems involve interrelationships between and among many variables and parameters that the best way to gain insight into their structure, organization and functioning is through the use of numerical models.
Numerical models are considered as imitations or approximations of prototypes. Models are not reality, and no model, however complex can be more than a representation of reality. While the models are only abstractions or simplifications of a system, they are valuable for simplification, reduction, experimentation, explanation, prediction and communication and they are also useful for providing insights for the generation of hypotheses. Numerical model allows complex equations to be solve with computational ease and since problems can be both linear and non-linear, numerical modeling can be successfully used to study various aspects of the coastal system. A Gulf is one such important component of the coastal system and the Gulf of Kachchh is ideal site for such study.

1.1 Environmental setup

The 170 km long and 75 km wide (at the mouth) Gulf of Kachchh (GoK) lies approximately between latitudes 22° to 23° N and between longitudes 69°00’E to 70°45’ E. It is a 7300 km² east west oriented indentation in the coastline of India at the western extremity (the inner gulf is, however, oriented NE-SW). The GoK is situated to the north of the Saurashtra peninsula, in Gujarat state. Bordering the Gulf at its head is the Rann of Kachchh, a desiccated region. The GoK presents a complex set up of a macro-tidal region, marked by existence of shoals, channels, inlets, creeks and islands (Figure 1.1).
Continuous data of sea surface temperature (SST) and air temperature observed at a few stations shows that during morning hours the sea surface is warmer than the air, and as the day progresses the air becomes warmer than the sea surface. On a few occasions, the difference between the air and sea surface temperature is found to be as high as 10°C. Though available information indicates that the water temperature in GoK may generally vary between 20 and 30°C, local increase up to 35°C can occur in inshore water pools formed in the intertidal zone during ebb tide. In general, temperature profiles reveal a nearly homogeneous water column in the GoK.

The large variation of air and water temperature and scanty rainfall, makes the GoK a high saline water body. In general, the maximum salinity ranges from 36.6 psu (at mouth) to 45.5 psu (at the head of GoK). There is no much salinity variation between the surface and bottom layers, confirming
that the waters are well mixed. Also salinity does not show any marked variation with the progress of winter to summer season. The reason for high saline waters in the GoK is low river runoff in the gulf and high evaporation rate of the order of 1m/y due to large variation in SST and air temperature. This feature along with tidal stages influences the diurnal variation of salinity. Salinity as high as 50 psu occurs in numerous creeks of the little Gulf of Kachchh during dry season and salinities of the order of 8 to 20 psu are encountered in some creeks due to fresh water flow from the brief spell of monsoon.

The GoK is under pronounced tidal influence. Tides in the GoK are mixed type and predominantly semi-diurnal with a large diurnal inequality. The time taken for a tidal wave to travel from the mouth to the head is approximately 3 to 3.5 hr (phase lag). Bathymetry, funnel shape of GoK, coastal configuration and orientation of the coast are probable reasons for the geometric effect contributing amplification of tide. Therefore, the tidal front enters to the Gulf from the west and due to shallow inner regions and narrowing cross-section, the tidal amplitude increases considerably upstream of Vadinar. Thus for instance, the mean high water spring tide of 3.47 m at Okha increases to 5.38 m at Sikka and further to 7.21 m at Navlakhi, at the head the of Gulf. The gulf has an average tidal range of 4 m. The Tidal result shows that ebb to flood takes slightly longer duration (6.25 hr) compared to flood to ebb, which is 6.0 hrs. It is seen that as celerity increases with depth, mid-gulf tides progress faster than the tides near the shore.

The wind pattern in the area is mainly seasonal with rare cyclonic disturbances. Predominant wind directions in the area are west southwesterly and north northeasterly during June to September and December to March respectively. Higher wind speeds are likely to occur during June to September with winds up to 74 km/hr from west and southwest (Srivastava and John 1977). It is noted that surface currents are driven mainly by tides,
except during a short spell (July-August), when surface currents are influenced by the monsoon winds. Study also show that surface and bottom currents are nearly the same, except at few places. Surface currents vary from 1.5 to 2.5 knots at the mouth to 3 to 5 knots in the central portions of the gulf (NHO chart 203). Presence of the numerous shoals gives rise to closed as well as open circulation cells. The currents are purely induced by tides with complete reversal over a tidal cycle. It is also noted that the reversal of flood to ebb is sharp and fast while ebb to flood is smooth and slower.

The 352 kms of Kachchh coastline chiefly have raised mudflats and raised beaches deposited during the high Holocene strandline and the present-day coastal deposits. On the basis of different morphological features, nature of sediments and depositional history, the coastal Holocene shoreline can be classified in to three well-defined segments:

1. The outer segment from Koteshwar in the north to Suthri in the south – Chiefly made up of extensive tidal mud flats and a series of offshore sandbars.
2. The middle portion of the coast between Suthri and Bhujpur overlooking partly the Arabian sea and partly the GoK – dominantly made up of sandy beaches with the coastal dune ridges and a rocky platform
3. The innermost segment extending from Bhujpur to Cherai in the east falls within the Gulf, and is marked by a featureless vast terrain, most of which comprises either tidal mud deposit or saline wasteland merging further east into the little Rann.

The E-W trending coast that lies inside the GoK is sandy and silty with narrow beaches; it merges into the little Rann to the east. The northern coast of Saurashtra trending E-W overlooks the Gulf and shows a crenulated rocky
shoreline with the subtidal zone consisting of channels, shoals, submerged islands, sandbars, coral reefs and mangroves.

1.2 Previous studies

The floor of GoK is highly irregular. The depth of GoK varies from a maximum of about 60 m at the mouth to less than chart datum at the head of the Gulf. Though water depths of 25 m exist in the broad central portion up to latitude of 70° E, the actual freeway is obstructed by the presence of several shoals. At the mouth of the gulf, Lushington shoal with depths nearly 5 m below chart datum is present. On the southeast side of Lushington, a channel with the depth of water varying between 30 and 50 m is present (Figure 1.1). Besides Lushington, there are other shoals in the area namely Gurur, Bobby, Ranwara etc. The presence of Chanka reef and Ranwara shoal narrows down the Gulf. The little Gulf of Kachchh is a vast marsh criss-crossed by innumerable big and small tidal creeks. The coastal configuration of the Gulf is very irregular with a number of islands, creeks, bays, marshes, reefs etc. (Navigation Chart No. 203).

The topography is very irregular at the mouth and the central part of the gulf and consists of pinnacles and scarps ranging in height from 6 to 32 m (Nair et al. 1982). Towards the head, the relief is subdued due to the covering of fine-grained sediments. A large area of the floor of the mouth of the gulf, at the depths greater than 20 m is covered with algal limestone, aragonite cemented sandstones and dead corals (Figure 1.2). On the low-energy margin of the gulf, especially on the southern side, wide tidal flats with patches of coral in the intertidal zone are present. The remainder of the gulf is floored by silt and clay with patches of fine sand (Hashimi et al. 1978).
Figure 1.2 Generalized surface sediment distribution (modified after Hashimi et al. 1978).

The floor comprises of numerous topographic irregularities, like pinnacles, as much as 10 m high, separated by flat-topped features. The topography of the mouth and at the middle of the gulf is relatively more rugged as compared to the head of the gulf. The southern shore is marked by low-level coastal plain with indentations, deep inlets, a number of offshore islands and several river mouths having inlets covered with brushwood and surrounded by the coral reef. The northern shore consisting mainly of sand and mud is infornted by numerous shoals.

The most conspicuous sedimentary formations are predominantly marine, tidal, littoral, or sub-littoral fluvial and aeolian deposits of quaternary age, border the study area. Geological formations from middle Jurassic to Holocene over a crystalline basement are reported from the study area (Biswas, 1971). The Gulf is bounded on the south by Deccan traps, which are found in the Saurashtra Peninsula. On the northern side in the interior of Kachchh area a complete series starting from Jurassic to Pleistocene is found. The Jurassic rocks occupy a large area and are bordered successively by Deccan Traps and Tertiary rocks which extend to the coast and have dips towards the south and southwest.
The region surrounding the Gulf was subjected to earthquakes. The great earthquake of Sind in 1819 is reported to have raised the central area of the northern border of the Rann of Kachchh by several feet. An east-west fault along the northern border of the Rann of Kachchh is reported and it is thought to be of lower or middle Pleistocene age (Hashimi et al. 1978).

The sediments distribution map (Figure 1.2) is based on samples collected from the area and shallow seismic data show presence of course sand with shells around the mid-shoal surficial sediments in the major portion of the kandla creek comprise of gravelly, shelly sand and pieces of rock. The sediments are poor to extremely poor sorted, the skewness is highly variable and there is no relation to either the texture or mean size of the sediment.

The mouth of GoK, however is marked by extensive occurrences of calcareous sandstone rocks, algal limestone, aragonite cemented sandstone and dead corals. Apparently the high tidal ranges in the gulf generate powerful currents that are not conducive to sediment deposition. On the low energy margin of the gulf, especially on the southern side, vide tidal flats with patches of coral in the inter-tidal zones are present. The reminder of gulf consists of silt and clay with patches of fine sand. The beaches consist of dominantly terrigenous sands and contain an appreciable amount abraded and unabraded mollusk shell fragments, foraminifers, ostracods, algae, corals etc.

The floor of the gulf can be divided into 3 distinct morphologic units: even, uneven, and rough (Figure 1.3). The area covering the eastern margin of the Gulf extending from the north of Sikka Creek to the head of the Gulf and the northern margins are marked by even topography.
The region of even topography is flat, gentle and smooth. The flatness of the surface is principally attributed to the land derived sediments masking the underlying topography. In case of the region of uneven topography, variations range approximately from 2 to 5 m. and in the region of rough topography variations ranges up to 25 to 30 m. The seabed in the area of rough topography consists of sharp pinnacles, ridges, valleys etc. The region of rough topography extends from the southern side of the entrance to the Gulf to a distance of about 50 km. In the central part of the Gulf the topography is uneven with a small patch of rough surface. The distribution of uneven and rough topography mainly coincides with the area where rock is exposed on the seabed that extends to a distance of about 75 km in the central part of the Gulf.

The Gulf abound in marine wealth with its diversified flora and fauna which include living corals, thriving as patches, rather than reefs, either on the intertidal sand stones or on the surface of the wave-cut eroded shallow banks and variety of mangroves, is considered to be one of the biologically richest marine habitats along the west coast of India. The high biodiversity is
due to the availability of different habitats like sandy, muddy, rocky, calcareous and coral beds in relatively sheltered waters. Because of this natural biorichness several stretches between Okha and Jodia including coral reefs and mangrove habitats covering an area of 16289 ha as Marine National Park and 45798 ha has been declared as Marine sanctuary. The core area of Marine National Park is centred around the Pirotan Island. The marine flora of GoK is highly varied and includes sand dune vegetation, mangroves, sea grasses, macrophytes and phytoplankton.

Until early nineties, the development along GoK was limited to salt works and isolated industrial pockets apart from major port related activities at Okha, Navlakhi and Kandla. However, decision to set-up two large grass-root refineries at Sikka and Vadinar as well as proposal to establish ports and new industries, is expected to accelerate all round development along the shore of GoK. Along the southern shore, the major industries like soda-ash industries at Mithapur, oil terminal at Vadinar and a thermal power plant and cement factory at Sikka, are established. The availability of relatively deep waters near southern shore and relative protection of monsoon waves has made the GoK attractive for the import of crude oil through Very Large Crude Carriers (VLCCs) and unloading the cargo via Single Point Mooring (SPM) systems to shore based tank farms. Two such SPM are already there and three more are proposed. Kandla port handles traffic of about $3.8 \times 10^7$ t/year of Petroleum Oil and Lubricants (POL) and industrial chemicals. Another major port is partially operational is at Mundra and two more are proposed at Bedi and Poshitra. A few more captive jetties are also proposed or some completed. At present, the traffic of tanker ships carrying POL and other bulk chemicals, which is estimated around 1000 ships per year and is expected to be more than double when proposed ports and jetties are completed. This multifold increase in traffic of crude oil and POL enhances the risk of oil spills due to tanker accidents, hose ruptures, sub-sea pipeline leakages, and operational discharges etc.
If these ports and other industries development are not planned, executed and managed in an environmentally conscious manner, the rich ecology of the Gulf which needs to be protected, may come under anthropogenic stresses. Hence, a comprehensive marine environment protection strategy encompassing the GoK is required to be evolved with a holistic approach. Periodic marine environmental monitoring is a key component of any marine environmental management strategy. Successful implementation of such a monitoring programme requires that the baseline status be establish and model development which will enable taking remedial measures.

Srivastava and John (1977) studied current regime in the GoK. From measured current data they concluded that the major steady currents exists in the area of tidal origin. However, during southwest monsoon period, strong westerly winds would generate wind driven currents; with surface speeds reaching about 0.5 m/sec. They also reported that density currents in the GoK are negligible. Though, vertical distribution of temperature and salinity in the GoK shows nearly homogeneous condition in the water column, Varkey et al. (1977) based on the analysis of their data collected, showed that some micro-fluctuations do occur within vertical distribution of temperature and salinity. Hashimi et al. (1978) collected and analyzed several samples from GoK and reported sediment characteristics, coarse fraction composition, texture, grain size variation and presented generalized surface sedimentation distribution. They inferred sources within the Gulf and from the River Indus. Based on the analyses of echo-sounding results Wagle (1979) demarcated prominent geomorphic features and classified rugged underwater GoK surface in three units – even, uneven and rough. Nair et al. (1982) recorded that difference in the bathymetry, bottom topography and the abundance of mica and clay minerals on the continental shelf north and south of GoK, a micro tidal bay, indicated presence of two sedimentary environments. After
considering the tide variation in the Gulf, the Central Electricity Authority of India (1985) investigated the possibility for tidal power development in the GoK.

Space observations provide synoptic and repetitive coverage of the ocean in contrast to the sparse and isolated in-situ ship observations. Certain measurements specific to the orbital platforms such as sea surface height have been possible only through satellite oceanography. Despite the fact that measurements provided by sensors pertains to the sea surface only, they do manifest the oceanic processes beneath. To monitor key relevant ocean parameters, a wide range of satellite systems and sensors are and will become available during coming decade. Microwave sensors acquire data independent of sunlight and clouds, and are used to monitor wind, waves, ocean currents, oil spills, and sea-ice. Visible and infrared (IR) sensors (e.g., NOAA/AVHRR (Advanced Very High-Resolution Radiometer), ERS-ATSR (Along Track Scanning Radiometer), IRS-P3-MOS, SeaWiFS) monitor sea-surface temperature (SST), fronts, currents, eddies, and ocean colour. Small-scale features such as oil slicks, near-shore circulation, and wave fields, can, under favourable meteorological conditions (normally wind speed must be in the range of 3-11 m s\(^{-1}\)), be monitored with high-resolution polar orbiting radar sensors.

Singh et al. (2001), based on digital analysis of IRS P4 OCM data, collected information prior to and after the Gujarat earthquake of magnitude 7.8 which occurred on 26 January 2001, have reported significant increase in suspended sediment concentration and chlorophyll distribution. Using image-processing techniques, Kunte et al. (2002b) processed Ocean Color Monitor (OCM) data gathered onboard Indian Remote Sensing Satellite, and mapped coastal and underwater features along with suspended sediment plumes. Their study indicated that the sediments are transported to the GoK from north as well as from south and are mainly season dependant. They also
numerically modeled that OCM data could also be derived from up to 20 m water depth (Kunte et al., 2003).

Numerical modeling studies in the Gulf of Kachchh have been carried out only in recent years. Shetye (1999) studied the amplification of tide in the GoK based on analytical and numerical model of linear, viscous and cross-section averaged equations for tidal motion and found that the semi-diurnal constituents $M_2$ and $S_2$ get amplified approximately threefold due to a combination of quarter wavelength resonance, geometric effect and sea bottom friction. Unnikrishnan et al. (1999) used 2D barotropic model to study tidal regime in the GoK and found that computed $M_2$ residual currents show the presence of topographically generated eddies. Their analysis of momentum balance shows a balance between the pressure gradient and friction near the coast. While in the central region, the local acceleration attempts balancing the pressure gradient. He also observed rapid increase in constituent $M_2$ and suggested a resonance at semidiurnal period. Sinha et al. (2000) proposed a vertically integrated model to study tide circulation and currents with tide forcing along the open boundary of the model domain for the construction of the proposed tidal barrage, and found the importance of the bathymetry of the Gulf in simulating the current field.

In the GoK, past numerical modeling investigations have been mostly carried out using measured and observed hydrographic data using two-dimensional models. Only main tidal components and bathymetry were mainly used as inputs. Remote sensing data was neither used as model input nor for validation of results. However, Zao, Kunte and et al. (2003) used a 3D numerical model to study tide variation, ocean currents, residual currents and sea surface temperature distribution and to understand ecosystem and sediment/pollutant transportation in high tide dominated GoK. The model performed well in simulating dynamical parameters and provided various results that are comparable with other earlier studies. Additionally they could
extract features from subsurface layers as well. They used wind speed and direction derived from satellite observation as input to the model along with air-sea heat flux and five components of tide. They validated model results with sea surface temperature derived from satellite observations.

1.3 Aim and objectives

The objectives of the present study are:

1. To detect and monitor the movements of dispersed suspended sediment pattern within GoK by image processing of ocean color monitor data.

2. To quantitatively assess suspended sediments of study area by digitally analyzing SeaWiFS data using SeaDAS software.

3. To use 3-dimensional numerical hydrodynamic model, to study tidal variation, ocean currents, residual tidal currents, sea surface temperature distribution etc. within Gulf of Kachchh region.
   - To retrieve sea surface temperature data from AVHRR/ NOAA for validation,
   - To extract wind components from satellite observation for using as input to the model.

4. To establish relation between residual tidal current with erosion, movement and deposition of sediments in the GoK.

   Figure 1.4 shows a concept diagram of COSMOS hydrodynamic model system, summarizing various inputs and outputs and the links between the various parts. The core is a hydrodynamic model linked to various input parameters like wind stress, SST, salinity, sea level and river input, and
output systems. The model is validated by in-situ data as well as data obtained from AVHRR/NOAA data. All possible links and feedbacks between these component models are shown here. The results from the model are applied to sediment transport studies within the Gulf of Kachchh.

The present study is organized in seven chapters. The first chapter includes, general introduction, description of the study area, review of earlier studies, and objective of the study. The second chapter covers various agents that trigger sediment transportation, ways and means and quantification of sediment transport. The third chapter is devoted to digital remote sensing data processing that includes ocean color remote sensing, qualitative and quantitative measurements of suspended sediments and extraction of SST and wind data. Fourth chapter describes COSMOS model, governing dynamical equations, boundary condition, data requirement, assumptions and calculation conditions. Fifth chapter describes model results and validation. Sixth chapter details sediment transport studies conducted, and its comparison with model results. Seventh chapter summarizes and concludes the entire study. It is followed by references and acknowledgements.
Figure 1.4. Concept diagram for an operational hydrodynamic model system.

- Initial Boundary Values (Monthly avg. values)
  - Quikscat
  - Windstress & Direction
- SST
- Salinity
- Sea Level
- River Input

COSMOS Hydrodynamic Model

- Output Maps
- Validation
  - JPL value-added products
  - NOAA-AVHRR Data
- In-situ Data

- SST
- Salinity
- Density
- Currents Tides Residual

Sediment Transport Application