

Suspended Sediment Concentrations in the Coastal Waters of Southwest India Derived from Satellite data: Significance for Coastal Zone Studies

A thesis submitted to the University of Hyderabad
in partial fulfillment of the award of a **Ph. D degree** in
Earth and Space Sciences

by

Sravanthi Nukapothula



Centre for Earth & Space Sciences

**University of Hyderabad
(P.O) Central University, Gachibowli
Hyderabad – 500 046
India**

December 2014

DECLARATION

I, Sravanthi Nukapothula, hereby declare that this thesis entitled **“Suspended Sediment Concentrations in the Coastal Waters of Southwest India Derived from Satellite data: Significance for Coastal Zone Studies”** submitted by me under the guidance of Prof. A.C. Narayana, is a bonafide research work which is also free from plagiarism. I also declare that it has not been submitted previously in part or in full to this University or any other University or Institution for the award of any degree or diploma. I hereby agree that my thesis can be deposited in Shodganga/INFLIBNET.

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Date: 30th December 2014

(A.C. Narayana)
Research Supervisor

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Dedicated to

My parents

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Chapter 1

Introduction

Chapter 1

Introduction

1.1 General Introduction

The hydrologic environment of coasts and bays is strongly influenced not only by ocean circulation from the tides and winds but also by river influx such as fresh water, nutrients, sediments and others. Large sediment flux during flood flow significantly impacts the bottom environment and coastal erosion. The transport and dispersal of sediments derived from Asian rivers and adjacent oceanic islands form > 60% of the global river discharge (Milliman and Meade, 1983; Milliman and Syvitski, 1992). The estimated suspended sediment flux to the world's oceans ranges from 9.3 Gt year⁻¹ to more than 58 Gt year⁻¹ (Holeman, 1968; Judson, 1964; Milliman and Meade, 1983).

Sediment concentrations and their distribution are controlled by the physical, chemical, biological and environmental processes in river systems and coastal oceans. The coastal erosion, promoted by the interaction of waves and rising sea-levels, resuspended bottom sediments by tidal currents and storm surges. Waves also bring the sediments in to suspension in the surf zone inducing high sediment concentrations in shallow water (Shi et al., 2013).

The variations in concentrations of suspended sediments have vital significance for coastal waters in terms of water quality and bottom topography. The transport and dispersal of suspended sediments in the coastal waters also affects the biological productivity such as phytoplankton and fisheries (Zhang et al., 2013). Re-suspension of sediments can cause increased biological oxygen demand and result in a fall of dissolved oxygen levels. Furthermore, suspended sediment transport processes also influence geology and geomorphology of continental shelf (Bian et al., 2010). Study of sediment composition and transport in coastal zones is necessary from the point of biological, civil engineering, and coastal zone management. Hence, knowledge of suspended sediments play an important role in understanding the coastal processes, and in management of coastal zone and navigation hazards, pollution hazards etc.

Remote sensing measurements provide priori tools to monitor the sediment transport and analyze the fate and distribution of suspended sediment concentrations (SSCs) in riverine and coastal waters since it offers a synoptic and instantaneous field of vision (Holyer, 1978; Sydor, 1980; Novo et al., 1989; Forget and Ouillon, 1998; Ahn et al., 2001; Doxaran et al., 2002; Ouillon, 2003; Wozniak and Stramski, 2004; Teodoro et al., 2010; Binding et al., 2012). Recently, remote sensing technology has been used extensively for SSCs measurement as it provides continuous, synoptic and long-term global observations. Various visible and near-infrared (NIR) band combinations have been proposed as SSC indicators in estuarine, lagoon/ lake, and other coastal environments. Recent advances in satellite technology, image acquisition and processing, and data accessibility have drawn much attention to remote sensing approach for determining SSCs.

In the perspective of remote sensing, waters are generally divided into different classes and a bipartite classification scheme, according to which oceanic waters are classified as Case 1 and Case 2 waters (Preisendorfer, 1976; Morel and Prieur, 1977; Gordon and Morel, 1983; Sathyendranath and Morel, 1983). Case 1 waters are those in which phytoplankton (with their accompanying and covarying retinue of material of biological origin) is the principal agent responsible for variations in optical properties of the water and mostly confined to deep ocean regions. Case 2 water refers to coastal waters that contain not only phytoplankton but also other constituents such as suspended sediments, dissolved organic matters, etc. These waters are more complex than Case 1 waters in their composition and optical properties. Interpretation of an optical signal from Case 2 waters can therefore be rather difficult.

A pictorial representation of these two types of waters (Prieur and Sathyendranath, 1981; Morel and Antoine, 1997; Dowell, 1998) is presented in figure 1.1. In this classification optical property (absorption or reflectance) at a certain wavelength and at a particular location and time is taken into account, and computed the fractional contributions due to phytoplankton (P), yellow substances (Y) and suspended material (S). This classification is based on the relative contributions of three types of substances - phytoplankton, suspended material and yellow substances (See Figure 1.2)



Figure 1.1 Diagrammatic representation of Case 1 and Case 2 waters (adapted from Prieur and Sathyendranath, 1981; Morel and Antoine, 1997; Dowell, 1998; IOCCG 3, 2000).

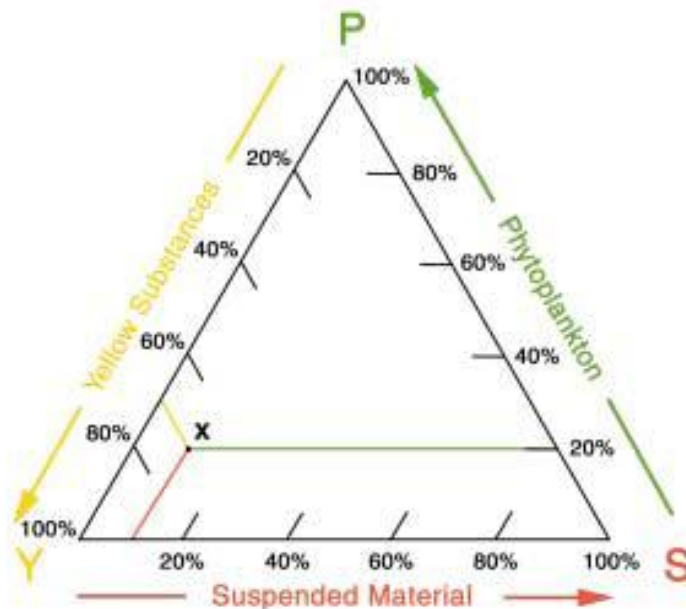


Figure 1.2 An illustration of the trilinear graph in use to classify the waters. The classification is based on the relative contributions of three components: phytoplankton, yellow substances and suspended material in relation to optical property (Prieur and Sathyendranath, 1981; IOCCG 3, 2000).

The geographic distribution of algorithms for Case 1 and Case 2 waters is variable. For example, waters of a given locality may drift between Case 1 and Case 2 conditions depending

on environmental forcing. Hence, there is a necessity for an algorithm to distinguish between Case 1 and Case 2 waters, and an algorithm developed for Case 2 waters may not be applicable to Case 1 waters.

The other optical properties such as suspended particle size, shape, and colour can influence the water - sediment optics (Baker and Lavelle, 1984; Curran and Novo, 1988; Stumpf and Pennock, 1989; Sydor and Arnone, 1997) which influence the algorithm development. Because of these optical complexities, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as bathymetry, coastal geomorphology, river input, regional coastal circulation patterns influence the SSCs distributions and hence the developed algorithm for one region may not be applicable to another region.

Earlier studies in remote sensing of SSCs were mainly focused on discovering and demonstrating the existence of connections between suspended sediments and spectral reflectance on which empirical methods were based (Ritchie et al., 1990; Schiebe et al., 1992). Most documented relationships between spectral reflectance and SSC in surface waters are linear. A linear correlation ($R=0.85$) between the spectroradiometer remote sensing reflectance of range of spectra 700-800 nm and *in situ* SSCs in Mississippi reservoirs was recorded by Ritchie et al. (1976). Spectral radiance recorded by an airborne multispectral scanner shows a positive correlation between SSCs and radiance analyzed by Curran et al. (1987). The relationship between SSCs and reflectance was log-linear relationship at wavelengths of 450 to 700 nm and linear relationship at wavelengths of 700 to 1050 nm as established by Chen et al. (1991). Novo et al. (1991) analysed the oxisol sediments and found that relationship between SSCs and reflectance was linear and constant in the wavelength range of 450 to 900 nm. Chen et al. (1992) examined derivative reflectance spectra and used this spectra for the estimation of SSCs, which show a strong inverse correlation between SSCs and derivative spectral reflectance both in the laboratory ($R^2 = 0.98$) and at sea ($R^2 = 0.83$). The error in SSCs estimates using derivative spectral reflectance in the laboratory was $< 8\%$ of the mean value (Chen et al., 1992).

Understanding of long term sediment movement in the nearshore environment is a necessary requirement for the design of shore structures and for navigational purposes. It is understood that movement of sediment is governed by complex interaction of winds, waves and

the nature of prevailing sediments in addition to morphology of coast (Wright et al., 1991). The significance of sediment transport in marine environment and coastal zone studies has been widely documented. Two dimensional model were developed for understanding of vertical flow and suspended sediment transport for the lake waters of Karhijarvi in Finland by Podsetchine and Hutulla, (1994) and for simulation of tidal currents in Tamar estuary southwest coast of England (Tattersall et al., 2003). Numerical modeling of hydrodynamics in the Indian coastal waters has been carried out by various reserachres (Shetye, 1999; Unnikrishnan et al., 1999; Babu et al., 2003; Vethamony et al., 2005; Chauhan et al., 2007; Kankara et al., 2007; Kunte et al., 2008; Sinha et al., 2010; Ratheesh et al., 2012). However, hydrodynamic simulation models alone cannot be effective in understanding sediment dynamics, and hence the use of remote sasing data in combination with the numerical modeling results are suggested to comprehend the sediment distribution patterns and source to sink pathways of sediment fluxes (Chauhan et al., 2007). Sediment transport along the Mangalore coast using model results, and the residual eddy currents patterns in the Gulf of Kachchh region from the simulated tidal currents were carried out by a few researchers (Babu et al., 2003).

The present study is at estimations of SSCs and their spatial and temporal variations along the southwest coast of India employing OCM-OceanSat-2 satellite data. These estimations in terms of spatial and temporal variations are helpful in understanding the dispersal patterns of SSCs in relation to rainfall, river discharge and wind forcing. As the global algorithms can not be used universally for all types of coastal waters, a regional algorithm is developed for estimation of seasonal and temporal variation of SSCs in coastal waters of southwest India. The developed regional algorithm for coastal waters of the southwest coast of India has been derived from the linear regression of combination of different wavelength bands of 490, 555 and 620 nm and remote sensing reflectance (R_{rs}) values. The algorithm has been used for the estimations of SSCs from Ocean Colour Monitor (OCM) data obtained onboard Oceansat-2 for a three year period from 2010 to 2012 on a monthly basis. However, the cloud free satellite data was not available for all the months in a calendar year.

The OCM satellite derived SSCs employing regional algorithm have been utilized as an initial condition of SSCs values in mud transport model of MIKE-21. The mud transport model

is run with simulation of SSCs and studied the sediment transport under the hydrodynamics of tides, winds and bathymetry prevailing along the central Kerala coast for the month of January 2011.

1.2 Sediment source and fine size sediments in coastal seas

Rivers draining the continental blocks are the major source for transport of solid and dissolved material to the oceans (Milliman and Meade, 1983; Milliman and Syvitski, 1992; Meybeck et al., 2007). Transportation of suspended sediments and nutrients from continents to the sea and their subsequent dispersal has many implications, including transport of carbon, minerals and pollutants to the oceans and their effects on biological productivity of the coastal seas (Eisma, 1981). Every year, about 20 billion tons of sediments are brought to the oceans by the rivers globally (Milliman and Syvitski, 1992).

Much of the river-derived sediment is either trapped in estuaries or deposited on adjacent continental shelves, and relatively a little escapes to the deep sea (Meade, 1996). Smaller rivers also play an important role in the transfer of terrigenous sediment to the global ocean (Milliman and Syvitski, 1992) and can have profound impacts on both the short-term and long-term characters of the coast (Syvitski and Saito, 2007) and sea floor (Milliman et al., 2007). Moreover, many smaller mountainous rivers discharge onto active narrow margins and/or deep canyon systems by which their sediment can be transported directly offshore (Milliman and Syvitski, 1992; Warrick and Milliman, 2003).

Numerous studies have documented the fate of these river-derived sediments after delivery to the ocean, especially from large rivers such as the Amazon (900×10^6 t/yr) (Nittrouer and DeMaster, 1996), Yellow River (1080×10^6 t/yr) (Huanghe) (Alexander et al., 1991; Liu et al., 2007); Ganges-Brahmaputra (1670×10^6 t/yr) (Goodbred and Kuehl, 2000) and Yangtze (478×10^6 t/yr) (Changjiang) (Liu et al., 2007). The significant contribution of the Ganges-Brahmaputra basin in global sediment production has been well recognized in the Indian Ocean (Milliman and Meade, 1983; Summerfield and Hulton, 1994). Within this megabasin, the Himalaya and in particular, the lower Himalayan ranges, including the Nepal middle hills and the Siwaliks, are considered to be the major sources of sediment supply, and deposition of these sediments dominates the Bengal Fan and Himalayan foreland (Sinha and Friend, 1994).

Ramakrishnan et al. (2013) have reported that Sabarmati, Mahi, Dadar, Narmada, Tapi, Ambika and Shetrunji debouch very high sediment loads to the eastern Arabian Sea (6×10^7 metric tons/year) with a large amount of sediment as suspended load into the west coast of India with an average monthly water discharge exceeding $2000 \text{ m}^3 \text{ s}^{-1}$. Rivers of southwest India (Kerala) - Muvattupuzha, Minachil, Manimala, Pamba, Achankovil, Periyar and Chalakudi - debouch 7, 32, 560 metric tons of sediments annually (Narayana and Priju, 2006).

Estimates derived from the interpolation/extrapolation of low frequency measurements of point SSCs acquired over relatively short periods of the major Nepalese rivers show that sediment yield fluctuates widely in the range $1000\text{-}7000 \text{ t km}^{-2} \text{ Year}^{-1}$ (Galay, 1989). Because of their high sediment production rates, small and medium rivers draining the mountainous terrains are responsible for most of the known hyperpycnal discharges (Mulder and Syvitski, 1995; Milliman and Syvitski, 1992). Climate, hinterland topography, geology, and geomorphic features are responsible for the sediment production by the rivers. Mountainous rivers commonly carry high sediment loads and yields followed by upland rivers and least load is associated with lowland rivers (Ahnert, 1970).

South Asian mountainous rivers have relatively higher sediment yield than those draining other mountainous areas of the world (Milliman and Syvitski, 1992). Sediment load and net gross precipitation has been correlated by many workers with varying results (Langbein and Schumm, 1958; Jansson, 1988) with a better relationship documented between the annual variability of rainfall and sediment transport; high sediment discharges recorded in years with high rainfall (Syvitski and Morehead, 1999). But some studies suggest a variety of sediment transport trends relative to precipitation (Langbein and Schumm, 1958; Warrick and Milliman, 2003).

Size of sediment grains is the most important parameter when determining the hydrodynamic activity of sediments, apart from shape and mineralogy (Shepherd and Sprigg 1976; Dagg et al., 2004; Devlin and Brodies, 2005; De'ath and Febricius, 2010). Fine-grained sediment is a natural and essential component of river systems and plays a major role in the hydrological, geomorphological and ecological functioning of rivers. Fine sediment ($< 2 \text{ mm}$)

load in rivers is generally increasing throughout the world in catchments that are impacted both directly and indirectly by human activities (Owens et al., 2005). The < 63 mm fraction of the suspended load is chemically active component of the solid load and thus many contaminants and nutrients are transported in association with this fraction making an important component in biogeochemical fluxes within river systems (Owens et al., 2001). It is also well understood that much of the fine-grained suspended load is cohesive and, thus, is not transported as individual discrete particles but rather as flocculated or aggregated particles (Petticrew and Droppo, 2000; Droppo, 2001). These fine-grained sediments are generally brought from the river and the continent-ocean interface is an area where marine and riverine particles are vigorously mixed due to strong tidal currents and wave reworking processes. Studies of mud flats in estuarine systems were carried out to understand the processes of deposition/erosion in coastal areas based on sediment characterization and sedimentation rates (Dyer et al., 2000).

The fine-grained terrigenous deposits on continental margins are the end result of production of sediment in different source areas and of the subsequent transport and dispersal of the sediment by wind and coastal waters. Upon entering the ocean, the behavior of fine sediments depends on the type of coastline (exposed, embayed, estuarine, etc.), wave and wind patterns, surface and deep currents, littoral currents, sub-marine topography, grain sizes and mineral composition of sediment (Griggs and Hein, 1980).

Suspended sediments mainly clay mineral particles and organic matter in coastal waters stay in flocculated state (Eisma, 1986). Since, flocs are highly sensitive to hydrodynamics and act as adsorption surfaces to dissolved materials including pollutants (Forstner and Wittmann, 1983) are particularly important to the sedimentary and biogeochemical cycle. Processes affecting floc formation and settling at river mouths are critical to understanding the fate of sediment delivered to the coastal ocean (Milligan et al., 2007). Hence, the knowledge of the dynamics of fine sediments can be used as a good approximation to the dynamics of pollutants in the coastal seas (Dyer, 1997). Generally, suspended sediments may retain temporarily in the maximum turbidity zone or settled in intertidal areas (Dyer, 1997).

1.3 Ocean Color Remote Sensing and its Application

Remote sensing of suspended sediments depends on their concentration variations and optical properties of the coastal waters. Measurement of SSCs and nephelometric turbidity in freshwater and estuarine environments were among the earliest hydrologic applications of satellite remote sensing (Ritchie et al., 1976; Holyer, 1978). Though, the methods of assessment of SSCs and/or turbidity have different variants, but there exists an empirical relationship with the remotely sensed reflectance values which is commonly used to compare the results (Ritchie et al., 2003). These relationships generally acquire the form of a linear, logarithmic and exponential regression equation or least square approach (Topliss et al., 1990; Tassan, 1994; Clark, 1997; Ruddick et al., 2003; Miller and McKee, 2004; Doxaran et al., 2005; Han et al., 2006; Chen et al., 2010; Wang et al., 2010; Bi et al., 2011; Long and Pavelsky, 2013; Ramakrishnan et al., 2013; Wang et al., 2014). The spectral mixture analysis has been carried out successfully for mapping SSCs in different coastal waters by various researchers (Smith et al., 1990; Gomez et al., 1995; Matsuhisa and Fukushima, 2008; Pavelsky et al., 2009).

The utilization of relationship between the remote sensing reflectance with SSCs developed in one locale to assess variations in sediment concentration in other areas is limited due to differences in sediment quality parameters such as color, particle size and the mineralogy (Ritchie and Cooper, 1991; Liu et al., 2003; Lathrop, 1992; Dekker et al., 2002; Ritchie et al., 2003; Doxran et al., 2005; Pavelsky et al., 2009).

A reflectance band ratio sediment algorithm for coastal zone color scanner (CZCS) data has been studied by various researchers (Viollier and Sturm, 1984; Amos and Topliss, 1985; Tassan and Sturm, 1986; Stumpf and Pennock, 1989; Topliss et al., 1990; Clark et al., 1980). Kritikos (1974) described the use of ERTS-A, more commonly known as Landsat 1, data for suspended particulate matter measurements. Holyer (1978) discussed the progress of universal multispectral suspended sediment algorithms, which seems optimistic in retrospect. The CZCS was the first satellite-borne sensor with radiometric sensitivity designed for the marine environment (Acker et al., 2005). This theoretical approach consists of numerical simulations and sensitivity analyses (Tassan and Sturm, 1986). Tassan (1994) introduced a pioneering results in

which the remote sensing reflectance and the SSCs relationships are interpreted using the Sea viewing Wide Field of View Sensor (SeaWiFS) data.

Band ratio between a red wavelength band such as Landsat thematic mapper (TM) band 3 and a short-wave infrared band such as TM band 5 has been used for the mapping of SSCs (Xia, 1993). Estimating SSCs in turbid coastal waters from SeaWiFS data in the Santa Barbara Channel incorporates the analyses of multiple wavelengthbands and a nonlinear calibration, which produce highly accurate results (Warrick et al., 2002), where SSCs ranging from 0-200 mg/l were recorded. The largest plumes were observed about a distance of 10-30 km off the coast and occurred immediately following large El Niño winter floods (Warrick et al., 2002). Ruddick et al. (2003) used medium resolution imaging spectrometer (MERIS) data for mapping of SSCs and chlorophyll concentrations using the validated regional algorithm in Belgian coastal waters. Shen et al. (2010) established a semi-empirical radiative transfer model with physically based empirical coefficients to estimate SSCs from MERIS data over turbid waters with a much wider range of SSCs. Wang et al. (2009) observed a regression relation between *in situ* SSCs and water reflectance of landsat enhanced TM+ Band 4. Based on the remote sensing reflectance retrieved by the Aqua-moderate resolution imaging spectroradiometer (MODIS) and SeaWiFS data, inversion algorithms of SSCs were evaluated using the *in situ* measured SSCs in the East China Sea (Cui., 2012). Ramakrishan et al. (2013) estimated the SSCs in Case - 2 waters of west coast of India based on spectral similarity between ocean color monitor (OCM) images and library spectra. These results were compared with other published data and observed to be more accurate ($R^2 = 0.95$ at 99% significance).

1.4 Objectives of Present work

The remote sensing application for estimation of SSCs along the coast of Kerala (southwest coast of India) is meagre. There are some studies confining to small areas but there are no studies covering the entire stretch of Kerala coast. Against this background, the present study is carried out with the following objectives.

- Development of a regional algorithm for the retrieval of suspended sediments in the coastal waters of southwest coast of India.
- Understanding spatial and temporal distribution of suspended sediment concentrations in the coastal waters and at river mouths.
- To understand the sediment transport in central Kerala coast employing MIKE - 21 Mud Transport Model.

1.5 Previous Studies

The quantification of suspended sediments and understanding of their dynamics are of major significance for sediment transport studies and in understanding land-shelf-ocean interaction processes (Wegner, 2003). Suspended sediments have a potential towards marine resources applications by providing chlorophyll/primary productivity estimates and spread of oil slicks. Wilber and Clarke (2001) studied the effects of increased turbidity and reduced water clarity on the feeding of fishes in the coastal waters. The monitoring and understanding of sediment dynamics, circulation patterns, coastal process and suspended sediment transport is an important issue for coastal engineering related activities in marine environment and also essential to keep strategical track of the pollutants and biological activities. Hence, estimations of SSCs in the coastal environment is very important.

Many measurement techniques have been developed in the last two decades and many of them are based on the assessment of surrogate quantities for estimating SSCs. Traditional point measurements of SSCs including the gravimetric analysis of filtered water samples (Strickland and Parsons, 1972), optical methods (Schoellhamer and Wright, 2002) and acoustical backscatterance sensor (Stone and Hotchkiss, 2007) methods are in use to quantify suspended sediments.

The capability of satellite remote sensing to provide synoptic, repetitive and multispectral data has proved to be very useful in the remote sensing of the ocean colour and thus interpreting the sediment concentration is a cost-effective method. Remotely sensed images provide regional coverage with the potential for monthly to daily coverage. The application of spectral mixture analysis for estimating concentrations of suspended sediment in coastal waters has been discussed by Smith et al. (1990). Remotely sensed seasonality in spatial distribution of the SSCs

in the southern North Sea studied with the help of wind induced wave action (Eleveld et al., 2008; 2012). Bain et al. (2013) recorded the distributions patterns of SSCs in yellow sea and east China Sea during the four seasons and the results showed that the hydrodynamic factors such as wind induced vertical mixing, and tidal currents played important role in the distributions patterns of SSCs in the coastal seas.

In order to use satellite imagery in quantifying SSCs, the relationships between the integrated data of satellite band/bands and sediment concentration in surface waters have been investigated by various researchers (Binding et al., 2012; Long et al., 2013). However, this relationship depends on a direct proportionality between reflectance and suspended solids, which may not be the case for very high sediment concentrations (Kirk, 1989). Harrington et al. (1992) reported that reflectance values of Landsat MSS 3 in NIR band is linearly related to SSCs within the range of 0-500 mg/l and nonlinear relationship at higher SSCs. Water reflectance Band 2 in the MODIS sensor exhibit a linear relationship with SSCs within the range of 74-600 mg/l and a nonlinear relationship in the range of 600-881 mg/l is recorded by Wang and Lu (2010). In addition to single bands, ratios of different bands i.e., reflectance values in the NIR to visible bands (red, green and blue), and from red to green band, have also been employed in estimation of SSCs in different coastal waters (Doxaran et al. 2009). Doxaran et al. (2006) pointed out that the use of reflectance ratios could reduce the effects of sky reflection, particle size, and refractive index variations. However, reflectance ratios work well only for highly turbid waters where scattering is sufficient to overcome the strong absorption by other optical materials in water at these wavelengths (Binding et al., 2012).

Although numerous studies have been carried out, there are several factors limiting the application of remote sensing to coastal waters. These include the characteristics of the sensor and the spatial and temporal resolution. From this perspective, the MODIS on Terra provides good temporal resolution. MODIS data (band 1) with 250 m resolution has been used by several researchers in studies related to the suspended sediments along various coastal regions. Hu et al. (2004) showed a simple relationship between in situ SSCs and remote sensing reflectance at 645 nm to derive time series of water quality in Tampa Bay using an empirical algorithm. Miller and McKee (2004) established a robust linear relationship between MODIS band 1 and in situ SSCs. Guzman and Santaella developed and validated an algorithm to estimate SSCs based on MODIS

250 M reflectance. Chen et al. (2011) analyzed the effect of rainfall on the sediment plume in the coastal waters of Apalachicola Bay by devising an enhanced remote sensing model using MODIS. Shi and Wang (2010) quantified the seasonal and inter annual variability of an offshore plume in the central East china sea using MODIS data. Son and Wang measured water properties in Chesapeake Bay also using MODIS ocean colour data. It has been observed that MODIS data have been extensively used in SSCs studies. Loisel et al. (2014) studied the variability of SSCs in coastal waters under the Mekongs influence from ocean colour remote sensing over the last decade using the MEdium Resolution Imaging Spectrometer (MERIS) data and analyzed for the oceanographic and hydrologic conditions.

A semi-empirical single wavelength band (at 859 nm) algorithm is assessed for the mapping of turbidity and SSCs and observed that this algorithm is performed well for the turbidity estimates within 12% and 22% of *in situ* values in the southern North Sea and French Guiana coast (Dogliotti et al., 2015).

Rugner et al. (2013) have ascertained the importance of distribution of suspended sediments in transport of pollutants, pathogens, etc, thereby making the study of sediment dynamics immensely important for evaluating the water quality and understanding the condition of a coastal system. Forces such as tides, waves, river discharge, and wind and turbidity currents alter the transport and distribution of suspended sediments. The variation in distribution of sediments off West Coast of India have been investigated by various workers (Stewart et al., 1965; Kolla and Kidd, 1982; Nair et al., 1978). The topography and nature of sediments of western continental shelf of India were studied by various researchers (Nair et al., 1978; Hashimi et al., 1978).

A few studies have been carried out on suspended sediments along the Indian coast employing remote sensing techniques. Rajawat et al. (2005) studied the coastal processes along the Indian coast based on synergistic use of IRS - P4 OCM and IRS - 1C/1D data. Kunte et al. (2008) used IRS-P4 OCM data to estimate the SSCs and understand their dispersal patterns in the Gulf of Khambhat. Distribution and dynamics of SSCs have also been analyzed in the Gulf of Kachchh. In most of these studies, OCM (OceanSat-1) datasets have been used for estimation. Ramakrishnan et al. (2013) developed a new technique for estimation of SSCs in very high

turbid coastal waters of the Gulf of Cambay using the OCM data. The Gulf is a high energetic system where the highest high tide reaches about 6.6 m at Kandla and 7.2 m at Navalakhi, causing amplification of the tidal constituents (Unnikrishnan and Luick, 2003); whereas Shetye (1999) considers that an additional amplification of constituents is due to the funnel-shaped geometry of the Gulf. Field measurements of *in situ* SSCs were used to understand the sediment characteristic of the Gulf of Cambay by earlier researchers (Hashimi et al., 1978; Nair et al., 1982; Ramaswamy et al., 2007). From the hydrodynamic simulation of tidal currents, the transport pattern between the outer and inner Gulf of Kachchh region was reported by Kankara et al. (2007) and Vethamony et al. (2005). Babu et al. (2005) studied the residual eddy currents within the Gulf of Kachchh using numerical modelling of tidal circulations.

Sediment transport on the continental shelf of Mangalore by Narayana and Pandarinath (1991) revealed that the transport direction is towards onshore where fluvial influence is absent and the direction is towards both onshore and offshore where the fluvial influence is prevalent. Wind induced circulation pattern and offshore transport of sediment plumes were studied by some researchers (e.g., Ji et al., 2002). With strong storm surges and tidal action, coastal erosion causes major re-suspension of bottom sediments which are transported across the outer shelf in surface plumes and as near bottom suspensions by wind driven currents (Forest et al, 2007; Walker et al., 2008). Hydrodynamic simulation studies were found to be ineffective in understanding various sediment dynamics and, hence, the use of satellite data in conjunction with the numerical results were opted by Kunte et al. (2005) and Chauhan et al. (2006) to comprehend the sediment distribution and source to sink pathways of sediment fluxes. Avinash et al. (2012) tuned a regional algorithm to study the seasonal variation of suspended sediment concentration using IRS-P4 Ocean Color Monitor data for the Mangalore coast.

Chauhan et al. (1996) have used the remote sensing data and field data to map the sediments in Tamilnadu coastal waters using chromaticity technique. Surendran et al. (2006) validated the SSCs derived from OCM data Off Chennai, east coast of India. Pradhan et al. (2005) improved a regional algorithm to retrieve SSCs using the IRS-P4 OCM data in the coastal waters of the Bay of Bengal. Chauhan et al. (2007) retrieved SSCs by refine algorithm applying in the Gulf of Kachchh region to obtain the SSCs distribution patterns. Their study compared OCM derived SSC with *in situ* SSCs, pass synchronous and random measurements and observed

that the OCM derived SSCs are underestimated by $\pm 25\%$. Pradhan et al. (2004) have utilized OCM derived sediment inputs to study the impact of tidal propagation on the sediment dynamics of the Gulf. Study of sediment movement and coastal processes along Mangalore coast (southwest coast of India) using satellite imageries have been successfully carried out by Santosh et al. (2002). Babu et al. (2003) studied the sediment transport along Mangalore coast using model results. Purnachandra Rao et al. (2011) studied the suspended sediment dynamics on a seasonal scale in the Mandovi and Zuari estuaries, central west coast of India and observed the turbidity maximum on a neap tide during post monsoon, which may be due to the erosion and resuspension of sediments from the tidal flats and transport of these turbid waters.

The southwest coast of India (Kerala coast) is characterized by the discharge of forty-one west flowing rivers originating from the Western Ghats. Large quantities of sediments are discharged into the Arabian Sea, particularly during southwest monsoon (Narayana and Priju, 2006; Chandramohan and Balachand, 2007). Their study noted that approximately 95 % of sediments were transported during the monsoon seasons. Coastal erosion and storm surges are commonly reported on the Kerala coast (Chattopadhyaya, 2010). Rajawat et al (2005) noted that Kerala coast is generally a wave dominated the coast and the net sediment transport is from north to south during the pre-monsoon periods and reversed transport of sediments in the monsoon months as inferred from the OCM images.

Although a number of studies have been conducted on fluxes of riverine discharges, sediment transport processes by means of sediment sampling, hydrodynamic measurement, and numerical modelling, the picture is far from being clear, particularly along the southwest coast of India. Further, monitoring the SSCs and their dispersal patterns along the Kerala coast is poorly documented. Some researchers studied the discharge rates of sediments from the west flowing river and the dispersal of the sediments along the Kerala coast from the conventional data (Chakrapani and Subramanian, 1993; Rajawat et al., 2005; Narayana, 2006; Chandramohan and Balachand, 2007). Remote sensing measurements of SSCs are an effective means for monitoring the SSCs and exploring the seasonal sediment transport processes along the Kerala coast. Therefore, the present work emphasizes the understanding of spatial and temporal distribution of SSCs with the help of satellite data and the source of fine sediments. A regional algorithm has

been developed for the retrieval of suspended sediments in the study area. Sediment transport is modelled, employing MIKE-21 Mud transport model, for central Kerala coast.

1.6 Study Area

The southwest coast of India under study extends from 08° 15' N - 12° 85' N latitude and 74° 55' E - 77° 05' E longitude, and covers over a distance of 560 km with a remarkable straight coastline oriented in NNW-SSE direction (Figure 1.1). The Kerala coast, synonymously referred as southwest coast of India, is characterized by various geomorphic features viz., rocky headlands, reef-like structure, tidal/mud flats, paleo beaches, ridges, estuaries, lagoons, barrier islands, spits, mangrove ecosystem etc. There are 44 rivers draining into the southeastern Arabian Sea which originate from the hills of the Western Ghats. Most of the rivers in central Kerala drain into the backwaters. The medium rivers are Periyar, Bharathappuzha, Chaliyar and Pamba which together deliver 35% of the average discharge. The rivers of Kerala swell up during monsoon with large amount of discharges. There are 34 lagoons and estuaries, locally called as kayals, along the Kerala coast. Among these 34 Kayals, Vemband lagoon is the largest (205 km²) followed by Ashtamudi Kayal further south. The present study area i.e., southwest coast of India is influenced by the strong southwest monsoon which brings high amount of rainfall and water and sediment discharge to the nearshore sea.

Chapter 2

Study Area – Southwest coast of India

Chapter 2

Study Area – Southwest coast of India

2.1 Introduction

The Arabian Sea, located between 07° N to 25° N latitudes and 55° E to 75° E longitudes, is characterized by its unique features composed of complex sea floor, seasonally changing hydrography, and covers an area of $\sim 3,863,000 \text{ km}^2$. The Arabian Sea is surrounded by arid land masses to the west and north and high lands of western India to the east. Circulation in the Arabian Sea is controlled by the seasonal reversal of winds caused by the alternating heating and cooling of the Tibetan Plateau and the resulting pressure changes (Kumar et al., 2010). During summer (June to September) strong southwest winds blow across the Arabian Sea, which cause offshore Ekman transport and upwelling along southwest coast of India and Oman and Somali margins and sporadic upwelling along the eastern Arabian Sea (Wyrski, 1973). However, upwelling does not occur during the northeast monsoon due to unfavourable wind direction. Thus the seasonal reversal of winds has a bearing on the biological productivity (Kobanova, 1968; Jayaram et al., 2010b) and the lithogenic and biogenic flux in the Arabian Sea (Nair et al., 1978).

Among many current circulation systems, Somali current of Arabian Sea is unique due to its strength and the reversal during monsoon season (Friedrich and Julian, 2001; Schott, 1983) (Figure 2.1). Several modeling studies (Jensen, 1991; McCreary et al., 1993) indicate a presence of two-gyre circulation system in the western Arabian Sea during south west monsoon, a great whirl in the Somali basin between 5°N and 10°N with clockwise rotation, and a secondary eddy towards its south (Schott, 1997); complicated pattern than the continuous northward or southward flow as seen in climatological atlases (Alvarinho and Kawamura, 2004). The two-gyre system is stable until August or September when the southern gyre propagates northward and merges with the great whirl as observed by Schott (1983).

Local and remote forces trigger the hydro-dynamic processes in South Eastern Arabian Sea. For example, wind jets in the equatorial Indian Ocean, between 5° S to 5° N, sets off

equatorial Kelvin waves which upon reflection from the eastern boundary of the Bay of Bengal, propagate along the perimeter as a coastal Kelvin wave and radiate Rossby waves (Yu et al., 1991). The coastal Kelvin waves propagate along the perimeter of the Bay of Bengal, bend around the Sri Lankan coast and further proliferates poleward along the west coast of India.

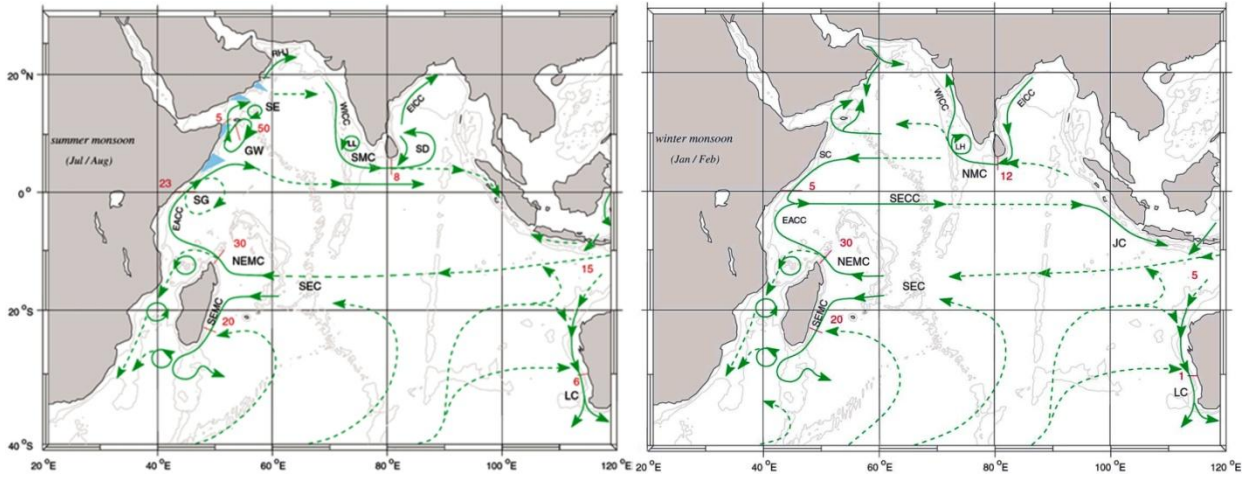


Figure 2.1 A schematic illustration representing current branches during the southwest and northeast monsoon respectively. The ocean current branches indicate south equatorial current (SEC), south equatorial countercurrent (SECC), northeast and southeast Madagascar current (NEMC and SEMC), east African coast current (EACC), Somali current (SC), southern gyre (SG), great whirl (GW) and associated upwelling wedges, Socotra eddy (SE), Rasal Hadd Jet (RHJ) and upwelling wedges off Oman, west Indian coast current (WICC), Laccadive high and low (LH and LL), east Indian coast current (EICC), southwest and northeast monsoon current (SMC and NMC), south Java current (JC) and Leeuwin current (LC) (Schott and McCreary, 2001).

Upwelling along the southwest coast of India is reported as an annually recurring phenomenon that occurs during the southwest monsoon (June to September). However, this upwelling phenomenon is relatively less intense than the other upwelling regimes of the Arabian Sea (like those at Somalia and Oman), but has profound impact on the coastal biological productivity and fisheries. While the west coast of India accounts for 70% fish yield of the total Arabian Sea production (Luis and Kawamura, 2004), the southwest coast alone accounts for 53% (Sanjeevan et al., 2009); hence this region is of considerable importance.

The southwest coast of India also called as the south eastern Arabian Sea extends to the whole of the Kerala coastal region. The coast experiences a moderate energy with monsoonal-

storm-dominated wave climate. The Central Kerala which is considered as “haffnehrung” type of coast with lagoons and back waters (Ahmad, 1972).

2.2 Physiography of hinterland

The Kerala State extends from 08° 18' N to 12° 48' N latitude and 74° 52' E to 77° 22' E longitude and covers over a distance of 560 km in the southern part of west coast of India. The geographical area varies in width encompassing a total area of 38,863 km² with varied physiographic features.

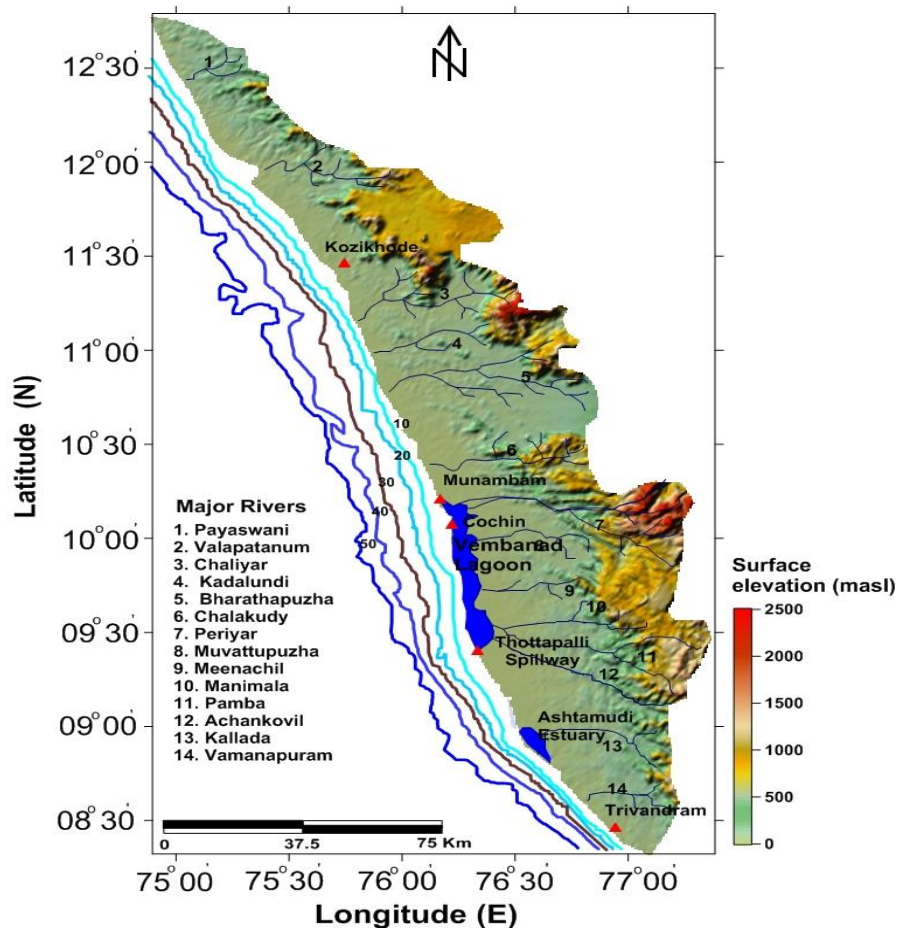


Figure 2.2 Map showing the study area i.e., the southwest coast of India. Hinterland physiography, rivers that drain the area and bathymetry of coastal sea are also shown.

A major part of this varied topography is dissected by numerous west-flowing rivers resulting in varied land forms (Figure 2.2). The mountains are essentially plateau remnants of

two or three altitudinal ranges, approximately around 1,800 m, 1200 m, and 600 m called as planation surfaces. These plateau remnants are considered to be the result of periodic uplift of this part of the Western Ghats. Wayanad plateau, hills of Kunda, Periyar and Nelliampathi plateaus, and Agasthya malai are all parts of this range at different elevations with peaks exceeding 2000 m in height; Anamudi (2695m) is the highest peak. Palghat Gap (30 km width) is a major break in Western Ghats with the elevation dropping below 300m. This gap is considered to have been formed by tectonic and erosional processes. The coastal plain of Kerala bears a few scattered hillocks with rocky cliffs.

There are 34 kayals (lagoons or estuaries) providing ample scope for inland navigation. The Vembanad lagoon along the central coastal region extends to a length of 110 km from Munambam to Alleppy, a largest (area of 205 km²) lagoonal system followed by Ashtamudi kayal, further south. Certain parts of the coastal plain, particularly between Cochin and Alleppey, a sequence of parallel to sub-parallel dune ridges occur. The Kerala coast presents an evidence of transgression and regression of the sea during the Holocene. Many parts of the coast are subjected to severe erosion. The continental shelf is wider in the south, particularly off Quilon.

2.3 Coastal Geomorphology

The Indian coastline is characterized by various features such as rocky headlands, coral reefs, reef-like structures, tidal inlets, estuaries, lagoons, barrier islands, bays etc. The west coast is highly irregular, cliffed and exhibits wave eroded character (Ahmad, 1972). The backshore and foreshore zones of beach environment is commonly marked by sand dunes/ beach ridges and tidal terraces. The plains of the west coast of India are confined to a narrow belt of about 10 to 25 km wide lying between the Arabian Sea and the Western Ghats extending from Gujarat to Kanya Kumari.

Kerala coast is a narrow strip of land with remarkable straight coastline oriented in NNW - SSE direction for a distance of 560 km. It is believed to have originated as a result of faulting during the late Pliocene (Krishnan, 1968). Coastal plains are much wider and less hilly than the rest of the west coast. The shoreline is dynamic and neotectonically active leading to considerable erosion and loss of surface area (Jayalakshmi et al., 2001). The elevation of the shoreline on ranges from 0-5 m. Intervening the ghats and the shoreline, exposures of Tertiary

formations such as the Warkalli beds of Miocene at Varkala in the south and Tellicherry-Cannanore in the north occur. North of Varkala for about 100 km there are coastal Tertiaries occupying the zone between the extremely narrow alluvial bars towards the shore and the edges of the gneisses and granites interior on the east. These consist of marine fossiliferous coral limestones and sands and clays with bands of lignite, and are frequently capped by laterite. The present shoreline is straight for over a great part of the length from Calicut to Quilon, but parts of northern Kerala (Cannanore) and southern Kerala (Trivandrum and Quilon) is characterized by indentations, cliffs and protuberances.

The width of the continental shelf along the Kerala coast varies widely from south to north. West flowing rivers are major contributions for the shelf deposits. There are 44 rivers flowing west into the Arabian sea which originate from the hills of the western ghats and drain into the backwaters. The major rivers are Bharathapuzha, Pamba, Periyar, and Chaliyar (Figure 2.1.) which together drain 35% of the state's average discharge. The rivers of Kerala swell up during monsoon season and shrinks into modest dimensions during summer months.. The dams constructed across many of these rivers for power generation and irrigation have considerable influence on the sediment budget of the coastal zone.

The beaches of Kerala are composed of fine to coarse grade sands (0.15 to 0.50 mm) mostly of sub-recent to recent sediments (Manoj Kumar et al., 1998). The coastal stretch from Quilon to Quilandy is covered by laterites and placer deposits of considerable economic importance. The concentration of heavy minerals like ilmenite, monozite, rutile and zircon from Neendakara to Kayamkulam is an important feature of the coast. The beach material comprises of shell fragments, magnetite, sillimanite and rare earths (Rao et al., 1984; Manoj Kumar et al., 1998; Kessarkar et al., 2003). Muddy bottom shelf extends 20-30 kms from the coast to a depth of 30 m beyond which the shelf slopes down steeply to 1000 m (Rao et al., 1983).

Coastal landforms

Lagoons and estuaries

An extensive estuarine system along backwaters on the southwest (Kerala) coast of India exists. Vembanad lake/lagoon is the largest, extending 110 km in a northwest and southeast

direction from Munambam in the north to Alleppey in the south. The width of the lagoon varies from 500 m to 4 km and the depth from < 1 m to 12 m (Priju and Narayana, 2007). Many of the lagoons, locally known as Kayals, are bestowed with numerous islands of different sizes. There are 34 Kayals (lagoons/estuaries) and Vembanad lake is the largest (205 sq.km) lagoon followed by Ashtamudi Kayal further south (Figure 2.2). The Vembanad lake/lagoon is characterized by its long axis running parallel to the coast and is separated from the sea by barrier spits interrupted by tidal passes. The Vembanad lake opens into the Arabian Sea at Cochin and Munambam. Six major rivers - Periyar, Pamba, Manimala, Achankovil, Meenachil and Muvattupuzha discharge into this lagoon. The Periyar River discharges into the northern side of lagoon from northern side and the Muvattupuzha River in the central part of the lagoon. The rivers Meenachil, Manimala, Achanakovil and Pamba discharge large amount of sediments into the southern part of the lagoon. Chitrapuzha, a small stream, also drains into the central part of the lagoon. These rivers carry annually 7,32,560 MT of sediments into the lagoon (Narayana and Priju, 2006).

The coastal landforms of the region consist of Quaternary sediments, overlying Precambrians consisting of granulites, gneisses and greenstones - primarily charnockites, gneisses, hornblende (biotite schists), khondalites and intrusive rocks. The Vembanad lagoon is mostly blanketed by a mixture of clay, silt and sand. The northern part of the Vembanad lake is covered with clayey and silty sand, central part covered with clayey sand and sandy silt, and the southern part is covered with silty sand and clayey silt (Veerayya and Murty, 1974; Narayana et al., 2002; Priju and Narayana, 2007).

Bars, spits, headlands and barriers

The south-west coast is well known for most well-developed bars, barriers and spits. Low cliffs alternating with pocket beaches, promontories, head-lands and bays are present along the coast of Kerala. North of Ponnani, the shore consists of mainland beaches, and north of Trivandrum, the coast is characterised by barrier beaches except at few places where rocky cliffs and head lands are present. Spits are present with or without submerged sand bars at places where the lagoon opens out into the sea across the bars. A well developed barrier is seen between Neeleswar and Cannanore. The Vypeen Island, north of Cochin, is about 23 km long and 2 km wide. Several barriers are observed near Quilon. The remarkable features of barriers are their elongated nature and narrow width (Priju and Narayana, 2007).

Mud banks

Mudbanks are calm regions of nearshore sea water devoid of any significant wave action due to very high concentrations of sediments in suspension (Tatavarti et al., 1998). Mudbanks are unique and occur at only a few locations in the nearshore waters of the world oceans. Along the Indian coasts they are known to occur on the south-west coast from Mangalore to Quilon. The mudbanks have socioeconomic implications as they are known for very high biological productivity (Damodaran, 1973; Gopinathan and Qasim, 1974; Nair et al., 1983; Rao et al., 1984) and, it prevents the otherwise rampant sea erosion during the south-west monsoon season along the Kerala coast. Although a number of studies were made on the formation, sustenance and disappearance of the mudbanks off Kerala, the phenomena still remains an enigma (Nair, 1976; Silas, 1984; Tatavarti et al., 1999; Tatavarti and Narayana, 2006 ; Narayana et al., 2008). The occurrence of mud banks provides secure and smooth anchorage even during the rough wave conditions of the south-west monsoon. At about 27 locations the mud banks occur along the Kerala coast. The mud banks are reported to be decisively affecting the equilibrium conditions thereby causing shoreline instability of the coast. They trap the littoral materials from either side thereby preventing it's downdrift, causing accretion within the mud banks and erosion on down drift sides. The Kerala mudbanks generally become more prominent with the onset of south-west monsoon (i.e., in the month of June), and less prominent with the withdrawal of the south-west monsoon season.

2.4 Geology

Kerala, bounded by the Western Ghats on the east and the Arabian Sea on the west is an integral part of the peninsular shield. It is mainly occupied by four major rock units - (i) Precambrian crystalline rocks - which include charnockites, garnet biotite gneisses, hornblende gneisses, khondalites, leptynites, cordierite manner of gneisses and other unclassified gneisses which occupy a considerable area of Kerala. (ii) Tertiary sedimentary rocks - which unconformably overlie the Precambrians, which extend as a narrow belt along the major part of Kerala coast, comprises continental (Warkalli beds) and marine (Quilon beds) facies. Carbonaceous clays with lignite / coal seams, china clays and friable sandstones form the continental facies and the marine facies composed of sandstones and carbonaceous clays with thin bands of fossiliferous limestones (Paulose and Narayanaswami, 1968). (iii) Laterites – are

the third major litho-unit covering about 60 % of the surface of Kerala, and (iv) Recent to sub recent sediments extending from Kasaragod in the north to Capecomorin in the south, which comprises fringes of coast parallel sand bars, sandy flats, alluvial sands and deposits of lacustrine (Brunn and Nayak, 1980).

Tertiary rocks in the Quilon-Warkala area is divided into (i) Quilon beds - consisting of limestone and calcareous clay and (ii) Warakalli beds -made of sandstone and clay with lignite (King, 1882). The calcareous beds exposed in Quilon area continue at subsurface levels into Chavara. Narayanan (1958) opined that the Warkalli and Quilon beds are different faces of rocks, but more or less of the same age. Desikachar and Subramanyan (1959) suggest that the Quilon and Warakalli beds continue far into the north up to Kainakari and Ambalapuzha.

Varadarajan and Balakrishnan (1976) suggest that the laterite along the coastal area formed part of the continental shelf and their occurrence as terraces of different elevations could be due to Neogene and Quaternary uplift. Desikachar (1976) identified four formations as (i) Mayyanad Formation, (ii) Azheekal Fromation, (iii) Ambalapuzha Formation and (iv) Kainakari Formation. Azheekal and Ambalapuzha formations are roughly equivalent to Quilon and Warkalli beds. Murty et al. (1976) have reported increased sedimentary thickness in the north west of Alleppey and Ponnani on account of the extension of the Achankovil shear zone and Palghat gap faults into the basin. Bose et al. (1976) suggest that the deepest part of the sedimentary basin is between Chellanam and Chavara, and around Alleppey the thickness of sediments may be about 600 m. Rao and Datta (1976) opined that the Wrakalli beds could be the continental equivalents of Quilon beds, a view expressed earlier by Narayanan (1958).

Lineaments and fractures are the major features cutting across the Precambrian terrains of Kerala through which rivers like Periyar, Achankovil and Pamba are flowing. Nair (1987) reports that Lineaments/ faults which are parallel, as well as at right angle to the coast are found to be neotectonically active and control the configuration of shoreline. The major shear zones are - E-NE trending Nilambur-Attapady-Kozhikode shear zone, E-W trending Achankovil shear zone, Periyar-Thamraparni shear zone, NNW trending Edamalayar shear zone, and SE trending Moyar-Bavali-Mercara shear zone. Minor fracture zones are widely reported all over the state by the Geological Survey of India (1995). The Central Kerala region consists of basic intrusive

rocks such as charnockites, khondalites, meta sediments, Quilon and warakalliformations, laterites and alluvium.

2.5 Climate

The study area is influenced by tropical climate. Monsoon is the main feature of tropical climate experienced in Kerala. Subtropical type of climatic regime is seen in certain areas in the eastern part of the State due to the high variation in relief from the coast to the hilly regions of the Western Ghats in the east. The location of the region and a high variation in relief from the coast to the Western Ghats influence the climatic characteristics to a large extent. Heat waves from the plains of Tamil Nadu enter in Kerala through Palghat Gap and Ariankavu pass. Kerala region experiences four seasons viz., hot weather period (the pre-monsoon season (March-May), southwest monsoon (June-September), retreating southwest monsoon i.e., onset of northeast monsoon (October-November), and winter (December-February).

Temperature

The atmospheric temperature reaches a maximum of 37° C during the pre-monsoon period and from June onwards the temperature gradually comes down once the monsoon sets in. March to May is the hottest period when temperature reaches a maximum of > 35° C. Land and sea breezes influence the coastal area, and the seasonal and diurnal variations of temperature are almost of the same range (5-7° C). However, the seasonal and diurnal variations of temperature are not uniform throughout the State. At Palghat, the mean seasonal variation is less than the diurnal variation; but in the high ranges, which are typically sub-tropical, the diurnal variation is very high (>15° in some months) - a typical example of a tropical climate remarkably modified by the higher altitude.

Rainfall

It is well understood that the rainfall distribution in the State is controlled by orography making the state to receive highest annual rainfall among other states of India, which is three times higher than the average rainfall of India (Ananthakrishnan et al., 1979). The annual rainfall varies from 100-400 cm with an average of about 300cm. The northeast monsoon is generally

weak along the west coast and the average annual rainfall is about 60 cm (Pisharody, 1992; Sampath and Vinayak, 1989). Based on the rainfall trend, the four seasons - winter (January-February), pre monsoon (March-May), monsoon (June-September) and post monsoon (October-December) - are identified.

During south-west monsoon, variability of rainfall is >50 %, but the general variability of rainfall in the State is observed to be 20 to 40 %. Variability of annual rainfall indicates that the comparatively low variability zones are concentrated in the southern part. The northern part, particularly, Cannanore district experiences relatively high variability (>50 percent) in the season.

The pattern of rainfall distribution during southwest monsoon is akin to the annual rainfall pattern. The foothill zones of the Wayanad plateau and Pirmed-Neriyamanagalam stretch towards the west of the Periyar plateau receive high rainfall (>300 cm). It is observed that the Malabar coast receives more rainfall compared to the Cochin-Quilon coast. Southern and eastern parts of the State (along the Western Ghats ridge) receive very low rainfall. The distributional pattern of rain in northeast monsoon season is quite different from that of other seasons, though the basic trend of higher rainfall in foothill zone prevails. In general, the northern part receives the less amount of rain compared to the south in this season, and the maximum rainfall (>100 cm) is recorded in Neriyamangalam. It gradually decreases towards east and west.

2.6 Drainage system and River input

State is drained by 44 rivers, of which 3 are east flowing. The streams originating from the Western Ghats are short and swift flowing, showing various stages of gradation and are marked by cascade and waterfalls in the upper reaches, although in the plains they show evidences of maturity of development. Some of these rivers have steep gradients (1/250 or more) in their initial reaches. In the case of Periyar and Chalakudi rivers, this extends for three –fourths of their course, while such gradients are also discernible in the upper reaches of Chaliyar, Valapattanam Ar. Karamana Ar etc. suggesting their youthful stages of development (cf. Resource Atlas of Kerala, 1984). Rejuvenation of the catchment area closely linked with the west coast faulting and later adjustments may, in all probability, be the reason for the youthful behaviour of the rivers, while high energy shoreline might have prevented delta in the river

mouths. The net annual discharge from all these rivers is estimated to be 77,900 MCM (CWRDM, 1995).

The general drainage patterns of the rivers of central Kerala is dendritic, although in places, trellis, sub-parallel and radial patterns are also noticeable. Most river courses are straight, indicating structural control. General course of the rivers coincides with the prominent lineament directions NW-SE and NE-SW. Of all the rivers, the Periyar, Pamba and Chalakudi rivers are conspicuous by their length and size of the area they drain.

The river Periyar having a length of 244 km is the longest river in Kerala (Table 2.1). It has a drainage area of 5398 km² (cf. Water Resource of Kerala, 1974). The catchment area spreads over the districts of Idukki and Ernakulam. Formed by the confluence of a large number of streams originating from the Sivagiri hills in the Western Ghats at an elevation of 1800 m, it initially follows a northward course. It passes through several gorges, the important one being the Idukki gorge. Major reservoirs like Idukki, Periyar, Anairangal, Mattupetti and Setuparvatipuram are within the basin area. The river originates and flows through a metamorphic terrain consisting of charnockite, garnet-sillimanite-gneiss, garnet-biotite and hornblende-biotite gneiss, besides migmatite and granite. Periyar River discharges 6901 Million Cubic Meter (MCM) and annual sediment load of 226518 tons annually (Table 2.1).

The Muvattupuzha River is one of the perennial rivers in central Kerala having a length of about 121 km and a catchment area of about 1,554 km² (Water Resource of Kerala, 1974). The river originates from the Western Ghats and drains mainly through highly lateritised crystalline rocks after which it debouches into the Vembanad estuary near Vaikom. Two major tributaries namely Thodupuzha and Kaliyar join the Muvattupuzha river near Muvattupuzha town. The river discharge ranges from 50 m³/sec (pre monsoon) to 400m³/sec (monsoon). Peak discharge is recorded during June to October. Considerable changes have taken place in the flow characteristics of the Muvattupuzha river after the commissioning of the Idukki hydroelectric project in 1976, across the adjoining Periyar river. The tailrace water (19.83-78.5m³/sec) was directed into the Thodupuzha tributary from Moolamattom power station. Muvattupuzha River discharges 4944 Million Cubic Meter (MCM) and sediment load of 147091 tons annually (Table 2.1).

Table 2.1 Characteristics of river basins, average annual runoff and average annual sediment load of rivers of SW India, for the period from 1986-2010 (CWC, 2012).

Name of the River	River Basin area (Km²)	Length (Km)	Slope (m/m)	Annual rainfall (mm)	Annual Average Discharge (MCM)	Annual Average Sediment load (tons)
Payaswini	957	105	0.012	3532.9	2269.1	203909.6
Valapatanam	1070	101	0.013	3269.9	3636	233598.2
Chaliyar	1876	169	0.012	3030.4	4176.5	329282.3
Bharathpuzha	5755	209	0.009	2117.6	4405.2	336491.3
Chalakydy	1342	120	0.01	3326.2	1801.1	47205
Periyar	4234	244	0.07	3043.6	6901.7	226518.1
Muvattupuzha	1208	92	0.011	3012.8	4944.7	147091.6
Meenachil	615	61	0.017	2769.9	1664.1	40625.2
Pamba	1654	176	0.009	2883.6	3729.8	65428.8
Achankovil	810	138	0.005	2596.1	1152.3	96041.5
kallada	1210	92	0.016	2194.3	1387.6	69702.9
Vamanapuram	540	88	0.024	2285.7	675.2	62487.4

The river Pamba is the third longest river (176 km) in Kerala, and has the fourth largest catchment area (2235 km²) rising in the hill ranges of Pathanamthitta district and the adjoining Pirmed plateau, and is formed by the confluence of Pambyar Ar, Kakki Ar, Arudai Ar, Kakkad Ar and Kal Ar. Pamba and Kakki are the major reservoirs in the basin. From Vadasserikkara to Chengannur, the river flows through midland terrain with minor meanderings downstream of Payipad, the Pamba River coalesces with other river distributories, which flow in the NNW direction to join the Vembanad Lake. Flowing through the crystalline rocks the basin displays dendritic to sub-dendritic and rarely rectangular and trellis drainage patterns. Pamba River discharges 3729 Million Cubic Meter (MCM) and sediment load of 65428 tons annually (Table 2.1).

The Chalakydy river has a length of 130 km and a drainage area of 1704 km². Five streams - Parambikulam, Kuriakutty, Sholayar, Karapara and Anakkayam form the Chalakydy river. Of these, Parambikulam and Sholayar rise in the Anaimalai hills at elevations above 1733

m and 1332 m, respectively. The river flows through thick forests and the channel has many waterfalls until it reaches the plains at Kanjirapally. The river debouches into the right arm of the Periyar at Puthenvelikkara. Poringalkuttu, Sholayar and Parambikulam are the major reservoirs in the basin. Charnockites and migmatitic gneisses are encountered along the river course. Pamba River discharges an amount of 1801 Million Cubic Meter (MCM) and sediment load of 47205 tons annually (Table 5.2).

The Achankovil River has a length of 128 km and a catchment area of 1484 km². The river has no prominent tributaries, other than small streamlets. The Achankovil river joins the River Pamba near Chennithala, before entering into the Vembanad lake. The Achankovil River has also connection with Pamba River at Payipad and flows to the sea through Thottappalli spillway. Achankovil River discharges an amount of 1152 Million Cubic Meter (MCM) and sediment load is 96041 tons annually (Table 5.2).

The Meenachil River has a length of 78 km and a catchment area of 1272 km²; Major part (38 km) of this stream runs through midland terrain, 21 km through the highland and the rest (16 km) is seen to flow through the low land terrain. The river assumes its name after the confluence of its two important affluents at Erattupetta , one coming from Poonjar and the other from Tikkoi area. The Poonjar branch has two main tributaries and many small stream lets joining it. The other main branch has two tributaries i.e. the Kalattukadavu Ar and Tikkoi Ar. The Meenachil flows in the westerly direction from Erattupetta to Palai . Kudamuruti Thodu is a tributary of this. Before reaching the town of Kottayam, seven other tributaries join the main stream. The Meenachil River drains into Vembanad lake at Kumarakom. Meenachil River discharges annually 1664 Million Cubic Meter (MCM) and a sediment load of 40625 tons (Table 5.2).

2.7 Coastal Oceanography

Processes like exchange of heat with atmosphere and other localized phenomena are also likely to influence the hydrographic conditions of the system. The temperature of water in estuary varies between 25 - 31° C. Low salinity values ranging from 0 to 10 x 10³ psu at the surface and 0 to 12 x 10³ psu at the bottom are observed during monsoons. This is brought by the

combined effect of land drainage from the prevailing monsoonal rains causing high freshwater discharge from the river and intrusion of saltwater from the sea. As the season advances to post and premonsoon, higher salinity values ranging from 10 to 22×10^{-3} psu at the surface and 12 to 24×10^{-3} psu at the bottom were observed (Anirudhan, 1988). The estuarine waters considerably get diluted near the river confluences.

Bathymetry

The inner shoreface gradient decreased seawards with a pronounced decrease at the 10 m isobath. The notable feature is that the nearshore bathymetric profile becomes steeper during the monsoon season ($\sim 1.5^\circ$ slope) and slowly becomes gentler as the monsoon season recedes ($\sim 0.6^\circ$ during post-monsoon and during pre-monsoon season). The nearshore profiles to the north and south of the study area are steeper relative to the central region of the study area, suggesting the role of mud bank on the bathymetric variations (Figure 2.1).

Waves and Tides

The wave activity in the west coast is very strong during June and July but the intensity reduces by August and September. The sea remains relatively calm during October to May (fair weather season). During fair weather season, long swells often mixed with the local sea winds prevail along the coast. The dominant energy along near shore is composed of gravity waves and mean currents of circulation. Far infra-gravity wave energy is about two orders of magnitude larger than that of gravity waves and evidence of edge waves in the infra-gravity band was demonstrated by Tatahari et al. (1996). Far infra-gravity waves may be a common feature in the nearshore oceans in the presence of alongshore currents (Bowen and Holman, 1989).

Energy mainly from wind, imparted to the water produces wave motion and are modified by the general configuration and contour of the near shelf. During south-west monsoon, due to the strong wind action, increase in wave activity with long swells and high breakers has been observed along the Kerala coast considering the orientation of the coastline (NNE - SSW). Wave directions varying between 180° - 340° are more significant in the shore processes. During the south-west monsoon season the predominant direction of waves is between west south west and west north west. The tides of Kerala are mixed, semidiurnal in nature and occur within the

microtidal range (~ 2 m). The coast experiences two high tides and two low tides in a 24-hour cycle.

Wind

Reversal of wind system during the monsoons is the most unique feature in the south eastern Arabian Sea. The reversals take place predominantly from south-west direction during May-September to north-east direction during December-March. Between these reversals are the transition periods during which weak and variable winds prevail. Along the west coast of India, the southwest (SW) monsoonal winds of oceanic origin are established by mid-May. During the SW monsoon, winds blow from southwest during May-September, but change to a northeasterly direction during the northeast (NE) monsoon. These winds continue to grow strong until June, when there is a sudden 'burst' or strengthening of the southwest. Southwest winds. The winds are the strongest during July and August, but become weak in September, ahead of the NE monsoon, which lasts through October and November. The wind speed is generally 15-20 km/hr during the SW monsoon, but lower (10-12 km/hr) during the NE monsoon.

The seasonally reversing wind pattern influences the southward littoral drift during the southwest monsoon, while a northward drift occurs during the northeastern monsoon. By the middle of May, the southwest monsoonal winds of oceanic origin are established. These winds continue to increase gradually until June when there is a 'burst' or sudden strengthening of the southwest winds. During July and August months, the winds have their highest strength, and in September the wind force decreases ahead of the fall transition, which lasts through October and November (Sharma, 1978).

Longshore currents and rip currents

One of the major effects of wave action in the shallow water is the generation of longshore current, which plays an important part in the longshore transport of sediments. As the waves arrive obliquely to a straight coastline and break at an angle to the beach, they generate longshore current flowing parallel to the shoreline. This wave induced current is confined to the nearshore, rapidly decreasing in velocity beyond the breaker zone.

Rip currents are the most noticeable of the exchange mechanisms between offshore and surf zone. Rip currents are relatively narrow jets of seaward flowing currents. The rips are fed by a system of alongshore currents. Bowen (1989) has shown that cell circulation with rip currents is produced by a longshore variation in the wave breaker heights. The longshore currents during SW monsoon are stronger than on-offshore currents along the Kerala coast (Tatavarti et al., 1998).

Littoral transport

The longshore current transports beach sediments for many kilometers in the alongshore direction. Littoral transport of sand occurs in two modes – (i) parallel to the shoreline due mainly to the effect of longshore current, which is referred to as longshore transport, and (ii) perpendicular to the shoreline due to swash and referred to as the beach drift (Sajeev et al., 1997). The direction of longshore transport varies from season to season, day to day or hour to hour depending upon the location and direction of the storm winds which generate waves. It results from the stirring-up of the sediments by breaking waves and movement of sediment by the longshore component of wave induced current (Prasanna Kumar et al., 1990). The beach drift occurs as a result of the stirring up of the bottom sediments in breaker zone, which tend to be carried up the beach to the limit of swash of the breaking wave and back with back wash. The volume of the beach drift is determined primarily by wave steepness, sediment size and beach slope (Sajeev et al., 1997).

Chapter 3

Materials and Methods

Chapter 3

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3.1 Introduction

The estimation of SSCs in ocean waters is a complex process, and the techniques varying from the conventional methods to recent high resolution satellite techniques are employed in estimation of these SSCs in spatial and temporal scales. Conventional methods include collection of water samples and measuring suspended sediments in water samples, turbidity measurements etc. Monitoring of SSC over large oceanic areas through *in situ* measurements are difficult, expensive, time consuming and give only point observations, whereas remote sensing-based techniques provide large area coverage and data on high resolution time intervals. The data obtained from satellite observations are more reliable, time saving and inexpensive.

Remotely sensed spectral radiance ($L(\lambda)$) measured by aircraft or satellite sensors can provide an alternative, synoptic, speedy and economic method for assessing the SSC of reservoirs (Ritchie et al., 1976); lakes and rivers (Goldman et al., 1974; McKim et al., 1984) and coastal waters (Khorram, 1985; Lindell et al., 1985; Curran and Wilkinson, 1985). Such information is useful for the management of water quality (Scherz, 1972; McCauley and Yarger, 1975; BNSC, 1986); monitoring water pollution (Johnson and Harris, 1980), modeling of sediment distribution in estuarine environments (Catts et al., 1985), and sediment budgeting in coastal zones (Mason, 1985).

The first systematic measurements of the colour of the sea from aircraft carried out in late 1960s were those of Clarke et al. (1970). Their studies based on the remote spectroscopy of the light backscattered from the sea in coastal waters near Woods Hole and in offshore waters from the Sargasso Sea across Georges Bank demonstrated the estimation of chlorophyll concentration within the upper layers. Tyler and Smith (1970) carried out field measurements of upward irradiance ($E_u(\lambda)$) and downward irradiance ($E_d(\lambda)$) in ocean waters. Subsequently, systematic determinations of the similar radiometric measurements were made during the SCOR WG-15 Discoverer 1970 Expedition (Tyler, 1973), and diffuse attenuation coefficients ($K_d(\lambda)$), and the

irradiance reflectance ($R(\lambda)$) were computed. The interpretation of this reflectance, a basic quantity in ocean-colour science, was given in the frame of radiative transfer (Gordon et al., 1975) and also in terms of optically-significant substances present in the water (Morel and Prieur, 1977; Smith and Baker, 1978).

In recent years, number of ocean-colour sensors designed to produce global ocean-colour products have been successfully launched. These include the coastal zone colour scanner (OCZS) (first satellite launched in 1978), Ocean Color Temperature Scanner (OCTS) from National Space Development Agency of Japan (NASDA) (now Japan Aerospace Exploration Agency (JAXA)), and Centre National d'Etudes Spatiales's (CNES) Polarization and Directionality of the Earth's Reflectances (POLDER)-1 (both launched on 17 August 1996), NASA Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (launched on 1 August 1997), NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra (launched on 18 December 1999), Ocean Colour Monitor (OCM) on board IRS (Indian Remote Sensing) - P4, called Oceansat-1, was the first ocean satellite launched by India (in May 1999) and Oceansat2 OCM (launched on 23 September 2009) as a continuation of Oceansat-1, European Space Agency's Medium Resolution Imaging Spectrometer (MERIS) (launched on 1 March 2002), NASA's MODIS on Aqua (launched on 4 May 2002), the Global Imager (GLI) from NASDA (now JAXA), POLDER-2 from CNES (both launched on 14 December 2002) and POLDER-3 on PARASOL (launched on 18 December 2004). SeaWiFS, MODIS-Aqua, MERIS, GLI, POLDER-2 and 3, and Oceansat-2 have been providing data on global ocean-colour continuously.

Various studies demonstrate that remotely sensed data can map suspended sediments over large areas (Stumpf and Pennock, 1989; Tassan, 1994; Miller and Cruise, 1995; Warrick et al., 2004); however, the routine use of remote sensing for monitoring sediment dynamics under different environmental conditions is limited. There are several factors that limit the application of remote sensing to coastal waters. The most common limitation is sensors's spatial or ground resolution. For example, the minimum spatial resolution of data from AVHRR, MODIS and SeaWiFS sensor is 1 km. The MODIS operates in 36 spectral bands ranging from 0.4 to 14.4 μ m with a spatial resolutions of 250 m (bands 1-2), 500 m (bands 3-7), and 1000 m (bands 8-36) with an orbital period of 1 day; however the spectral sensitivity of sensor decreases as the spatial

resolution increases. Although these data are adequate for studying mesoscale and large scale processes on the continental shelf, 1 km spatial resolution data are often too large to examine coastal horizontal gradients, particularly in estuaries and bays (Nittrouer and Wright, 1994). In distinction, the series of Landsat sensors (Thematic Mapper, Enhanced Thematic Mapper) have a spatial resolution of 30 m, but the orbital characteristics of the Landsat satellites yield a revisit time of about 16 days and Landsat sensors cannot capture the temporal dynamics of coastal waters. With the advantage of high spatial resolution (360 m), alternate day coverage and high sensitivity of OCM images from Oceansat-2 were useful to retrieve the oceanic parameters.

Many studies suggest significant correlations between SSC and remote sensed spectral radiance ($L(\lambda)$) (Holyer, 1978; Johnson and Munday, 1983; Fischer, 1985); but only a very few studies have successfully employed spectral radiance ($L(\lambda)$) in estimation of SSCs (Whitlock et al., 1982; Curran et al., 1987). This has been attributed to many factors including changes in water parameters during the acquisition of SSC data; changes in atmospheric transmission and acquisition geometry during the collection of $L(\lambda)$ data; inadequate geometric correction of $L(\lambda)$ and a small sample size in relation to the known areal, vertical and temporal variability in SSC (Miller et al., 1977; Curran et al., 1987). In addition, there are statistical problems associated with the sampling of the data and the use of SSC vs $L(\lambda)$ relationship for estimation of SSCs (Munday and Alfoldi, 1979; Whitlock et al., 1982; Curran and Hay, 1986).

Empirical algorithms can be used to derive information about water constituents (optical properties, particulate concentrations) from the estimated radiance of surface waters. Such information is useful for the management of water quality, monitoring of water pollution, sediment transport modeling and budgeting in coastal environments. Algorithms were first designed to estimate SSCs in open ocean waters as a function of chlorophyll concentration in the deep sea mainly concentrations of plankton and associated organic detrital matter (Morel, 1980; Viollier and Sturm, 1984). The commonly adopted algorithms for chlorophyll and SSC are the reflectance band ratios, characterizing the high absorption of chlorophyll around 440 nm and low absorption at 550 nm. However, chlorophyll and SSC do not co-vary in coastal waters because of the presence of particles in suspension from shore erosion or river discharge. The algorithm derived from blue and green band ratios is considered as unsuitable for SSC retrieval (Tassan, 1993, 1994). Therefore, robust algorithms are required to convert radiance or reflectance values

into estimates of water constituents. In sediment dominated coastal waters, refined algorithms are particularly needed to estimate accurately the suspended particulate concentrations from remotely sensed ocean color data (Robinson et al., 1998; Moore et al., 1999).

Several researchers have attempted to estimate SSCs in coastal waters based on the remote sensing reflectance, absorption, and scattering of light by water (Tassan and Strum, 1986; Tassan, 1994; Green and Sosik, 2004; Pradhan et al., 2005; Wang et al., 2010; Avinash et al., 2012; Wang et al., 2012; Wu et al., 2013). Earlier studies on the relationship between SSC and reflectance values in coastal waters suggest that algorithms derived from single band reflectance values may be adopted, where the SSCs increase with increasing reflection of wavelength bands (Curran et al., 1987; Novo et al., 1989). Empirical calibration of different data sets was carried out using different combinations of wavelength bands for laboratory measured total suspended matter, *in situ* reflectance data, and for satellite-derived reflectance data (Chen et al., 1991; Forget and Ouillon, 1998; Hu et al., 2004; Vilmaliz and Fernando, 2009). The reflectance model of Gordon et al. (1988) developed for open ocean water and validated for inland turbid waters by Dekker et al. (1997) has been extensively used to retrieve SSCs in estuarine waters (Stumpf and Pennock, 1989), and in coastal and deep ocean waters (Van Der Woerd and Pasterkamp, 2004; Eleveld et al., 2008). Doxaran et al. (2002, 2003, 2005) used the near-infrared (NIR) band ratio (850 and 550 nm) model to remove the effects of particle size distribution and the bidirectional variation of the remotely sensed reflectance for sediment dominated coastal waters. Some researchers have adopted analytical approaches to solve the reflectance model and considered water constituents as the unknown parameterization of specific inherent optical properties (Forget et al., 1999; Haltrin and Arnone, 2003). Nechad et al. (2010) propose a single band algorithm for total suspended matter retrieval based on reflectance model and calibrated the results using the seaborne reflectance and total suspended matter measurements of the southern North Sea.

In general, the optics of water–sediment mixtures are highly nonlinear, and many factors such as suspended particle size, shape and colour can influence the water–sediment optics (Stumpf and Pennock, 1989; Sydor and Arnone, 1997). Because of these optical complexities, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as coastal geomorphology, river input, local coastal circulation influence the

SSCs and hence the algorithm developed for one region may not be applicable to another region. Against this background, we have developed a regional algorithm for coastal waters of the southwest coast of India. The details of regional algorithm developed for the present study area are discussed in Chapter 4.

The techniques/methods adopted in this study for retrieval, estimation, mapping of SSCs and modeling of dispersal patterns are presented in Figure 3.1.

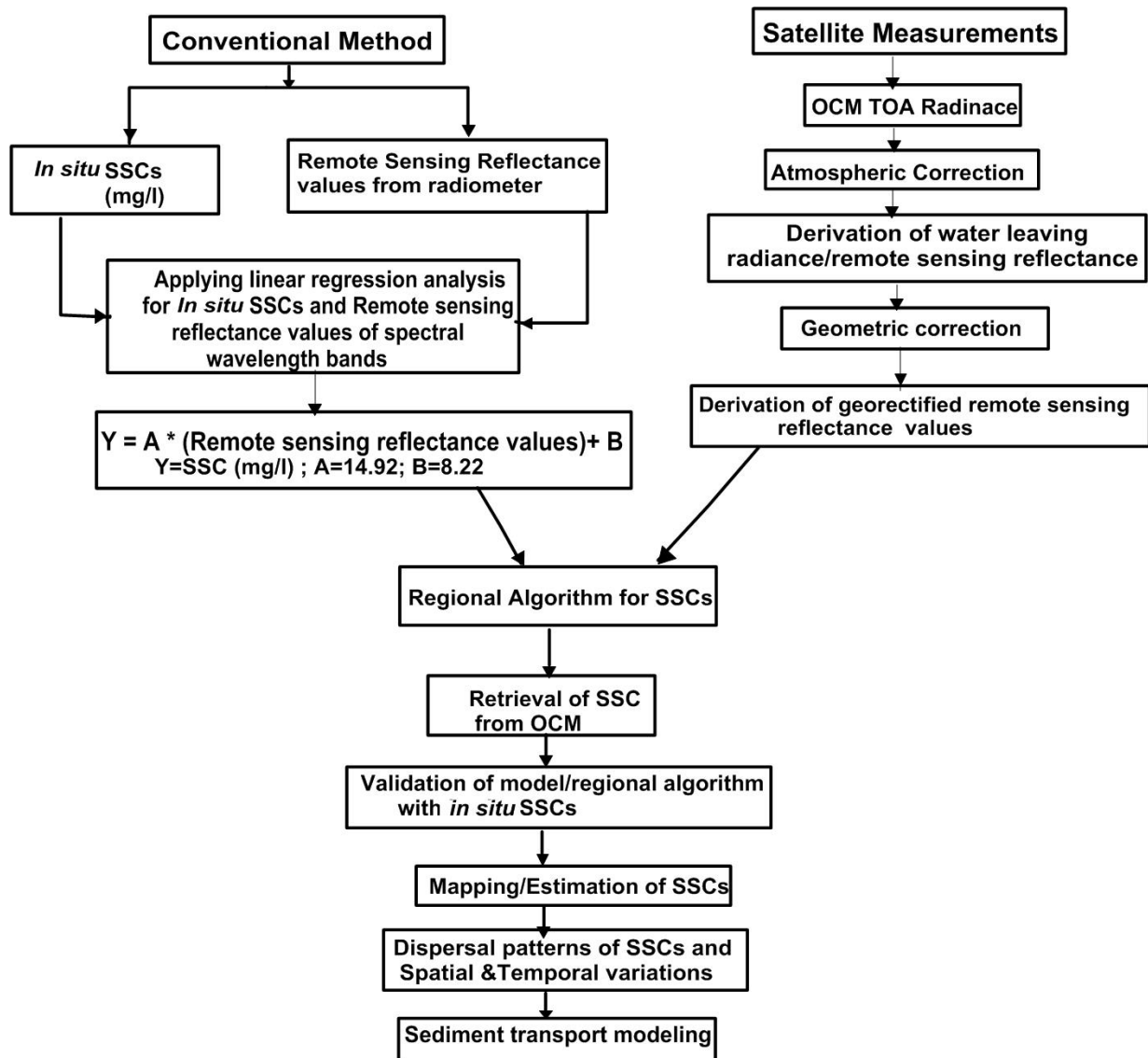


Figure 3.1 Flow chart showing procedure for the retrieval of SSCs from OCM satellite data and application of SSC data.

3.2 Data products

3.2.1 Field measurements: water samples and *in situ* SSCs

The measurement of suspended sediments in coastal waters, particularly in field settings, is important in understanding the dispersal patterns of fine sediments in the marine environment. Field measurements of *in situ* total SSCs in coastal waters off Cochin, southwest of India (Figure 3.2) were carried out, and the details of water samples collected for *in situ* SSC measurements are given in Table.3.1. The water samples were collected at 8 stations on each day for a total of four days. The water samples in the nearshore sea were collected using a Niskin sampler at a depth of 0.5 m in the water column from the sea surface for the period October - November 2010 and January - February 2011 onboard the research vessel of Central Institute of Fisheries Technology (CIFT, Cochin, India) for estimation of total SSCs.

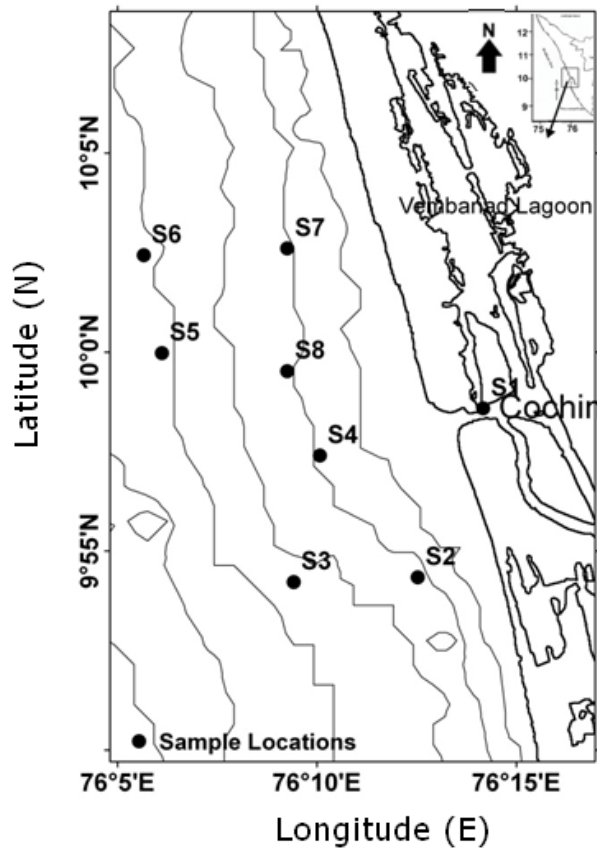


Figure 3.2 Map showing locations of water samples collected for estimation of *in situ* SSCs and remote sensing reflectance measurements carried out using a radiometer in the coastal waters off Cochin, southwest coast of India.

Locations were fixed with the help of a Global Positioning System. Suspended sediments at each location were gravimetrically measured based on Strickland and Parsons (1972) method. Water samples were filtered through a pre-weighed Whatmann GF/F glass fiber filter paper. The filter paper was washed thrice with distilled water to remove the salts and dried in an oven at 75° C for 48 hours. The dried filter paper was weighed using an analytical balance and final weight was noted to estimate the SSCs (mg/l). The estimated *in situ* SSCs from the water samples were used for the development of regional algorithm.

Table 3.1 Field measurements of *in situ* SSCs in coastal waters off Cochin, India. Locations of sample stations and suspended sediment concentrations in surface waters at each station are shown.

Station. No	Location of water samples (Lat/ Long)	In situ SSC values (mg/l) in water samples during sampling days				Remarks
		17 Oct 2010	21 Nov 2010	21 Jan 2011	22 Feb 2011	
S1	9° 58' 16" N 76° 15' 32" E	23.28	14.6	29.5	32.82	Cloud sky was observed on 17 October & 21st November 2010.
S2	9° 54' 34" N 76° 12' 47" E	19.06	15.93	18.4	17.79	
S3	9° 54' 28" N 76° 09' 40" E	16.12	14.27	14.78	16.35	
S4	9° 57' 40" N 76° 10' 10" E	19.17	20.56	22.00	21.58	
S5	10° 00' 02" N 76° 06' 05" E	16.62	10.61	8.56	12.66	Clear sky was observed on 21 January & 22 February 2011.
S6	10° 02' 37" N 76° 05' 58" E	15.59	10.11	8.10	13.61	
S7	10° 02' 58" N 76° 09' 15" E	16.80	9.20	7.05	5.40	
S8	9° 59' 57" N 76° 09' 15" E	28.13	12.72	14.14	13.53	

3.2.2 Hyperspectral radiometer measurements

Radiometric measurements of underwater light for ocean color applications is to measure and derive spectral water-leaving radiance ($L_w(\lambda)$) with least uncertainty and high accuracy under all conditions. Many studies were carried out on the falling objects in water to understand their behaviour during their fall and trajectories. Most of the studies were carried out in calm water conditions with isotropic properties of temperature, salinity and density (Chu et al.

2002; Holland et al. 2004; Chu et al. 2005; Abelev et al. 2007) and for rheological applications (Joseph and Liu, 1993; Vaidya, 2004).

Solar light entering the water undergoes scattering and absorption processes by the constituents present in water such as water molecules, dissolved matter and detrital materials, suspended matter and phytoplankton and hence there will be a change in spectral characteristics of light in water. Thus the light emerging from the surface of water known as water leaving radiance ($L_w(\lambda)$) provides information about the optical properties of water and the optically active constituents in water. Downwelling solar irradiance ($E_d(\lambda)$) is defined as the amount of solar radiation per unit area, per wavelength ($W/m^2/nm$) and water leaving radiance is defined as the amount of light leaving the ocean surface per unit area, per wavelength and per solid angle ($W/m^2/nm/sr$). Hence, in ocean colour studies, the properties of solar light available at the surface of water (downwelling solar irradiance) and also those emerging from the water (water leaving radiance) are essential optical parameters required to derive information about the constituents in water and they are often used to model or develop algorithms to derive various parameters such as chlorophyll, suspended matter, colour dissolved organic matter (CDOM) and other related parameters. Water leaving radiance ($L_w(\lambda)$) and downwelling solar irradiance ($E_d(\lambda)$) are measured using a spectral radiometer, mounted on a platform above water or a profiling underwater radiometer (Mueller and Austin 1995; Mueller et al. 2003). The acceptable uncertainty in $L_w(\lambda)$ is $< 5\%$ for satellite validation (Hooker and Esaias 1993; Hooker et al. 2002).

A Satlantic hyperspectral ocean colour radiometer (HyperOCR) (Figure 3.3) has been used for measuring downwelling irradiance ($E_d(\lambda, z)$), and water leaving radiance ($L_w(\lambda, z)$) for estimation of remote sensing reflectance ($R(\lambda)$). The technical specifications of hyper spectral radiometer used in this study are given in Table 3.2. Remote sensing reflectance (R_{rs} in Sr^{-1}) values were obtained at an average water depth of 3 m with the help of HyperOCR during the period coinciding with sea water sampling in the coastal waters off Cochin and these values are employed in the development of regional algorithm. Radiometer provided by the Central Institute of Fisheries Technology, Cochin, was employed for these measurements. Water samples for estimation of SSCs were collected simultaneously at the same time and at the same locations as per details given in Table 3.1.

Table 3.2 Specifications of Hyper Spectral Radiometer (<http://satlantic.com>)

Characteristics	Irradiance Air	Irradiance Water	Radiance Air	Radiance Water
Spatial	Cosine	Cosine	3°	8.5°
Field of View	3% 0 – 60°	3% 0 – 60°		
	10% 60 – 85° (350-800 nm)	10% 60 – 85° (350-800 nm)		
Depth Rating	300 m	300 m	300 m	300 m
Operating Temperature	-10 to +50 °C	-10 to +50 °C	-10 to +50 °C	-10 to +50 °C
Spectral Characteristics				
Spectrograph range		305-1100 nm		
Factory Calibration		350-800 nm		
Spectral sampling		3.3 nm/pixel		
Spectral accuracy		0.3 nm		
Spectral resolution		10 nm		
Stray light		< 1 × 10		
Detectors		256 channel silicon photodiode array		
Entrance slit		70 × 2500 µm		
Pixel Size		25 × 2500 µm		

Hyper OCR effectively measures the downwelling irradiance ($E_d(\lambda, z)$), and upwelling radiance ($L_w(\lambda, z)$), which captures the optical properties of sea water through 255 channels with wavelengths ranging from 300 to 1200 nm (350 to 800 nm standard) with a bandwidth of ± 10 nm in visible bands and ± 20 nm in NIR bands. At each station hyperspectral radiometer was operated with utmost care to avoid ship shadow, maintain the vertical velocity of 0.5 – 1 m/s and minimized the instrument tilt. As a part of initial quality control, the profiles having tilt of more than 5° and vertical velocity < 0.5 m/s were discarded. The data retrieved from radiometer are processed using ProsoftTM software.

Remote Sensing reflectance

Field measurements of the water leaving radiance signal, L_w , and down-welling irradiance signal $E_d(0+)$ just above the water surface, lead to the determination of remote sensing reflectance values ($R_{rs}(\lambda)$) as defined by Mobley (1999):

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda, 0^+)} \quad , \text{ where } \lambda \text{ (in nm) is the wavelength}$$

Remote Sensing Reflectance (R_{rs}) signal is related to SSCs and dissolved organic matter in the surface waters. These R_{rs} values are used in the development of regional algorithm for the study area.

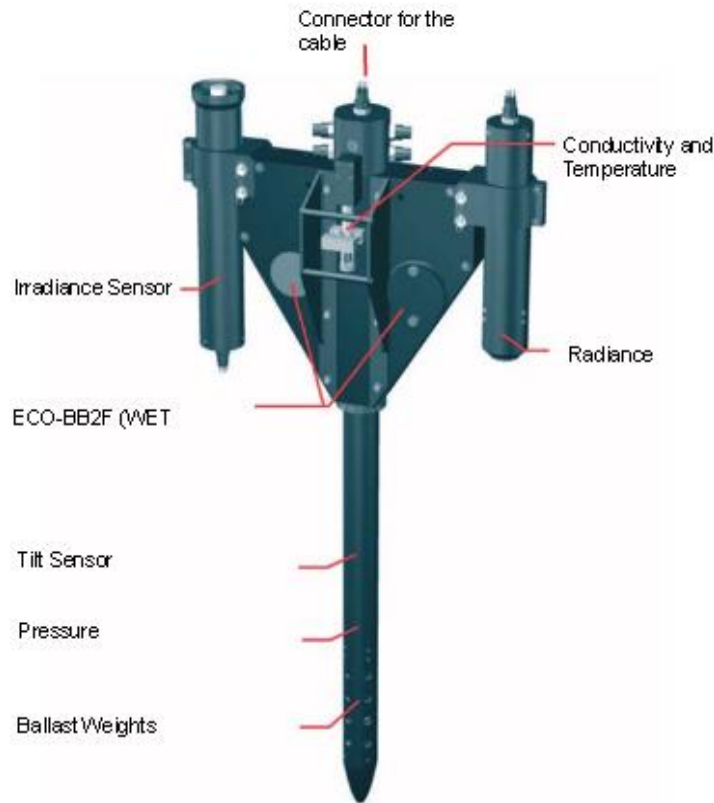


Figure 3.3 Hyperspectral radiometer employed for remote sensing reflectance measurements (www.satalantic.com).

3.3.2 Oceansat-2 satellite data

Oceansat-2 spacecraft of Indian Space Research Organization (ISRO), the second generation satellite in ocean series (launched on September 23, 2009) provides data on chlorophyll, suspended sediments, marine aerosol optical depth and vertical diffuse attenuation coefficient (K_d). The Oceansat-2 satellite carries three main instruments, namely (i) Ku band

pencil beam scatterometer, (ii) modified Ocean Colour Monitor (OCM) and (iii) Radio Occultation Sounder of Atmosphere (ROSA) instrument of Italian Space Agency (ASI). The OCM sensor onboard Oceansat-2 is mainly designed to provide continuity to the Oceansat-1 OCM sensor and to obtain quantitative information of ocean-colour variables, e.g. chlorophyll-a concentration, K_d and total SSCs in coastal waters, apart from ocean-colour information. OCM data will also be useful for studying the aerosol transport, the terrestrial biosphere, and identification of potential fishing zones. Hence, OCM has application in the fields of biological oceanography (assessment of marine living resources, primary production estimates, potential fishing zones, algal bloom detection in the coastal areas); geological oceanography (fluvial fluxes in the coastal and marine environment); bio-geochemical cycles and transport of aerosols in the marine environment. The OCM of Oceansat-2 is optimally designed for the estimation of SSCs and coastal processes viz., sediment dynamics, sediment erosion/deposition, dispersal patterns of SSCs.

The optical sensor in OCM onboard Oceansat-2 has eight spectral bands; out of which, six are in the visible spectrum of electromagnetic radiation and two are in the near infrared (NIR) region. All these bands are in the range of 402–885 nm with spectral resolution of 20 nm in the visible bands and 40 nm in NIR bands. A tilt of $\pm 20^\circ$ is provided to avoid sun glint and the revisiting period of Oceansat-2 is once in every two days. Central wavelength bands of OCM are 412, 443, 490, 510, 555, 620, 740, 865 nm with a push broom scanning technology with linear charge coupled device detector arrays. It provides an instantaneous field of geometric field of view of 360 m and ground sample distance of 236 m (long track) covering a swath of 1420 km. The specifications of the Oceansat-2 satellite and spectral applications of OCM sensor on board Oceansat-2 are given in Table 3.3. and Table 3.4.

The ocean colour data used in this study are acquired from the OCM sensor onboard Oceansat-2. This sensor is optimally designed to estimate/monitor the coastal and oceanic parameters such as total suspended sediments, chlorophyll, phytoplankton blooms and atmospheric aerosols (Nagamani et al., 2008; Simha et al., 2012).

Table 3.3 Technical specifications of the OceanSat-2 satellite and Ocean Colour Monitor (OCM) Sensor onboard OceanSat 2.

Parameters	Specifications
Instantaneous Geometric Field of View (m)	360 x 250
Swath (km)	1420
Number of spectral bands	8
Spectral range (nm)	402-885
Quantization Bits	12
Along track steering	+20°, 0, -20
Data rate	20.8 Mbits/s
Repeativity	2 days
Equatorial crossing time	12 noon
Path and row	10 and 14

Table 3.4 Spectral bands of OCM sensor onboard Oceansat-2 and their applications in ocean water studies (www.isro.gov.in).

Band No	Wavelength (nm)	Central wavelength band	Band width (nm)	Application
1	404-424	412	20	Yellow substance absorption
2	431-451	443	20	Chlorophyll absorption
3	476-496	490	20	Chlorophyll and other pigments
4	500-520	510	20	Turbidity and suspended sediments
5	546-566	555	20	Chlorophyll-a reference
6	610-630	620	20	Total SS matter estimation
7	725-755	740	30	Atmospheric correction
8	845-885	865	40	Atmospheric correction/Aerosol optical thickness

The cloud free images of OCM data for the period of 2010, 2011 and 2012 (path 10 and row 14) were procured from National Remote Sensing Centre (NRSC), Hyderabad, and the images were processed for spatial and seasonal variation of SSCs. The acquisition dates of the satellite data products used in this study are given in Table 3.5.

Table 3.5 Acquisition dates of the OCM sensor data products used in the study.

S. No	Satellite data acquisition period		Remarks
	Year	Date and Month	
1.	2010	1 January, 16 February, 16 March, 13 April, 2 June, 8 July, 13 December	Cloud -free images are only used in the present study.
2.	2011	20 January, 21 February, 07 March, 04 April, 17 May, 27 September, 01 October, 14 November, 8 December	
3.	2012	07 January, 14 February, 02 April, 06 May, 4 July, 21 September, 03 October, 28 November, 02 December	

3.3 Satellite data processing

The estimation of SSCs employing OCM onboard Oceansat-2 satellite data in nearshore waters involves three major steps such as atmospheric correction of visible channels to obtain normalized water leaving radiances, calculation of remote sensing reflectance ($R_{rs}(\lambda)$) and retrieval of total suspended sediment concentrations (Figure 3.1).

3.3.1 Atmospheric correction

The atmospheric correction in the remote retrieval of ocean constituents involves the removal of the atmospheric and surface effects from the signal measured by the satellite-sensor, thus deriving the radiances coming from the ocean waters. Measurements from altitudes ranging from 152 to 3050 m showed the effect of increasing ‘airlight’ on the upward radiance received by the sensor, and thus the need for an ‘atmospheric correction (Austin, 1974; Clarke and Ewing, 1974). The signal received by the remote sensor, whether on aircraft or on satellite, contains an optical return from the atmosphere.

Atmospheric correction for ocean-colour data need to be carried out to evaluate the atmospheric optical properties accurately and precisely, so that one may compute what the ocean-colour signal would have been, in the absence of an intervening atmosphere. Models of

the atmospheric processes employed in the development of ocean-colour algorithms generally incorporate a treatment of Rayleigh scattering (molecular scattering) and Mie scattering effects (aerosol scattering) (Duggin, 1985). In the ocean colour remote sensing, the total signal received at the satellite altitude is dominated by radiance contributed through atmospheric scattering processes, and only 8 - 10 % of the signal corresponds to oceanic reflectance. Therefore, it is mandatory to correct for atmospheric effects in order to retrieve any quantitative parameter from space (Chauhan et al., 2001).

For the ocean-atmosphere system, the top of the atmosphere (TOA) radiance ($L_t(\lambda)$) can be partitioned linearly into various distinct physical contributions such as (i) the contribution arising from Rayleigh scattering, (ii) the contribution arising from aerosol contribution, (iii) the water leaving radiance diffusely transmitted to the top of the atmosphere (Miller et al., 1977; Holyer, 1979; Whitlock et al., 1982). The radiance received by a sensor at the top of the atmosphere in a spectral band located at λ_i , $L_t(\lambda_i)$ can be divided into the following components (Chauhan et al., 2001):

$$L_t(\lambda_i) = L_a(\lambda_i) + L_r(\lambda_i) + T(\lambda)L_g(\lambda_i) + t(\lambda_i)L_w(\lambda_i) \text{-----}(1)$$

where L_a and L_r are the reflectances generated along the optical path by scattering in the atmosphere due to aerosol and Rayleigh scattering, L_g is the specular reflection or sun glitter component, L_w is the desired water leaving reflectance. T and t are the direct and diffuse transmittance terms respectively.

Typically, atmospheric correction techniques for Case 1 (open ocean) waters rely on the fact that the water-leaving radiance approaches zero in the near-infrared domain. The signal that reaches the satellite sensor in this spectral domain is analysed to infer optical properties of the atmosphere in the same spectral domain, and the results are extrapolated to the visible domain using optical models of the atmosphere (Gordon and Wang, 1994; Gordon, 1997). This allows computation of the water-leaving radiance in the visible domain.

Gordon and Clark (1981) have shown that in near-infrared (NIR) wavelength bands the water leaving radiance coming out of clear open ocean waters can be assumed to near zero

because of strong water absorption, and if the effect of sun glitter is also assumed to be negligible, as in the case of OCM sensor, which has provision for a tilting mechanism to avoid sun glitter, then equation 1, can be written as

$$L_t(\lambda_i) = L_r(\lambda_i) + L_a(\lambda_i) \quad \text{for } \lambda_i > 740 \text{ nm, i.e. } L_w \approx 0 \text{ ----- (2)}$$

From equation (2), it can be understood that the TOA radiance in 740 nm and 865 nm wavelength bands over the clear ocean water regions, mainly correspond to the contribution coming only from the atmosphere, as the water-leaving radiance L_w (740 and 865 nm) can be safely assumed to be equal to zero (Gordon and Clark, 1981). The Rayleigh radiance ($L_r(\lambda)$) is computed using the well established theory. By applying equation (2), once L_r is known, L_a can be determined as

$$L_a(\lambda_i) = L_t(\lambda_i) - L_r(\lambda_i) \quad \text{for } \lambda_i \geq 740 \text{ nm---(3)}$$

Oceansat 2 OCM payload has 740 nm and 865 nm wavelength bands in NIR region and using these two bands a relationship is obtained for the spectral dependence of the aerosol optical depth on a pixel by pixel basis as suggested by Ramana et al. (2000) and Chauhan et al. (2001). Gordon and Wang (1994) proposed an exponential relationship for spectral behavior of aerosol optical depth compared to a power law based spectral relationship of aerosol optical depth for marine aerosols. The exponential of aerosol reflectance is computed through an exponential function depending upon the atmospheric correction parameters ($\varepsilon(i, j)$) can be defined as suggested by

$$\varepsilon(i, j) = \frac{L_a(i)}{L_a(j)} \text{ ----- (4)}$$

where $L_a(i)$ is the single-scattering aerosol reflectance at band 7 (i.e., 740 nm) of OCM sensor, and $L_a(j)$ is the single scattering aerosol reflectance at band 8 (i.e., 865 nm). The value of $\varepsilon(i, j)$ characterizes the spectral variation of the aerosol properties, which include the aerosol optical depth, aerosol scattering phase function, and single-scattering albedo. The water leaving reflectance in the smaller wavelengths was then computed using the following equation:

$$L_w(\lambda_i < 740) = (L_{ac}(\lambda_i) - L_a(865)).\exp[\log(\varepsilon) / (865 - 740) * (865 - \lambda)] / t(\lambda) \text{ ----- (5)}$$

where $L_{ac}(\lambda)$ is the Rayleigh and ozone corrected radiance for $\lambda < 740$ nm, and $t(\lambda)$ is the diffuse transmittance term. Using the equation 5 water leaving radiance images were generated for shorter wavelength bands of 412, 443, 490, 510, and 555 nm in this study.

The estimated water leaving reflectance is converted to normalized water leaving reflectance $L_w(\lambda)_N$ as suggested by Gordon and Clark (1981), which is defined as

$$L_w(\lambda)_N = \frac{L_w(\lambda)}{t(\lambda, \theta_0)}$$

and remote sensing reflectance is expressed as $R(\lambda_i) = \frac{L_w(\lambda)_N \Pi}{F_0(\lambda) \cos \theta_0}$

where $t(\lambda, \theta_0)$ is the atmospheric diffuse transmittance with the solar zenith angle θ_0 , F_0 is the extraterrestrial solar irradiance and θ_0 is the solar-zenith angle. The estimated value of normalized water-leaving radiance/ reflectance values in different spectral bands are used to generate ocean colour products such as suspended sediment concentrations.

The normalized water leaving radiance values obtained, after removing the atmospheric path radiances, are subsequently utilized for the estimation of SSCs by applying regional algorithms developed for the present study area.

3.3.2 Geometric correction

The satellite images acquired by Earth Observation Systems cannot be transferred to maps because of geometric distortion and these distortions are due to the errors in the satellite position in its orbit (Legeckis and Pritchard, 1976; Richards, 1986). There is need to remove these distortions by applying the geometric correction for satellite images. A geometric correction was applied to the acquired OCM images, using ERDAS Imagine 9.1, digital image processing software. The image was geometrically rectified to geographic latitude and longitude, and to Datum WGS84. Ground Control Points (GCPs) were selected from predefined ground control points and resampled using nearest neighbour interpolation technique with the help of ERDAS Imagine 9.1 software. For the spatial interpolation portion of the geometric correction, a second-order polynomial was used and the nearest neighbour resampling technique was chosen as done in the geo-rectification process.

3.3.3 Regional algorithm

The interrelationship between sediment concentration and spectral reflectance of water helps in the development of algorithms based on the interrelationship between SSC and spectral reflectance with measurements ranging from laboratory to satellite scales (Tasaan, 1994; Moore et al., 1999; Doxaran et al., 2002; Binding et al., 2003, 2005; Miller and McKee, 2004; Wang et al., 2010; Wang et al., 2012; Binding et al., 2012, Cui et al., 2013, Wu et al., 2013).

Understanding bio-optical properties of coastal waters are a key issue to improve the accuracy of derived water constituents of ocean color data (e.g., Babin et al., 2003a,b; Hamre et al., 2003). Various studies in coastal waters have demonstrated the need for regional algorithms to obtain a better estimation of water constituents (Kahru and Mitchell, 1998; 1999; 2001; Reynolds et al., 2001; D'Sa et al., 2002). The optics of water–sediment mixtures are highly nonlinear, and many factors such as suspended particle size, shape, and colour can influence the water–sediment optics (Stumpf and Pennock, 1989; Sydor and Arnone, 1997). Because of these optical complexities, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as coastal geomorphology, river input, local coastal circulation influence the SSCs and hence the algorithm developed for one region may not be applicable to another region.

A three-component model proposed by Tassan, (1994) applied to case 2 waters of India for estimating and mapping of SSC by many researchers (Santosh et al., 2002, Rajawat., 2005; Surendran et al., 2006; Ramaswamy et al., 2007; Sridhar et al., 2008; Ramakrishnan et al., 2013). This algorithm captures the inherent sigmoid relationship between $R_{rs}(490)$, $R_{rs}(555)$ and $R_{rs}(620)$ band ratio and computes SSC. The water-leaving radiance at different wavelengths is transformed to the reflectance values at those wavelengths and is used in the algorithm. For suspended sediments retrieval, the variable $X_s = [R_{rs}(555) + R_{rs}(670)] * [R_{rs}(555) / R_{rs}(490)]^{1.5}$ and fitted equation between the *in situ* SSCs and variable X_s is expressed as

$$\text{Log}(S) = 1.83 + 1.26 \text{ Log } X_s$$

where S is SSC in mg/l and X_s is a variable defined as defined above and R_{rs} is remote sensing reflectance in respective wavelengths. Tassan's (1994) algorithm uses the SeaWiFS radiometer

reflectance values of spectral wavelength bands of 490, 555 and 620 nm for retrieval of SSCs the coastal waters of the Gulf of Naples (Mediterranean Sea) and suggests, this algorithm is adjusted to the local conditions.

Pradhan et al. (2005) observations found that the standard error of estimates 15 mg/l between the *in situ* and derived SSCs from OCM and most of the *in situ* observations of SSCs were within the continental margin (average depth of ~45 m). Shanti et al., (2013) studied that retrieved SSC values derived from modified Tassan (1994) algorithm on OCM data were not well correlated with *in situ* SS concentration and underestimates four times lesser than the *in situ* measurements, especially near the coast, where the SSCs were high. As Tassan's (1994) algorithm does not suit for estimation of SSCs in coastal waters of all regions, and, hence, there is a need to tune the algorithm for local conditions, and hence a regional algorithm is developed for estimation of SSCs in SW coastal region of India.

In this study, the regression analysis is applied for the remote sensing reflectance of spectral bands at 490 nm, 555nm and 620 nm obtained from radiometer and *in situ* SSCs to develop the SSC–reflectance relation to the coastal waters of the southwest, India. Such regression relation was applied to the OMC data for retrieval of SSCs across the world. The retrieved SSCs derived from the OCM are used in validation technique to check the robustness of SSC and remote sensing reflectance relationship. Some of the researchers used the leave-one-out cross validation technique (Schlerf et al., 2005; Sterckx et al., 2007; Martin et al., 2008; Wang et al., 2010; 2011) for this purpose.

The details of the regional algorithm developed and its validation process for the southwest coastal waters of India are discussed in chapter 4.

3.3.4 Estimation and Mapping of SSCs

Spatial assessing of the quantum of fine sediments and mapping of spatial distribution provide information on favorable zones for transportation and deposition, oceanographic dynamics that influence distribution patterns etc. The regional algorithm developed for the study area (discussed in detail in Chapter 4) has been applied for estimation of SSCs at pixel level (each pixel covers 360 m spatial resolution). The study area is divided in to several grids, each

grid encompassing an area of 10' minutes along the coast and 40 minutes perpendicular to the coast as shown in figure 3.4. The grids, generally extending 10' (latitudinally) and 40' (longitudinally) is shown as rectangular bars. The southwestern part of the study area is covered by high SSCs to a larger distance offshore, i.e., extending up to 60-80 km offshore. Hence the estimation of SSC in this area is carried out for the entire period of study. The SSCs, retrieved by applying a regional algorithm, and their spatial distribution are shown on the maps (Figures 5.1-5.3) for the study period from 2010-2012.

The study area is divided into the three sectors viz., southern sector extends from of 8° to 9° 10'N latitude, central sector extends from 9° 10' to 10° 50'N latitude, and northern sector extends from 10°50' to 12°30'N. The hinterland of southern sector is characterized by very few rivers that drain in the narrow land mass between western ghats and the coast, and cliffed coastline at some places. The hinterland of central sector is characterized by six rivers of medium size and wider coastal plains and plaeobreak ridges. The hinterland of northern sector of coast is characterized by cliffed coastline and elevated laterite plateaus at some places. A few medium size rivers drain this area.

SSCs are estimated up to a distance of 74 km in the coastal waters of Kerala from these sectors (10' along x 40' across the coast) for better understanding of SSCs. Of the 41 rivers that flow into the eastern Arabian Sea, Kallada and Vamanapuram Rivers discharge into southern Kerala; Bharathapuzha, Chalakudy, Periyar, Muvattupuzha, Meenachil, Manimala, Pamba, Achankovil Rivers discharge into the central part. The Muvattupuzha, Minachil, Manimala, Pamba, Achankovil discharging into southern part of Vemband lagoon in the south; Periyar and Chalakudi rivers into the northern part of Vemband lagoon. Vemband lagoon is a major coastal water body which influences the sediment load and oceanography of the nearshore sea, particularly in the monsoon season. Payaswani, Valapatanum, Chaliyar, Kadalundi discharge into the northern sector of the study area.

The spatial distribution of SSCs were mapped and their concentrations are shown in different colours to indicate the different ranges of concentrations of suspended sediments (Figure 3.4.). The SSC values are divided into five major classes such as very low concentrations (< 5 mg/l), low concentrations (5-10 mg/l), moderate (10-20 mg/l) and moderately high (20-30

mg/l) and high concentrations (30-40 mg/l). The temporal and spatial distributions maps of SSCs map are prepared to evaluate their concentrations and dispersal patterns of SSCs for the period of 2010 to 2012. SSC values in coastal waters of SW India during the study period vary largely from 1 to 40 mg/l. The frequency distribution of SSCs follows the right skew distribution (Figure 3.5).

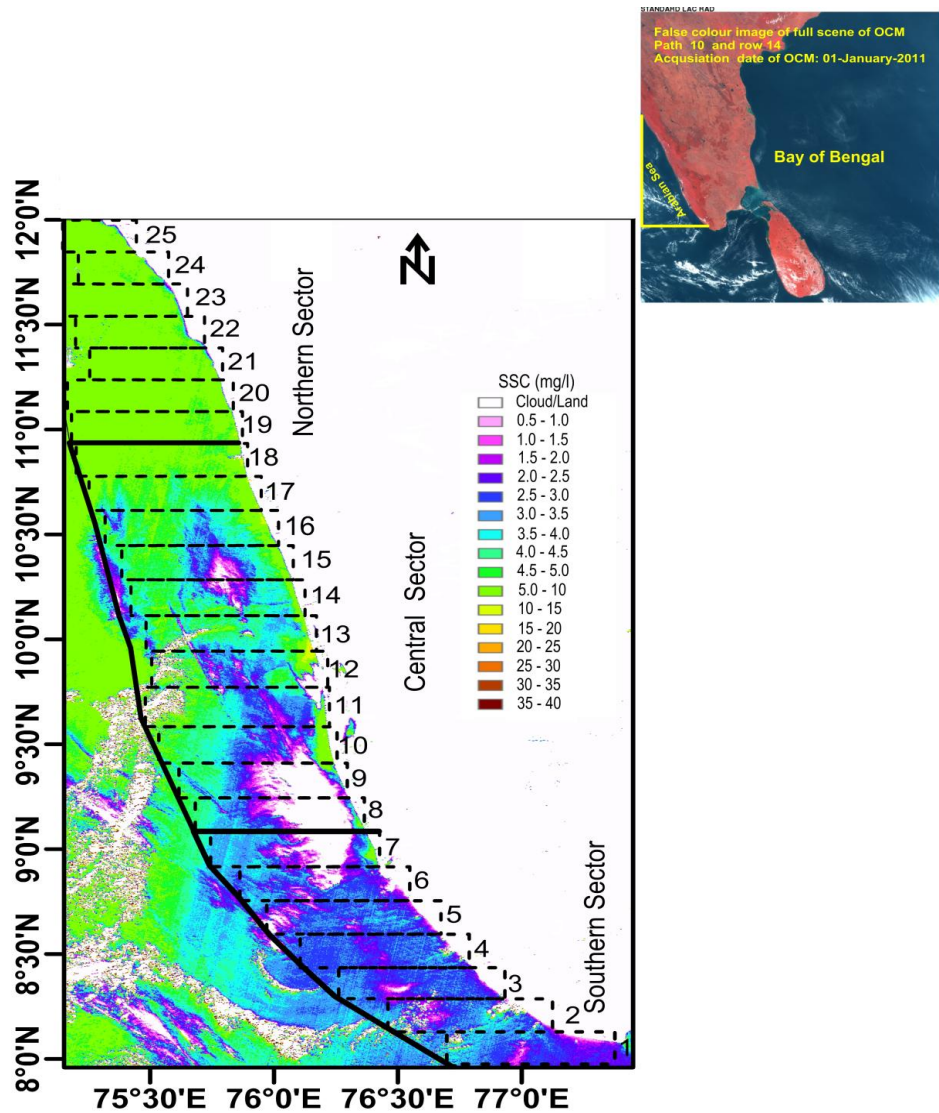


Figure 3.4 Map showing the study area divided into three sectors - southern, central and northern. Each sector is divided sub-sectors with 10' x 10' spacing along the coast and 10' x 40' spacing across the coast. The SSCs are computed for each subset of 10' x 10' spacing.

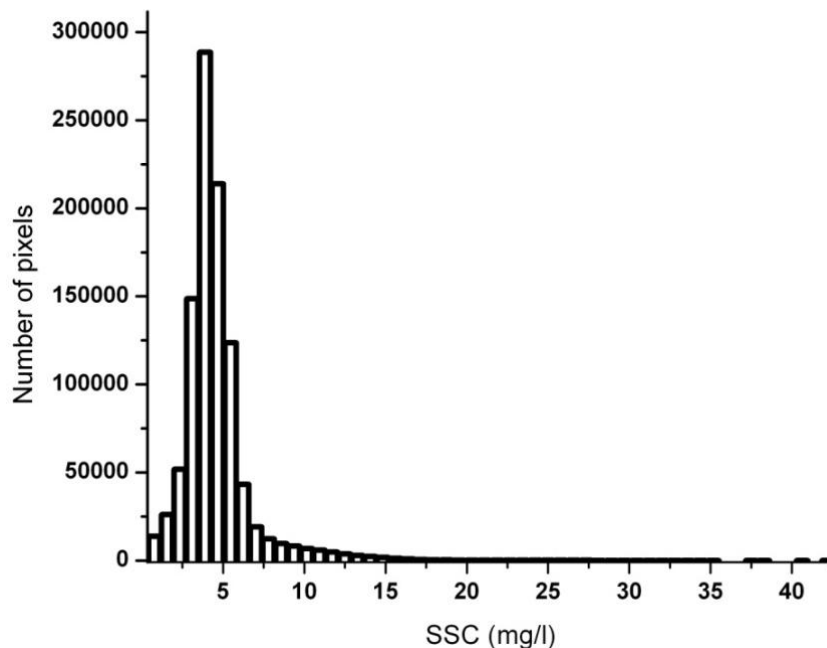


Figure 3.5 Distribution of SSCs along the coastal waters of Kerala. The distribution follows the positive skewness, the SSCs distribution is concentrated on the left and skewed to the right.

3.5 Statistical analysis

Statistical analysis of any data is essential in ensuring the correct interpretation and to establish the meaningful, significant relationship and the data is not simply chance occurrence. A ‘statistic’ is a numerical value that describes properties of a data set. The most commonly used statistics are mean, and the standard deviation, which is a measure of the variability within a data set around the mean.

The statistical analysis of SSCs data includes the weighted average / mean (M), standard deviation (SD) and coefficient of variation (CV) for each subsector in spatial and temporal terms, and the statistical variability is studied for all sectors for the whole of study period from 2010 to 2012.

The mean and standard deviation of suspended sediments of three sectors for the period from 2010 to 2012 were computed employing following formulae (Taylor, 1982)

$$WA = \frac{\sum_i^n w_i x_i}{\sum_i^n w_i}$$

$$SD = \sqrt{\frac{\sum_i^n w_i x_i^2}{\sum_i^n w_i} - \left(\frac{\sum_i^n w_i x_i}{\sum_i^n w_i} \right)^2}$$

x_i is the pixel value of SSC in a subset and w_i number of pixels of SSCs (x_i) in the subset is called as weights of a given subset.

Coefficient of Variation (CV) is the ratio of the standard deviation of the mean of SSCs, which can be defined as

$$\text{Coefficient of Variation (CV)} = \frac{SD}{M} \times 100$$

ANOVA

It is a statistical tool used for making simultaneous comparisons between two or more means. This method yields the values that can be tested to determine whether a significant relation exists between variables or not. The ANOVA is used to determine the impact of independent variables on the dependent variable in a regression analysis. After the ANOVA test is performed, the analyst will be able to perform further analysis on the systematic factors that are statistically contributing to the variability of data sets.

One-way analysis of variance (abbreviated as one-way ANOVA) is a technique used to compare means of two or more samples within the group, e.g., temporal or spatial data (using the F distribution) (Schindler et al., 2012). The two-way analysis of variance is an extension of the one-way analysis of variance used to compare the mean values of two different groups, e.g., temporal and spatial variations of the variable and this technique can be used only for numerical data.

ANOVA tests the null hypothesis that two or more groups are drawn from populations with the same mean values. The ANOVA produces F-statistic, the ratio of the variance calculated among the means to the variance within the samples and ‘F’ distribution under the null hypothesis. Typically, ANOVA is used to test for differences among the groups/mean values (Gosset, 1908).

The null hypothesis in ANOVA is that the means are equal. In other words,

$$H:\mu_1=\mu_2=\mu_3$$

$$H_1:\mu_1 \neq \mu_2 \neq \mu_3$$

where μ_1 , μ_2 , μ_3 are the means of the groups.

If the means are all from the same population, it indicates the acceptance of the null hypothesis. If the means are all different, it indicates a rejection of the null hypothesis and the calculated value of F statistics is greater than the critical value and significantly with 95% confidence level ($p < 0.05$). In this study, two - ANOVA is applied to the weighted averages of SSCs of each sector for the study period from 2010 to 2012.

Analysis of variance (ANOVA) is also carried out on the mean values of SSCs to study the difference in the means in temporal and spatial scales at a confidence level of 95 % ($p < 0.05$).

Auto correlation function

Autocorrelation function is a correlation coefficient, measure of similarity between successive observations. It refers to the correlation of a time series with its own past and future values (Box and Jenkins, 1976).

In this study auto correction function is applied to determine the degree of dependence present in the values of a time series, separated by an interval called lag time. The lag time is considered as differences between the successive months. The temporal patterns of SSCs in three sectors were examined up to 12 lags to understand the effect of SSCs for the period of 2010 to 2012.

It is defined as

$$r_1 = \frac{\sum_{t=1}^{N-1} \left(x_t - \bar{x}_1 \right) \left(x_{t+1} - \bar{x}_2 \right)}{\left[\sum_{t=1}^{N-1} \left(x_t - \bar{x}_1 \right)^2 \right]^{1/2} \left[\sum_{t=2}^{N-1} \left(x_t - \bar{x}_2 \right)^2 \right]^{1/2}}$$

where $\bar{x}_1$ is the mean of SSCs the first N-1 observations and $\bar{x}_2$ is the mean of SSCs of the last N-1 observations.

3.5 Sediment Transport Model

Understanding of suspended sediment transport in the marine environment is essential for coastal engineering activities, navigational purposes, assessment of pollutants and biological activities in the coastal waters. The hydrodynamic model together with the Mud Transport (MT) module embedded in MIKE 21 Model is used for simulation of SSCs for the central Kerala coast during the period of January 2011. The data used in the study include ECMWF winds, tides, bathymetry and the satellite derived SSCs. MIKE 21 MT model - combined with currents and SSCs - is used for understanding the distribution and transport of fine sediments. The simulated SSCs are compared with satellite and with *in situ* SSCs. The results of the model are discussed in chapter 6.

Chapter 4

Regional Algorithm and Suspended Sediment Concentrations Estimations

Chapter 4

Regional Algorithm and Suspended Sediment Concentrations Estimations

4.1 Introduction

Algorithms for determination of suspended sediment concentrations from satellite data have traditionally been based either on colour changes (through reflectance ratios) or brightness of reflectance (through single-band reflectance) (Doerffer et al., 1989; Tassan, 1994; Carder et al., 2004; Chen., et al., 2007; Ramakrishnan et al., 2013). Many studies presented a wide range of empirically derived relationships between suspended sediments and reflectance functions (Curran and Novo, 1988; Tassan, 1986; Green and Sosik, 2004; Binding et al., 2005; Eleveld et al., 2008; Vilamaliz and Fernando, 2009; Wang et al., 2010; Wang et al., 2012; Wu et al., 2013). There has been little agreement to date on algorithms developed for estimation of SSCs, particularly in their form and wavelength selection. This has been attributed to many factors including variations in the range of sediment concentrations, variations in particle properties such as size, shape or mineralogy, and errors incurred through the presence of co-varying in water constituents such as chlorophyll and yellow substance (Novo et al., 1989).

The algorithms based on visible wavelength colour ratios has been successfully employed to regions where mineral sediments are likely to dominate the optical signal, such as the Bay of Fundy (Amos and Topliss, 1985; Topliss, 1986) and the Humber Estuary (Robinson et al., 1998). Binding et al. (2003) observed that algorithms based on colour ratios in limited visible wavelength bands of sensors such as SeaWiFS have limited success, particularly in the presence of other optically active constituents. They further state that the level of success of the red to green colour ratio will be strongly influenced by the degree of presence of sediments that dominate the inherent optical properties (IOPs) of the water body. It was suggested that the measurement of brightness through the use of single-band reflectance, rather than colour ratios, may be the most reliable method for the derivation of suspended sediment concentrations in these moderately turbid waters (Binding et al., 2003).

Algorithms designed to estimate SSCs in open ocean waters, as a function of chlorophyll concentration in the deep sea, rely mainly on concentrations of plankton and associated organic detrital matter (Viollier and Sturm, 1984). The commonly adopted algorithms for estimating SSCs are based on the reflectance band ratios, characterizing the high absorption of chlorophyll around 440 nm and low absorption at 550 nm wavelength bands. However, chlorophyll and concentration of SSCs do not co-vary in coastal waters as of the occurrence of particles from resuspension, shore erosion, and river discharge. Hence, the algorithm derived from blue and green band ratios is considered as unsuitable for retrieval of SSCs as observed in coastal waters of Gulf of Naples (Tassan, 1993; 1994). Therefore, robust algorithms are required to convert radiance or reflectance values into estimates of water constituents. Tassan's (1994) algorithm, which uses SeaWiFS radiometer reflectance values of spectral wavelength bands of 490, 555 and 620 nm, has been employed for retrieval of SSCs in the coastal waters of Gulf of Naples (Mediterranean Sea). Tassan (1994) states that this algorithm had been adjusted to the confined conditions.

Many factors influence the optics of sediment mixtures, such as particle size, shape, and colour, which depend on the optical properties of the sediments (Duan, 1983; Baker and Lavelle, 1984; Ferguson, 1986; Curran and Novo, 1988; Walling and Webb, 1988; Stumpf and Pennock, 1989; de Vries and Klavers, 1994; Sydor and Arnone, 1997; Phillips et al., 1999; Asselman, 2000; Holtschlag, 2001; Doxaran et al., 2002; 2005; 2006; Tabari, et al., 2010; Ondrusek et al., 2012).

Single wavelength band reflectance values, such as the advanced very high resolution radiometer (AVHRR) visible band (580–680 nm), have been employed by various researchers in estimation of SSCs in different coastal seas (for example, in Delaware Bay - Stumpf and Pennock, 1989; the North Sea-Aguirre-Gomez, 2000; the Bay of Biscay - Froidefond et al., 1998; and the Irish Sea - Bowers et al., 1998) with varying degrees of success. However, it is known that variations in particle size and type of particle strongly influence scattering behaviour and thus reflectance (Baker and Lavelle, 1984), and therefore significant errors may take place in the simple R_{rs} algorithms. The effect of particle scattering properties (incorporating particle size distribution and refractive indices) on reflectance has been studied through theoretical considerations (e.g., Forget et al., 1998; 1999) and laboratory experiments (Novo et

al., 1989; Moore et al., 1999). It was suggested that the variability in reflectance resulting from changes in particle characteristics could be avoided by using reflectance ratios (Moore et al., 1999; Doxaran et al., 2002; 2003). Reflectance ratios with wavelengths in the near infra-red (NIR) appear to work well in extremely turbid environments where sediment concentrations exceed up to 1000 mg/l (Moore et al., 1999; Doxaran et al., 2002a, b). The successful use of NIR wavelength bands, however, is dependent on the fact that in highly turbid waters where there is sufficient scattering to overcome the strong absorption by water at these wavelengths. Doxaran et al. (2002) show that reflectance in the band range 700–900 nm was close to zero for sediment concentrations below 50 mg/l. Doxaran et al. (2003; 2005) used an NIR band ratio model to remove the effects of particle size distribution in very turbid waters and of the bidirectional variation of the remote sensed reflectance. Therefore, the effectiveness of reflectance ratios incorporating NIR wavelength bands may be limited to these extreme turbidity levels, and hence cannot be applicable to moderate concentration ranges in shelf seas. In less turbid waters, the wavelengths suitable for algorithm development may be restricted to the visible region where it has been shown that colour ratios are highly sensitive to other optically active constituents. Some researchers have adopted analytical approaches to solve the reflectance model and considered water constituents as the unknown parameterization of specific inherent optical properties (Forget et al., 1999; Haltrin and Arnone, 2003).

Because of these optical complexities, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as coastal geomorphology, river input, local coastal circulation may influence the SSCs and hence the algorithm developed for one region may not be applicable to another region and the application of previously formulated ocean colour algorithms is generally limited by site-specific factors (Hellweger et al., 2004). Therefore, there is a need to develop regional algorithms for the site specific regions. Against this background, a regional algorithm for coastal waters of the southwest coast of India has been developed, using combinations of reflectance values derived from a radiometer at 490, 555 and 620 nm and *in situ* SSCs in coastal water samples estimated by conventional methods.

4.2 Spectral signature of water samples

The presence of suspended sediment and/or organic materials in coastal sea waters cause increasing reflectance in the visible region of the electromagnetic spectrum. However, the reflectance of sediment and water will be generally low in the near infrared region, unless there is a significant amount of algae is present (Ritchie et al., 2000).

A positive correlation between the suspended sediments and spectral reflectance in the visible and near infrared wavelengths was reported by Alfoldi (1982). Several researchers have studied the relationships between SSCs and spectral reflectance or radiance. The best fit from linear regression analyses between SSCs and reflectance occurred between wavelength bands of 700 and 800 nm (Ritchie et al., 1976). Curran et al. (1987) analyzed spectral radiance recorded by an airborne multispectral scanner and found a positive correlation between SSC and radiance. Novo et al. (1989) conducted a laboratory study on the effect of sediment type on reflectance and observed that the strength of the relationship was affected by sediment type, with the fine sediment differing from coarse sediment. Bhargava and Mariam (1990) studied the spectral reflectance of turbidity caused by different clay materials. They have noted a linear relationship between turbidity and reflectance values for bentonite clay and black cotton soil, but a curvilinear association for kaoline and gray soil. Chen et al. (1991) observed that the relationship between SSC and reflectance as log linear at wavelengths of 450 to 700 nm and linear at wavelengths of 700 to 1050 nm. Novo et al. (1991) reported that the relationship between total suspended sediment concentrations and reflectance values was linear and constant from 450 to 900 nm wavelength bands in oxisol sediments. Chen et al. (1992) examined the usage of derivative reflectance spectra in estimating SSC and found a strong correlation under both controlled and uncontrolled experiments. Mantovani and Cabral (1992) studied the optimum depth for the assessment of spectral reflectance from suspended sediment and concluded that the determination of the optimum tank depth depends on the sediment type and concentration. Han and Rundquist (1994) investigated the response of both underwater light field and surface reflectance to varying SSC. The relationship between SSC and reflectance was linear at low SSC and non-linear at high SSC. Ferrier (1995) found the variability in the SSC-reflectance relationship due to changing of viewing angle and different particle shapes. Han and Rundquist (1996) compared the spectral signatures generated from two texture types of clay and found that

the reflectance from the finer clay increased faster with SSC than that from the coarse clay particles. They also demonstrated the utility of the integral of reflectance for estimating SSC. Doxaran et al. (2005) observed that the variability in reflectance bands of, resulting from changes in particle characteristics could be avoided by using the reflectance ratios of 850 nm and 550 nm wavelength bands.

A linear relationship with suspended sediment concentrations ranging between 76-600 mg/l and non linear relationship for the SSCs that range in concentration between 600-881 mg/l in the band 2 spectra of MODIS data was recorded by Wang et al. (2010). Harrington et al. (1992) reported a linear relationship between the reflectance values and SSCs in the range of 0-500 mg/l derived from Landsat MSS 3, while the nonlinear relationship is recorded as the suspended sediments increase in concentrations. Various spectral bands and sensors are in vogue for estimation of SSC incoastal waters. For ex., Landsat TM Bands 2 (green) and 3 (red) is suggested as more suitable for estimating SSC in lake waters if SSCs range from 0-50 mg/l (Dekker et al., 2001);in spectra of Landsat TM band 3 show strong significant correlations with SSC of lake waters (SSC<60 mg/l) as reported by Tyler et al. (2006). Binding et al. (2005) recorded a robust relationship between SSC (<25 mg /l) and reflectance in the red region in the Irish Sea. Sterckx et al. (2007) used NIR bands of the Airborne Hyperspectral Scanner sensor as a SSC indicator in estuarine waters (where SSCs range between 0-400 mg/l). Harrington et al. (1992) observed that Landsat MSS Band 3 (NIR) was suitable for estimation of SSCs varying 0-500 mg/l, and MSS Band 4 (NIR) was suitable for higher SSC. In general, it seems that NIR bands are more appropriate for higher SSC waters, whereas visible bands are appropriate for lower SSC waters.

In the present study, field measurements of *in situ* SSCs were carried out in the coastal waters of central Kerala for the period October and November 2010 and for January and February 2011 as discussed in Chapter 3.2.1. The remote sensing reflectance spectra (R_{rs}) at different wavelength bands recorded from radiometer are presented in figure 4.1. It is observed from the figure 4.1 that the R_{rs} values increase from bands 400-600 nm with an increase in SSCs ranging from 5.4 mg/l to 29.5 mg/l. The reflectance value from 450 nm onwards (in the blue to green spectral region) generally increases with increase of SSC while the reflectance around 600 nm (red band) remains quite insensitive to an increase in SSC. The shape of the reflectance curve

is characterized by a peak located at 555 nm. As observed from figure 4.1, the peak at 600 nm exhibits low SSC values, and the spectral reflectance increases monotonically all the way from wavelength range from 450-590 nm of the spectrum for all sampling sites. A spectral signature of high peak in the red wavelength band is inconsistent with observations made by others elsewhere (e.g., Ritchie et al., 1976; Forget et al., 1999, Wang et al., 2012, Wang et al., 2010).

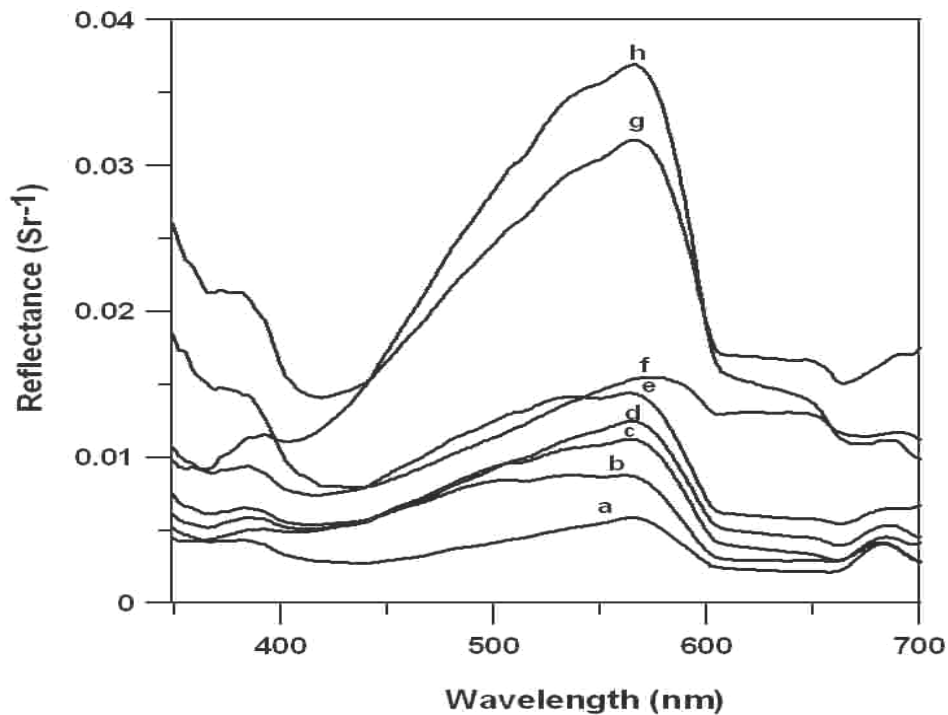


Figure 4.1 The plots show reflectance spectra obtained from radiometer for different suspended sediment concentrations derived from *in situ* measurements of water samples. The curves represent different sediment concentrations: (a) 5.4 mg/l; (b) 9.2 mg/l; (c) 12.72 mg/l; (d) 13.53 mg/l; (e) 14.78 mg/l; (f) 16.35 mg/l, (g) 18.4 mg/l; (h) 29.5 mg/l.

The statistical parameters computed for measuring reflectance values at different wavelength bands-490, 555, 620 nm-in coastal waters of the southwest coast of India are presented in Table. 4.1. The minimum reflectance was observed in the wavelength bands of 490, 620 nm with average values of 0.0128 and 0.0092 (sr^{-1}) and maximum reflectance (0.0361 sr^{-1}) in the wavelength bands of 555 nm band with an average 0.0086 sr^{-1} . The standard deviation is high (0.0086) in 555 nm wavelength band than those of 490 and 620 nm spectral bands, which means that the variability of reflectance in the wavelength band of 555 nm is high (Table 4.1).

Table 4.1 Statistics of reflectance values at different wavelengths 490, 555, and 620 nm measured in coastal waters off Cochin, southwest coast of India. These wavelength bands are used for the development of regional algorithm.

Wavelength bands (nm)	Remote sensing reflectance (Sr^{-1})			
	Minimum	Maximum	Mean	Standard Deviation
490	0.0012	0.0272	0.0128	0.0073
555	0.0056	0.0361	0.0164	0.0086
620	0.0010	0.0253	0.0092	0.0069

4.3 Relation between Single Wavelength Band, Band Ratios and *in situ* SSCs

The optical wavelength bands used to measure substances (e.g., suspended solids, chlorophyll and yellow substance) in waters depend on factors such as varying concentrations of substances, different wavelength bands of sensor employed to capture these particulate matter and so on (IOCCG, 2003). The combinations of single wavelength bands and/or ratios of wavelength bands employed to develop empirical algorithms and the merits and demerits of the band ratios were discussed by various researchers (Lathrop and Lillesand 1986; Tassan, 1993; Pattiaratchi et al., 1994; Miller and McKee, 2004; Doxaran et al., 2005; Wu et al., 2013).

The algorithms based on the visible wavelength band and colour ratios are restricted to regions where sediments are likely to dominate the optical signal in the coastal waters (Amos and Toplis, 1985; Topliss, 1986). In developing single wavelength reflectance algorithms, the visible wavelength bands for different coastal waters have been utilized with varying degree of success (Stumpf and Pennock, 1989; Bowers et al., 1998; Froidefond et al., 1998; Aguirre-Gomez, 2000). Nechad et al. (2010) propose a single band algorithm for total suspended matter retrieval based on reflectance model and calibrated the results using the seaborne reflectance and total suspended matter measurements of the southern North Sea. However, it is known that variations in particle size and type strongly influence scattering behavior and thus reflectance (Van de Hulst, 1957; Baker and Lavelle, 1984). Some earlier studies suggest that the variability in reflectance resulting from changes in particle characteristics could be avoided by using the reflectance ratios (Moore et al., 1999; Doxaran et al., 2002a, b).

It was suggested that reflectance ratios of wavelength bands in the near infra-red (NIR) region give good results in extremely turbid environments, where sediment concentrations are about 1000 mg/l (Moore et al., 1999; Doxaran et al., 2002a,b; Doxaran et al., 2005). The successful use of NIR wavelength bands, however, is dependent on the fact that in highly turbid waters where there is sufficient scattering to overcome the strong absorption by water at these wavelengths. The effectiveness of reflectance ratios incorporating the near infrared wavelength bands may be limited to these extreme turbidity levels and would not be applicable to the more moderate concentration ranges measured in the shelf area (Doxaran et al., 2002b). In less turbid waters, the wavelength suitable for development of algorithms for suspended sediments may be restricted to the visible region where it has been shown that reflectance ratios are highly sensitive to optically active constituents (Binding et al., 2005). Therefore, measurements of reflectance of the single wavelength band in moderately turbidity waters and the ratios of different wavelength bands in the visible and near infrared regions in high turbidity waters may be the most reliable method for the derivation of concentrations of suspended sediments.

The results of correlations between different wavelength bands (490, 555, 620 and 841 nm) and SSCs in the present study area are examined using the Pearson correlation coefficient (R^2) of regression analysis. A linear relationship between *in situ* SSCs and R_{rs} values of single wavelength bands such as 490, 555, 620 and 841 nm are presented in table 4.2 and figure 4.2. The remote sensing reflectance (R_{rs}) at 620 nm showed the significant linear correlation than the single wavelength bands of 410, 490, 510, 555 nm with the *in situ* SSC ($R^2=0.35$) and 841 nm wavelength band showed an insignificant relation ($R^2=0.018$).

In addition to single wavelength band reflectance values, reflectance values of different wavelength bands from the visible to NIR wavelength bands (blue, green and red), as well as the ratio of the red band to the green band, and red to blue band have been applied in this study. The ratio of different wavelength band combinations of 490, 555, 620 and 841 nm with *in situ* SSCs is shown in figure 4.3. It can be observed from the figure 4.3 that the band ratios of 620 and 490 nm exhibit a good regression relation with *in situ* SSCs. Various researchers suggested that use of reflectance ratios could reduce sky light reflection and the influence of particle grain-size and refractive index variations (Topliss et al., 1990; Doxaran et al., 2009; Doxaran et al. 2002).

A weak correlation is observed between single wavelength band R_{rs} values and *in situ* SSCs, particularly weak correlation between the ratio of $R_{rs}(841)$ and $R_{rs}(555)$ and *in situ* SSC values (Figure.4.3). However, a strong correlation is observed between the ratio of square of $R_{rs}(620)$ and $R_{rs}(490)$ and *in situ* SSCs (Figure 4.3).

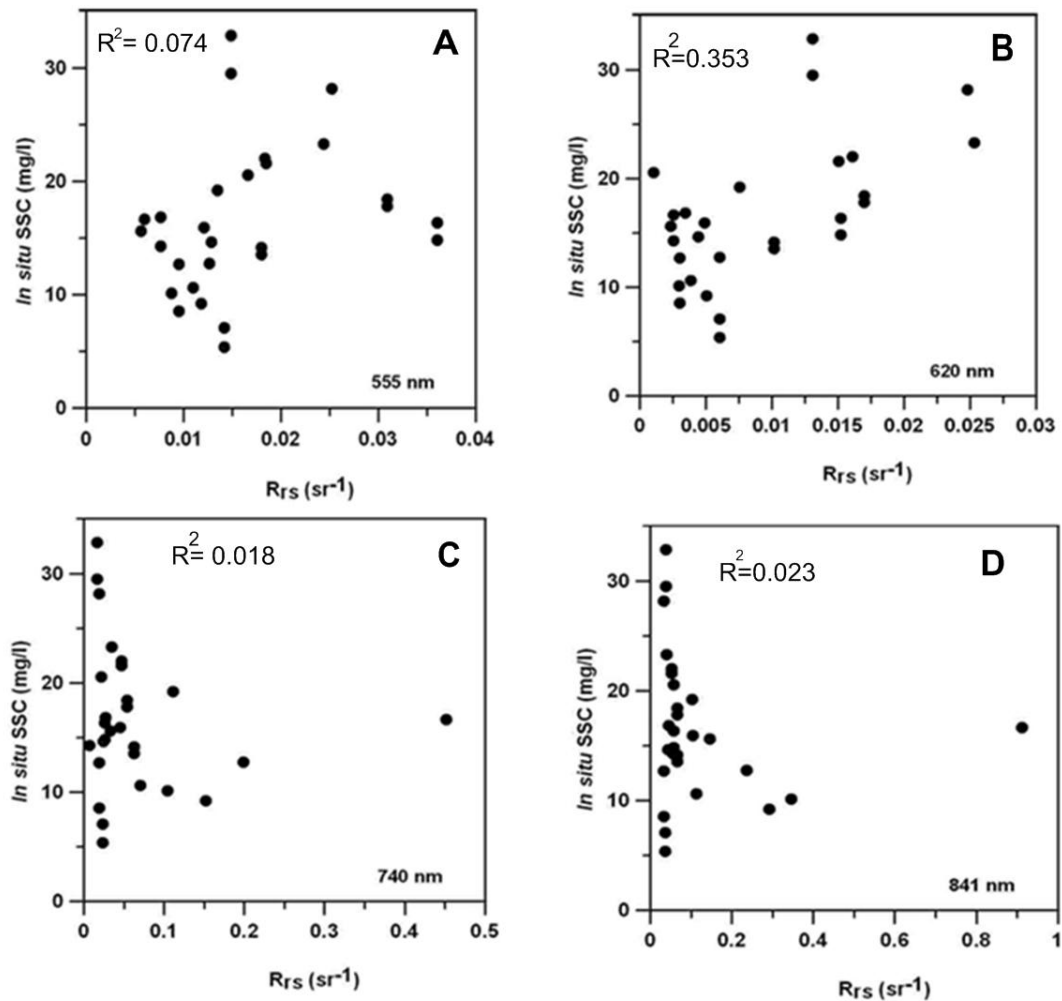


Figure 4.2 Plots of remote sensing reflectance (R_{rs}) values at different wavelength bands against *in situ* SSCs: (A) 555 nm; (B) 620 nm; (C) 740 nm; (D) 841 nm. The coefficients of variation (R^2) values for respective spectral bands are 0.074, 0.353, 0.018, and 0.023. A good correlation ($R^2=0.353$) is observed between the remote sensing reflectance values of 620 nm and *in situ* SSCs when compared with other wavelength bands.

A linear relationship between the band ratios of reflectance in the near IR (e.g.850 nm) and visible wavelength (e.g. 550 nm) bandshasbeen observedby Doxaran et al. (2005); D'Sa and Miller(2003) state that the relationship follows a power law in the sediment dominated coastal

waters. Wang et al. (2010) have also observed a strong relationship between *in situ* SSCs and the difference in spectral values of wavelength bands 2 and 5 of MODIS data than the relationship between the *in situ* SSCs and single band spectral values.

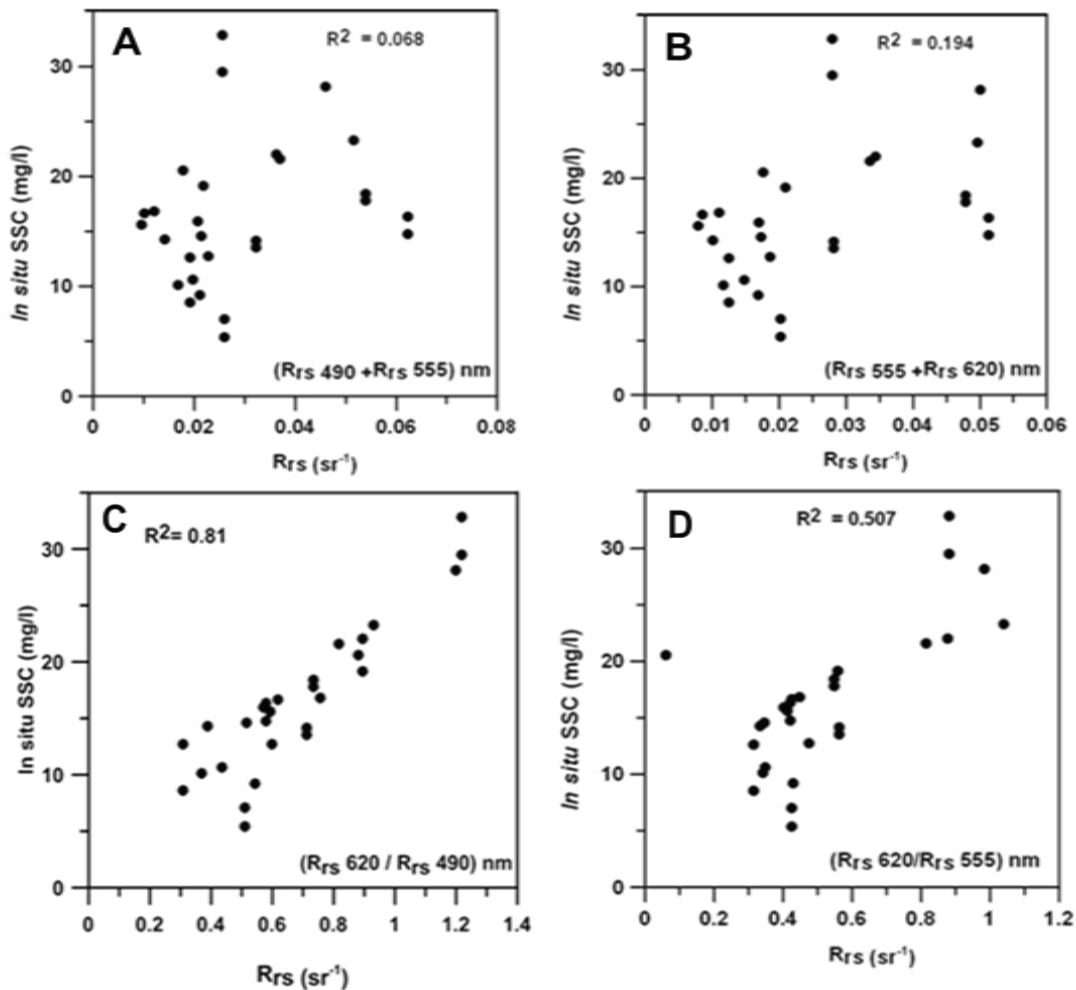


Figure 4.3 Remote sensing reflectance values (R_{rs}) for different wavelength band combinations plotted against *in situ* SSCs. Corresponding equations and coefficients of determinations of linear regressions are given in Table 4.2. The ratio of 620 and 490 nm shows strong correlation ($R^2=0.81$, $p < 0.05$ with 95 % confidence level).

In this study, the relationships are derived with combination (sum of the band with *in situ* SSCs and difference of the bands with *in situ* SSCs) of different wavelength bands as shown in Table 4.2. No significant relation is observed between the single and the sum of the wavelength bands at 490 nm, 555nm and 620 nm with respect to the *in situ* SSCs (Table 4.2), but the sum of

ratio of the bands of 555 and 620 nm to the wavelength bands of 555 and 490 nm exhibit strong correlation ($R^2=0.779$, $p<0.05$).

Table 4.2 Coefficient of determination (R^2) and root mean square error (RMSE) of different regressions for various combinations of the wavelength bands. The highest coefficient of determination values (>0.60) are shown in bold.

Remote sensing reflectance ($R_{rs}(\lambda)$)	Regression equation	R^2	RMSE	t	P
555	$Y=203 X+13.08$	0.074	6.19	1.45	0.159
620	$Y=565.6 X+11.32$	0.353	5.18	3.77	0.0009
740	$Y=-10.07 X+17.15$	0.018	6.38	-0.69	0.494
841	$Y=-5.71 X+17.16$	0.023	6.36	-0.78	0.438
490+555	$Y=110.45 X+13.28$	0.068	6.21	1.38	0.1787
555+620	$Y=198.04 X+11.44$	0.194	5.78	2.51	0.0187
(555+620)/(555+490)	$Y=48.35 X-25.04$	0.779	3.02	9.57	5.1E-10
620/490	$Y=23.26 X+0.61$	0.81	2.77	10.69	5.2E-11
620/555	$Y=19.95 X+6.08$	0.507	4.52	5.17	2.16E-05
840/490	$Y=-0.095 X+17.5$	0.037	6.43	-0.98	0.3332
840/555	$Y=-0.248 X+18.3$	0.119	6.40	-1.83	0.0777
840 -740	$Y=-5.906 X+16.8$	0.007	6.35	-0.43	0.6727
(620/490)²	$Y=15.15X+8.48$	0.839	2.58	11.67	7.8E-12

4.4 Regional algorithm for the study area

The optics of water-sediment mixtures is highly nonlinear and many factors such as suspended particle size, shape, and colour can influence the water-sediment optics (Stumpf and Pennock, 1989; Sydor and Arnone, 1997). Because of these optical complexities, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as coastal geomorphology, river input, local coastal circulation influence the SSCs and hence the algorithm development for one region may not be applicable to another region. There is no universal algorithm which can give robustness, and, hence, requires an independent algorithm for each region for retrieval of SSCs. Various studies in coastal waters have demonstrated the need

for regional algorithms to obtain a better estimation of water constituents (Kahru and Mitchell, 2001; Reynolds et al., 2001; D'Sa et al., 2002). Regression analysis is the traditional empirical method applied for estimation of oceanic parameters such as suspended sediments, chlorophyll and yellow substance (Whitlock et al., 1982; Schiebe et al., 1992; Tassan, 1993; 1994; Doxaran et al., 2002; Miller and McKee, 2004; Wang et al., 2010; Wang et al., 2011; Colleen et al., 2013; Wu et al., 2013). A robust empirical linear regression relationship is observed between *in situ* SSC and the combination of wavelength bands $\{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620) / R_{rs}(490)]^2\}$ as seen from a graph plotted between the band combination of remote sensing reflectance of 490, 555 and 620 nm against *in situ* SSCs (Figure 4.4). This relationship is stronger than the relationship obtained by employing a single wavelength band, and band ratio with *in situ* SSC. The results of regression analysis of different band combinations are presented in Table 4.2. The regression equation is derived from the combination of wavelength bands of 490, 555 and 620 nm and *in situ* SSCs is expressed in the equation

$$Y = 14.92 X + 8.22 \text{ ----- (1)}$$

where Y is the SSC in mg/l, $X = \{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620) / R_{rs}(490)]^2\}$, $R^2 = 0.84$, $t > 2$ and $p < 0.05$ with 95% confidence level. Further, a t-test was conducted on the remote sensing reflectance values with wavelength band combinations of 490, 555 and 620 nm and *in situ* SSCs, which shows that the t-test can be accepted with 95 % confidence level ($P < 0.05$ and $n=28$). At the level of significance of 0.05, the calculated t-value (11.77) is greater than the upper critical value (2.03); hence, the null hypothesis is rejected. At the same time, the Pearson coefficient (R^2) of 0.842 is greater than the critical values of the Pearson coefficient (0.11), so it can be assumed that a significant relationship exists between the *in situ* SSCs and the reflectance values of band combination of $\{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620) / R_{rs}(490)]^2\}$.

The algorithm developed for the present study area is employed for retrieval of SSCs from ocean colour monitor (OCM) of Oceansat-2. OCM bands of water leaving radiance at spectral wavelength bands of 490, 555 and 620 nm were converted in to the remote sensing reflectance values following the procedure of atmospheric correction (details of atmospheric correction procedure given in the chapter 3) and geometric correction for the satellite data as

discussed in chapter 3 (section 3.3.2 and 3.3.3). The regional algorithm that has been used to compute SSCs from OCM data is given in equation 1. Proficiency of algorithms was evaluated by comparing estimated and observed values in root mean square error (RMSE) analysis. It is considered that the estimated SSCs and *in situ* SSCs are matched, if the estimated error is small; if the error is higher, the estimated SSCs and *in situ* SSCs are not of the same order.

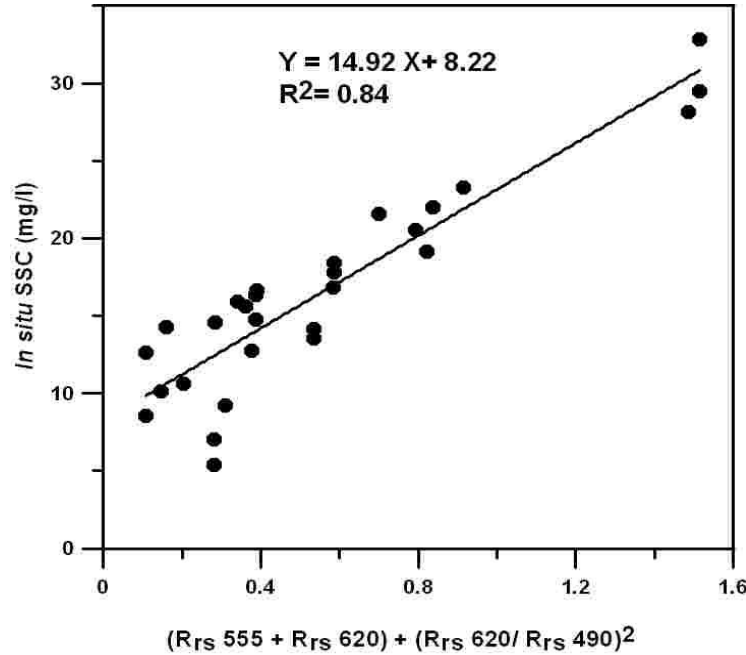


Figure 4.4 The linear regression fit between *in situ* SSC and R_{rs} measurements used for development of regional algorithm.

The combination of reflectance wavelength bands of 490, 555 and 620 nm measured from radiometer are employed in global Tassan's algorithm ($\text{Log}_{10}S = 1.83 + 1.26 \text{Log}_{10}X_s$; where S is the SSC in mg/l and $X_s = \{[R_{rs}(555) + R_{rs}(620)] \times [(R_{rs}(555)/R_{rs}(490))^{-1.2}]\}$), and the algorithm has been tested with *in situ* SSC data obtained by conventional methods. However, no significant relation ($R^2 = 0.16$) is observed between the results derived from Tassan's algorithm and *in situ* SSC measured by conventional methods in our study area i.e. coastal waters of southwest India. Avinash et al. (2012) modified Tassan's algorithm by replacing the global coefficients of Tassan's algorithm with regression coefficient values for estimation of SSCs in the coastal waters of the west coast of India. As the SSC values are low with the application of Tassan's algorithm, these authors have employed the algorithm of SAC (2004) in estimating SSCs.

4.5 Validation of Regional algorithm

The validation of satellite ocean color data products is a critical component in establishing the uncertainties in measurements, assessing the scientific utility, and identifying conditions on which their reliability depends. A considerable amount of high quality *in situ* data and consistently processed satellite mission lifetime data are required for validation of results (Bailey and Werdell, 2006). Much research on ocean color validation focuses on comparisons of satellite-derived oceanic parameter retrievals with regional *in situ* data sets, and many of which are based on specific field campaigns (e.g. Barbini et al., 2005; D'Ortenzio et al., 2002; Gohin et al., 2002; He et al., 2000; Smyth et al., 2002).

Studies by various researchers demonstrate that a number of benefits are realized with a rigorous validation activity such as (i) the assignment of a measure of accuracy to satellite-derived products, which lends confidence to their scientific utility in higher-order derived products (Behrenfeld and Falkowski, 1997b), (ii) the verification of on-orbit satellite calibration (Barnes et al., 2001), (iii) the evaluation of the long-term stability of satellite measurements (Franz et al., 2005), and (iv) the identification of conditions, either oceanic, atmospheric or satellite specific, for which satellite-derived products are invalid.

In the present study, regression analysis is applied for estimation of SSCs in the coastal waters of southwest India and regression relation was then validated using the *in situ* measurements. When OCM satellite derived SSCs using Tassan's algorithm were validated for coastal waters of India, it was found an underestimation of SSCs with *in situ* SSCs (Pradhan et al., 2005; Shanti et al., 2013).

SSCs are retrieved from OCM data using the regional algorithm for the coastal waters of the southwest coast of India and their distribution patterns of SSCs for the study period (2010-2012) are shown in the figure 4.5. The SSCs derived from satellite data by employing the regional algorithm are used for validation with *in situ* SSCs for twenty five samples in the coastal waters of the west and east coasts of India. It can be observed from the figure.4.6 that the coefficient of determination is significant ($R^2=0.81$) and the algorithm is quite robust for retrieval of SSCs in coastal waters of the region.

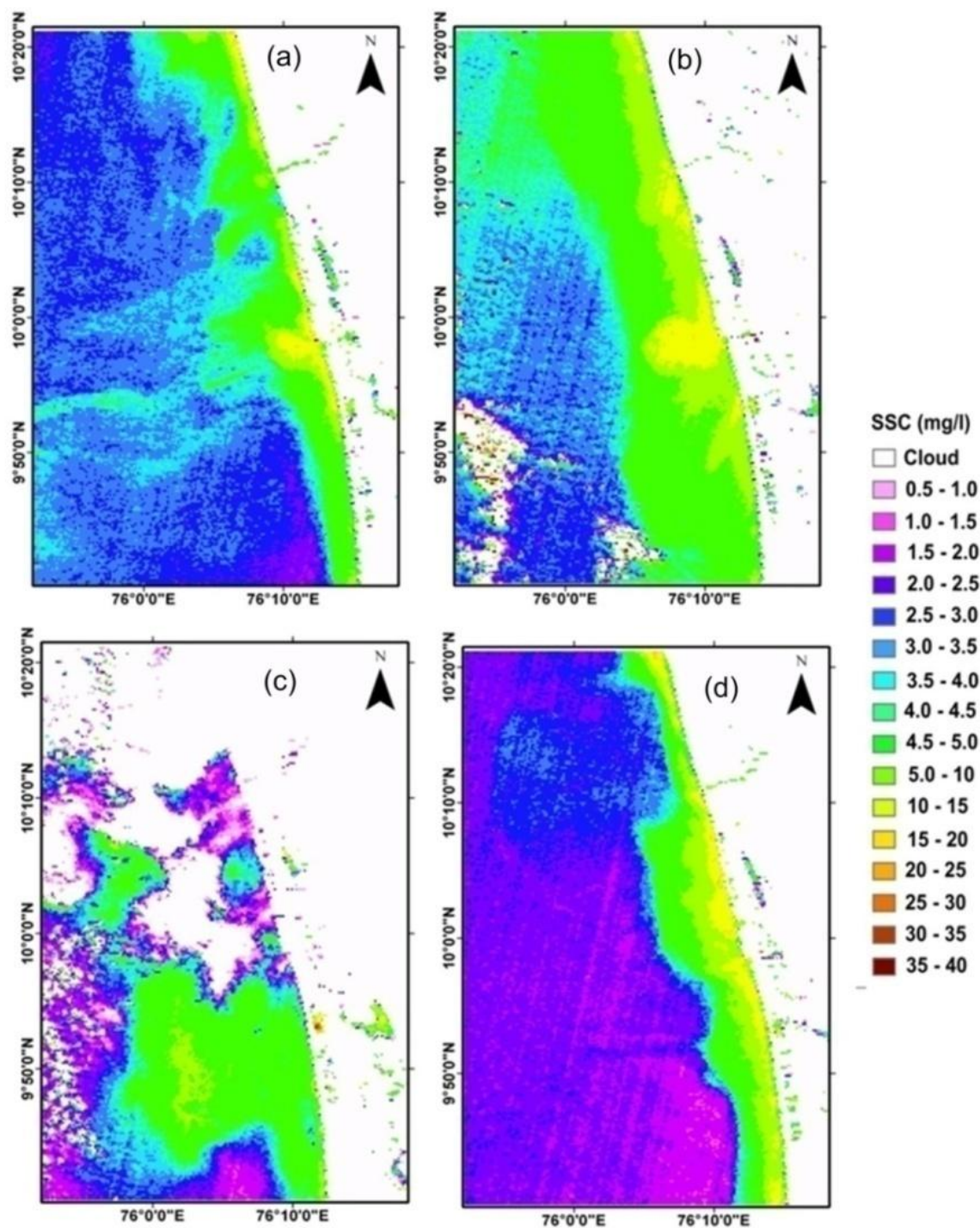


Figure 4.5 Distribution of SSCs derived from the OCM sensor onboard OceanSat-2 acquired on (a) 17th January 2010; (b) 21st February 2011; (c) 2nd October 2011; and (d) 8th December 2011 along the central coast of Kerala. The retrieval of SSCs carried employing the regional algorithm developed in this study and the data were validated with *in situ* SSCs.

In addition, the *in situ* SSC measurements with satellite derived SSCs were compared using the Tassan's algorithm. It is found that the SSCs retrieved from OCM data using Tassan's algorithm are lower than the *in situ* SSC values, and the corresponding coefficient of determination ($R^2=0.03$; RMSE=11.43 mg/l) is insignificant. A statistical relationship has been established between the *in situ* SSCs and R_{rs} values at different wavelength bands such as 490, 555 and 620 nm for improving the accuracy of SSC retrieval. A good correlation ($R^2= 0.81$, RMSE= 5.2 mg/l, n=25) was observed between the *in situ* SSCs and retrieved SSC values from satellite data using the regional algorithm (Figure 4.6). As observed from the figure 4.6, the estimated error is small. The regression relationship developed for the coastal waters of southwest India is found to be suitable for SSC retrieval as reflected in low RMSE values (5.2 mg/l). Further, these results indicate that the best wavelength bands for estimating SSCs are 490, 555 and 620 nm in the present study. The results derived from these wavelength bands are more accurate and precise than the results achieved from the customary use of the single wavelength band. No *in situ* measurements could be carried out during the southwest monsoon season (because of hostile weather during monsoon period), but the validated SSC values for non-monsoonal season establish that regional algorithm developed in this study provides accurate estimates of SSCs in coastal waters off southwest India.

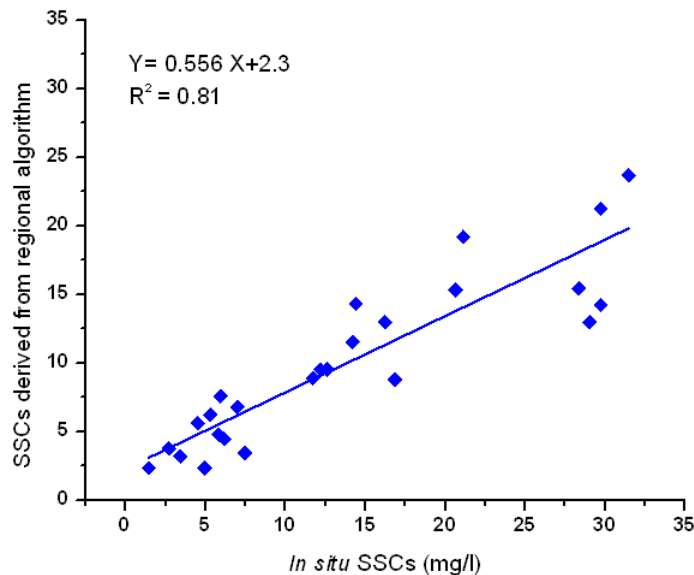


Figure 4.6 Validation of developed regional algorithm employing satellite derived SSCs and *in situ* SSCs. Strong coefficient of determination ($R^2=0.81$, n=25) is noted.

4.6 Summary

In this study, a regional algorithm for estimation of SSCs in coastal waters of southwest of India has been developed by employing measured *in situ* SSCs, radiometer reflectance values and SSCs retrieved from Oceansat-2 satellite data.

An empirical relationship has been established between R_{rs} values and concentrations of suspended sediments in the coastal waters off Cochin, southwest India. A good correlation ($R^2=0.84$; linear regression) is recorded between the R_{rs} values derived from band combinations of 490, 555 and 620 nm and *in situ* SSCs. The suitability of this algorithm with respect to the SSCs retrieved from satellite data has also been tested. For this purpose, the regional algorithm developed by us has been implemented for retrieval of SSCs from Oceansat-2 OCM sensor data and these results were validated. The regional algorithm has been validated with *in situ* measurements of SSCs and concentrations of suspended sediments were quantified. A good correlation ($R^2=0.81$) is observed between *in situ* SSCs and retrieved SSCs from satellite data using the regional algorithm developed in this study.

The present study helps in estimation and validation of suspended sediment concentrations in coastal waters on a local and regional scale, which in turn will help in coastal zone management and maintenance of navigational channels.

Chapter 5

Spatial and Temporal Distribution of Suspended Sediments

Chapter 5

Spatial and Temporal Distribution of Suspended Sediments

5.1 Introduction

Coastal waters are often characterized by high concentrations of suspended organic and inorganic material derived from seabed resuspension and discharge from particle laden rivers. Coastal margins that are influenced by major rivers are an important source of dissolved and particulate material to the ocean and to global biogeochemical fluxes. The distribution and flux of suspended sediments in coastal environments are highly variable in time and spatial scales. The fine size particles get transported along with significant amount of biogeochemical fluxes from the rivers to oceans. Fine sediments play an important role in the productivity of coastal and marine ecosystems because of their association with organic particles (House and Warwick, 1999).

The spatial and temporal distribution of suspended sediment concentrations (SSCs) are strongly affected by the seasonal river discharges, tidal currents, waves, wind-driven resuspension of the bottom sediments (Geyer et al., 2004; Lawson et al., 2007; Krisvtsov et al., 2009; Min et al., 2012). High concentrations of suspended materials in coastal waters directly affect water column characteristics and phytoplankton productivity (May et al., 2003), nutrient dynamics (Mayer et al., 1998) and transport of pollutants (Martin et al., 1990).

Suspended sediments in coastal waters are mostly comprise of clay particles and organic matter (Eisma, 1986), and are particularly important to the sedimentary and biogeochemical cycles, as these are highly sensitive to hydrodynamics and act as adsorption surfaces to dissolved materials, including pollutants (McKee et al., 2000; Volpe et al., 2011). Knowledge of dynamics of suspended sediments in coastal areas is of great importance in determining the fate and transport of suspended sediments and sediment adherent contaminants. The knowledge of fine sediment dynamics is helpful in understanding the dynamics of pollutants in estuaries and coastal seas (Dyer, 1997).

Many coastal environments worldwide are characterised by the presence of large amounts of fine-grained cohesive and non-cohesive sediments (Dagg et al., 2004; Bian et al., 2010; Bainbridge et al., 2012). Understanding the spatial and temporal distribution and variability of suspended sediments is of great scientific interest as SSCs play a major role in controlling the penetration of light into the sea and hence has a huge impact on primary productivity and ecology. SSCs also transport chemicals and resuspend pollutants, and organic components associated with fine sediments are an important constituent of the carbon cycle (Turner and Millward, 2002).

Suspended sediment concentrations (SSCs) in coastal waters are influenced by tidal dynamics and, consequently, may vary on semidiurnal, fortnightly and seasonal time scales. Tidal dynamics are one of the key factors governing the variability of SSCs, especially in muddy tidal environments. Tidal (semidiurnal or diurnal) and neap-spring cyclic variations are dominant scales of temporal variations in suspended sediment dynamics and have received significant attention (Gelfebaum, 1983; Ridderinkhof et al., 2000).

Significant understanding of sediment movement in shallow sea regions under wind and wave conditions is evidenced (Heathershaw, 1981). Surface gravity waves are an important energy sources in littoral zones, where the majority of the wave energy is dissipated. The hydrodynamic disturbances associated with waves in the littoral zone affect abiotic as well as biotic processes. Even though the wave-induced mass transport is negligible, compared to the wind-driven currents, wind waves in shallow waters can substantially increase sediment resuspension.

The transport and deposition of sediments also influence the geomorphic processes and shaping the physical landscape and regulating ecological systems (Knighton, 1998). Therefore, observation of spatial and temporal patterns of suspended sediments helps in understanding the formation and function of these environments and their response to natural and anthropogenic perturbations. Hence, the study of SSCs is of interest to coastal engineers dealing with dredging, maintenance of safe navigation routes and harbour access (De Kok, 1992).

The spatial distribution of SSCs in coastal areas is influenced by the supply of fine material and also by the circulation pattern of tides, coastal currents and waves. It is necessary to monitor transport and discharge of suspended matter for understanding the changes in sedimentary environments. Variability of SSCs renders most traditional field sampling methods as inadequate to resolve sediment dynamics in complex coastal waters (Miller et al., 2003). Ocean color satellite imageries are of great help in monitoring and understanding spatial and temporal variations of SSCs (Ritchie and Cooper, 1988; Stumpf and Goldschmidt, 1992; Robinson et al., 1998; Chen et al., 2006; Vanacker et al., 2007; Eleveld et al., 2008; Wenjuan et al., 2008; Min et al., 2012; Wang et al., 2014). Spatial mapping of the distribution of suspended particulates is critical to scientific and environmental studies in the coastal waters (Miller et al., 2004; Tao et al., 2014), and it helps environmental managers to understand the transport of materials over large areas of a coastal region.

The study of spatial and temporal variations of SSCs for the entire Kerala coast (southwest coast of India) for the period 2010, 2011 and 2012 has been carried out and results are presented in this chapter. The coastal region under study is divided into three sectors viz., southern, central and northern sectors and these sectors are further divided into sub-sectors (Figure 3.4). The southern sector is divided into seven sub-sectors (1-7), central sector into ten sub-sectors (8-18), and northern sector into seven sub-sectors (19-25). The estimated SSCs in spatial and temporal terms for each sector are discussed. The concentration of suspended sediments derived from OCM-Oceansat-2 images are statistically computed in terms of weighted averages/mean, standard deviation, coefficient of variations and analysis of variance (ANOVA) in order to understand the spatial and temporal distribution patterns of these sediments in coastal waters. An attempt has also been made to understand dispersal patterns of SSCs in relation to rainfall, river discharge and wind forcing for the study period.

5.2 Spatial and Temporal variability of SSCs

In general, SSCs largely vary from 0.5 to 40 mg/l in the coastal waters of southwest coast of India (Kerala Coast) during the study period. The concentration of suspended sediments are divided into five classes such as very low concentrations (< 5 mg/l), low concentrations (5-10 mg/l), moderate (10-20 mg/l) and moderately high (20-30 mg/l) and high concentrations (30-40

mg/l). The spatial distributions of SSCs in the coastal waters off Kerala for the study period are presented in figures 5.1-5.3, Table 5.1 and Appendix 1-3.

As seen from figure 5.1, the whole northern part and southwest part of the study area (i.e towards offshore) is covered with green colour suggesting uniformly distributed low SSCs (5-10mg/l), whereas the southeastern strip hugging the coastline is covered with blue colour indicating very low SSCs in the month of January 2010. In the month of February 2010, the combination of green and yellow patches is observed as a thin line along the coast of northern part of the study area. This indicates that moderate amount of suspended sediments are concentrated towards the coast. The distribution of SSCs in March 2010 is almost similar to the month of February 2010 where more than half of the coastline is covered with moderate SSCs. In April 2010, the central part is covered with green and yellow coloured patches indicating moderate concentrations of suspended sediments in a small stretch of area hugging the coastline. It can be further observed from figure 5.1 that in June 2010 the width of the green and yellow coloured patch slightly increased along the coastline, particularly in the central part; whereas in July the concentrated cells of SSCs are observed in the central part of the study area. In December 2010, the width of green and yellow (moderate SSCs) patches are observed to be increased along two thirds of the coastline of the study area (Figure 5.1).

The spatial distribution of SSCs observed from the processed satellite data of the year 2011 is slightly different from that of the year 2010 (Figure 5.2). In the months of January and February 2011, wide patches of green and yellow colour hugging the coastline are observed along two thirds of the Kerala coast; whereas in March 2011 thin green and yellow linear patch is seen hugging the coastline in the northern half of the study area. The similar pattern of distribution of green and yellow coloured patches is wide spread in April 2011, which is similar to that of the months of January and February 2011 (Figure 5.2) suggesting the widely distributed moderate concentrations of suspended sediments. In the month of September 2011, a slightly wider patche of green and yellow colour hugging the coastline is recorded in the northern half of the study area. Low concentrations (5-10 mg/l) of suspended sediments (seen as green colour) are widely distributed in the larger part of the study area in the months of October and November 2011. The spatial distribution of SSCs in December 2011 is almost similar to that

of January 2011, except a reduction in width of green patch along the northern half of the study area (Figure 5.2).

In the year 2012, a linear patch of green and yellow colour indicating moderate concentrations of suspended sediments, hugging the coastline in the northern half of the study area is observed in the months of January, February and April (Figure 5.3). In May 2012 also the thin linear patch of moderate SSCs along the coast of the northern part of study area is observed. No clear picture with respect to spatial distribution of SSCs is seen in the months of June and September 2012 because of poor quality of OCM images. SSCs of moderate values are distributed along the coast as a thin line in northern half of the study area in the month of October 2012. In the months of November and December 2012, the green and yellow patches occur in entire study area indicating moderate concentrations ranging from 5 to 20 mg/l (Figure 5.3).

The quantitative estimations of SSCs derived from the OCM images in terms of spatial and temporal variations in each sector are discussed in detail in the following section (5.2.1). The spatial and temporal variations of SSCs in three sectors - southern, central and northern - of the study area (Figure 3.4) expressed in terms of minimum, maximum and mean values, and their standard deviation, coefficient of variation and number of pixels for all the three years of study period are presented in Table 5.1. The basic statistical variables (minimum, maximum, mean, standard deviation and coefficient of variation and number of pixels) of each subsector representing spatial interval of 10'x 40' along and across the coast respectively are computed. The SSC variations in subsectors (1-7) of southern sector, subsectors (8-18) of central sector, and subsectors (19-25) of northern sector for the total study period are presented in Appendix 1-3. It is observed from Table 5.1 that southern sector recorded high (> 30 mg/l) amount of SSCs in June 2010; in February, March, September, October of 2011; and in May, September, December of 2012. In January, February, March, June and July of 2010; in February, March, May, September, October, November of 2011; and in January, May, July, September, October, November and December of 2012 the high SSCs (> 30 mg/l) were recorded in the central sector. In the northern sector, high (> 30 mg/l) SSCs are recorded in the months of February, June and July of 2010; in February, March, September, October, November, December of 2011; and in January, February, May, July, September, October, November of 2012. An attempt has been

made to understand the dispersal patterns of SSCs in relation to rainfall, river discharge and wind forcing.

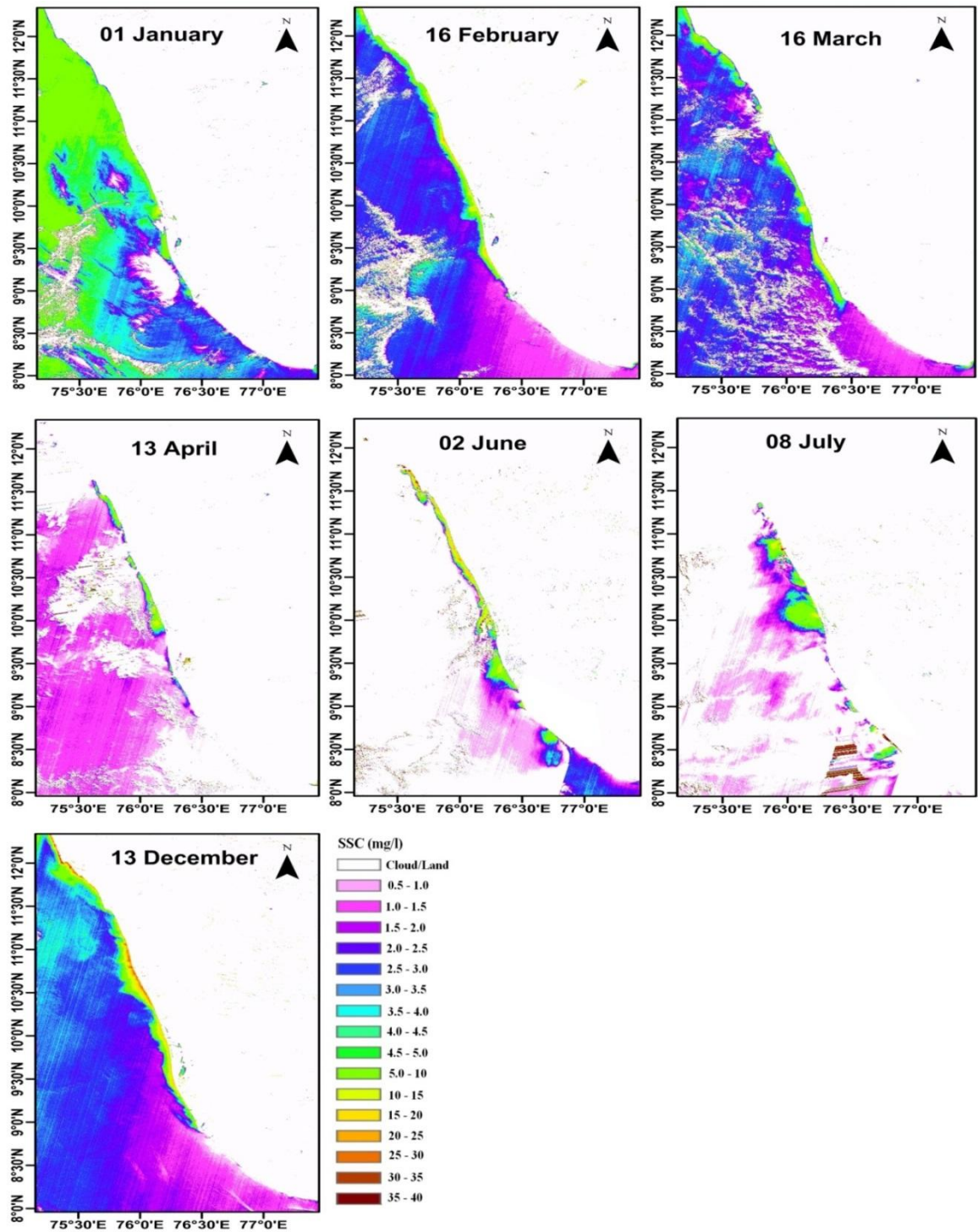


Figure 5.1 Spatial distribution of SSCs in the coastal waters of Kerala in different months of the year 2010.

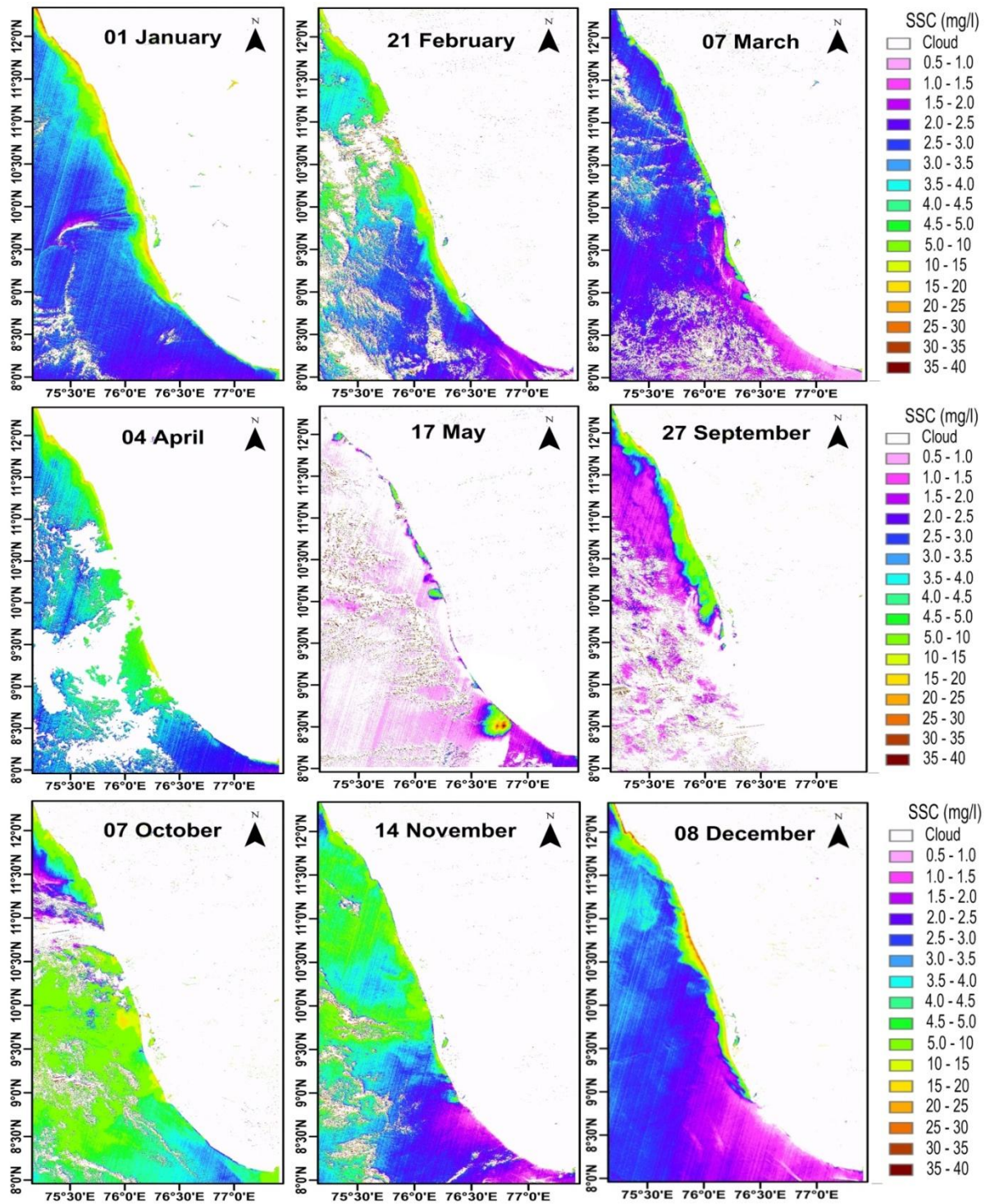


Figure 5.2 Spatial distribution of SSCs in the coastal waters of Kerala in different months of the year 2011.

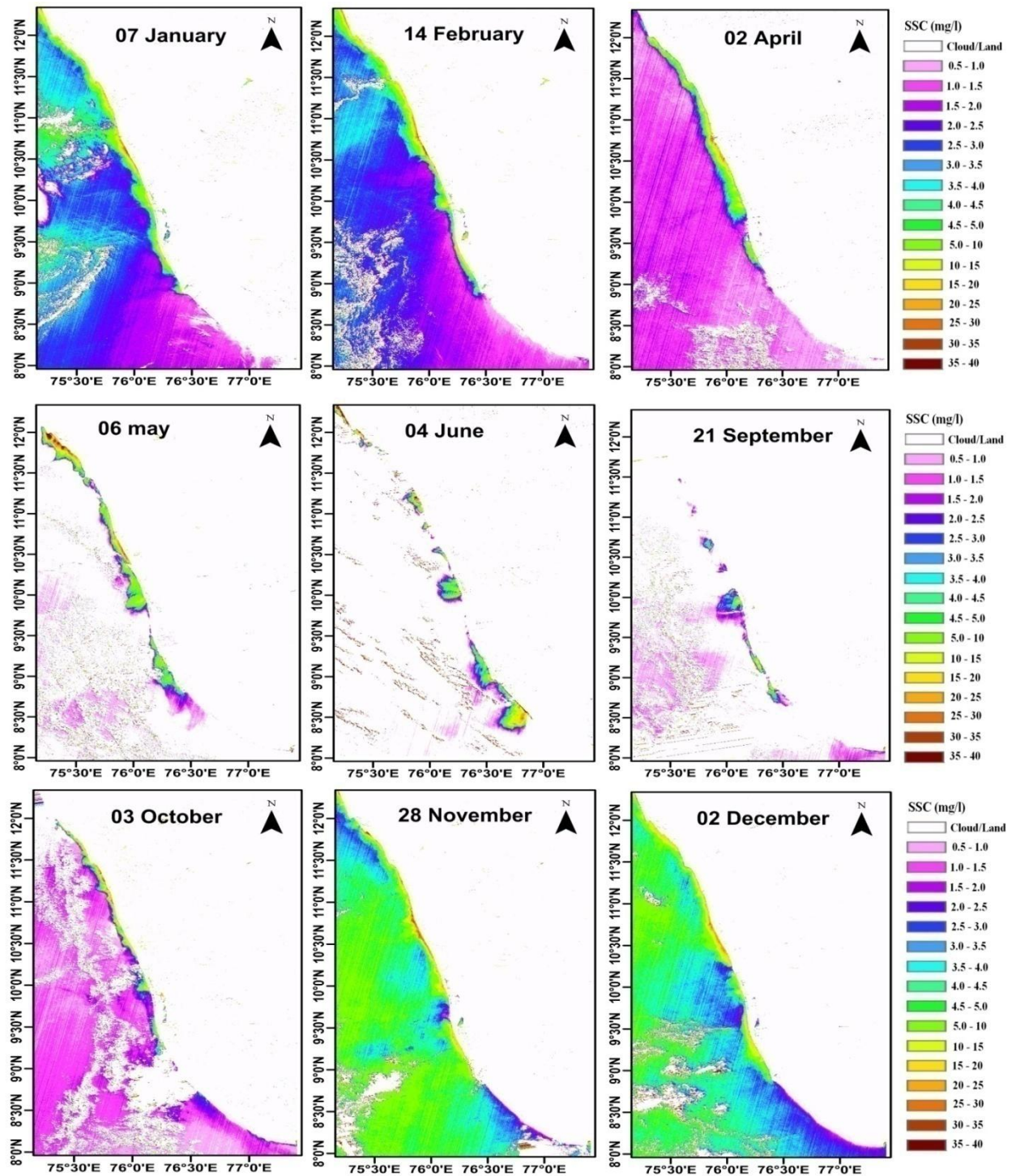


Figure 5.3 Spatial distribution of SSCs in the coastal waters of Kerala in different months of the year 2012

Table 5.1 Oceansat-2 OCM derived suspended sediment concentrations (mg/l) in the coastal waters of southern, central and northern Kerala for study period 2010, 2011 and 2012. Statistical parameters of SSCs are also shown in this Table (Note that SSCs are estimated only for the cloud free satellite images).

Year	Month	Southern Kerala						Central Kerala						Northern Kerala					
		Min	Max	M	SD	CV	N	Min	Max	M	SD	CV	N	Min	Max	M	SD	CV	N
2010	January	0.57	29.91	2.76	1.02	37.0	105118	0.61	31.18	3.89	1.52	39.07	154336	0.53	19.86	1.97	1.14	57.79	102919
	February	0.55	8.96	1.7	0.50	29.2	113568	0.87	31.49	3.17	1.92	60.47	160152	0.54	29.93	3.31	2.10	63.47	94158
	March	0.51	23.51	2.89	1.40	48.4	104998	0.53	29.91	2.86	1.7	59.44	144728	0.78	22.46	2.96	1.72	58.11	75595
	April	0.5	21.16	1.46	0.61	42.1	18201	0.69	27.6	2.69	1.43	53.01	98527	0.79	25.72	3.54	0.86	24.29	19573
	June	0.55	30.93	3.06	1.94	63.3	18264	0.51	32.28	7.60	4.65	61.19	44181	0.58	32.84	10.00	6.38	63.71	13780
	July	0.57	26.67	1.9	0.97	51.0	4155	0.52	34.91	6.8	4.58	67.24	39264	0.51	30.00	9.84	6.35	64.57	4134
	December	0.51	15.41	1.46	0.28	19.2	119579	1.23	13.53	3.67	1.39	37.87	172402	1.56	23.51	3.85	1.21	31.46	26828
2011	January	0.87	20.45	2.96	0.85	28.9	116413	0.86	18.95	4.07	3.21	78.89	170839	0.52	23.39	5.25	1.77	33.67	114676
	February	0.55	32.86	2.66	1.70	63.7	102278	0.61	35.69	5.00	2.92	58.45	129881	0.54	32.30	5.07	2.05	40.42	79400
	March	0.6	31.1	2.27	1.05	46.2	77868	0.55	37.96	2.71	1.28	47.05	165115	0.55	33.56	3.22	1.90	58.92	101614
	April	0.58	10.42	3.26	2.20	67.6	85989	0.53	16.89	4.43	3.81	85.96	83572	0.54	22.83	4.90	3.11	63.38	98378
	May	0.53	23.89	3.16	1.71	54.0	14383	0.56	35.79	2.24	1.05	46.65	10006	0.52	26.02	2.80	1.82	64.94	3668
	September	0.78	29.89	4.3	2.89	67.2	145	0.55	35.79	6.11	6.19	101.32	25123	0.52	32.30	6.43	4.44	69.08	25141
	October	0.72	30.53	4.51	3.8	84.2	103416	0.54	38.98	6.60	6.58	99.83	132046	0.55	37.40	3.97	1.76	44.33	72768
	November	0.63	22.74	2.1	0.92	44.0	104772	0.9	34.82	4.28	4.12	96.16	161174	0.55	30.13	4.96	3.14	63.38	26374
	December	0.57	9.85	5.09	4.13	81.1	111081	1.24	21.02	8.66	7.12	82.23	171796	1.07	29.36	6.20	1.68	27.04	117932
2012	January	0.51	10.72	3.5	2.22	63.4	99694	0.56	30.42	3.50	3.22	91.96	160496	0.62	31.28	4.78	2.26	47.31	92000
	February	0.57	9.97	1.53	1.12	73.5	114490	0.69	27.96	2.85	2.35	82.30	172531	0.77	30.08	4.25	2.2	51.76	115116
	April	0.58	19.64	1.41	1.05	74.7	62710	0.59	10.6	1.76	0.96	54.44	281484	0.51	10.44	2.26	1.38	61.01	108589
	May	0.58	33.59	2.95	1.66	56.3	7201	0.57	37.58	6.43	4.28	66.57	19156	0.68	35.12	10.07	5.66	56.19	13868
	July	0.61	26.71	5.26	4.55	86.5	16035	0.53	29.78	5.42	4.31	79.50	24643	0.73	32.75	5.80	4.89	84.39	10468
	September	0.64	32.94	3.27	2.5	76.4	8446	0.66	35.75	3.48	2.12	60.88	25946	0.83	33.76	1.64	0.66	40.04	1474
	October	0.61	20.62	0.56	0.4	71.1	16721	0.54	34.14	1.8	1.1	61.15	64427	0.6	32.14	2.43	1.75	71.77	54046
	November	0.66	28.47	4.42	3.43	77.6	93868	0.67	36.93	5.27	5.23	99.32	162247	0.95	29.70	5.00	1.6	32.03	107120
	December	0.73	31.49	4.41	2.06	46.7	151086	0.64	33.28	4.64	3.8	81.88	225955	0.66	28.88	5.44	2.0	36.69	126363

Min = Minimum; Max = Maximum; M = Mean; SD = Standard Deviation; CV = Coefficient of Variation; N=Number of pixels

5. 2.1 Sectorwise variation of SSCs

Southern Sector

The annual variations of SSCs range from 0.5 to 30.9 mg/l with a weighted average / mean of 2.2 mg/l and standard deviation of 0.8 mg/l in 2010; 0.5 to 32.9 mg/l with a mean value of 3.3 mg/l and standard deviation of 2 mg/l in 2011; and vary from 0.5 to 33.6 mg/l with a mean of 3.1 mg/l and standard deviation of 2 mg/l in 2012 (Table 5.1, 5.2).

In the year 2010, low concentrations of suspended sediments (8.9 mg/l) are recorded in February; moderate SSCs (15.4 mg/l) in December; moderately high (29.9 mg/l; 23.5 mg/l; 21.2 mg/l; 26.7 mg/l) SSCs in January, March, April and July; and high (30.9 mg/l) SSCs in June 2010. These high concentrations of suspended sediments are observed in the northern part of the southern sector (Figure 5.4). During the year 2011, moderately high (> 20 mg/l) SSCs and high (> 30 mg/l) SSCs are recorded in January, February, March, May, September, October and November; and moderate SSCs (10.4 mg/l) in April and low (9.8 mg/l) SSCs in December 2011 are recorded (Figure 5.4).

In 2012, May, September and December months have recorded high concentrations (> 30 mg/l); moderately high concentrations (26.7 mg/l; 20.6 mg/l; 28.5 mg/l) in July, October and November; moderate concentrations (10.7 mg/l; 19.6 mg/l) in January and April; and low concentrations (9.9 mg/l) in February 2012. In summary, high (> 30 mg/l) SSCs are recorded in June 2010; in February, March, September and October 2011, and in May, September and December 2012 (Table 5.1 and Figure 5.4). As seen from the Table 5.2 annual average variations are slightly higher in 2011 and 2012 than in 2010.

The northern part of the southern sector (i.e., subsectors 5-7) witnessed SSCs ranging from 10 to 20 mg/l during February, March, April, and June of 2010 where the discharge of large amount of sediments from Kallada River and Thottapally spillway might have influenced the SSCs. Low SSCs (< 10 mg/l) are recorded in the southern part of southern sector (i.e., subsectors 1-4) in December 2010 and very low concentrations (< 5 mg/l) are observed towards offshore (Appendix 1-3).

Table 5.2 Annual variations of SSCs in southern, central and northern sectors of Kerala coast during study period.

Sector	Year	Minimum (mg/l)	Maximum (mg/l)	Mean (mg/l)	Standard Deviation	Coefficient of Variation (%)
Southern	2010	0.51	30.93	2.17	0.82	37.56
	2011	0.53	32.86	3.31	2.11	63.96
	2012	0.51	33.59	3.22	2.03	63.24
Central	2010	0.51	34.91	3.71	1.91	51.41
	2011	0.53	38.98	5.13	0.81	15.83
	2012	0.54	37.58	3.44	0.82	23.83
Northern	2010	0.51	30.00	3.23	0.17	17.28
	2011	0.52	37.40	4.90	0.44	9.05
	2012	0.62	35.14	4.34	2.00	46.14

Central Sector (9°10' - 10° 50' N)

In general, SSCs varied annually between 0.5 to 34.9 mg/l with a mean concentration of 3.6 mg/l and standard deviation of 1.8 mg/l in 2010; 0.5 to 38.9 mg/l with a mean of 5.1 mg/l and standard deviation of 4.2 mg/l in 2011; and range from 0.5 to 37.6 mg/l with a mean of 3.6 mg/l and standard deviation of 2.9 mg/l in 2012 in the coastal waters of central Kerala (Table 5.2.) Monthly variations during 2010 suggest that high amount (> 30 mg/l) of SSCs are recorded in the months of January, February, June and July; moderately high (> 20 mg/l) SSCs in March, April and moderate (13.5 mg/l) SSCs in December 2010 (Table 5.1 and Figure 5.4).

In the year 2011, January and April months recorded a moderate concentration of suspended sediments (18.9 mg/l; 16.9 mg/l), moderately high (> 20 mg/l) SSCs in December, and higher concentrations (> 30 mg/l) are recorded in February, March, May, September, October, and November 2011. Similarly, the months of January, May, July, September, October, November, December in 2012 have witnessed higher (> 30 mg/l) SSCs; February and September of 2012 recorded moderately high values (> 20 mg/l) of SSCs, while the month of April recorded a moderate (10.6 mg/l) SSCs during the year 2012 (Table 5.1).

In general, high SSCs (> 30 mg/l) are observed in May and September in the years 2010 and 2012 in the coastal waters of central Kerala (Figure 5.4). Spatially high amount of SSCs is more pronounced in June and September (30 mg/l) as discrete patches along the coastline. This may be due to influence of discharge from rivers such as Bharathapuzha, Chalakudy, Periyar, Muvattupuzha, Meenachil, Manimala, Pamba, and Achankovil that bring large amount of eroded material in the hinterland to the Vemband lagoon (Narayana and Priju, 2006; Chandramohan and Balchand, 2007). The other important factor is the high amount of rainfall in the central Kerala during southwest monsoon period, i.e., from June to September. Moderate SSCs (~ 15 mg/) are dispersed towards the offshore region in the monsoon months (Figures 5.1-5.3). High concentration of suspended sediments (> 30 mg/l) tend to occur along the coastal shallow region (< 30 m depth), where resuspension of bottom sediments takes place by waves and winds (Wright et al., 1991; Pavelsky et al., 2009).

SSCs of moderate concentrations (~ 20 mg/l) recorded in subsectors(8 -18) in the months of January, February and December 2010; slightly higher SSCs (> 20 mg/l) in all sub-sectors in the months of March, April, May, September, October, November and December 2011; and low concentrations (~ 10 mg/l) in subsectors of 13-16 (Appendix 1-3). Dispersal of fine sediments from river mouth (lagoon) towards offshore i.e., 15 km away from the shoreline is clearly evidenced (Figures 5.1-5.3). Suspended sediments brought by the rivers (Chalakudy, periyar, Muvattupuzha, Meenachil, Manimala, Achenkovil, Pamba) are first debouched into Vemband lagoon, subsequently escape the lagoonal system because of excess freshwater out flows during the monsoon months. Similar observations were made off the mouth of Yellow River by Bian et al. (2013). The sediment load and discharge details of rivers of central Kerala can be seen in Table 2.1.

Northern Sector ($10^{\circ}50'$ - $12^{\circ}30'N$)

The average annual concentrations of suspended sediments in northern sector of Kerala coast varies from 0.51 to 30 mg/l with a mean of 3.5 mg/l and standard deviation of 1.7 mg/l in 2010; from 0.5 to 37.4 mg/l with a mean of 5 mg/l and standard deviation of 2.5 mg/l in 2011; and from 0.6 to 35.1 mg/l with a mean of 4.7 mg/l and standard deviation of 2.2 mg/l in 2012 in the coastal waters of northern Kerala (Table 5.2). The monthly variations of SSCs in terms of

minimum, maximum, mean and standard deviations of SSCs in the northern sector for the study period are shown in Figure 5.4.

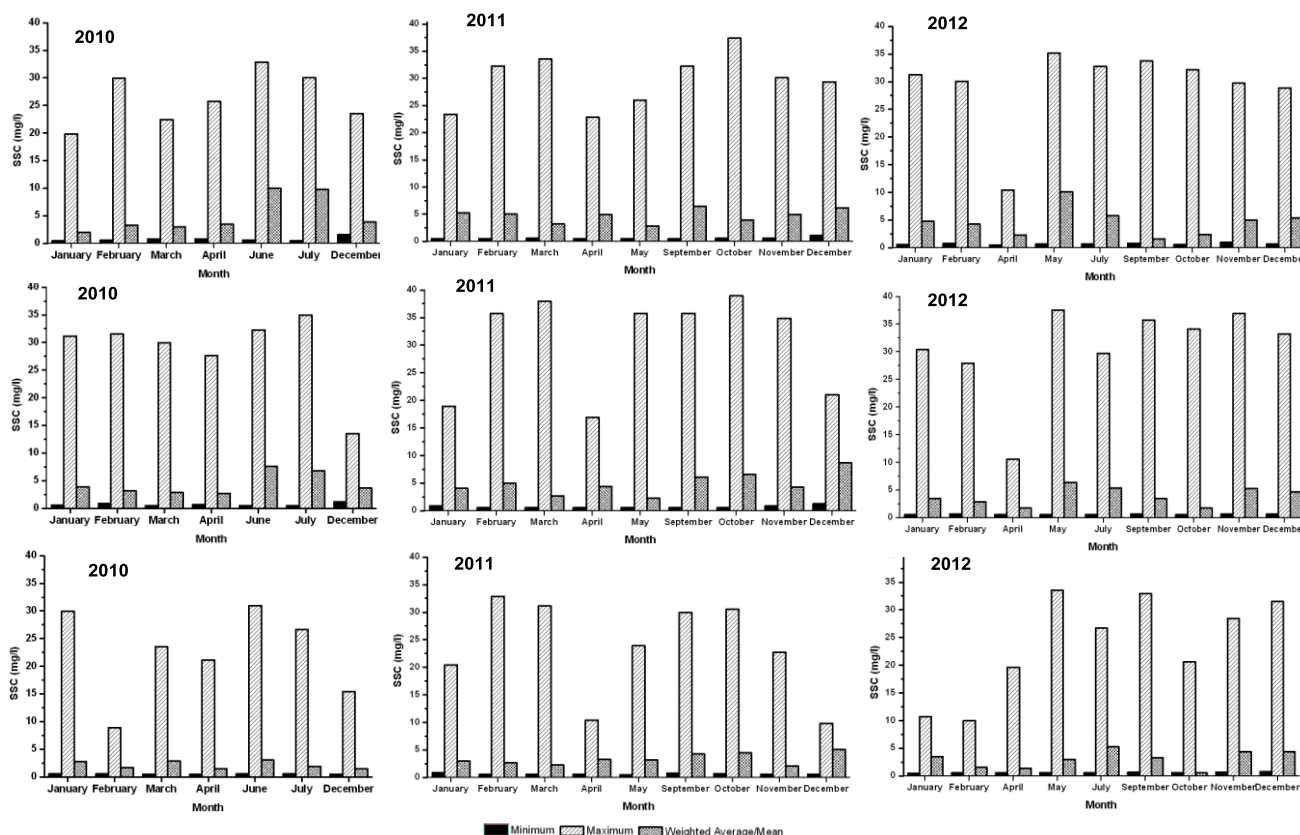


Figure 5.4 Minimum, maximum and averages of SSCs in the three coastal regions of Kerala during the study period. Bottom horizontal panel represents southern Kerala; Middle horizontal panel represents central Kerala; and Top horizontal panel represents northern Kerala.

As seen from figure 5.4, the monthly SSCs are high (> 30 mg/l) in June and July 2010; in February, March, September, October, and November 2011; and in January, February, May, July, September and October 2012. Moderately high (> 20 mg/l) SSCs are recorded in February, March, April and December 2010; in January, April, May, and December 2011; and in November and December 2012. Moderate SSCs (10-20 mg/l) are recorded in January 2010 and April 2012.

Sub-sector wise observations suggest that the suspended sediments are of moderate concentrations (< 20 mg/l) in subsectors 19-25 of the northern sector in the months of January, February, March, April and December of 2010; in January, April and May of 2011; and in April

and December of 2012. High concentrations (> 30 mg/l) are recorded in June 2010; in February, March, September, October, November and December of 2011; and in January, February, May, July, September, October and November of 2012. Moderately high amount (> 20 mg/l) of suspended sediments are recorded in subsectors 19, 20, 24 and 25(see Appendix 1-3), which might have been influenced by the supply of sediment load from Bharathapuzha, Chaliyar, Payaswani and Valapatanam rivers (Table 2.1).

5. 2. 2 Coefficient of variation and analysis of variance

Coefficient of variation (CV) is calculated to assess the variability of SSCs in the study area for the period 2010-2012. It is observed that CV ranges from 19.18 to 101.32 % with a mean of 60.21 and standard deviation of 19.04. It indicates that variability of SSC is very high in all the three sectors (Table 5.1). Further, the coefficients of variations are categorized into four classes as proposed by Garcia (1989) as low, medium, high and very high (Table 5.3).

Table 5.3 Classification and ranges of CVs of SSCs (after Garcia, 1989).

Category	Criteria (as per Garcia)	Class
Low	$CV \leq (M - SD)$	Low (< 41.17)
Medium	$(M - SD) < CV \leq (M + SD)$	Medium (range from 41.17 to 79.25)
High	$(M + SD) < CV \leq (M + 2SD)$	High (range from 79.25 to 98.29)
Very High	$CV > (M + 2SD)$	Very high (> 98.29)

If the $CV \leq 41.17$, then it is taken as a low variation of SSCs during the month; if the CV ranges from 41.17 to 79.25 it is considered as a medium variability in that month; if the CV values range from 79.25 to 98.29, then it is considered as a highly variable; and if the CV is > 98.29 it is taken as very high variability (Table 5.3).

In southern sector, low variability of SSCs is observed in the months of January, February and December 2010 and January 2011(Figure 5.5). Medium range of CVs (values) was observed in March, April, June and July of 2010; February, March, April, May, September, and November of 2011; and in January, February, April, May, September, October, November and December of 2012. High variability (ranging from 79.25 to 98.29) of CVs in southern sector was observed in the months of October and December 2011 and in July 2012 (Figure 5.5).

In the central sector, low CV values are recorded in the months of January and December 2010; medium range CV values in February, March, April, June and July 2010; January, February, March and May 2011; and in April and May of 2012. High CV values (79.25-98.29) are recorded in the months of April, November and December 2011; in January, February and April of 2011; and in July and December of 2012. A very high variability of CV values (> 98.29) are recorded in September 2011 and November 2012 (Figure. 5.5). In the northern sector, low CV (< 41.17) values are observed in April and December 2010; in January, February and December 2011, and in September, November and December 2012; while the rest of the study period exhibits medium range values of CV (ranging from 41.17 to 79.25).

High variability in CVs was observed mostly in the monsoon months i.e., June-September during the study period. The high variability (CV > 79.25) recorded in central and northern sectors may be the result of nearshore turbulence caused by the strong winds (> 7 m/s) during the monsoon period (June-September). The strong turbulence may induce seabed erosion, which in turn induces resuspension of sediment particles. Further, river discharge and sediment flux from the medium size mountainous rivers also contribute suspended sediments in varying amounts as observed by Bian et al. (2013).

Analysis of Variance (ANOVA) Statistics

Analysis of variance (ANOVA) is applied to check whether the mean values of SSCs are the same throughout the study period in all the three sectors. Equality of means is tested with null hypothesis which exhibits that at least two months / two regions mean values of SSCs differ. The null hypothesis is rejected at 95 % level of confidence ($P < 0.05$) and this suggests that the mean values differ significantly at 95 % level of confidence both through space and time.

The results of two way ANOVA statistical test depicting the spatial and temporal variations of SSCs are presented in Table 5.4. The relationship between temporal and spatial variability of SSCs is statistically significant ($p < 0.05$). The difference in mean values of SSCs in spatial and temporal scales suggests that a statistically significant relation ($p < 0.05$) was observed for the study period (2010-2012) at a 95 % level of significance; where critical value is greater than the table value i.e., $F = 7.92 > 3.89$ in 2010; $F = 7.1 > 3.63$ in 2011 and $F = 5.04$

>3.63 in 2012 in spatial; and $F = 4.32 > 2.99$ in the 2010; $F = 5.48 > 2.59$ in 2011 and $F = 9.19 > 2.59$ in 2012 in temporal levels (Table 5.4).

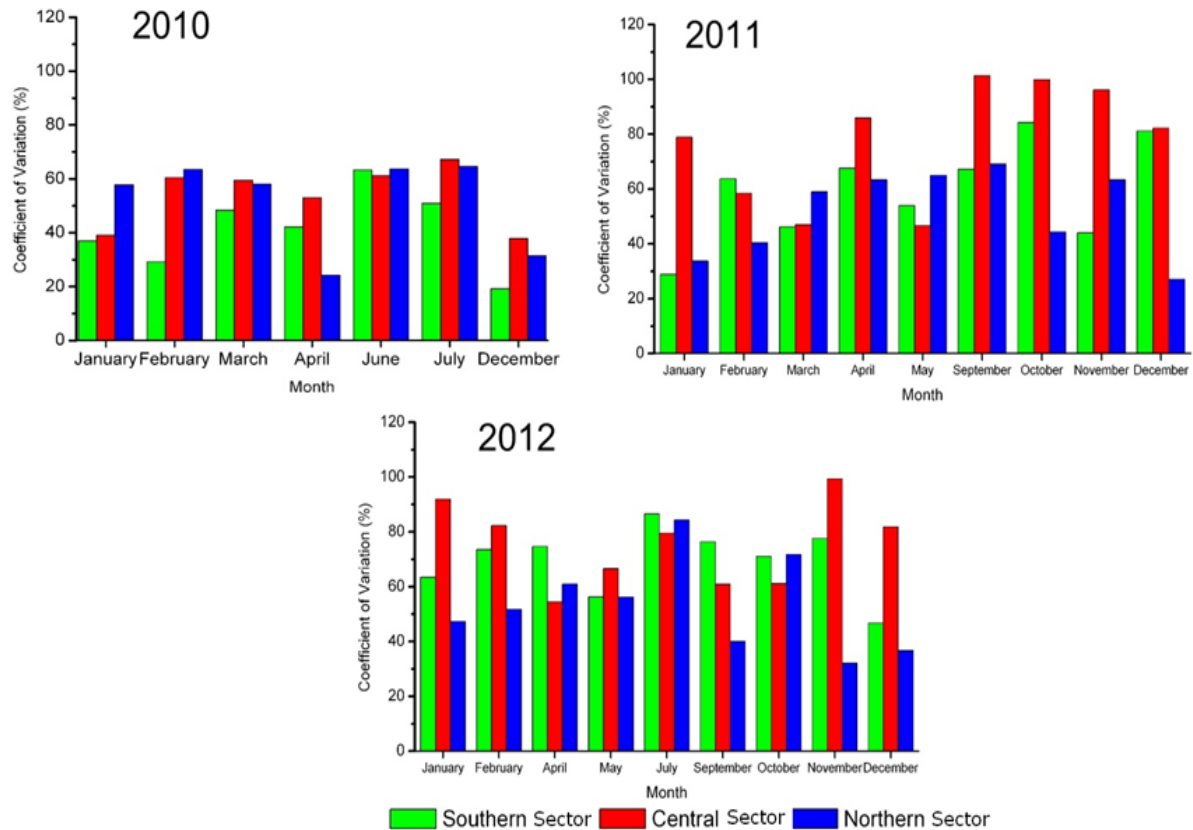


Figure 5.5 Spatial and temporal variations of coefficient of variations (CVs) of SSCs during the period of 2010 - 2012. High CVs (79.25) are recorded in southern sector in October 2011 and July 2012; while in central sector in the months of April, September, October November and December of 2011; and in northern sector high CVs are noted in July 2012. The high variability is caused by the nearshore turbulence which drifts the bed material into suspension and also discharge of sediments to the coast.

Table 5. 4 Statistical derivatives and mean values of SSCs in terms of spatial and temporal variations derived from ANOVA test.

Year	Spatial/ Temporal	Sum of Squares	degree of freedom	Mean Square	F Statistics (Calculated)	P-value	F Statistics Critical Value (Table Value)
2010	Spatial	32.06	2	16.03	5.62	0.02	3.89
	Temporal	60.54	6	10.09	3.54	0.03	3.00
2011	Spatial	12.89	2	6.44	7.68	0.0046	3.63
	Temporal	38.98	8	4.87	5.80	0.0014	2.59
2012	Spatial	11.48	2	5.74	3.70	0.048	3.63
	Temporal	69.08	8	8.64	5.60	0.002	2.59
2010- 2012	Spatial	2.94	2	1.47	52.3	0.001	6.94
	Temporal	3.16	2	1.58	56.2	0.001	6.94

Auto Correlation Function

Autocorrelation analysis has been carried out on the mean values of SSCs in different sectors to find out the possibility of persistence in the time series for the period of 2010-2012. The autocorrelation values at Lags 1, 2, and 3 for the southern, central and northern sectors are presented in Table 5.5. It is clear that the magnitude of these correlations, particularly at Lag 1 is weak. This demonstrates confirms that there is no persistence in the time series of the suspended sediment concentration in all the three sectors.

Table 5.5 Sector wise variations of correlation coefficient values in different lags.

Number of lags	Southern sector	Central sector	Northern sector
1	-0.1	0.12	0.38
2	0.03	0.15	0.02
3	-0.08	-0.23	-0.24

5.3 Discussion

5.3.1 Rainfall and its influence

SSCs in the coastal waters, in general, are controlled by several factors such as rainfall, river discharge, and turbidity in the water column. Rainfall during the southwest monsoon shows high variability, both at seasonal and sub-seasonal time scales (Shetye et al., 2007). During

rainfall events, large amounts of sediments erode from the banks, flow into the river, creating a concentrated discharge flow with a high suspended load and bed load concentration. The climatological and hydrodynamical conditions are an important factor for the suspension of sediments in coastal areas (Kosyan, 1985). Perillo and Cuadrado (1990) suggest that the fine SSCs in the coastal waters is not a product of resuspension of bottom sediments, but the influx of river waters, the action of wave-generated turbulence keeps the small particles suspended for a longer time in the water column and a situation which is reflected in higher values of SSC.

Distribution of SSCs in the study area is influenced by southwest monsoon and discharge of streams. Rainfall and river discharge are highly seasonal, suspended sediments are mainly related to river discharge but appears to be due to resuspension of sediments by tidal currents (Narayana et al., 2006). Higher rainfall during June to September (Figure 5.5 and Table 5.6) and subsequent high turbid input from river runoffs mainly contribute to the sediment variability in the study region.

Table 5.6 Monthly variations of rainfall (mm) in three sectors of Kerala during the period 2010-2012 (www.imd.gov.in).

Month	2010			2011			2012		
	Southern sector	Central sector	Northern sector	Southern sector	Central sector	Northern sector	Southern sector	Central sector	Northern sector
January	177	43	72	213	71	11	111	18	1
February	4	NA	14	358	23	53	104	21	24
March	388	92	23	249	85	35	315	106	21
April	904	600	468	965	619	727	1169	1006	547
May	1365	729	709	934	540	368	559	402	243
June	2291	2958	4005	2693	3317	4809	999	1823	3329
July	2073	2578	4151	1599	2218	3690	1252	1507	2155
August	1376	1404	2157	1338	2322	3038	1785	2011	3271
September	1241	1251	1349	1449	1725	2302	784	980	1606
October	2512	1993	1699	881	1034	1127	972	891	738
November	2006	1436	1330	948	655	709	634	475	509
December	567	132	58	714	93	16	86	33	23

The results indicate that higher amount of monthly rainfall corresponds to the high sediment concentrations ($> 30 \text{ mg/l}$) in June 2010 in southern sector; in June and July of 2011 in central sector; and in June and July of 2010 in northern sector which could transport riverine inputs to the coastal and offshore waters (Table 5.7; Figure 5.6). Narayana (2006) studied the relation between the rainfall variability, run-off and sediment discharge of the rivers of Kerala and attributed that higher the rainfall, the larger the sediment to the coastal waters. It can be inferred from these observations that river discharges during monsoon periods influence the suspended sediment load to supply the coast of Kerala.

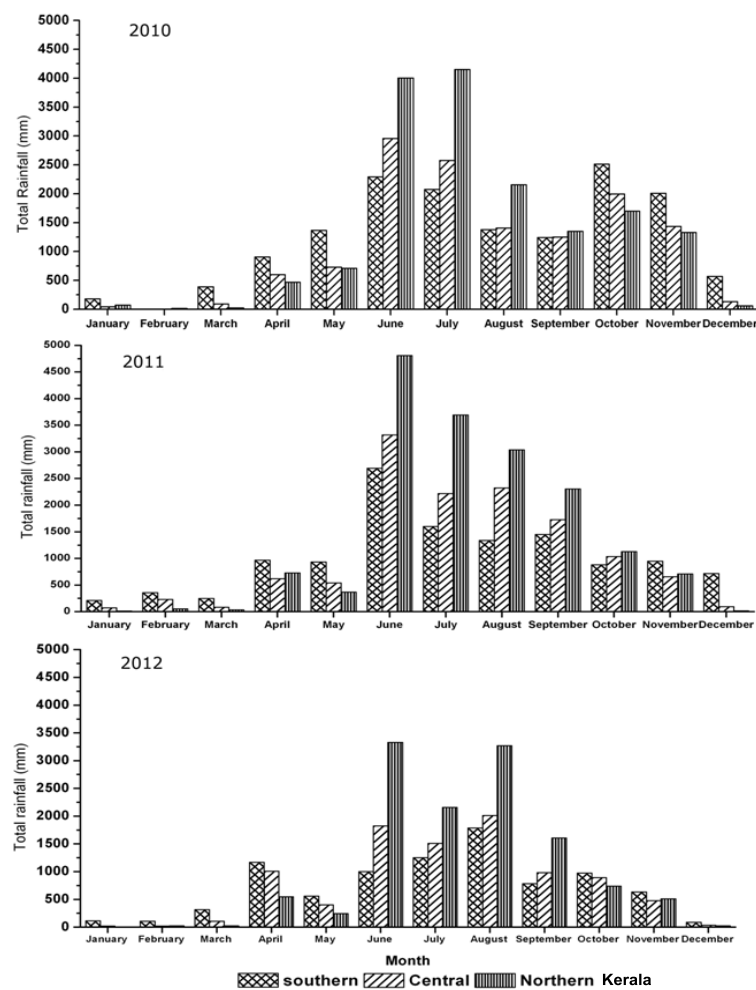


Figure 5.6 Shows the total monthly rainfall (mm) in the study area for the study period of 2010 – 2012. High amount of rainfall was recorded during the month of June 2011 (4809 mm) in central Kerala and low rainfall (4 mm) in February 2010 in southern Kerala.

5.3.2 Influence of river influx

The run-off from continents produces a total riverine discharge of approximately $10^6 \text{ m}^3/\text{s}$ to the oceans globally (Broeker, 1974; Berner and Berner, 1996). Although this is a small number relative to the transport in ocean currents, the density contrast between fresh-and salt waters provides an important driving force for coastal circulation. Milliman and Syvitski (1992) estimated that 10-20 billion metric tons of sediments are transported annually by the world's rivers. The delivery of sediment to the marine environment and the ultimate fate of this sedimentary material are controlled by a sequence of fluvial, estuarine and marine processes.

Riverine outflow into the inner continental shelf may be stratified/well mixed depending on the strength of the outflow relative to the intensity of mixing in the inner shelf. Outflows from shallow receiving waters and strong tide/wind-driven mixing exhibit a well-mixed region of the inner shelf adjacent to the river mouth (Geyer et al., 2004). The Yellow River enters a shallow shelf region at a water depth about of 5m and produces strong tidal currents that fabricate a well-mixed zone (Wright et al., 1995). The Amazon River enters inner shelf zone at 5-10 m deep with tidal currents of 1-2 m/s producing a well-mixed zone that extends approximately 150 km seaward from the river mouth (Geyer and Kineke, 1995). The Atchafalaya outflow enters Louisiana waters and strong winds intermittently produce a well-mixed zone in the shallow inner shelf approximately at a depth of about 5m deep (Allison et al., 1995).

The Rivers of Kerala contribute the sediment load to the coastal sea, particularly during the monsoon period. Periyar River discharges large amount of water (6901 Million Cubic Meter (MCM)) and Vamanapuram discharges the least (675 MCM). Chalakudy (472×10^2 tonnes) and Vamanapuram (624×10^2) Rivers supply minimum sediment load and Bharathapuzha River supplies maximum sediment load (3364×10^2 tonnes) (Table 2.1). The rivers Periyar, Muvattupuzha, Meenachil, Pampa and Achankovil supply about 5757×10^2 tonnes of sediments annually into the coastal sea and this makes the sea more turbid with high SSCs. The total monthly runoff/discharge and total suspended sediment of the different rivers of Kerala for the period 2010-2012 reveal that Periyar, Muvayyupuzha, Bharathapuzha River discharge large amounts of water (~ 179776 MCM, ~ 161794 MCM, ~ 139247 MCM respectively) and Vamanapuram discharge the least (~ 775 MCM) during the study period 2010-2012 (Table 5.7;

Figure 5.7). The SSCs, in general, are high in concentration at river mouths as most of these fine sediments are derived from the hinterland. The OCM images exhibit varied annual distributions of SSCs near the rivers mouths in all the three sectors of the study area (Figure 5.8). Higher amount (40 mg/l) of SSCs is recorded at the rivers mouths off Periyar, Muvattupuzha, Chaliyar, Bharathapuzha and Pamba, whereas the river mouths off Valapatanam, Kadalundi, Chalakudy, Achankovil and Kallada show moderate SSCs (16 mg/l) during the study period (Figure 5. 9).

Hydrodynamic forcing agents such as winds, tidal currents and river discharge play a significant role in determining the SSC distribution (Bian et al., 2013). Higher concentrations of suspended sediments along the coastal waters are mostly controlled by the supply of fine size sediments by the rivers, circulation pattern, bathymetry and coastal configuration (Ridderinkhof et al., 2000; Hans et al., 2012).

The distribution of rainfall, sediment load and run-off from different rivers and their interrelationships studied by Narayana (2006) suggest that the low rainfall years have documented low run-off and sediment discharge from rivers of Kerala. The annual variability of sediment discharge reflects the variable rainfall (Warrick and Milliman, 2003). The positive relationship among rainfall, run-off and sediment discharge suggests that rainfall and run-off exert a first order control on the sediment discharge of Kerala rivers. A good linear relationship was documented between the annual variability of rainfall and sediment transport; and high sediment discharges are recorded in years with high rainfall (Syvitski and Morehead, 1999; Narayana, 2006).

Sediment discharge from different rivers of Kerala such as Payaswani, Valapatanam, Chaliyar, Kadalundi, Bharathapuzha, Chalakudy, Periyar, Muvattupuzha Manimala, Achankovil, Manimala, Pamba, Kallada and Vamanapuram influence the suspended sediments and their concentrations at the river mouths. The SSCs derived from satellite data at these river mouths are recorded and correlated with the daily discharge and total suspended sediment concentrations. The correlation of daily discharge and total suspended sediment of rivers with respect to the satellite SSCs for the study period exhibits a positive correlation ($R=0.386$ and 0.232), particularly a day after satellite pass (Table 5.8).

Table 5.7 Total annual runoff and annual total suspended sediment for the different rivers of southwest coast of India during the period 2010-2012 (CWC, 2012).

Name of the River	Discharge (MCM)			Total Suspended Sediment (mg/l)		
	Year			Year		
	2010	2011	2012	2010	2011	2012
Payaswani	71110.4	83377.04	976	11522	9007	839
Valapatnam	96098.9	122932.5	1998.5	6588	5632	1954
Chaliyar	112633.8	150480.1	NA	6320	5993	NA
Kadalundi	31018.1	44224.3	564.8	5103	6418.7	236
Bharathapuzha	139247.3	165075.0	NA	5224	8791	NA
Periyar	179776.9	179288.2	NA	1339	1061	NA
Muvattupuzha	161794.8	174292.2	35493.3	4869	3785	1318
Kaliyar	35350.5	30845.7	NA	3570	818	NA
Meenachil	57711.0	55087.3	1810.1	2022	2783	412
Manimala	64950.0	54036.5	3477.9	2864	2459	208
Pamba	142622.8	110135.9	5631.9	1838	1321	71
Achankovil	65077.7	29866.6	1665.9	7904	3387	478
Kallada	78064.2	46951.2	8778.2	7074	8450	1989
Vamanapuram	31724.4	14515.3	775.6	7760	3430	155

Table 5.8 Correlation (R) of daily discharge, total suspended sediment load of 14 rivers of Kerala and satellite SSCs.

Day of river discharge and total suspended sediment	River discharge Vs. Satellite SSCs (Sample size = 104)	Total Suspended Sediment Vs. Satellite SSCs (Sample size = 97)
Before day	0.337	0.083
Same day	0.358	0.189
Day 1	0.386	0.232
Day 2	0.362	0.204

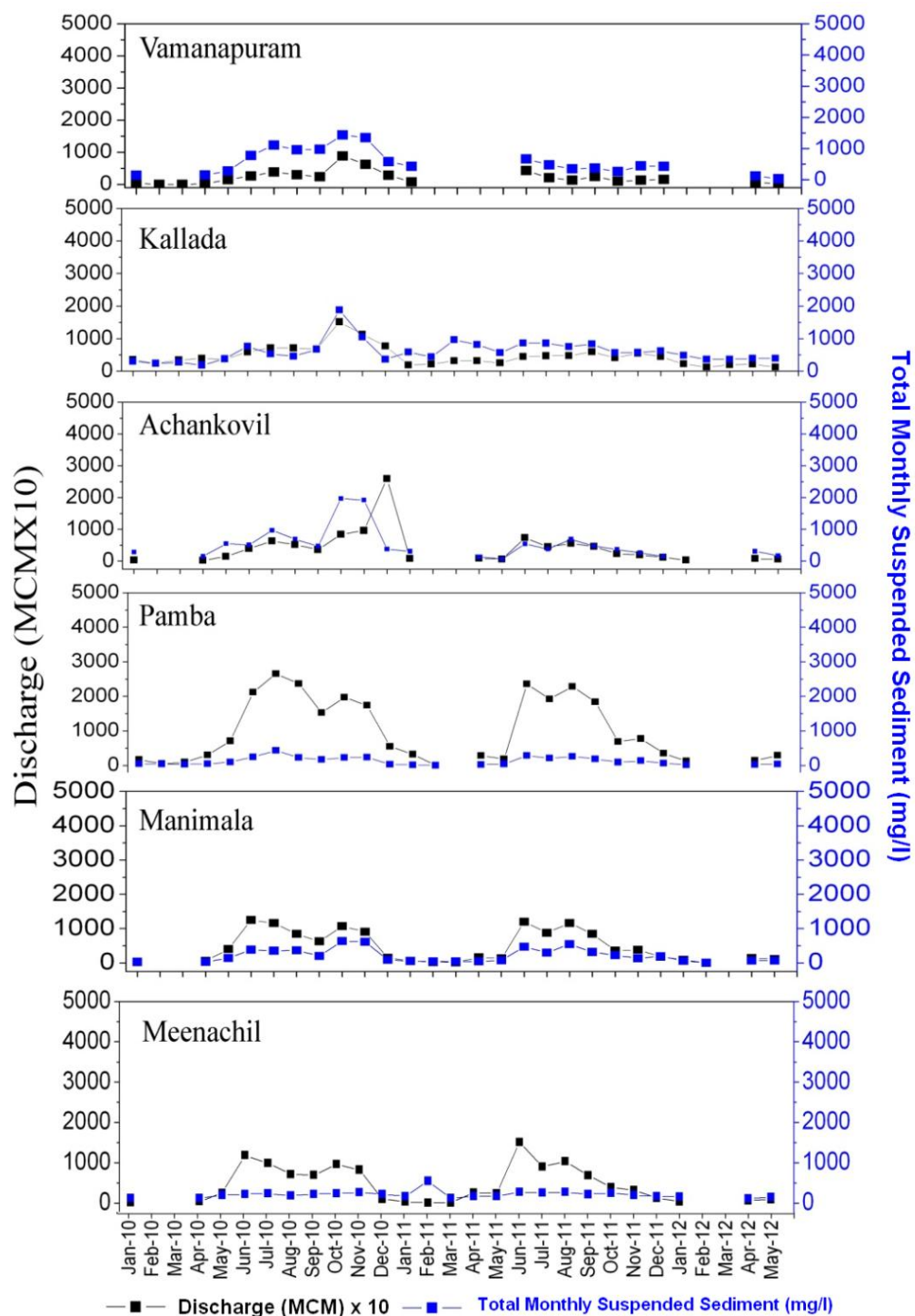


Figure 5.7A Monthly variations of total suspended sediment (mg/l) and discharge (MCM) of different rivers of Kerala (Vamanapuram, Kallada, Achankovil, Pamba, Manimala and Meenachil) for the period 2010-2012.

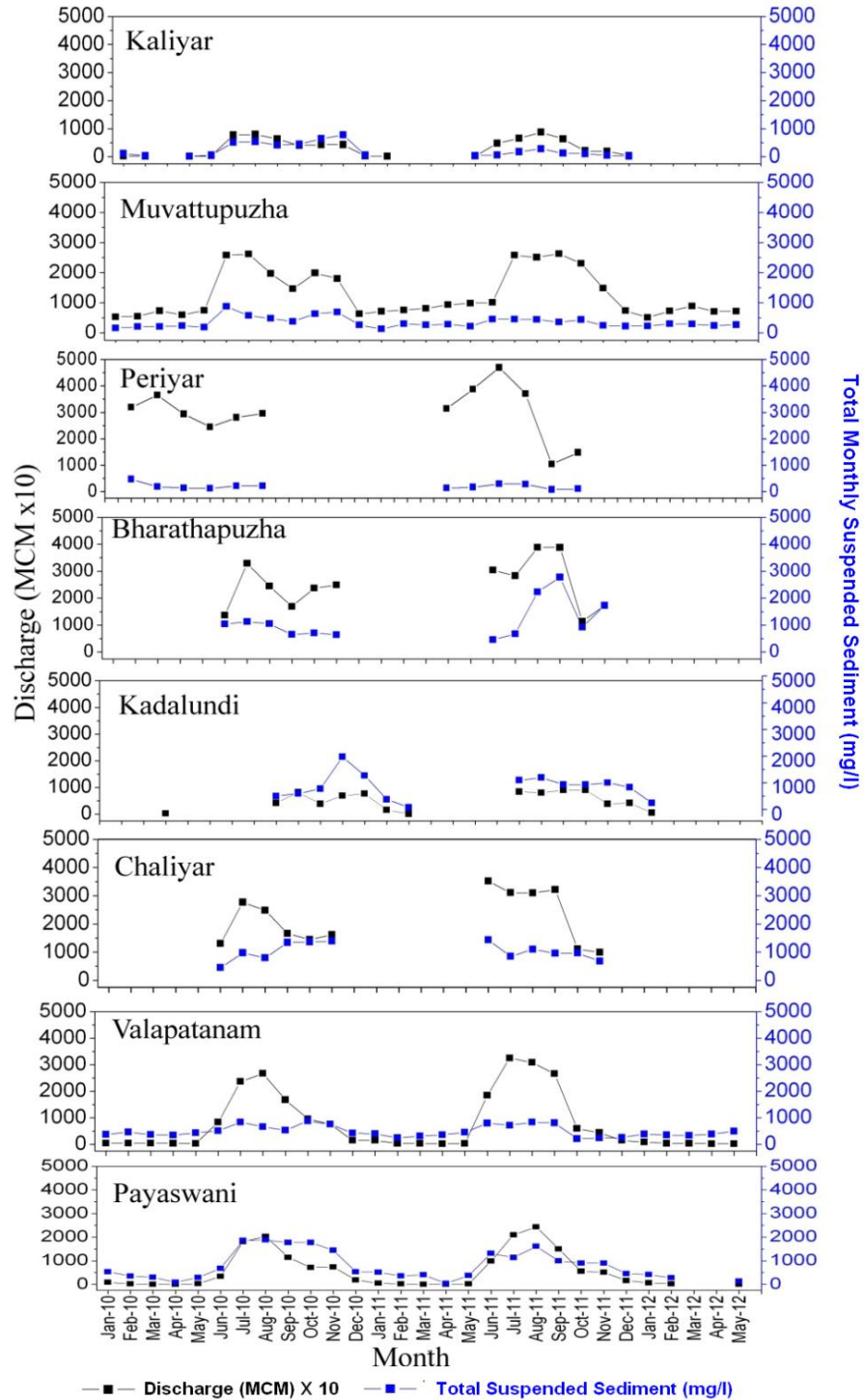


Figure 5.7B Monthly variations of total suspended sediment (mg/l) and discharge (MCM) of different rivers (Kaliyar, Muvattupuzha, Periyar, Bharathapuzha, Kadalundi, Chaliyar, Valapatanam, Payaswani) of Kerala for the period 2010-2012. Muvattupuzha, Periyar, Bharathapuzha, Kadalundi, Chaliyar, Valapatanam, and Payaswani discharge large amount of SSCs to the coastal region of Kerala in June-September (monsoon period).

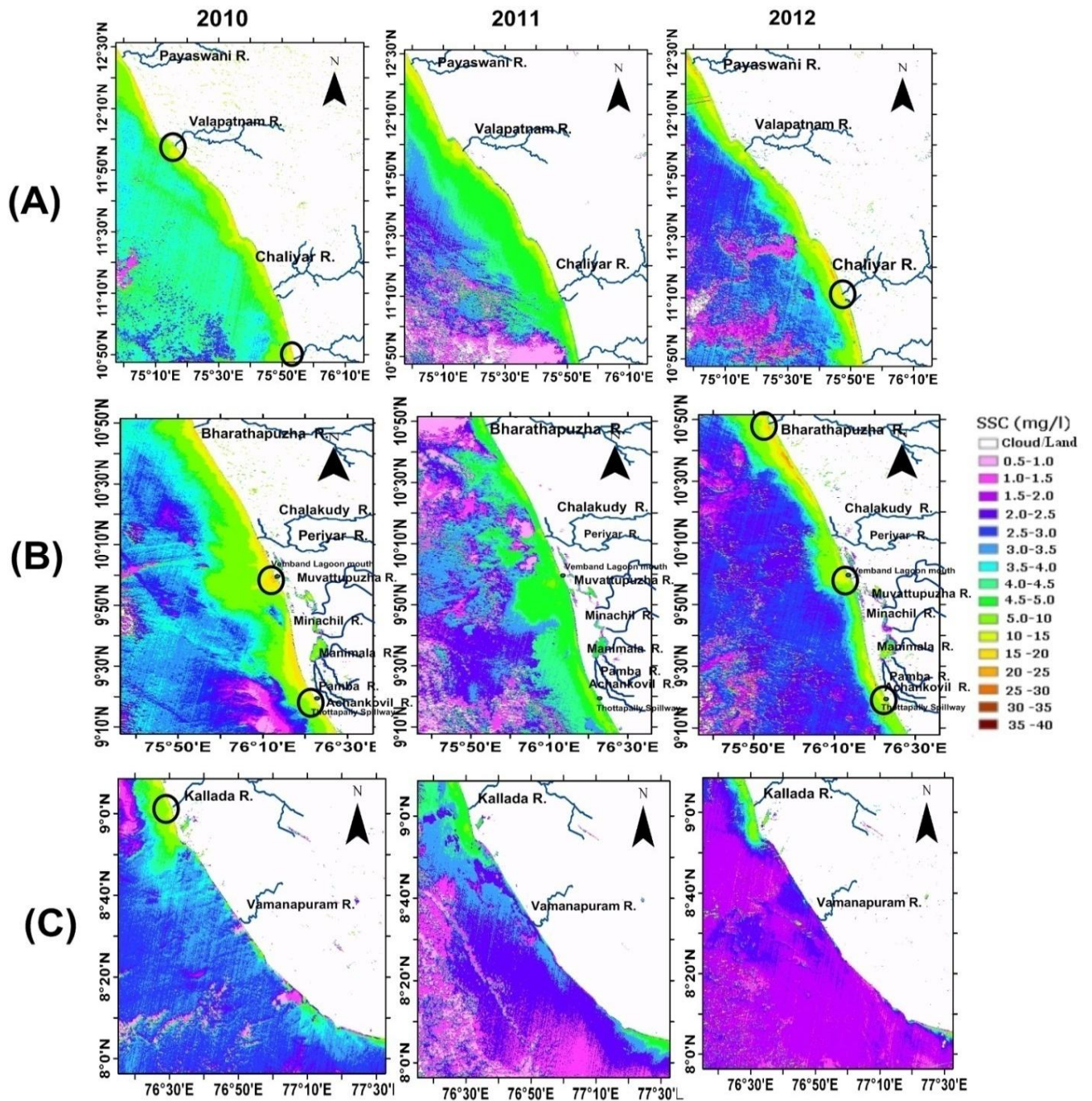


Figure 5.8 The average annual variations of SSCs at river mouths in three sectors (A: northern sector; B: Central sector; C: Southern sector) of Kerala region for the period of 2010 - 2012. Chaliyar, Bharathapuzha, Vemband lagoon mouth recorded moderately high amount of sediments (> 20 mg/l) and Thottapally spillway of central Kerala recorded high amount of sediments during the study period.

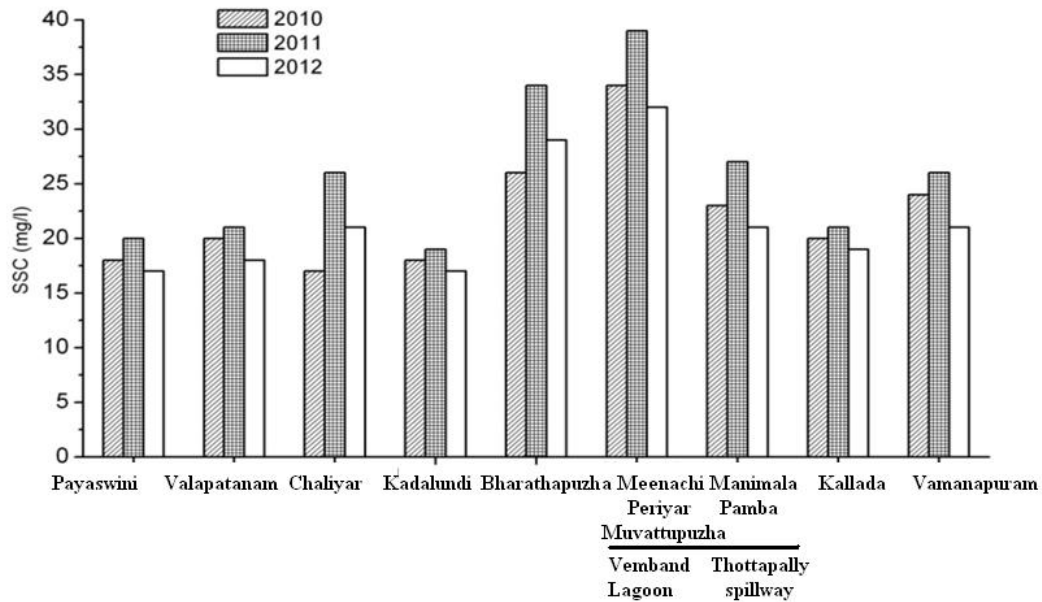


Figure 5.9 Histograms showing SSCs at the river mouths derived from OCM data of the years 2010-2012. Vemband lagoon and Thottapally spillway recorded high amount of SSCs (>25 mg/l) during the study period.

5.3.3 Role of winds in dispersal of suspended sediments

Wind influences the distribution pattern of SSCs in two ways- (i) the bottom shear stress associated with wind waves near the seabed stirs the sediment into the water column in the shallow seas, and (ii) the vertical turbulent mixing induced by surface wave breaking and the vertical shear of the wind-driven currents transport the bottom layer suspended sediment upwards to the sea surface (Lu et al., 2011; Bian et al., 2013). Resuspension of sediments is also induced by shear stress at the sediment-water interface which is considered to be the result of wind and wave action (Bailey et al., 1997). Further, wind-induced waves can reach the bottom boundary layer and seabed leading to the resuspension of sediments in shallow seas, which generally consist of sands with intercalated mud laminae (Eisma, 1981; Eisma and Kalf, 1987; McCandless et al., 2002; Bian et al., 2013).

Intense sediment resuspension occurs within the well-mixed zone due to the influence of the tides or wind-driven currents, and the absence of stratification allows turbid sediment to mix through the water column. Sediment distribution patterns tend to be highly variable in the well-

mixed zone, due to varying of tidal currents, wind-driven motions cause the wave resuspension and riverine outflow (Wright et al., 2001).

In monsoon months (June-September), the strong wind induced vertical mixing of the bottom layer causes the sediment upwards and leads to the high SSCs in the surface layer. However, in summer (April-May), the weak winds induce minimal vertical mixing which is controlled in the upper layer of the ocean. As a result, the bottom sediment cannot be carried to the surface layer and the surface SSC may be the lowest in April and May i.e., in summer (Bian et al., 2013). The Suspended materials are transported to a distance of ~ 15 Km toward the offshore (Figures 5.1-5.3) during the monsoon at the mouth of Vemband lagoon.

Suspended materials spreading into the continental shelf and mixing with the ambient shelf water due to strong northwest wind in winter in the coastal waters of the Eastern seaside of Hokkaido Island has been observed by Lihan et al. (2008). Suspension of sediments in shallow water by wind waves is the most valid explanation for these elevated levels of surface suspended material (Hetland, 2005; Walker et al., 2005; Warricka, 2010; Kelderman et al., 2012). The distribution patterns of SSCs in the Yangtze River estuary is mainly affected by the combined effects of tides, bathymetry, wind speed, runoff and sediment running out from river mouth (Han et al., 2006). The lateral structure of wind-driven flows in a stratified water column is observed in the bay of Gulf of California (Winant et al., 2014).

Close observations of dispersal of SSCs in satellite images indicate that the littoral drift is from north to south during the southwest monsoon, while it is from south to north during the northeast monsoon. Similar observations have been made by several researchers (Chandramohan and Nayak, 1996; Sanjeev et al., 1997; Narayana et al., 2001; Kunte et al., 2003; Jayappa et al., 2003; Rajawat et al., 2005; Kumar et al., 2011). Chandramohan et al. (1992) studied the longshore current and sediment transport along the southwest coast of India and opine that the sediment transport was southward from August to May and northward during the rest of the year. Although bathymetry can also influence the distribution of SSCs, its role in the study region may not be significant as the bathymetry is homogeneous up to 50 m depth contour, except that the seafloor is wider and gentler at 10 m depth contour, particularly between 9° and 10° N latitudes (Figure 2.1).

The distribution patterns of SSCs are compared with the wind speed and direction along the Kerala coast for the study period. The wind data are derived from advanced scatterometer (ASCAT) (<http://apdrc.soest.hawaii.edu/datadoc/ascats.php>) with a resolution of 25x25 km resolution and seen in figures 5.10-5.12. The wind speeds varied from 0.5-12 m/s during the study period.

From the figure 5.10, it was observed that the direction of wind is northerly irrespective of the season. In January, wind speed near the coast was in the range of 6-7 m/s in the region of latitude 8°30' N to 10°30' N except in the northern region and direction is northeasterly. In February, the winds in the range of 4-5 m/s observed in the southern region where low wind speed was observed in central and northern region. Here, in February, the wind direction all along the coast northerly. In the inter monsoon period of March, the wind speed, except near the southern tip, was less than the 2 m/s. The wind direction is northwesterly along the coast and northerly direction in the offshore region.

By April, the entire region was prevailed by northwesterly winds though the strength was high (3-7 m/s) except the northern tip of the study region. The wind speed is high during the June and July compared to other months in 2010. This implies that the region was dominated by only summer monsoon winds and there is a feeble impact of winter monsoon. By June, southwest monsoon regime was set over the entire region and a significant rise in wind speed (5-9 m/s) was observed and ~ 8m/s in the eastern side of the study area. Low wind (< 2 m/s) pocket observed during June spread towards the offshore region in the southern region. The wind direction is predominately northwesterly along study area (Figure 5.10). During July, which is a peak monsoon time, the wind speed spreads were greater than 7m/s in the study area and low wind curve was observed across the coast in the latitude of 10° 30' N to 11° 30' N. These scatterometer winds are in conformation with other observed/reanalyzed wind products such as the daily NMC reanalysis for the period, which are shown for 2 June and July, for example, in the Appendix-4. In the final stage of northeast monsoon, during December, the wind speed was observed < 4 m/s with a strong low wind region in the southern tip of region and central region of 10° 30'N to 11° 30' N.

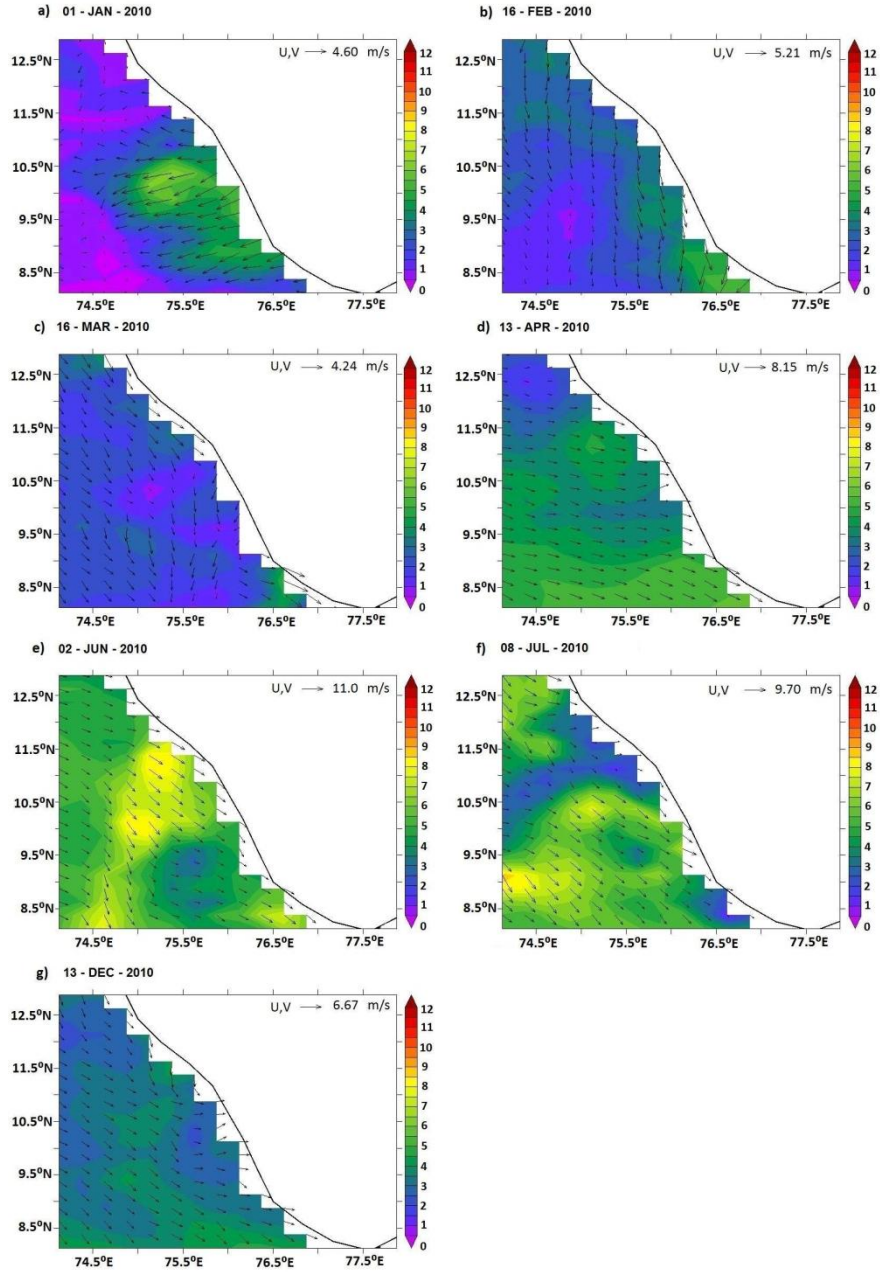


Figure 5. 10 Shows the wind speed and direction derived from advanced scatterometer (ASCAT) along the coastal waters of Kerala for the year 2010 (Note: The wind speed and direction maps are the same dates of the OCM images).

From the figure 5.11, it is observed that in January 2011, the wind speed is 4-5 m/s occupied by the two third of the coast and direction is northeasterly. In February, the wind speed is increased slightly with a range of 3-5 m/s all along the coast and wind direction is northwesterly. In the march, the wind speed is decreased to < 3 m/s except in the central region and direction is northwesterly. By April, the wind speed is slightly higher in the range of 3-5 m/s all along the coast follows northwesterly direction. During the May, the low wind speed was observed all over the coast except in the northern tip of study area, while to the south, it was perfectly westerly direction (zonal component). During the receding phase of southwest monsoon, in September, the wind direction was completely northwest and speeds all over the region were 5-7 m/s except in the northern tip of study region. By October i.e., during the inter monsoon period of October, the wind speed reduced to 5 m/s all over the region and direction is northwesterly. By November, the wind speed is very low < 3 m/s was observed along the coast, indicated northeast in the central region and completely northerly in the offshore. In December, the wind speeds were increased to 5 m/s in the offshore and the two low wind regions < 3 m/s were observed and is extended towards the coast (Figure 5.11).

In the year 2012, it is observed that the high wind plume was observed in the central region with a high wind speeds (> 7 m/s) and is extended to offshore region in northeasterly direction in January. Low wind speed < 3 m/s in the southern and northern tip with north westerly wind direction along the coast is observed. In February, the wind speed is increased to 3 to 5 m/s in offshore region and direction is northwesterly along the coast and completely northerly in offshore region. By April, the wind speed is reduced to very low < 2 m/s all along the coast. By May, the wind speed is > 7 m/s all over the coast and prominently dominated by the northwesterly direction winds. By June, which is the monsoon time, the wind speed was > 6 m/s all over the region. High wind (> 9 m/s) pocket was observed in the southern region (75° to $76^{\circ} 30' E$). By September, the wind speed is reduced very low < 3 m/s except in the northern tip of study region and direction is northwesterly. By October, the wind speed is high in the northern part of region and direction is southwest. In southern region, the wind speed was 2-3 m/s and prominently in the zonal direction. By November, the low speed pocket of wind is observed in the central region moving in northwesterly direction along the coast and northerly in offshore. In December, high wind pocket was observed in the central region following the northeasterly

direction. A low wind speed (< 2 m/s) is observed in the southern region and direction is northeasterly in December 2012 (Figure 5.12).

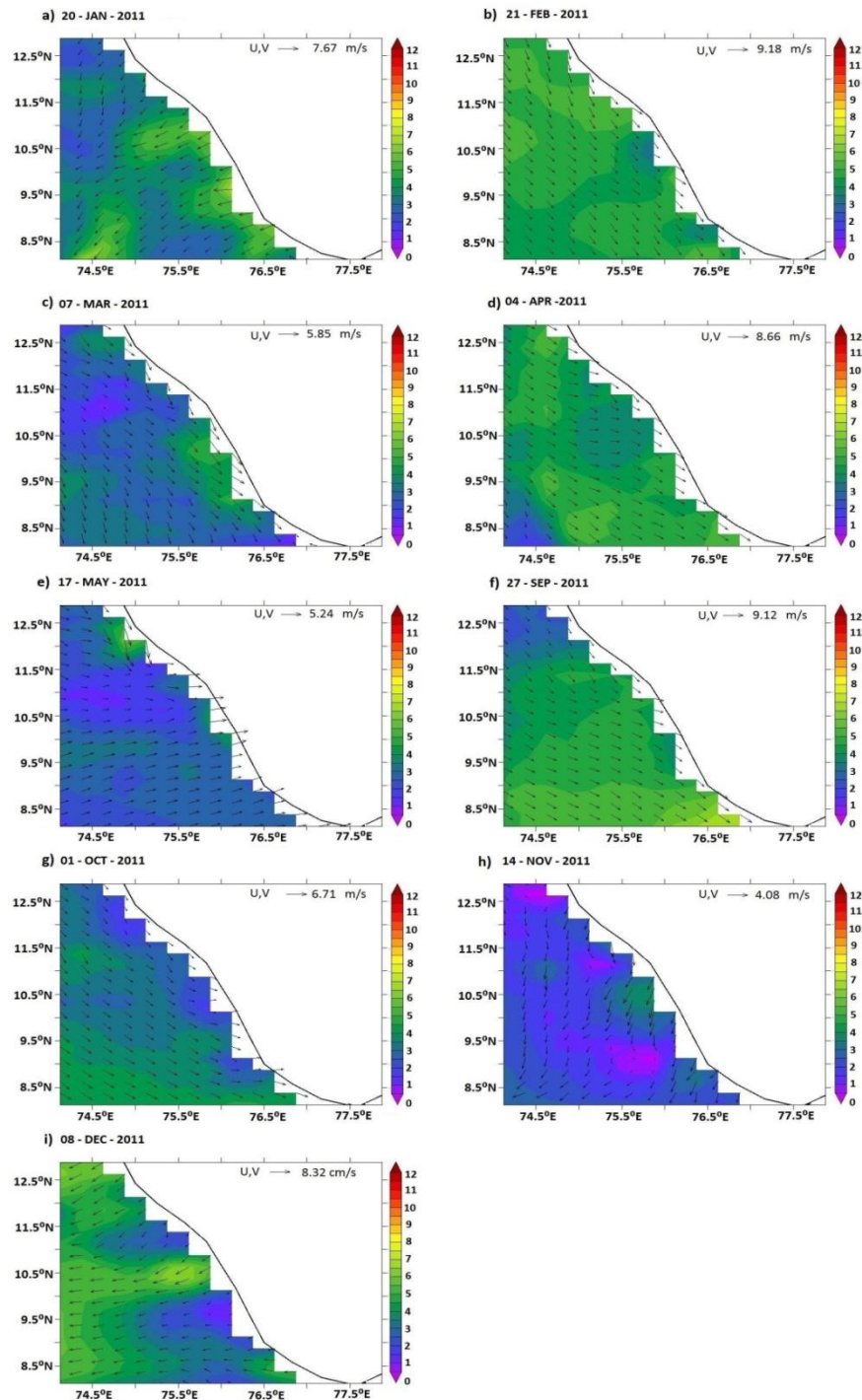


Figure 5. 11 Shows the wind speed and direction derived from advanced scatterometer (ASCAT) along the coastal waters of Kerala for the year 2011 (Note: The wind speed and direction maps are the same dates of the OCM images).

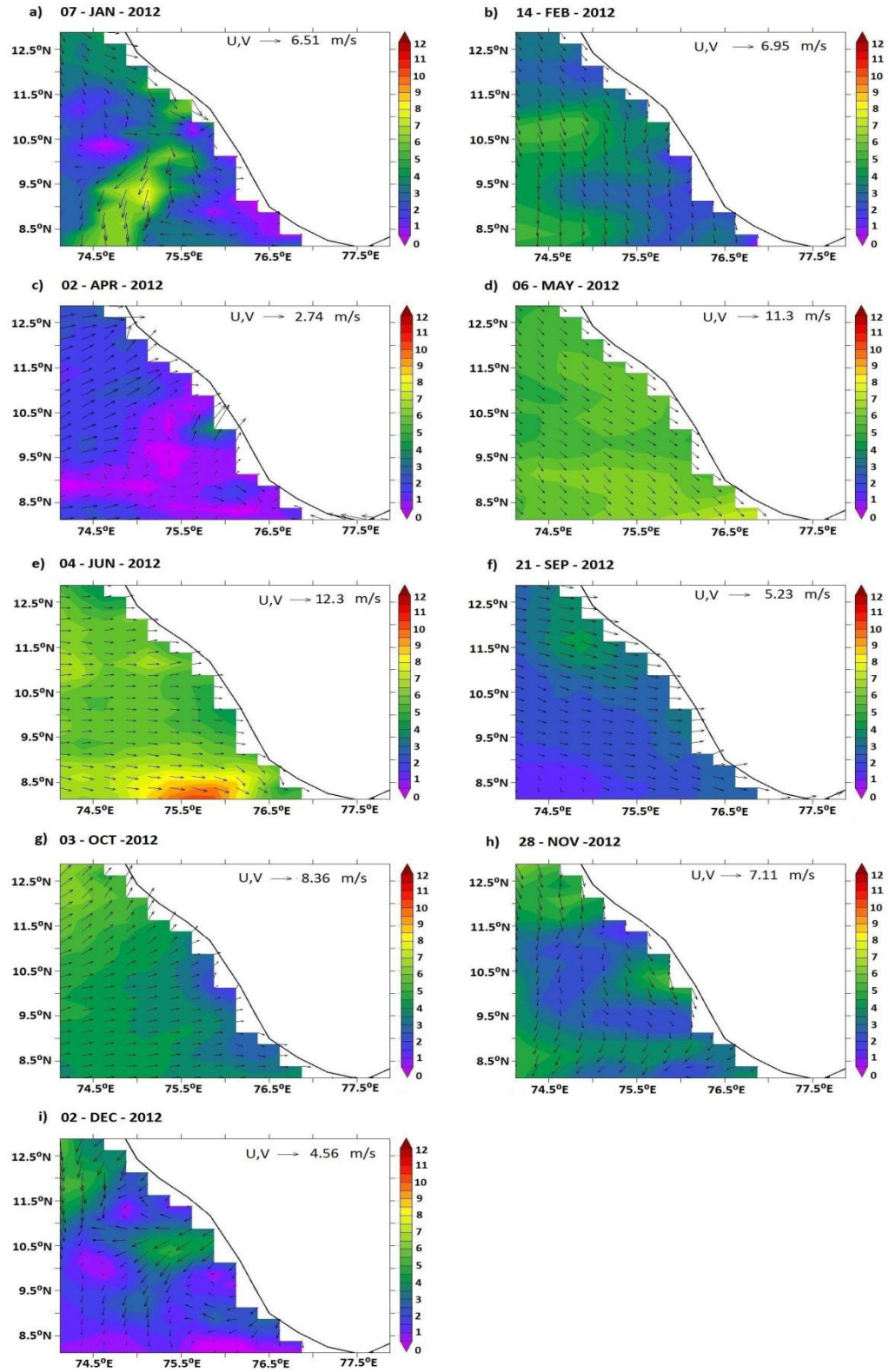


Figure 5.12 Shows the wind speed and direction derived from advanced scatterometer (ASCAT) along the coastal waters of Kerala for the year 2012 (Note: The wind speed and direction maps are the same dates of the OCM images).

The distribution of SSCs is observed from the overlaid maps of SSCs and wind direction maps for the study period 2010-2012 (Figures 5.13-15). The wind direction is northwesterly along the coast during the February, March, April, June, July and December of 2010, except in January 2010 where wind direction is northeasterly. In year 2011, the direction of wind is northwesterly from February, March, April, May, September, October and in January, November and December of 2011, direction of wind is northeasterly. The direction of wind is northwesterly in February, March, June, September except in January, October and December of 2012 and the direction of wind is northeasterly whereas in November the direction is northerly. In the monsoon season, movement of the fine sediments is towards the southward direction as observed from the increasing concentration of SSCs coinciding with the wind direction.

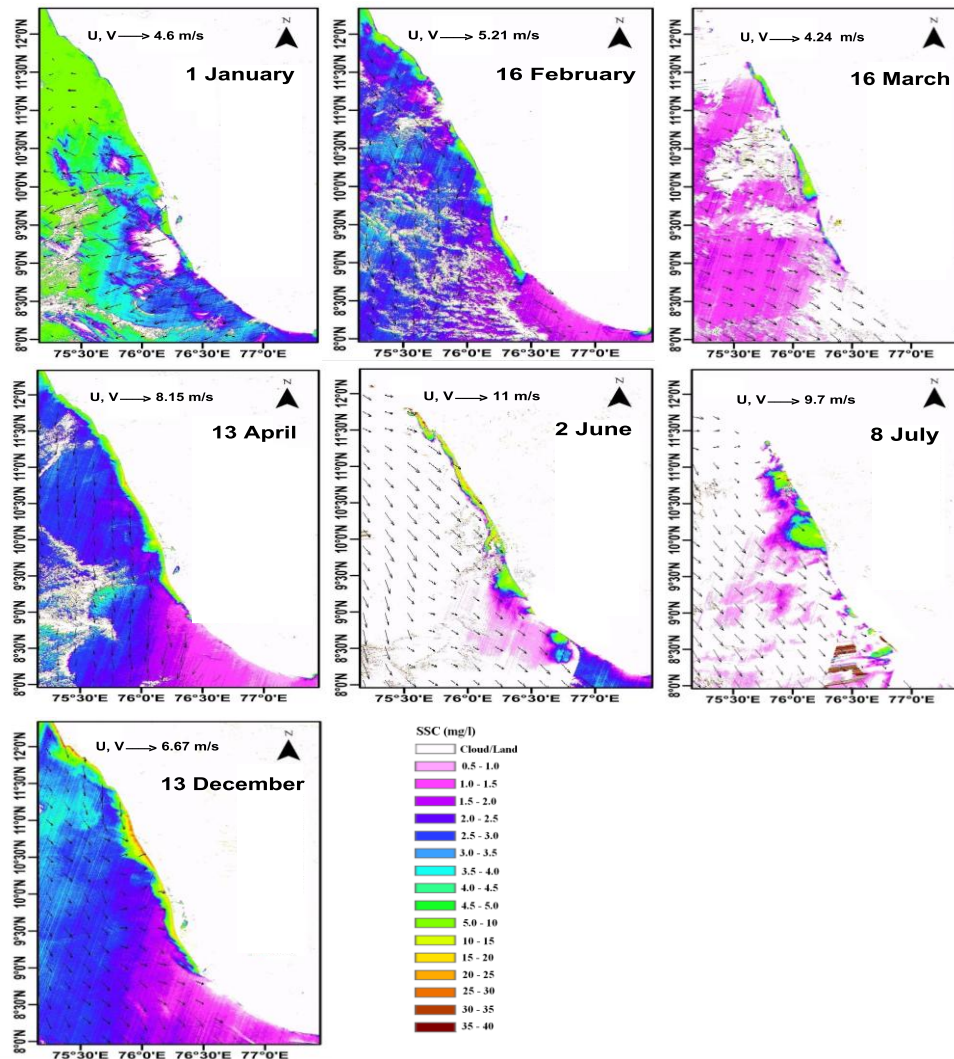


Figure 5.13 Map showing the overlay of wind direction and SSCs along the coastal waters of Kerala in different months of the year 2010.

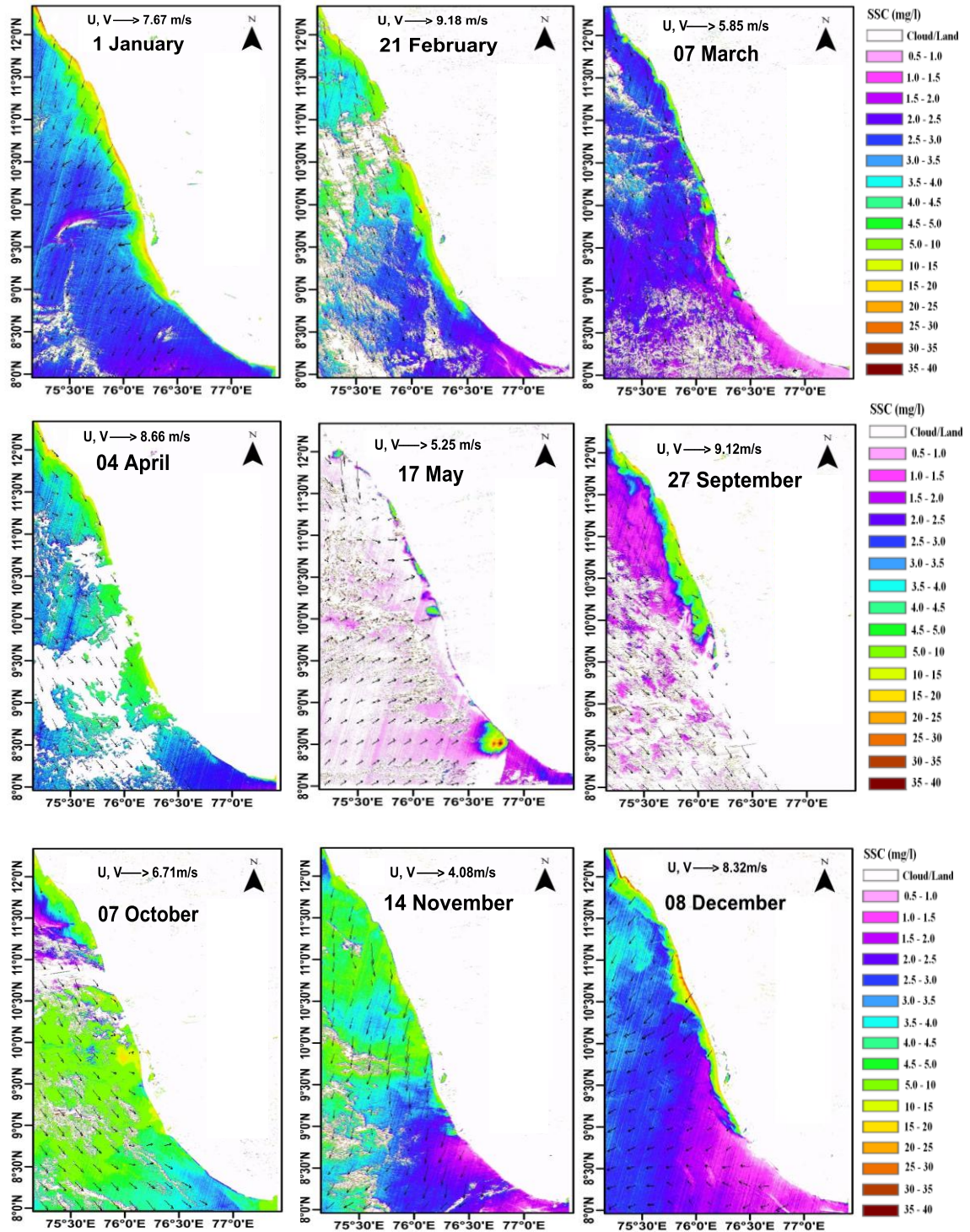


Figure 5.14 Map showing the overlay of wind direction and SSCs along the coastal waters of Kerala in different months of the year 2011.

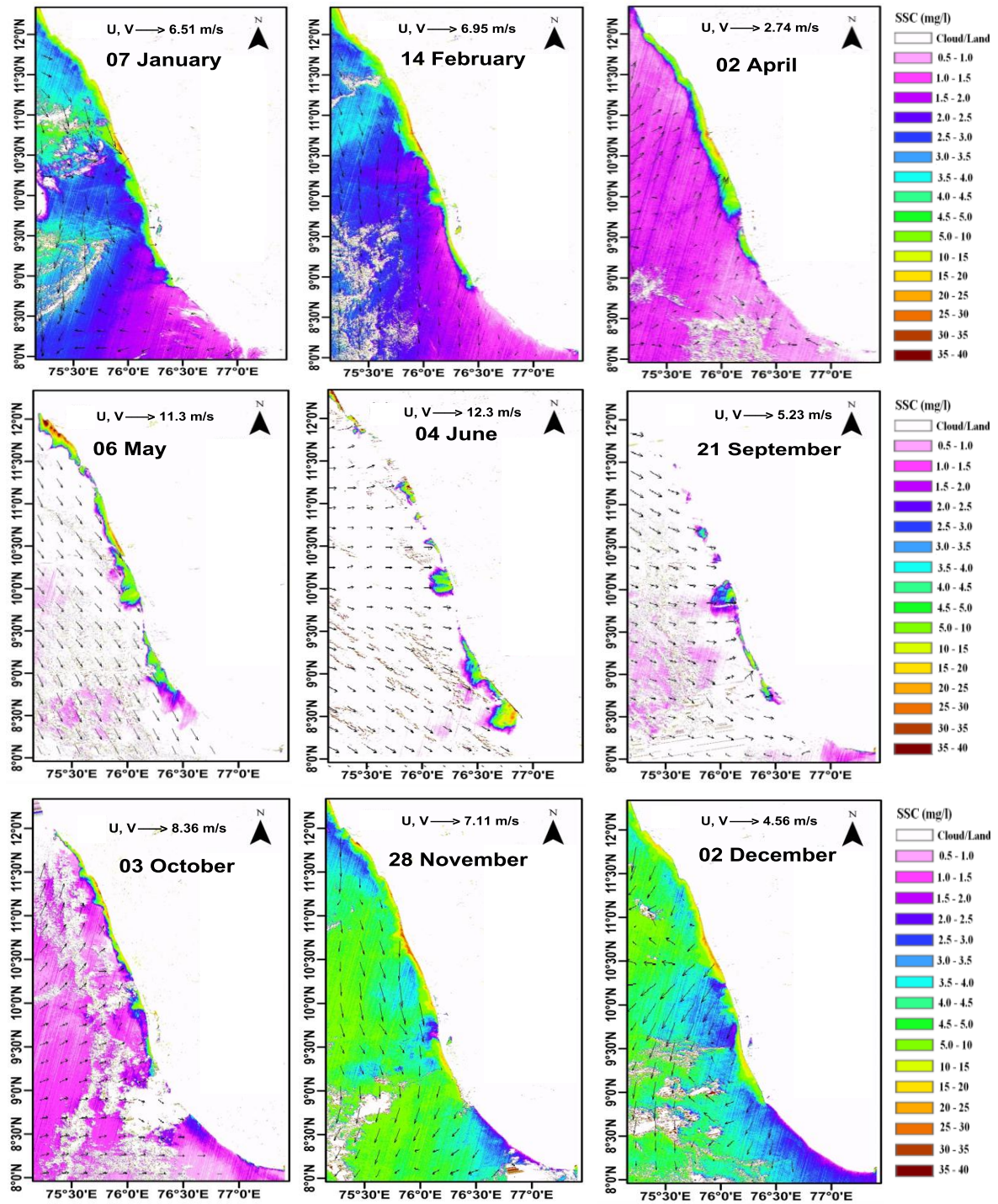


Figure 5. 15 Map showing the overlay of wind direction and SSCs along the coastal waters of Kerala in different months of the year 2012.

5.4 Summary

OCM data were analyzed for spatial and temporal variations of SSCs and their distribution patterns were studied along the Kerala coast. An attempt has been made to understand the dispersal patterns of SSCs in relation to rainfall, river discharge and wind forcing. The results show that the high (> 30 mg/l) SSCs was recorded in central Kerala; northern Kerala and moderate SSCs recorded in southern Kerala during the study period. Southern sector recorded high (> 30 mg/l) amount of SSCs in June 2010; in February, March, September, October of 2011; and in May, September, December of 2012. In January, February, March, June and July of 2010; in February, March, May, September, October, November of 2011; and in January, May, July, September, October, November and December of 2012 the high SSCs (> 30 mg/l) were recorded in the central sector. In the northern sector, high (> 30 mg/l) SSCs are recorded in the mouths of February, June and July of 2010; in February, March, September, October, November, December of 2011; and in January, February, May, July, September, October, November of 2012. High values of coefficient of variation (79.25) are recorded in southern sector in October 2011 and July 2012; while in central sector in the months of April, September, October November and December of 2011; and in northern sector high CVs are noted in July 2012. These high values may be due to turbulence, caused by monsoon activity, which drifts the bed material into suspension and also may be due to large amount of sediment received from the rivers through Vemband lagoon.

The variability of SSCs in three sectors significantly exhibit different mean values of SSCs derived from the ANOVA analysis at 95 % level of confidence ($p < 0.05$) both through space and time.

Higher amount (40 mg/l) of SSCs is recorded at the rivers mouths off Periyar, Muvattupuzha, Chaliyar, Bharathapuzha and Pamba and moderate SSCs (16 mg/l) are recorded at the river mouths off Valapatnam, Kadalundi, Chalakudy, Achankovil and Kallada. Higher rainfall during June to September during the study and subsequent high turbid input from river runoffs mainly contribute to the sediment variability in the study region. The results indicate that higher amount of total monthly rainfall (> 2500 mm) corresponds to the high sediment concentrations (> 30 mg/l) in June 2010 in southern sector; in June and July of 2011 in central

sector; and in June and July of 2010 in northern sector which could transport riverine inputs to the coastal and offshore waters. The rainfall variability, run-off and sediment discharge of the rivers of Kerala and attributed that higher the rainfall, the larger the sediment to the coastal waters. It can be inferred from these observations that river discharges during monsoon periods influence the suspended sediment load to the coast of Kerala. The Rivers of Kerala contribute the sediment load to the coastal sea, particularly during the monsoon period. Periyar River discharges large amount of water and Vamanapuram discharges the least.

The suspensions of fine sediments triggered by the wind driven circulation is observed for the distribution and dispersal patterns of SSCs. The wind speed varied from 0.5 to 12 m/s during the study period. The wind speeds are high (> 7 m/s) during monsoon months, especially June, July in 2010; September 2011; June 2012 and direction is prominently northerly in 2010 and northwesterly in 2011 and 2012. In the non-monsoon period, the wind intensity is decreased and direction is northeasterly. In the months from June to September the strong wind (>7 m/s) induced vertical mixing of the sediment from the bottom layer upward leading to the high SSCs in the surface layer. However, in December-May, the weak winds are in the range of 3-5 m/s and induced vertical mixing was restricted in the upper layer of the ocean due to the existence of the clines. As a result, the bottom sediment could not be carried to the surface layer, hence low SSCs are recorded in the surface waters April and May. The wind direction is northwesterly along the coast during the February, March, April, June, July and December of 2010 except in January of 2010 direction is northeasterly. In year 2011, the direction of wind is northwesterly from February, March, April, May, September, October, and in January, November and December of 2011 the wind direction is northeasterly. The direction of wind is northwesterly in February, March, June, and September; in January, October and December of 2012 the direction is northeasterly whereas in November of 2012 the direction is northerly. Particularly, in the monsoon season, movement of the fine sediments is towards the south direction during the study period. Wind generated waves might be the most important forcing agents for sediment resuspension in the coastal areas during monsoon period. The SSCs distribution pattern is mainly influenced by southwest monsoon rains followed by stream discharges.

Chapter 6

Suspended Sediment Transport: MIKE 21 Model

Chapter 6

Suspended Sediment Transport: MIKE 21 Model

6.1 Introduction

The coastal zone undergoes continuous changes due to natural processes and land-ocean interaction processes. The importance of the coastal zone, with respect to safety, ecology, economy and recreation, demands a management strategy in which each of these aspects is taken into account. The hydrodynamic and transport processes in the coastal waters and the estuaries are very complex due to the presence of irregular coastlines, islands, shoals, channels and some man-made structures, the mixture of fresh water and saline water, and the concurrent factors of river discharge, tides, winds, waves and offshore currents. Monitoring and understanding the sediment dynamics and suspended sediment transport is an important issue for coastal engineering related activities. A study of the transport mechanism of suspended sediments in the marine environment is essential not only for the safeguard of marine installations or navigational channels, and also for the coastal structure design, environmental protection and disaster reduction. Such studies also help in assessment of pollutants and other biological activities in the region. An accurate description of the sediment transport, caused by waves and tidal or wave – induces currents, is of great importance in predicting coastal morphological changes. Numerous numerical models were developed to simulate the processes of currents, waves, salinity and sediments in the coastal waters and estuarine areas (Backhaus, 1983; Blumberg and Mellor, 1987; Chen et al., 2003; Carniello et al., 2012), POM (Blumberg and Mellor, 1987) and its commercial version ECOM-si (Blumberg, 1994), and FVCOM (Chen et al., 2003) for estuarine circulations; ECOMSED (Blumberg, 2002) for sediment transports; SWAN (Booij et al., 1996) for nearshore wave transformations; and some model systems, ROMS (Shchepetkin and McWilliams, 2005), MIKE 3 by DHI Water and Environment, and Delft 3D by WL|Delft Hydraulics, for comprehensive simulations as these models help in predicting coastal morphological variations and sediment dynamics.

Wu et al. (2000) studied 2D numerical model for the circulation patterns and sediment transport in the open channels from a coupled hydrodynamics/sediment transport model which includes the waves and currents (Lou and Ridd, 1997). Various studies a numerical modelling has been carried out in the past twenty years on the circulations patterns (Larsen et al., 1985; Chen et al., 2007) and transports (Sternberg et al., 1985) in the coastal waters for the better understanding of the coastal environments, two-dimensional horizontal (2DH) models were widely used to simulation of waves, tides, currents, salinities and sediment transport (Dou et al., 1999; Hu et al., 2009). 2DH calculation has an advantage for increase computational speed or time, especially in some cases where a rapid prediction is required. In their 2DH model, the water level is determined from a 2D Poisson equation derivative of depth-averaged momentum equations. Suspended sediment transport is simulated through the general advection-diffusion equation with an empirical settling velocity term. 2D depth-averaged models is used for the simulation of the tidal currents and SSCs in the Tamar estuary located in the south west coast of England studied by Tattersall et al. (2003). Gleizon et al. (2003) developed a model for vertically resolving sediments in estuaries to simulate water, sediment, and sediment-bound contaminant transport in vertically stratified and relatively narrow micro tidal Ribble estuary. In order to consider the hydrodynamic and transport processes more realistic and more accurate, 3D models should be set up since the real phenomena is 3D. Various functional 3D models have been developed to determine the currents and salinities (Zheng et al., 2002), which can reflect vertical variations in the water column.

Coastal currents are affected by wind-driven, tidal, surface wave and geostrophic flows. As the distance from the coast increases, the currents are subjective to large scale near surface flow in the open sea. The contributions depend on the geostrophic location, continental slope and the coastal orientation. Circulation patterns along the west coast of India are studying mostly through analyzing the physical and chemical properties of sea water (Shetye et al., 1990). Various researchers (Unnikrishnan and Antony, 1990; Anil Kumar et al., 2002; Dinesh Kumar and Srinivas, 2007; Shetye et al., 2008) studied the coastal currents off west coast of India in detail from current measurements. A number of numerical studies carried out for the Indian coast emphasized the importance of local and remote forcing for the circulation in the Arabian Sea

(Shankar and Shetye, 1997; Shenoi et al., 2004). Examination of the mechanisms forcing the seasonally reversing, trans-basin monsoon currents in the open ocean is presented in detail by Shankar et al. (2002). These authors state that western India coastal current was driven by local winds only at periods less than ~ 10 days, with remote forcing contributing at longer periods. Spatial and temporal changes in surface topography in coastal region is a response to the balance of pressure gradient forces with combined effects of irregular bathymetry, varying bed resistance, wave effects and fresh water discharge (David et al., 1993; Shetye et al., 2008).

The numerical simulation of sediment transport is achieved by hydrodynamic-transport coupled model system. The simulation of sediment transport models is based on the field observations and the measurements, which are used in validating the transport model (Dou et al., 1999; Douillet et al., 2001; Liang et al., 2007; Ulses et al., 2008). Quillon and Caussade (1991) utilized the satellite data in modeling of sediment transport with the coupled *in situ* measurements for the lagoon waters of New Caledonia.

Conventional methods of monitoring of SSCs through *in situ* measurements are difficult, expensive and are point observations, whereas remote sensing-based data provide large area coverage and provide repetitive observations which are more reliable and quick to obtain. Satellite derived SSC data obtained from IRS Oceansat - 2 OCM have been found to be useful for Indian coasts because of its high spatial (360 m) and spectral resolution, and good temporal resolution. The initial distribution of sediment concentrations is of critical importance for sediment transport modelling (Lee et al., 2007). Often, the initial concentrations are assumed to be constant for the entire model domain or uses field observations which are rather scattered point observations.

A two-dimensional hydrodynamic model (HD) MIKE 21 is an advanced numerical model for modeling hydrodynamics, waves, sediment transport and ecological aspects. This model has been extensively used in the simulation of hydrodynamics, water quality, wave dynamics and related processes in coastal areas (Chubarenko et al., 2001), tide driven currents and residual eddies in the Gulf of Kachch (Babu et al., 2005). The estimation of dissolved oxygen, biochemical oxygen demand off Kochi is studied by Babu et al. (2006), oil spill

movement along the Goa coast by Vethamony et al. (2007). The present study utilizes the sediment concentration values derived from OCM data onboard Oceansat-2 as initial sediment concentrations in a numerical model to simulate its transport under the hydrodynamics that prevail in the coastal waters off Kerala. SSCs derived from OCM using the regional algorithm (details of the algorithm have been discussed in the Chapter 4) for the study period of 18th to 24th January 2011.

6.2 Model setting and methods

Simulation of tides and currents has been carried out by solving the 2D shallow water equations of mass and momentum from the HD model of MIKE 21. To solve 2D shallow water equations using finite difference numerical methods, structured numerical grids were used to define the bathymetry of the study area.

The domain selected is the central Kerala that lies between the latitude of 9° to 10° 10' N and longitude of 75° to 76° 20' E. Available hydrographic chart of the National Hydrographic Office (NHO) is used to infer the bathymetry area shown in Figure. 6. 1. The model domain is bounded with 130 x 140 grid points along the x and y directions and the resolution of bathymetry is chosen as that of the spatial resolution of OCM, which is 360 m. The Eastern boundary of the domain is open, particularly at the river mouths where the depth is < 5 m. The western boundary is taken along, where the depth values are 50 m, at a distance about 35 km across the coast. Alignment of bathymetry in the domain follows northwest – southeast direction. There are five open boundaries: west, north, south and two on the eastern side. The tidal levels with appropriate phase lag and cross flow conditions at the boundaries are used to simulate prevailing flow. The surface tidal elevations were generated at the boundaries - northern boundary (10° 30' N and 75° 30' E), southern boundary (9° 30' N and 75° 30' E), southeastern boundary (9° 30' N and 76° 30' E), and northeastern boundary (10° 30' N and 76° E).

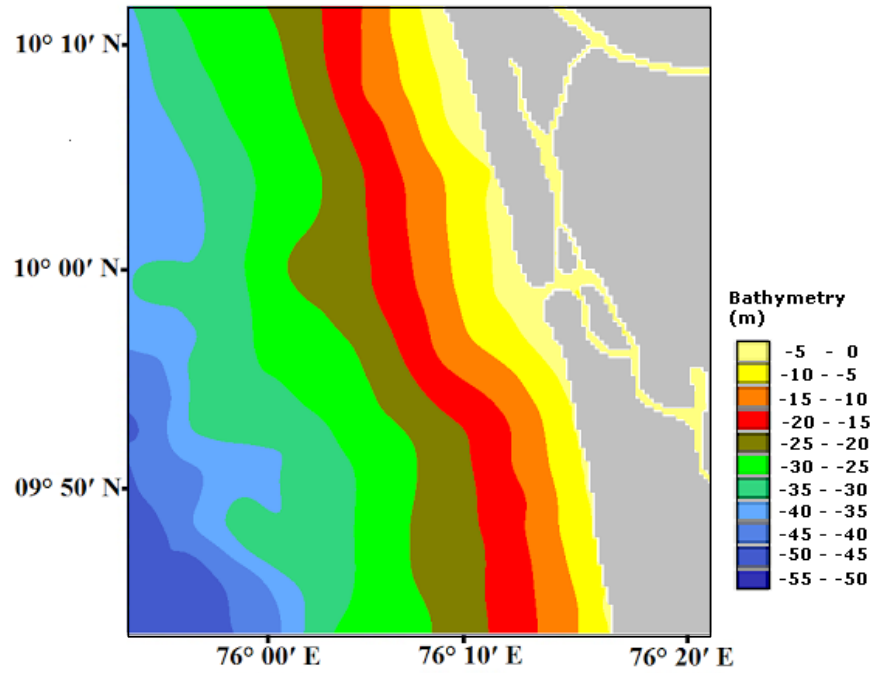


Figure 6. 1 Model domain and the bathymetry of the central Kerala, southwest coast of India.

The tidal levels are generated at these boundaries using a global Finite Element Solution (FES) prediction of tides. The FES tides are results of hydrodynamic model which are assimilated with tide gauge records and the altimetric TOPEX/Poseidon analyses. The FES tidal levels are predicted from the eight major tidal constituents which are M2, S2, N2, K2, 2N2, K1, O1, and Q1. The tide elevations of these stations were obtained from the linear interpolation method to attain the water level for boundaries, and these were used for forcing the HD model. The tide height at the western boundary is interpolated between the values of north and south water levels, whereas the eastern boundaries of tidal heights at the river mouth are from the simulated tidal heights. The daily wind data obtained from ECMWF model are used for the HD model. The quality of the blended winds has been checked by comprising them with buoy winds and the comparison has produced good results (Bentamy et al., 2007). In the present study, the winds of ECMWF are used for this study period and average wind speed is 6.1 m/s and direction of wind is predominantly in northwestern direction. The simulation of HD and MT are carried out for January 18th – 24th of 2011 to study the sediment transport along the coastal waters of

central Kerala. The calibration coefficients in the HD model are wind friction factor (0.0026), manning's number ($32 \text{ m}^{1/3} \text{ s}^{-1}$), and horizontal eddy viscosity ($0.5 \text{ m}^2 \text{ s}^{-1}$).

6.2.1 Simulation of tidal currents

Simulation of currents along the coastal waters of central Kerala for the study period is analyzed from HD module of MIKE-21, developed by the Danish Hydraulic Institute, Denmark. The software package contains a comprehensive modelling system for 2D free-surface flows. The flow field is calculated from the solution of depth integrated equations of conservations of volume and momentum in x and y directions (Abbott, 1979) and is expressed as

X-momentum:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{pq}{h} \right) + gh \frac{\partial \eta}{\partial x} + \left(g \frac{\sqrt{\frac{p^2}{h^2} + \frac{q^2}{h^2}}}{C^2} \right) - f V V_x - \frac{h}{\rho_w} \left(\frac{\partial P_a}{\partial x} \right) - \Omega q - E = S_{ix} \quad (1)$$

Y-momentum

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left(\frac{p^2}{h} \right) + \frac{\partial}{\partial y} \left(\frac{pq}{h} \right) + gh \frac{\partial \eta}{\partial x} + \left(g \frac{\sqrt{\frac{p^2}{h^2} + \frac{q^2}{h^2}}}{C^2} \right) - f V V_y - \frac{h}{\rho_w} \left(\frac{\partial P_a}{\partial x} \right) - \Omega q - E = S_{iy} \quad (2)$$

The equation of continuity:

$$\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = S - e \quad (3)$$

P and q are the flux in x and y directions respectively, h is water depth, t is time, Pa atmospheric pressure, ρ_w density of water, g is acceleration due to gravity, η is surface elevation (m), e is the evaporation rate (mm/day), C is Chezy's coefficient, f is wind friction factor, V is coriolis force, S_{ix} and S_{iy} source impulse in x and y direction, E is eddy viscosity coefficient, and Ω is coriolis parameter.

6. 2. 2 Satellite derived SSCs as initial conditions for MIKE 21

Coupling of remote sensing data and numerical models and its applicability of remote sensing to provide initial data or boundary forcing to a numerical model was discussed in detail by different researchers (Quillon et al., 1998; Ratheesh et al., 2012; Yang et al., 2014). In the present study, the synoptic distribution of SSCs derived from OCM for 18th January 2011 (Figure 6.2) is taken as the initial condition of sediment concentration in the numerical model to simulate the suspended sediment transport. Geometrically corrected OCM scene is brought to geographic projection as that of bathymetry file prepared for the numerical simulation. The error limit was restricted to one pixel which made sure that the SSC maps derived from OCM exactly fit to the bathymetry file. The OCM derived sediments (shown in Figure 6. 2.) are then advected by the currents simulated from MIKE-21 HD imparting dispersion. The sediment transport models are configured to run in conjunction with the hydrodynamic model. The MIKE-21 MT model is used to simulate suspended sediment transport along the coastal waters of central Kerala. The MT module describes the sediment transport under the action of currents and winds. The governing equation for the sediment transport model is

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + \frac{\phi_r - \phi_s}{h} \quad \text{---(4)}$$

where C is depth-averaged concentration of suspended sediment, u and v are x and y components of depth-averaged of current velocity derived from the hydrodynamic model, K_x , and K_y are depth mean dispersion coefficients in x and y directions, ϕ_r is re-suspension flux, ϕ_s is sedimentation flux, and h is total depth.

Various statistical metrics, including the Mean Bias Error (MBE), Mean Absolute Error (MAE), Root Mean Squared Error (RMSE), correlation coefficient (R), and Index of Agreement (IA) are calculated to compare the predictive performance of the model. The SSC values derived from subsequent OCM images acquired on 20th, 22nd and, 24th January 2011 are used for the statistical evaluation of the model results.

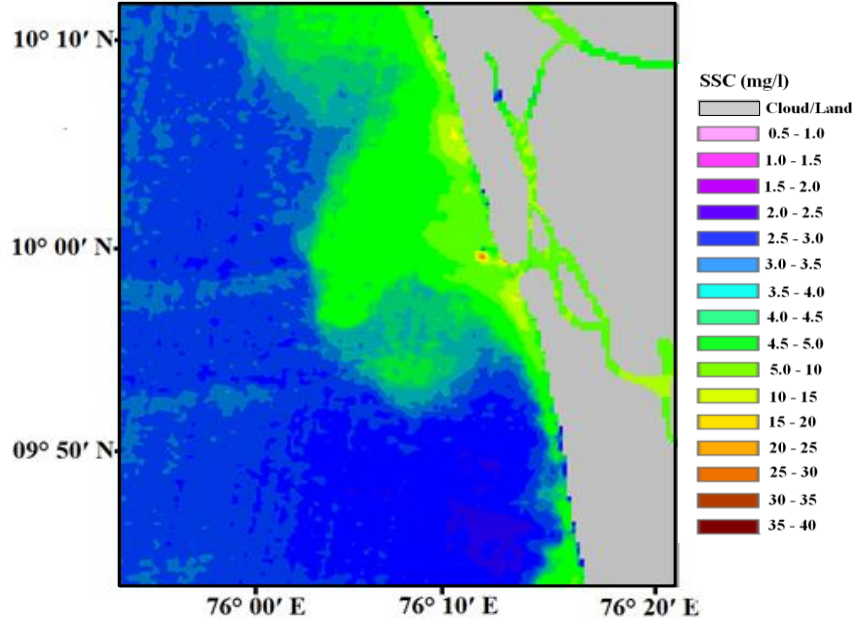


Figure 6. 2 Distribution of SSCs (mg/l) derived from OCM satellite acquired on 18th January 2011 is used as initial concentration for simulation of sediment transport model for the study period.

6.3 Results and Discussions

6.3.1 Tidal Simulation

Simulation is carried out to obtain the currents along the coastal waters of central Kerala for 18th to 24th January of 2011. In the absence of synchronous current measurements, the simulation is validated with predicted tidal elevation for river mouths in the eastern side of the domain (open boundary). The comparison of the model and predicted tidal elevation (Figure 6.3) confirms that the model reproduces the phase and amplitude with the predicted tide. Figure 6.4 (a-b) depicts the surface current distribution during ebb and flood current. The distribution of ebb current is with a maximum speed of 0.75 m/s. During the high tide, the current enters the estuarine mouth with a maximum speed of 0.95 m/s. Mathematical modeling has been demonstrated by the Carniello et al. (2012) while studying the morphological evolution of shallow tidal basins, which is the result of the combined effect of tidal currents and wind waves. These authors also state that the morphological evolution of shallow tidal systems is proximity of

the inlets and within the channel network, whereas tidal current mainly acts enhancing the bottom shear stress of re-suspension process due to wind waves and redistributing sediments within the basin. The tide height in the coastal waters off central Kerala is varied in the range between 0.11 and 1.11 m during the study period. From simulation results the current velocity was found to be in the ranges of 0.7–0.95 m/s. High velocity (~ 0.95 m/s) is primarily observed near the estuarine mouth.

The tidal currents oscillate mainly in the alongshore direction during the study period. During the ebb currents (Figure 6.4a), the current is observed to be flowing northwards (Figure. 6.4a), and during the flood currents (Figure 6.4b) the current is towards south. These currents play a vital role in the sediment dispersion along the coastal region of the central Kerala coast. The hydrodynamic and sediment transport models have demonstrated the importance of spatial asymmetries and residual flows associated with tidal currents on sediment relocation in inlets and estuaries (Mallet et al., 2000; Van Leeuwen and de Swart, 2002). The simulation result shows an increase in SSCs near the river mouth when the current velocity is higher.

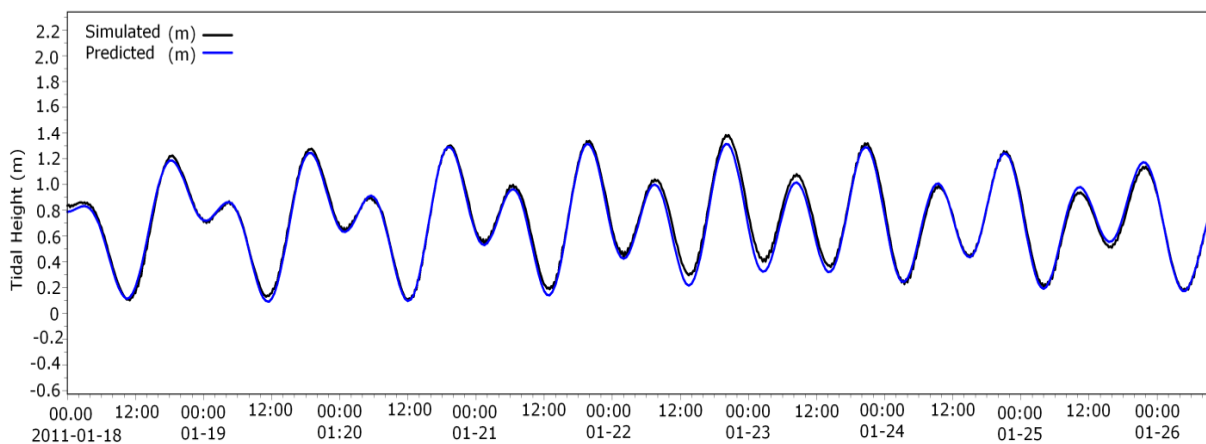


Figure 6. 3 Comparison of simulated and predicted tidal elevation for Cochin, central Kerala.

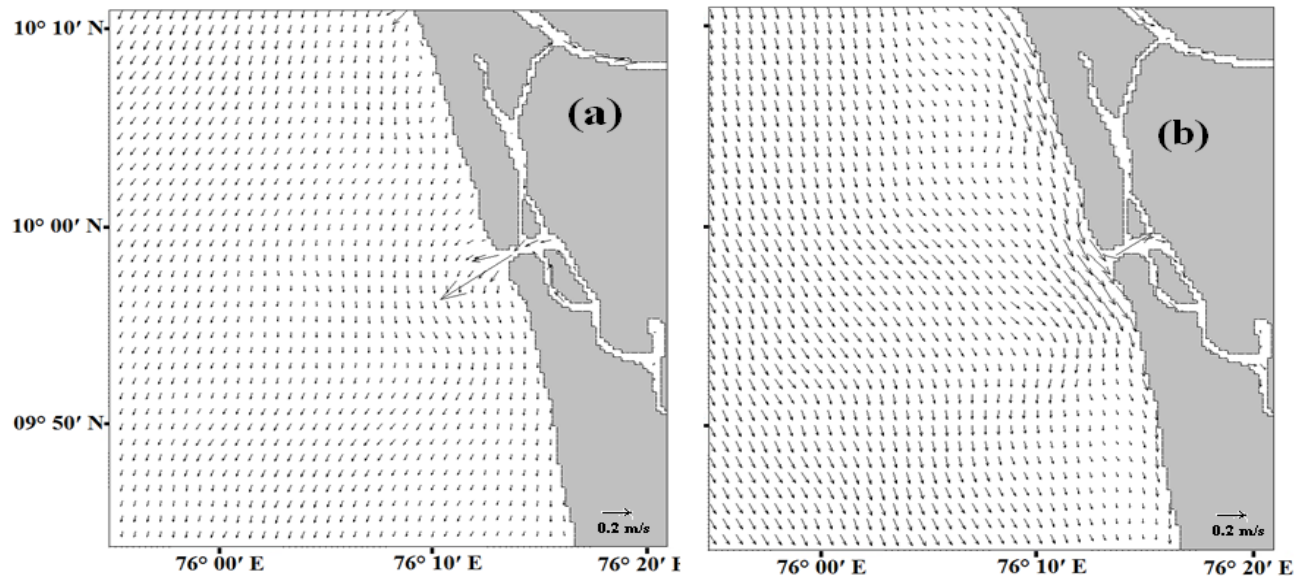


Figure 6. 4 (a) Ebb current pattern; (b) flood current pattern in the coastal waters of central Kerala derived from HD model.

6.3.2 Simulation of suspended sediment transport

Simulation of suspended sediment transport is carried out by optimizing the model control parameters such as settling velocity and critical shear stress for erosion. Simulation of sediment transport is carried out from 18th January 2011 by taking OCM-derived SSC as the initial concentration. SSCs obtained from the model at 12:00 hrs for 20th, 22nd and 24th January 2011 is visually compared with the corresponding sequence dates of 20th, 22nd, and 24th January in 2011 at 12:00 hrs of OCM derived SSCs (Figure 6. 5). A statistical comparison is between the simulated SSCs and SSCs derived from the OCM during the study period and presented in a scatter plot (Figure 6.5). The RMS error is found to be 2.25 and 1.69 mg/l for 20th and 22nd January, and for 24th January 2011 the RMS error is 2.65 mg/l. The correlation coefficient (R^2) and Index of Agreement (IA) for 20th January 2011 is 0.625 and 0.836; for 22nd January is 0.55 and 0.835; for 24th January 2011 is 0.449 and 0.724. Further, the SSC values derived from the model are compared with *in situ* SSCs acquired on 21st January 2011, show good correlation ($R^2=0.658$). The model evaluation results of statistical output are presented in Table 6. 1. From OCM and corresponding simulated results, SSCs are extracted across as shown in Figure 6.7.

Along the profiles at different depth intervals such as 5m, 10m and 15m, SSCs are extracted along the coast and shown in Figure 6. 8.

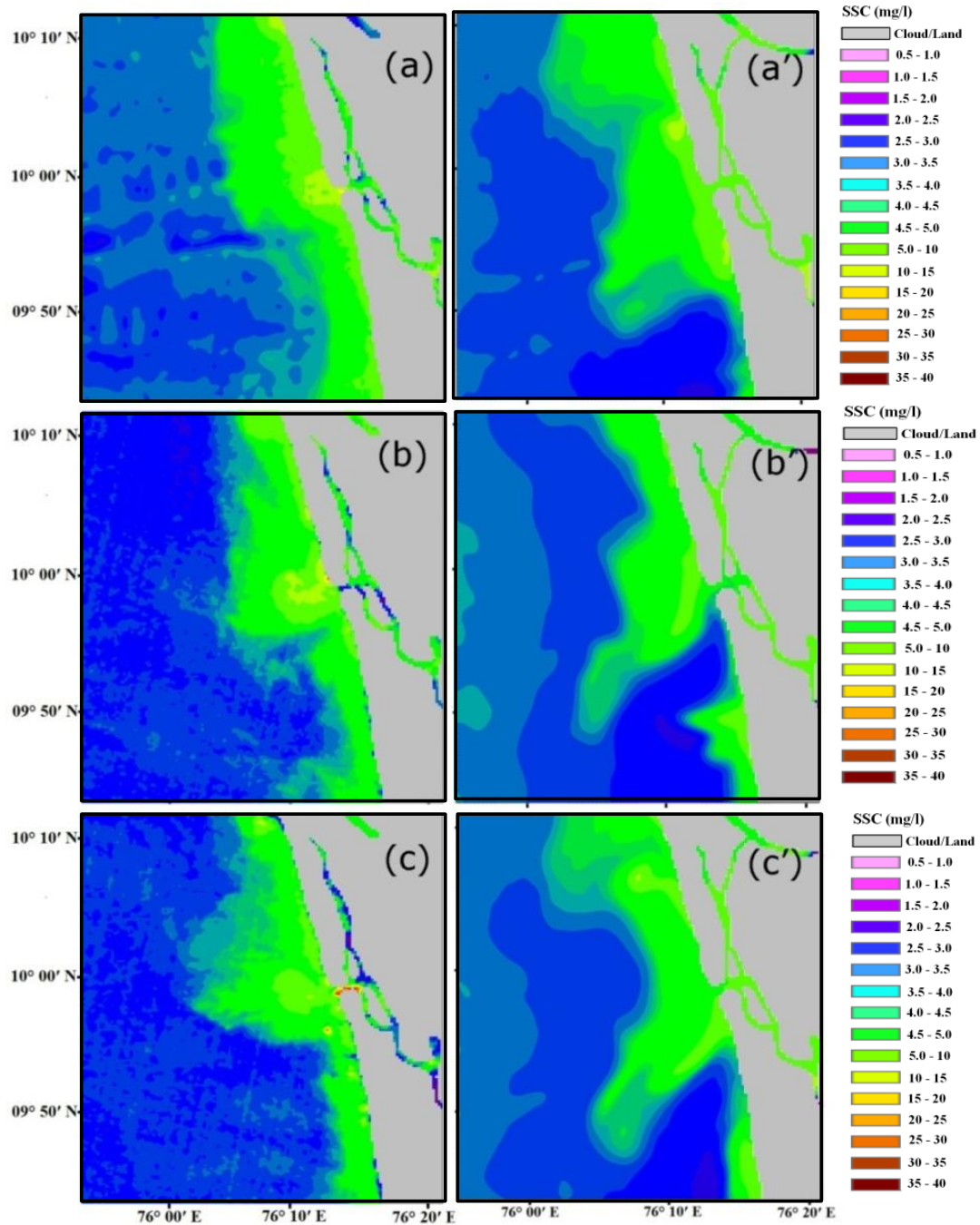


Figure 6. 5 Comparison of simulated SSC with OCM derived SSC (mg/l); (a-c) OCM SSCs; (a'-c') Model SSCs on 20th, 22nd and 24th January 2011.

Table 6. 1 Evaluation parameters of the model used in the study for three days January 2011.

Parameter	20 January	22 January	24 January
Mean Bias Error (MBE)	0.965	-0.05	1.01
Mean Absolute Error (MAE)	1.35	1.074	1.59
Mean Absolute Percentage Error (MAPE %)	26.79	28.93	32.24
Root Mean Square Error (RMSE)	2.25	1.698	2.65
Relative RMSE %	44.85	45.73	53.53
Correction Coefficient (R)	0.626	0.555	0.449
Index of Agreement (IA)	0.836	0.835	0.742

The SSC values are observed to be moderately high (> 15 mg/l) in both the OCM and model up to about 10 km from the coast and is decreased substantially afterwards (Figure 6.7). At a depth of 5m, 10m and 15m, SSCs are high (> 15 mg/l) during the period as observed from the results of OCM and simulated SSCs at the mouth of Vemband lagoon. The model simulates the pattern of SSC prevailing within the region, where high SSCs are observed in the coastal region and the gradual decrease of sediment concentration towards the open ocean. The comparison of alongshore profiles of the simulated SSCs with OCM derived SSCs shows the coastal sequestering of suspended sediments along the southern part of central Kerala Coast and the SSC values get decreased to a value of < 5 mg/l for the profiles of 25 m depth contour. From figure 6.8, it is observed that the shift in the movement of SSCs derived from the model outputs, and the direction is southward. Hence, the direction of sediment transport is southward during the study period.

The OCM observation shows moderately high SSCs (> 15 mg/l) towards the estuary mouth (Figure 6. 5) in the study period. The Vemband lagoon carries suspended sediment output which gets debouched into the Arabian Sea forming sediment plumes at the estuarine mouth. Even though due to the coastal sequestering, the sediment plume does not form extended plumes to the offshore region, the formation of the plumes is distinct at the estuarine mouth. Pattern of high SSCs, is observed to be more prominent to the immediate north of the estuarine mouth than

towards its south (Figure 6.5). The coastal region immediate north of the eastern mouth is observed to be shallower than its south (Figure 6.1). Current velocities are observed to be higher near river mouths. The swift action of the tidal current along the shallow region scours the bottom sediment in these regions and may trigger the re-suspension of the sediment.

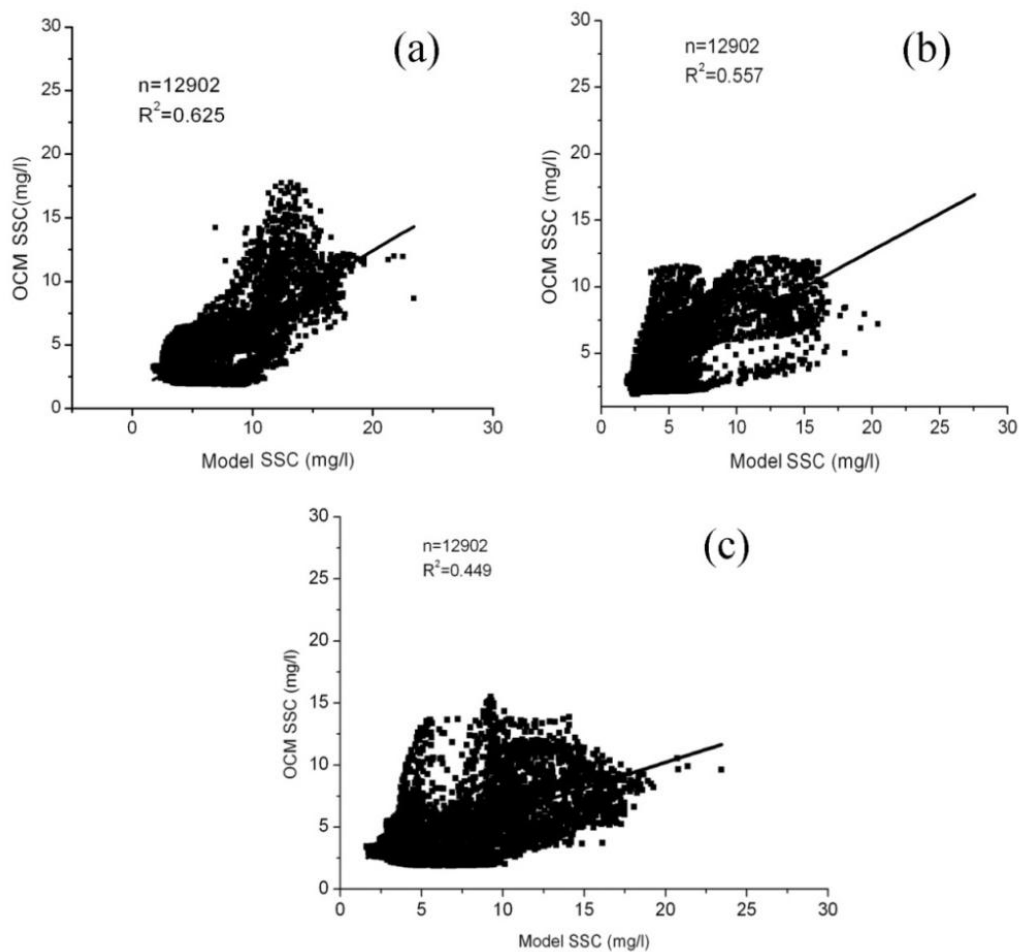


Figure 6. 6 Scatter plot showing the comparison of simulated SSC with OCM derived SSC (a) 20th January 2011; (b) 22nd January 2011and; (c) 24th January 2011.

Valle-Levinson (2001) studied the effect of advective accelerations and showed the response of downwind flow over shoals and upwind flow in the channel. It has been shown that the wind-driven circulation pattern can be modified from laterally sheared to vertically sheared by the shape of the bathymetry. Over relatively flat cross sections with no well-defined channel,

the wind-driven exchange flow is vertically sheared with the downwind flow at the surface and upwind flow underneath (Valle-Levinson, 2011).

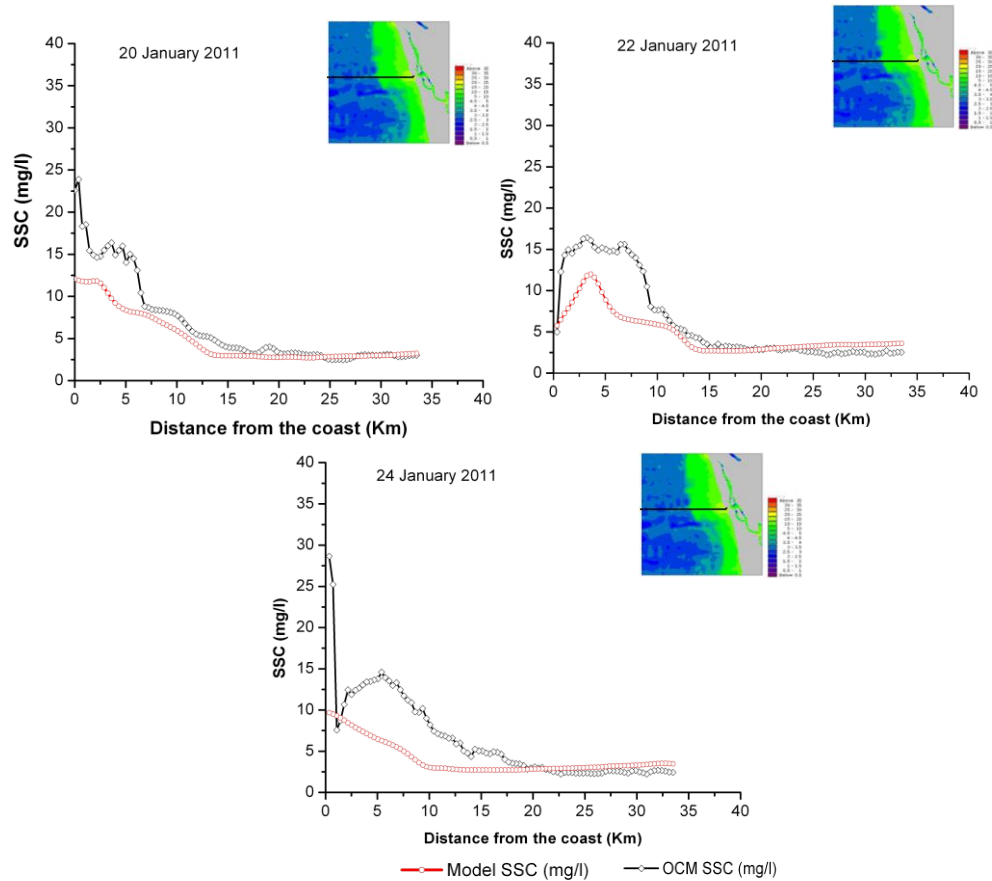


Figure 6. 7 Comparison of simulated SSCs and OCM derived SSCs extracted across the line, i.e., from the river mouth to the open ocean.

The SSCs derived from OCM image overlaid the simulated current velocity vectors of the coastal region of central Kerala for the period of 20th January 2011(Figure 6.9). From the figure 6.9, it is observed that the simulated currents move towards the southward direction, and from SSCs it can be inferred that the direction of movement is southwards. Chandramohan et al. (1993) recorded the daily longshore currents data at different stations along the south Maharashtra coast, states that the sediment transport is southward from August to May and northward during June and July.

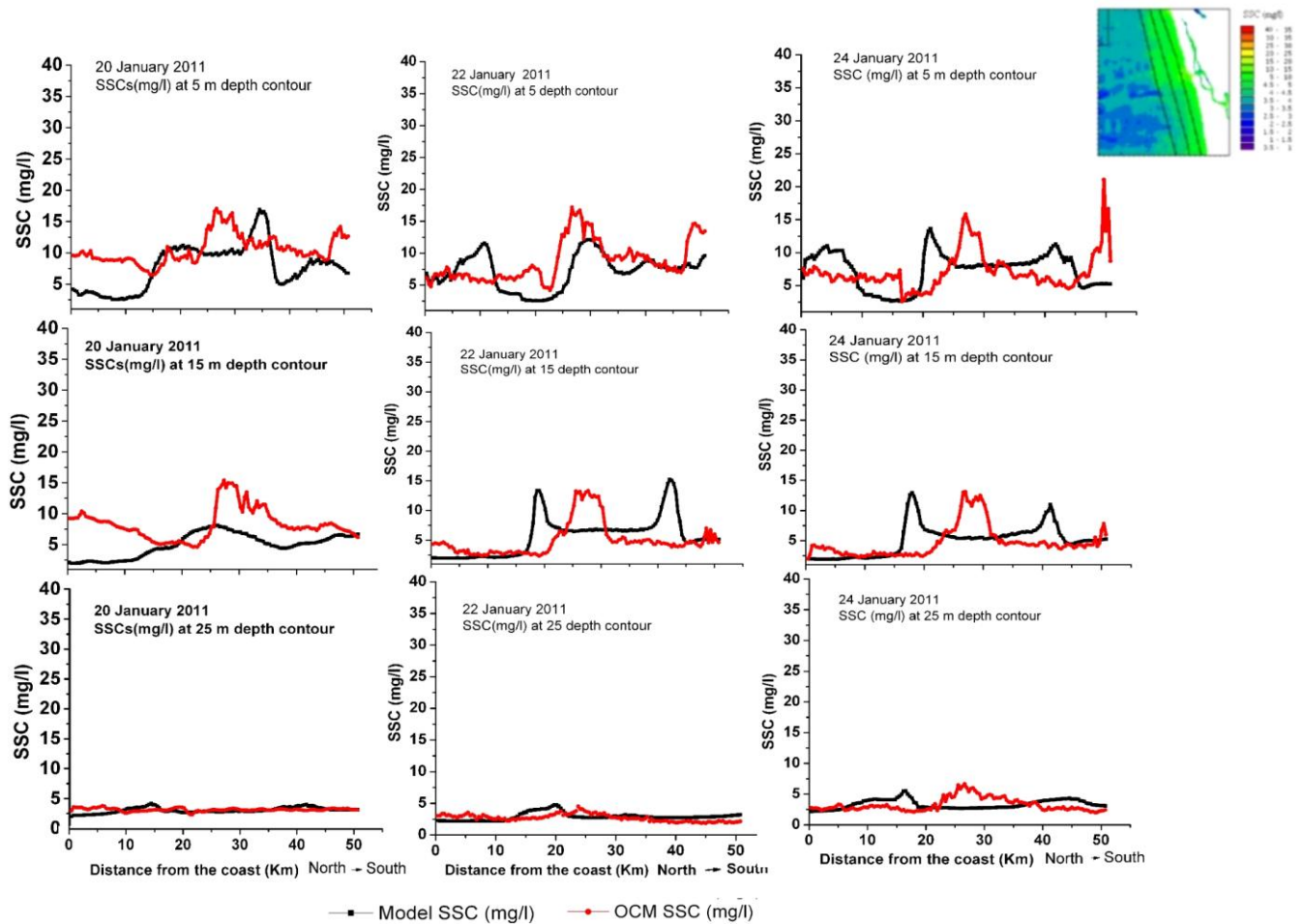


Figure 6.8 Longshore profiles of SSCs derived from OCM and model, at different depth intervals 5m, 10m and 15m for the period of 20th, 22nd and 24th January in 2011. The high SSCs (> 15 mg/l) is observed at the mouth of the Vemband lagoon at water depths of 5 m and 10 m.

Babu et al. (2003) studied the modeling of sediment transport along Mangalore coast using the MIKE 21 and inferred that offshore movement is dominant only in the monsoon season due to higher wave activity and in the non-monsoon season onshore movement is predominant. They suggest that the net longshore is negligible and the direction of sediment transport is from north to south in all seasons. The study of coastal circulation off Ratnagari, west coast of India, during monsoon period employing MIKE 21 HD model by Samiksha et al. (2014) suggested that stronger winds of the order of 8m/s, persisted for a longer period which contributed to the

southward flowing coastal current and also states that the meridional current has a prominent southward direction with a maximum alongshore speed.

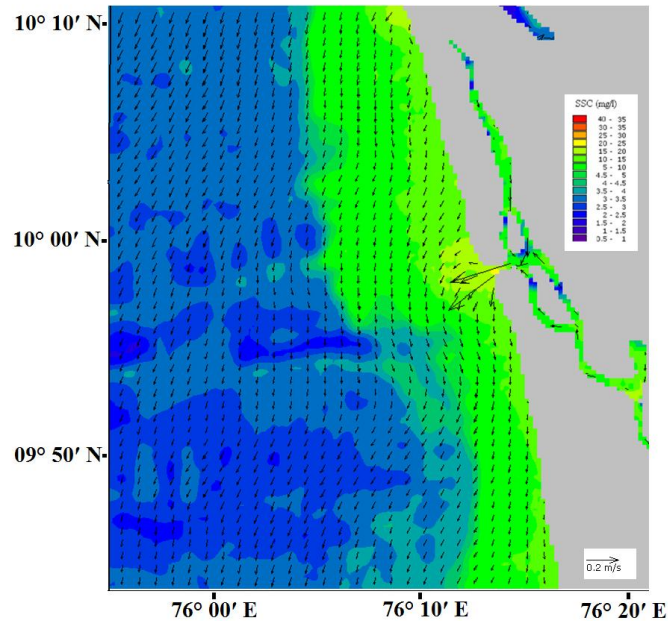


Figure 6.9 SSCs derived from OCM acquired on 20th January 2011 overlaid with simulated currents of the same time period.

6.4 Summary

Sediment transport along the central Kerala coast has been studied using MIKE 21 model. The sediment concentrations derived from OCM satellite data have been used in this modelling. Statistical comparison of simulated SSCs of MIKE 12 model and satellite derived SSCs has been carried out. The study reveals that sediment dynamics are primarily controlled by tidal currents and the river input. It is also observed that dispersion is influenced by wind force.

The results of the study further suggest that coastal sequestering of suspended sediments prevents the formation of sediment plumes towards the offshore region. However, there is a significant movement of fine sediments towards south. Resuspension processes along the central Kerala coast are mostly controlled by the river input and tidal ranges suggesting that the tidal scouring of the shallow coastal region is a primary ocean state parameter that controls the distribution pattern along the river mouths in the central Kerala region.

Chapter 7

Summary and Conclusion

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Rivers are the major source for transport of solid and dissolved material to the oceans. Transportation of suspended sediments and nutrients from continents to the sea and their subsequent dispersal has many implications, particularly for biological productivity of the coastal seas. These fine-grained sediments brought from the river to the marine environment vigorously mixed due to strong tidal currents and wave reworking processes. A distribution and dispersal pattern of SSCs is very important for the study in marine environment is essential not only for the safeguard of marine installations or navigational hazards but also to make out an assessment on the pollutants and biological activities in the coastal waters.

Monitoring and better understanding of sediment flux and processes in coastal environments are important to maintain water quality, geomorphologic balance, marine installation, navigational hazards but also make assessment of water quality parameters, can produce non-point source pollution. High concentrations of suspended sediment reduce light penetration through the water column affecting primary production of an ecosystem. Therefore estimation and distributions is of great importance when evaluating the condition of a coastal system.

Monitoring of SSCs through *in situ* measurements are difficult, expensive, time consuming and give only point observations. Hence, new technologies such as remote sensing based techniques are employed as they provide large area coverage and high resolution data in time and space.

Numerous sensors such as AVHRR, MERIS, SeaWiFS, MODIS, IKONOS, Landsat TM, ETM+ and OCM have been developed for the ocean colour applications and water quality assessments in the coastal waters. Variations in temporal and spectral resolutions, data availability, calibration of the sensor and temporal coverage are the most important factors determining the selection of the sensor for a particular study period.

MODIS provides a good temporal resolution (1 day) for monitoring of ocean colour applications but the spatial resolution is low (1km) as compared to the OCM (360 m). Hence, OCM covers a spatial resolution of 360m contains potential data to estimation the concentrations of suspended sediments. Oceansat-2 OCM sensor is the continuation of Oceansat-1 is to obtain quantitative information of ocean-colour variables e.g. chlorophyll-a concentration, vertical diffuse attenuation of the light (K_d) and concentrations of suspended sediments in coastal waters, apart from ocean-colour information OCM data will also be useful for studying the aerosol transport and terrestrial bio-sphere. The high resolution OCM sensor is a push broom linear charge coupled device with 8 spectral bands in visible and near infrared region (central wavelength bands of 412, 443, 490, 510, 555, 620, 740, 865 nm). The OCM provides a radiometric resolution of 12 bits, and swath width of about 1420 Km and repeativity is two-day time interval for any given area. OCM data covering the coastal regions Kerala region (path 10 & row 14) were used to derive concentration of suspended sediments.

In the present study, regional algorithm has been developed for the retrieval of suspended sediments in the coastal waters of southwest coast of India. The estimations of spatial and temporal variations of SSCs are derived from the regional algorithm is helpful in understanding the dispersal patterns of SSCs in relation to rainfall, river discharge and wind forcing and SSCs at the river mouths. MIKE - 21 Mud Transport Model employed to understand the sediment transport in central Kerala coast. The satellite SSCs derived from regional algorithm of OCM data is used an initial condition of SSCs values in mud transport model of MIKE-21 for the study of sediment transport under the hydrodynamics with the help of tides, winds and bathymetry prevailing along the central Kerala coast for the month of January 2011.

As the global algorithms cannot be used universally for all types of coastal waters because of the optical complexities such as suspended particle size, shape, and colour can influence the water, it is difficult to propose a universal algorithm for estimation of SSCs. Further, various other parameters such as bathymetry, coastal geomorphology, river input, regional coastal circulation patterns influence the SSCs distribution and hence the developed algorithm for one region may not be applicable to another region. Hence, a regional algorithm is developed for estimation of spatial and temporal variations of SSCs in the coastal waters of southwest coast of India/Kerala coast.

The analyses were carried out to develop a regional algorithm using *in situ* SSCs and R_{rs} derived from radiometer data collected on research cruises for coastal waters of central Kerala. The study analyzed the spatial and temporal variations of SSCs for the entire Kerala coast of OCM data for a three year period 2010, 2011 and 2012. Atmospheric correction and aerosol scattering developed by Gordon (1997) and Ramana et al. (2000) are carried out and the geometric correction is applied to OCM datasets for removing image distortion and brings them to a standard geographic projection.

The relation between single wavelength band(s) of 490, 510, 555 and 620 nm and *in situ* SSCs, shows an insignificant relation, whereas the band ratio of $(620/490)^2$ with *in situ* SSCs showed a significant positive correlation. Further, the linear regression, is based on the wavelength band (s) combinations of 490, 555 and 620 nm with *in situ* SSCs shows very strong statistically significant relation ($R^2=0.84$ and $t>2$ and $p<0.05$) and this linear significant relation is employed for the OCM R_{rs} values at these wavelength bands and used for the estimations of SSCs along the Kerala coast. The regression equation derived from the combination of wavelength bands of 490, 555 and 620 nm and *in situ* SSCs is expressed as:

$$Y=14.92 X+8.22 \text{ ----- (1)}$$

where Y is the SSC in mg/l, $X = \{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620) / R_{rs}(490)]^2\}$, $R^2=0.84$, $t > 2$ and $p < 0.05$ with 95% confidence level.

Best validation results ($R^2= 0.81$) were observed between *in situ* SSCs and satellite derived SSCs using the regional algorithm. This study compared the Tassan's global algorithm with *in situ* SSCs, showed a weak correlation ($R^2=0.16$). This study suggests that wavelength bands at 490, 555 and 620 nm give more precise results than the customary single wavelength bands and band ratios of different wavelength bands.

Applying this regional algorithm, SSCs are estimated in spatial and temporal scales for Kerala coast for 3 year period 2010, 2011 & 2012 in order to understand the dispersal patterns with the help of the rainfall, river input, and wind forcing. The SSCs are estimated in the three sectors and subsector spatial scales. The southern sector comprises into seven sub-sectors (1-7), and SSCs are recorded high (> 30 mg/l) amount in June 2010; in February, March, September,

October of 2011; and in May, September, December of 2012. Central sector comprises into ten sub-sectors (8-18) and SSCs are recorded high (> 30 mg/l) in the months of January, February, March, June and July of 2010; in February, March, May, September, October, November of 2011; and in January, May, July, September, October, November and December of 2012. Northern sector comprises into seven sub-sectors (19-25) and SSCs are recorded high (> 30 mg/l) in the months of February, June and July of 2010; in February, March, September, October, November, December of 2011; and in January, February, May, July, September, October, November of 2012. In summary, it is observed that SSCs are higher in the coastal waters of central Kerala when compared to the northern and southern regions of Kerala coast. Further, moderately high concentrations (> 20 mg/l) of suspended sediments are observed the along the stretch of coastal waters in comparison with offshore waters.

The concentrations of suspended sediments are statistically computed in terms of weighted averages/mean, standard deviation, coefficient of variations (CV) and analysis of variance (ANOVA) in order to understand the spatial and temporal distributions. High variability in CVs ($CV > 79.25$) was observed mostly in the monsoon months i.e., June-September during the study period. The high variability recorded in central and northern sectors may be the result of nearshore turbulence caused by the strong winds (> 7 m/s) and high amount of river input during the monsoon period (June-September). The strong turbulence may induce seabed erosion, which in turn induces resuspension of sediment particles. The spatial and temporal variations of SSCs with help of statistical analysis of variance showed statistically significant (at 95% confidence level & $p < 0.05$) variation in the mean values of the SSCs in spatial and temporal.

The distributions of SSCs are varies due to the influence of hydrodynamic forcing such as rainfall, river discharge and wind driven processes. These distributions are controlled by the various factors such as supply of sediment by rivers, bathymetry, coastal circulations and coastal morphology. Higher amount (40 mg/l) of SSCs is recorded at the rivers mouths off Periyar, Muvattupuzha, Chaliyar, Bharathapuzha and Pamba and moderate SSCs (16 mg/l) are recorded at the river mouths off Valapatanam, Kadalundi, Chalakudy, Achankovil and Kallada.

Total amount of rainfall (>2500 mm) in June in the whole region of southern sector corresponds to the high sediment concentrations (>30 mg/l); and similar scenario in June and

July of 2011 in central sector; and in June and July of 2010 in northern sector which could transport riverine inputs to the coastal and offshore waters. Narayana (2006) studied the relation between the rainfall variability, run-off and sediment discharge of the rivers of Kerala and attributed that higher the rainfall, the larger the sediment to the coastal waters. It can be inferred that river discharges during monsoon periods influence the suspended sediment load to the coast of Kerala.

The SSCs are highly variable and mostly concentrated at the mouths due to river discharge. It is inferred that the freshwater input from the hinterland is the major source of SSCs along the Kerala coast. The total monthly runoff/discharge and total suspended sediment (mg/l) for the different rivers of Kerala for the period reveal that Periyar, Muvayyupuzha, Bharathapuzha River discharge large amounts of water (~179776 MCM, ~ 161794 MCM, ~ 139247 MCM respectively) and Vamanapuram discharge the least (~ 775 MCM) during the study period. The positive relationship among rainfall, run-off and sediment discharge suggests that rainfall and run-off exert a first order control on the sediment discharge of Kerala Rivers.

The suspensions of suspended sediments triggered by the wind driven circulation is observed for the distribution and dispersal patterns of SSCs. The wind speed varied from 0.5 to 12 m/s during study period. The wind speeds are high (>7 m/s) during monsoon months, especially June and July in 2010; September 2011; June 2012 and direction is prominently dominated by northerly in 2010 and northwesterly in 2011 and 2012. In the non-monsoon period, the winds intensity is decreased and direction is northeasterly. The movement of the fine sediments is towards the southward direction predominately dominated in monsoon period. In the months of June-September the strong wind (>7 m/s) induced vertical mixing gentle the bottom layer sediment upward leading to the high SSCs in the surface layer. However, in December-May, the weak winds are in the range of 3-5 m/s induced vertical mixing was restricted in the upper layer of the ocean due to the existence of the clines. As a result, the bottom sediment could not be carried to the surface layer, hence low SSCs are recorded in the surface waters April and May. Wind generated waves might be the most important forcing agents for sediment resuspension in the coast areas in monsoon period.

The other important aspect that has been studied is sediment transport applying MIKE-21 Mud Transport (MT) model. The inputs for this model are data on winds, tides, bathymetry and satellite derived SSCs. A combination of MT and Hydrodynamical (HD) module is used for quantification and the movement of fine sediments along the central Kerala coast. In HD module, the water level variations and flows are simulated in response to a variety of forcing functions in coastal areas. The tidal height in the coastal waters off central Kerala ranges between the 0.11 and 1.11 m. The current velocity ranges from 0.7-0.95 m/s as observed from simulations during the study period. Suspended sediment transport in the coastal waters of central Kerala is using the MIKE-21 MT model for the period from 18th to 24th January 2011. The SSCs on 18th January 2011 are considered as the initial condition in model and simulated. The simulated SSCs are compared with satellite derived SSCs, where coefficient of determination (R^2) for the simulated period is 0.63; 0.56; 0.45. The simulated SSC of 21st January is compared with the *in situ* SSCs shows the good coefficient of determination (0.66). Sediment dispersion patterns are explained in relation to simulated tidal currents, dominated by the southward flowing coastal currents, which are more consistent in its direction and magnitude along the coast. The results of the study further suggest that coastal sequestering of suspended sediments prevents the formation of sediment plumes towards the offshore region. However, there is a significant movement of fine sediments towards south. Resuspension processes along the central Kerala coast are mostly controlled by the river input and tidal ranges suggesting that the tidal scouring of the shallow coastal region is a primary ocean state parameter that controls the distribution pattern along the river mouths in the central Kerala region. It is observed that tides, winds and currents are the important physical factors that control the dispersal patterns. The results suggest that sediment transport is from north to south during the study period i.e., in January 2011. The SSCs estimations and distribution patterns from the *in situ* and satellite derived SSCs, used for the application of algorithm developments and models simulations, helps in understanding of coastal zone management of navigational channels.

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Appendix-1

Spatial and temporal distribution of SSCs (mg/l) of 10' along x 40 'across the coast in three sectors derived from OCM in January, February and March 2010.

Sector	Subsectors (10' along x 40' across)	January						February						March					
		Min	Max	M	SD	CV(%)	N	Min	Max	M	SD	CV(%)	N	Min	Max	M	SD	CV(%)	N
Southern	1	0.57	16.51	2.86	1.21	42.18	16441	0.59	5.92	2.02	1.09	53.88	16464	0.53	18.44	3.15	1.51	47.96	14236
	2	1.04	29.91	2.74	2.32	84.69	12519	0.64	2.79	2.07	0.81	39.00	15081	0.54	15.13	2.95	2.10	71.10	13009
	3	0.97	18.02	2.65	0.94	35.54	15819	0.55	3.88	1.20	0.21	17.85	16329	0.51	12.05	2.43	0.78	32.06	16144
	4	1.40	8.81	2.72	0.68	25.20	16155	0.87	8.96	1.36	0.37	26.99	16248	0.51	13.96	2.45	1.38	56.39	13902
	5	0.67	10.27	2.66	0.66	24.79	16133	0.78	12.70	1.54	0.22	14.06	16598	0.52	19.16	3.98	1.74	43.79	15846
	6	0.68	8.72	2.57	0.70	27.15	15140	1.03	16.45	1.81	0.40	22.09	16178	0.55	11.33	2.55	0.67	26.08	17230
	7	1.31	7.43	3.15	0.85	27.01	12911	1.09	13.92	1.93	0.40	20.86	16670	0.58	23.51	2.71	1.72	63.37	14631
Central	8	0.66	5.98	2.95	0.76	25.73	10678	1.26	16.15	2.72	1.56	57.39	16620	0.53	13.24	3.37	1.33	39.41	15791
	9	0.96	6.24	3.02	0.85	28.04	11185	1.07	26.62	3.01	2.29	75.91	16670	0.54	18.19	2.36	0.86	36.36	15534
	10	1.33	6.29	3.58	1.00	27.95	16454	1.07	31.49	4.78	2.51	52.50	13485	0.56	17.37	2.32	0.72	31.25	15735
	11	0.63	14.44	3.87	1.62	41.99	16978	1.02	26.85	3.29	3.52	106.99	14234	0.64	15.52	2.39	1.02	42.54	16700
	12	0.59	13.85	3.92	1.87	47.64	14844	0.87	7.82	2.56	1.61	62.80	16212	0.67	27.09	2.64	1.53	58.10	15390
	13	0.61	31.18	4.34	2.17	49.96	16297	1.27	10.73	3.43	2.11	61.72	16039	0.59	26.16	2.94	2.64	89.88	12651
	14	0.57	19.19	4.22	1.13	26.71	17011	1.55	7.26	3.53	2.53	71.59	16065	0.61	29.91	3.58	2.59	72.27	13977
	15	1.11	7.40	3.63	0.82	22.56	16706	1.53	7.02	2.82	1.64	58.09	17038	0.64	27.35	2.47	1.78	72.12	15855
	16	1.39	6.37	4.05	0.79	19.58	17082	1.60	5.89	2.84	0.88	31.01	16903	0.69	18.05	3.87	2.11	54.55	13586
	17	1.98	7.68	4.68	0.85	18.05	17101	1.68	10.12	3.10	1.07	34.56	16886	0.77	27.04	2.97	3.51	118.16	9509
Northern	18	2.87	13.45	1.09	1.79	163.87	17249	1.86	8.81	3.51	1.36	38.75	17027	0.78	26.24	2.97	1.21	40.68	8631
	19	3.60	13.47	1.62	0.61	37.55	17357	1.01	13.80	3.22	2.26	70.30	16656	0.68	28.86	3.15	2.12	67.38	10269
	20	3.77	8.35	2.95	1.53	52.03	17217	1.27	19.54	3.22	2.01	62.43	15470	0.81	25.47	2.87	1.48	51.49	12216
	21	2.08	13.88	1.96	1.00	51.13	12409	0.57	29.93	3.76	2.37	62.89	10608	0.60	30.37	3.58	1.47	41.12	8622
	22	2.17	10.16	2.63	1.67	63.32	11934	0.55	19.57	3.18	2.11	66.42	10318	0.78	29.84	3.24	2.87	88.39	7807
	23	2.23	7.46	1.80	1.60	88.54	12692	0.57	20.42	3.07	1.88	61.15	10408	0.82	17.73	3.52	2.01	57.11	11844
	24	2.60	9.73	1.76	1.29	73.00	7202	1.06	11.88	3.08	2.90	94.15	11735	0.85	18.63	2.11	1.46	69.01	7857
	25	0.61	12.61	2.16	2.09	96.98	6859	0.62	8.92	3.49	3.13	89.68	1936	0.91	15.85	1.95	1.14	58.38	8349

Min = Minimum; Max = Maximum; M =Mean; SD = Standard Deviation; CV = Coefficient of Variation; N= Number of pixels

Appendix – I continued

Spatial and temporal distribution of SSCs (mg/l) of 10' along x 40' across the coast in three sectors derived from OCM in April, June and July 2010.

Sector	Subsectors (10' along x 40' across)	April						June						July					
		Min	Max	M	SD	CV (%)	N	MIN	MAX	M	SD	CV (%)	N	Min	Max	M	SD	CV (%)	N
Southern	1	NA	NA	NA	NA	NA	NA	0.56	3.95	1.73	0.50	28.77	7206	0.57	26.67	1.90	0.97	50.97	4155
	2	NA	NA	NA	NA	NA	NA	1.56	2.34	1.20	0.44	36.99	2894	NA	NA	NA	NA	NA	NA
	3	NA	NA	NA	NA	NA	NA	1.02	27.50	2.86	2.76	96.40	794	NA	NA	NA	NA	NA	NA
	4	0.50	21.16	1.92	1.36	70.67	16	0.78	30.93	5.57	4.39	78.84	2487	NA	NA	NA	NA	NA	NA
	5	0.71	16.22	3.99	1.98	49.63	122	0.65	26.71	6.63	5.62	84.82	274	NA	NA	NA	NA	NA	NA
	6	0.52	11.89	1.47	1.15	78.31	8786	0.67	30.93	5.21	3.78	72.63	3026	NA	NA	NA	NA	NA	NA
	7	0.53	14.66	1.42	0.09	6.25	9277	1.56	22.65	3.88	2.83	72.94	1583	NA	NA	NA	NA	NA	NA
Central	8	0.79	3.34	1.61	0.09	5.73	9039	1.19	21.64	6.80	6.10	89.71	3674	NA	NA	NA	NA	NA	NA
	9	0.93	4.14	1.72	0.23	13.19	9517	0.60	31.11	5.75	5.29	91.99	2899	0.53	15.25	4.03	2.39	59.45	6980
	10	0.93	6.00	1.93	0.26	13.75	9929	0.90	32.28	6.96	3.05	43.82	1323	0.52	32.86	5.85	3.16	54.06	4490
	11	1.41	5.26	2.27	1.99	87.78	10255	1.27	28.15	5.20	3.63	69.81	1485	0.83	34.91	5.71	5.41	94.64	1817
	12	0.70	20.42	2.42	1.46	60.58	9528	1.98	28.04	6.03	3.01	49.96	6690	0.51	32.48	8.99	6.62	73.60	2838
	13	0.97	18.27	3.11	2.52	80.88	8109	1.68	30.66	9.37	3.45	36.87	3377	2.34	31.34	8.70	5.65	64.95	1925
	14	0.91	27.60	3.12	2.61	83.65	10421	1.73	30.08	6.42	2.36	36.66	5635	3.29	38.20	8.24	5.48	66.52	2653
	15	1.23	25.16	3.93	2.23	56.62	10857	1.67	31.28	8.32	6.69	80.48	6092	4.19	38.28	8.32	5.70	68.50	6095
	16	1.41	9.21	3.48	2.47	70.93	10531	1.48	31.40	8.52	5.54	65.09	6513	4.13	34.91	8.52	5.59	65.66	6513
	17	1.99	6.69	3.14	0.31	9.95	10341	0.52	26.39	9.71	5.61	57.78	6493	0.52	26.39	9.72	6.54	67.34	5953
Northern	18	2.11	5.57	2.88	0.19	6.70	3300	0.59	26.72	10.35	6.47	62.55	6147	0.59	29.73	10.84	6.77	62.48	554
	19	1.57	11.19	2.96	0.35	11.96	2783	0.78	30.47	11.0765	5.34	48.19	1103	0.80	29.47	11.77	5.33	45.31	368
	20	0.79	17.25	2.94	0.33	11.31	2874	1.01	30.95	8.88968	6.02	67.73	1979	0.52	21.30	6.31	5.72	90.58	477
	21	1.27	8.72	2.84	0.80	28.06	3340	0.67	31.64	9.58022	5.58	58.24	1297	0.67	30.64	9.58	5.59	58.32	432
	22	1.45	25.73	5.09	1.55	30.46	3212	0.73	32.84	11.8367	7.23	61.06	945	1.09	26.21	7.32	5.02	68.53	761
	23	1.56	21.73	4.33	1.09	25.25	2694	1.01	26.18	9.90225	6.83	69.02	1666	2.07	27.99	9.46	6.38	67.38	986
	24	0.84	10.82	4.09	2.75	67.28	1368	0.98	25.89	5.29372	6.21	117.38	222	0.72	29.19	13.97	8.95	64.04	417
	25	NA	NA	NA	NA	NA	NA	0.90	31.00	7.638	8.26	108.09	421	0.57	30.00	17.64	11.26	63.83	140

Min=Minimum; Max=Maximum; M=Mean; SD=Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix – I continued

Spatial and temporal distribution of SSCs (mg/l) in three sectors derived from OCM in December 2010.

Sector	Subsectors (10' along x 40' across)	December					
		Min	Max	M	SD	CV (%)	N
Southern	1	0.52	5.41	1.30	0.34	25.91	16985
	2	0.64	4.30	1.31	0.27	20.19	17817
	3	0.75	2.48	1.33	0.98	73.29	16766
	4	0.66	3.88	1.28	0.27	21.17	16992
	5	0.75	2.11	1.39	0.27	19.43	16120
	6	0.83	3.67	1.57	0.70	44.82	16985
	7	1.13	14.15	2.02	1.27	62.83	17914
Central	8	1.23	7.43	2.13	0.61	28.63	17847
	9	1.33	7.52	2.45	0.90	36.79	17877
	10	2.49	8.83	6.08	2.06	33.84	14637
	11	1.79	13.55	5.59	1.52	27.23	15990
	12	1.94	25.53	4.68	2.51	53.52	16222
	13	1.60	16.58	2.70	1.09	40.59	18148
	14	1.45	17.75	3.02	1.69	56.04	17922
	15	1.97	18.29	2.87	0.72	25.04	17906
	16	1.81	9.94	3.72	1.56	41.86	17917
	17	2.18	9.96	4.22	1.49	35.34	17936
Northern	18	2.15	10.53	3.94	1.44	36.55	4484
	19	2.21	7.37	3.61	0.90	24.95	4412
	20	1.96	11.11	3.60	0.39	10.79	4201
	21	2.17	7.13	3.45	0.47	13.55	3363
	22	1.88	17.19	3.36	1.02	30.28	3288
	23	2.25	9.79	3.46	1.73	50.02	3136
	24	1.57	19.02	4.91	1.51	30.85	2184
	25	2.23	23.52	5.90	3.90	66.13	1762

Min=Minimum; Max=Maximum; M= Mean; SD= Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix -2

Spatial and temporal distribution of SSCs (mg/l) in three sectors derived from OCM in of January, February and March 2011.

Sector	Subsectors (10' along x 40' across)	January						February						March					
		Min	Max	A	SD	CV (%)	N	Min	Max	A	SD	CV (%)	N	Min	Max	A	SD	CV (%)	N
Southern	1	1.63	11.29	2.74	1.24	45.16	16442	0.59	13.11	2.12	1.47	69.39	12186	0.62	12.17	1.82	0.60	33.01	8659
	2	1.50	6.74	2.54	0.48	18.73	17380	0.55	22.48	1.97	1.11	56.55	15632	0.60	18.33	1.96	0.90	46.10	10279
	3	1.43	14.25	2.61	0.54	20.81	16557	0.62	24.23	2.41	2.28	94.61	13509	0.63	28.86	2.51	1.00	39.65	10306
	4	0.87	20.45	2.76	1.49	53.85	15804	0.86	14.47	2.46	1.91	77.56	15313	0.70	29.66	2.87	1.76	61.35	8943
	5	1.46	9.02	2.84	0.45	15.99	16806	1.05	21.71	2.74	1.49	54.19	15098	0.74	30.68	2.15	0.48	22.11	12714
	6	1.66	8.96	3.23	0.85	26.26	16416	0.62	23.33	3.19	1.64	51.33	15085	0.63	31.10	2.24	1.43	64.04	12746
	7	1.65	8.60	3.98	0.98	24.71	17008	0.62	32.86	3.63	2.18	60.10	15455	0.71	26.10	2.36	1.18	49.86	14221
Central	8	1.85	8.50	4.31	1.21	28.11	16879	0.72	26.11	4.06	1.86	45.75	15884	0.55	14.40	2.11	0.68	32.40	16520
	9	2.10	9.14	4.44	4.40	99.00	16863	0.64	28.82	4.15	2.31	55.76	15494	0.59	15.30	2.44	1.19	48.83	16671
	10	2.05	9.93	4.78	4.33	90.72	16917	0.63	29.13	3.84	2.01	52.42	15548	0.58	14.17	2.56	1.05	40.83	16728
	11	1.79	9.95	3.16	1.36	43.07	17934	0.75	24.97	3.99	2.47	61.95	14787	0.66	10.76	2.41	0.74	30.69	17359
	12	0.86	28.95	3.54	2.84	80.19	16354	0.61	34.54	4.84	2.91	60.21	14746	0.62	19.41	2.24	0.63	28.04	17181
	13	0.96	9.63	3.81	3.75	98.18	18014	0.82	35.69	5.49	3.20	58.42	14975	0.54	15.94	3.02	1.12	37.16	18019
	14	1.66	10.03	3.86	3.40	88.16	17048	0.65	23.29	5.39	2.69	49.84	14433	0.60	23.41	3.08	1.35	43.71	16510
	15	2.14	8.32	3.90	2.17	55.56	17073	0.65	27.79	6.17	3.33	54.00	12429	0.71	37.96	3.47	3.27	94.36	13854
	16	2.30	8.39	4.41	4.16	94.44	16886	0.78	19.06	7.49	5.69	75.93	7264	0.56	28.55	3.05	2.08	68.20	15659
	17	2.45	9.44	4.55	4.53	99.52	16871	0.78	29.72	9.17	7.87	85.78	4321	0.69	16.76	2.88	1.08	37.58	16614
Northern	18	1.49	14.23	4.64	1.61	34.83	16988	0.79	29.21	8.79	7.89	89.77	3691	0.64	33.56	3.17	1.44	45.46	14663
	19	2.41	17.03	5.80	2.00	34.40	16349	0.78	32.30	7.18	7.50	104.44	4065	0.57	25.12	2.96	1.44	48.47	16211
	20	1.18	19.46	5.05	1.75	34.63	16899	1.23	27.61	4.46	2.10	47.10	14796	0.61	23.20	3.16	1.93	61.17	15778
	21	2.30	14.89	5.02	1.38	27.49	16903	1.73	15.71	4.25	0.85	19.93	16437	0.69	19.04	3.46	2.93	84.81	14312
	22	2.00	9.66	4.92	1.26	25.59	16186	0.72	15.32	4.39	1.45	33.08	11187	1.13	18.59	3.23	1.77	54.90	13115
	23	2.58	11.64	5.61	1.51	26.93	12406	0.58	26.25	4.37	1.13	25.85	11975	0.55	20.65	3.17	1.98	62.38	9723
	24	2.37	11.98	5.45	2.01	36.78	11605	0.91	23.04	5.11	1.56	30.59	11288	0.56	18.58	3.38	2.10	62.05	9750
	25	1.67	23.39	6.26	3.74	59.69	7340	0.54	21.38	7.78	1.82	23.43	5961	0.53	16.14	3.28	1.53	46.61	8062

Min=Minimum; Max=Maximum; M= Mean; SD= Standard Deviation; CV = Coefficient of Variation; N= Number of pixels

Appendix – II continued

Spatial and temporal distribution of SSCs (mg/l) derived in three sectors from OCM in April, May and September 2011.

Sector	Subsectors (10' along x 40' across)	April						May						September					
		Min	Max	M	SD	CV (%)	N	Min	Max	M	SD	CV (%)	N	Min	Max	M	SD	CV (%)	N
Southern	1	1.18	10.28	2.54	0.92	36.14	16514	0.83	23.89	2.60	2.36	90.87	2019	NA	NA	NA	NA	NA	NA
	2	0.83	5.95	2.65	2.02	76.47	16736	0.53	11.04	1.68	0.40	23.68	2850	NA	NA	NA	NA	NA	NA
	3	1.08	5.53	3.03	2.72	89.75	15321	0.53	7.66	1.71	0.36	21.17	2407	NA	NA	NA	NA	NA	NA
	4	0.58	7.34	3.31	2.58	78.18	11267	0.80	23.32	1.79	1.04	58.28	3472	NA	NA	NA	NA	NA	NA
	5	0.60	7.46	3.60	3.03	84.33	8090	0.63	20.51	1.55	1.03	66.27	1706	NA	NA	NA	NA	NA	NA
	6	0.58	10.42	4.36	2.80	64.21	10605	0.78	22.49	4.65	2.69	57.89	886	NA	NA	NA	NA	NA	NA
	7	0.64	9.46	4.68	2.00	42.70	7456	0.78	23.63	2.88	1.44	49.97	1044	0.78	29.89	4.30	2.89	67.21	145
Central	8	0.70	9.66	5.14	4.03	78.42	9274	1.33	33.81	2.45	1.11	45.33	1591	NA	NA	NA	NA	NA	NA
	9	1.70	13.92	6.09	5.80	95.21	7266	1.49	13.65	2.03	1.78	87.71	218	0.67	5.83	2.50	1.28	51.37	524
	10	1.47	13.11	5.87	4.09	69.75	5131	0.56	35.79	0.96	1.04	108.88	1671	0.55	12.12	2.23	2.16	96.92	1298
	11	1.30	10.71	5.23	4.18	79.89	3772	0.71	22.27	3.19	1.66	52.00	221	1.56	20.63	3.52	2.31	65.75	2948
	12	0.69	10.31	3.80	4.74	124.88	5784	0.54	16.98	0.87	0.43	49.57	2142	0.66	28.97	5.82	2.18	37.52	3504
	13	0.85	14.64	4.16	3.06	73.69	10151	0.64	27.51	3.22	1.59	49.27	403	0.78	35.79	5.44	2.22	40.81	3427
	14	0.58	14.09	3.99	3.68	92.23	12569	1.57	15.39	5.00	1.50	30.00	1247	1.08	25.90	6.37	2.68	42.13	3045
	15	0.61	14.64	3.96	3.73	94.32	12909	0.63	11.07	1.72	0.48	27.69	1253	1.23	26.09	7.51	3.39	45.17	3509
	16	0.68	15.48	3.71	3.14	84.72	8736	0.57	14.60	3.85	1.94	50.55	683	0.78	28.43	8.25	4.68	56.75	3281
	17	0.53	16.89	3.84	2.82	73.38	7980	0.88	15.62	2.80	1.47	52.59	580	0.54	24.55	7.55	3.41	45.16	3587
Northern	18	0.54	19.84	4.44	2.65	59.79	8374	0.52	13.15	1.23	0.83	67.25	1954	0.53	20.96	7.14	5.42	75.89	3403
	19	0.56	19.43	4.21	3.20	76.04	12529	1.51	20.25	5.78	4.75	82.16	358	0.63	30.25	7.14	5.42	75.93	3403
	20	0.59	16.05	4.78	4.14	86.57	14888	0.78	19.62	5.37	2.07	38.52	496	0.59	24.12	5.98	3.28	54.82	3189
	21	1.22	16.17	4.79	1.43	29.85	15521	0.54	11.16	2.63	1.71	65.01	91	0.59	22.86	4.77	3.62	75.93	3209
	22	1.53	15.07	4.62	3.93	84.90	15807	0.53	16.31	2.71	2.11	77.97	249	0.72	11.91	2.98	1.75	58.81	3280
	23	2.32	8.71	4.82	3.75	77.90	12274	0.63	19.29	4.07	2.31	56.75	434	0.68	32.30	8.24	6.28	76.22	2829
	24	2.36	11.04	4.93	2.09	42.39	11622	1.59	16.13	5.68	8.05	141.87	44	0.52	29.19	9.85	4.59	46.64	2908
	25	3.22	22.83	7.61	3.74	49.15	7363	0.59	26.02	4.98	6.87	137.97	44	0.60	26.92	5.78	5.40	93.50	2920

Min=Minimum, Max=Maximum, M= Mean, SD= Standard Deviation, CV=Coefficient of Variation, N= Number of pixels

Appendix – II continued

Spatial and temporal distribution of SSCs (mg/l) in three sectors derived from OCMin October, November and December 2011.

Sector	Subsectors (10' along x 40' across)	October						November						December					
		Min	Max	M	SD	CV (%)	N	Min	Max	M	SD	CV (%)	N	Min	Max	M	SD	CV (%)	N
Southern	1	1.57	16.62	4.31	3.84	89.06	16559	0.63	9.76	1.61	0.63	39.43	14990	0.57	9.85	2.40	0.33	13.94	15676
	2	0.77	17.61	3.65	3.21	88.13	16086	0.69	31.80	2.07	1.73	83.65	13800	0.60	3.85	3.65	0.08	2.132	16852
	3	0.72	22.46	3.74	3.00	80.10	14733	0.76	20.75	2.18	1.16	53.06	14313	0.79	2.98	5.45	0.03	0.608	15701
	4	0.87	26.94	4.09	3.73	91.17	14781	0.82	3.18	1.90	0.25	13.38	15564	0.66	5.07	4.45	0.15	3.262	15454
	5	1.68	25.68	4.58	3.60	78.71	13996	0.74	5.47	1.86	0.33	17.83	15638	0.74	2.67	4.98	0.03	0.605	14763
	6	1.49	30.53	5.07	4.10	80.80	13441	0.75	17.04	2.30	0.95	41.18	15237	0.80	3.45	2.33	5.67	243.3	15663
	7	0.84	28.36	6.40	5.29	82.62	13820	0.93	22.74	2.79	1.53	54.98	15230	1.06	7.54	3.45	3.50	101.4	16972
Central	8	0.83	38.97	6.96	5.97	85.84	12471	0.90	17.77	3.05	2.85	93.29	16134	1.30	6.58	2.26	0.12	5.331	16824
	9	1.15	36.17	5.70	4.89	85.81	14216	1.35	13.24	3.50	3.68	105.08	16268	1.41	9.42	2.69	0.20	7.574	16895
	10	0.70	38.98	5.80	5.33	91.86	14953	1.22	17.56	3.71	3.65	98.41	16290	1.62	8.62	3.25	1.47	45.21	16947
	11	1.07	23.52	6.13	5.94	96.93	15544	0.76	34.82	4.46	3.89	87.17	15798	1.55	9.24	3.09	1.28	41.31	17407
	12	0.91	33.39	8.01	7.96	99.42	15968	0.70	25.36	5.25	4.88	92.95	14513	1.45	6.53	3.00	1.12	37.46	17361
	13	0.54	31.55	8.50	8.31	97.81	14040	0.62	19.03	5.14	5.11	99.49	16798	1.48	9.76	3.44	1.32	38.22	18017
	14	0.57	36.70	5.61	5.13	91.47	14599	1.91	12.50	4.37	4.28	98.12	16340	1.24	7.60	3.45	1.22	35.31	17103
	15	0.80	29.19	5.44	5.40	99.20	10730	1.92	20.59	4.15	3.99	96.10	16286	1.69	7.73	3.18	1.05	32.92	17157
	16	0.76	36.15	7.00	6.58	94.09	10985	2.47	9.21	4.33	4.12	95.22	16391	1.65	10.07	4.41	1.78	40.27	17026
	17	0.75	36.93	6.66	6.58	98.78	8540	2.65	11.38	4.92	4.78	97.15	16356	1.86	21.02	5.03	1.64	32.58	17059
Northern	18	0.76	37.40	8.65	10.00	115.60	841	3.03	10.96	5.28	3.34	63.24	4114	1.87	11.10	4.84	1.88	38.91	17179
	19	0.56	24.43	3.47	3.24	93.29	5201	1.56	12.68	4.90	4.23	86.35	4118	1.85	10.68	7.06	1.94	27.54	17197
	20	0.55	22.35	3.12	2.22	70.97	11087	0.68	30.13	4.96	4.01	80.87	3721	1.62	13.19	4.13	0.19	4.501	17398
	21	0.59	14.34	3.66	1.66	45.30	12561	0.66	14.42	4.85	3.18	65.58	4011	1.66	10.09	5.73	2.12	36.99	17075
	22	0.58	8.37	3.10	1.08	34.79	14586	0.99	18.91	4.78	3.01	63.05	2795	1.64	5.60	6.67	2.08	31.15	16502
	23	1.30	8.68	3.92	0.90	23.00	11297	2.56	6.64	4.72	3.04	64.38	2995	1.74	9.99	8.52	3.11	36.46	12677
	24	1.66	11.12	4.75	1.50	31.64	10726	1.51	8.76	4.78	2.20	46.01	2833	1.87	12.91	5.48	0.14	2.569	12041
	25	1.33	15.94	6.61	2.39	36.24	6469	1.55	14.90	5.65	0.12	2.07	1788	1.07	20.01	9.27	2.19	23.58	7863

Min=Minimum; Max=Maximum; M=Mean; SD= Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix -III

Spatial and temporal distribution of SSCs (mg/l) in three sectors derived from OCM in January, February and March 2012.

Sector	Subsectors (10' along x 40' across)	January						February						April					
		Min	Max	A	SD	CV(%)	N	Min	Max	A	SD	CV (%)	N	Min	Max	A	SD	CV (%)	N
Southern	1	0.510	8.513	1.25	0.33	26.15	10948	0.61	6.07	1.22	1.18	96.54	16243	0.54	13.79	0.86	0.72	83.33	6387
	2	0.51	10.72	1.33	0.09	6.43	14158	0.70	2.16	1.23	1.07	86.81	16376	0.56	18.24	1.40	1.11	79.05	4566
	3	0.53	10.04	1.35	0.11	8.09	14890	0.76	2.45	1.31	1.03	78.57	15836	0.68	14.65	1.90	1.94	102.36	7117
	4	0.81	8.20	3.95	2.58	65.43	10760	0.84	2.33	1.39	1.17	83.95	15675	0.70	13.68	5.38	2.43	45.17	4295
	5	0.73	7.27	4.66	3.18	68.29	16028	0.75	2.42	1.52	1.10	72.60	15987	0.52	12.58	0.99	0.82	83.56	11994
	6	0.82	8.43	5.93	4.15	69.87	16114	0.57	4.09	1.81	1.09	60.34	16761	0.58	19.64	0.90	0.57	63.19	14836
	7	0.98	9.23	4.99	4.13	82.74	16796	1.24	9.97	2.14	1.20	56.03	17612	0.54	3.98	1.07	0.99	92.35	13515
Central	8	0.82	15.99	2.70	2.11	77.90	16205	0.69	19.69	2.43	2.20	90.48	13748	0.59	3.68	1.16	0.33	28.77	13748
	9	0.99	20.25	3.55	2.58	72.83	14893	0.81	27.96	2.68	2.12	79.02	16545	0.58	5.11	1.54	0.68	43.86	16545
	10	1.21	28.86	3.75	3.50	93.24	15557	0.86	21.33	2.70	2.00	74.19	96133	0.65	3.03	1.42	0.88	62.08	96133
	11	1.22	15.19	3.36	3.21	95.63	17209	1.04	20.48	2.64	2.50	94.80	14747	0.74	5.13	1.58	0.89	56.49	14747
	12	1.47	5.85	2.98	2.62	87.82	17186	0.88	18.48	2.37	2.17	91.53	15843	0.71	8.41	1.53	0.98	64.16	15843
	13	1.65	10.10	3.30	3.22	97.51	17862	0.77	14.05	3.25	3.12	95.94	17162	0.85	6.55	2.33	1.11	47.54	17162
	14	1.72	7.88	3.53	3.31	93.85	16891	1.31	8.57	2.82	2.12	75.21	56757	0.62	3.21	1.69	0.76	44.87	56757
	15	1.00	15.13	3.14	3.13	99.92	15002	0.92	11.46	2.58	2.28	88.21	16981	0.87	10.06	2.33	1.91	82.02	16981
	16	0.56	24.32	3.79	3.65	96.27	15131	1.32	11.45	3.70	3.20	86.49	17060	0.86	6.32	2.51	1.15	45.73	17060
	17	0.62	30.42	5.14	5.12	99.56	14560	2.00	12.44	4.01	3.89	96.89	16508	0.60	10.60	3.15	1.68	53.20	16508
Northern	18	0.62	29.26	5.48	0.34	6.27	15296	1.71	12.84	4.38	0.17	3.78	16458	0.67	9.84	2.89	1.67	57.84	16458
	19	0.86	24.39	5.10	2.62	51.33	10792	2.02	10.36	4.20	2.18	51.86	16985	0.66	9.67	2.24	1.35	60.03	16985
	20	0.68	31.28	4.97	2.13	42.88	14407	1.38	14.88	4.05	3.17	78.18	17197	0.51	7.87	1.94	1.17	60.47	17197
	21	1.36	11.77	4.76	2.12	44.51	12344	1.06	30.08	4.24	3.23	76.18	16648	0.52	5.62	1.67	1.03	61.66	16648
	22	1.58	10.25	4.53	2.06	45.46	11651	0.82	27.98	4.43	2.12	47.82	11927	0.51	5.73	2.09	1.02	49.04	11927
	23	2.04	11.23	3.94	2.68	67.96	12308	0.77	15.13	3.93	2.11	53.69	10896	0.51	10.05	2.82	1.82	64.61	10896
	24	1.42	5.89	3.44	3.12	90.59	8968	1.00	14.93	3.88	2.22	57.22	11850	0.50	7.95	1.97	1.23	62.39	11850
	25	2.32	25.80	6.15	4.56	74.10	6234	1.27	23.93	5.32	2.45	46.07	6628	0.52	13.04	2.92	2.30	78.77	6628

Min=Minimum; Max=Maximum; M= Mean; SD= Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix – III continued

Spatial and temporal distribution of SSCs (mg/l) in three sectors derived from OCMin May, July and September 2012.

Sector	Subsectors (10' along x 40' across)	May						July						September					
		Min	Max	A	SD	CV (%)	N	Min	Max	A	SD	CV(%)	N	Min	Max	A	SD	CV(%)	N
Southern	1	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.64	12.45	1.60	1.52	94.91	1185
	2	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.95	5.15	1.45	0.56	38.79	475
	3	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	0.75	5.05	1.61	0.55	34.24	493
	4	0.58	27.06	2.66	8.26	310.15	47	0.79	29.69	2.29	1.54	67.22	1254	0.94	8.71	2.20	1.46	66.27	795
	5	1.00	2.86	1.02	0.29	28.15	2025	1.61	29.88	5.35	5.46	102.06	2720	0.93	15.69	1.38	0.91	65.74	512
	6	0.79	33.59	2.86	2.35	82.45	2239	0.78	36.71	3.22	2.80	87.19	1537	0.99	25.06	3.95	3.06	77.50	4154
	7	1.56	28.90	4.39	1.98	45.15	2890	0.61	25.85	5.88	4.93	83.71	10524	1.23	32.94	6.43	5.29	82.27	832
Central	8	1.56	29.98	5.62	4.45	79.23	2337	0.68	23.28	6.35	4.46	70.18	6856	0.66	35.75	6.45	4.95	76.74	2838
	9	0.99	35.93	5.17	3.87	74.90	1265	0.80	35.12	4.74	3.85	81.36	2997	0.72	15.89	4.95	3.26	65.78	1770
	10	0.78	37.58	5.46	5.30	97.04	901	0.85	29.98	6.84	6.80	99.44	2747	1.02	8.68	2.91	1.85	63.68	1684
	11	1.80	10.22	2.36	1.92	81.24	109	4.60	29.40	5.02	4.68	93.27	4238	1.24	5.10	1.75	0.75	43.06	1376
	12	0.57	12.10	2.66	1.70	63.73	1343	0.78	3.90	1.90	1.20	63.16	34	0.96	8.77	2.14	0.97	45.15	5250
	13	0.99	24.75	7.11	3.12	43.87	3574	0.53	3.22	1.47	0.69	47.19	31	0.82	24.28	4.23	2.75	65.01	6588
	14	1.05	29.78	5.54	2.29	41.30	2880	0.63	35.36	4.45	3.27	73.38	2752	1.29	10.00	3.10	1.79	57.68	1186
	15	1.52	29.78	5.17	2.94	56.90	2549	0.64	39.78	4.78	3.19	66.74	3945	1.01	4.96	1.97	0.75	38.19	1504
	16	0.57	19.84	8.00	7.35	91.85	2196	0.78	35.93	2.76	3.40	122.88	670	1.00	3.04	1.43	0.71	49.70	232
	17	1.04	20.30	11.31	9.02	79.77	2002	0.78	20.31	7.53	4.63	61.53	373	0.78	6.32	2.83	1.27	44.81	3518
Northern	18	1.12	20.69	9.94	8.35	84.00	1589	0.72	27.67	4.38	3.53	80.75	3601	1.28	33.76	1.57	0.65	41.08	554
	19	0.68	19.45	5.87	4.28	72.84	1953	0.97	21.44	3.65	2.53	69.44	1848	0.96	23.01	1.57	0.61	39.02	304
	20	1.06	20.81	6.26	3.26	52.09	1686	0.77	37.75	7.48	7.15	95.55	517	0.83	22.48	1.43	0.38	26.56	356
	21	1.00	10.26	3.60	2.11	58.51	562	0.78	32.81	6.24	5.50	88.05	932	0.92	25.16	2.17	1.12	51.45	260
	22	0.78	20.60	4.06	2.99	73.59	1499	0.78	38.21	7.29	6.44	88.39	2114	NA	NA	NA	NA	NA	NA
	23	0.88	22.91	6.10	3.99	65.33	1718	0.89	35.15	8.90	7.90	88.76	1234	NA	NA	NA	NA	NA	NA
	24	1.02	35.12	12.73	7.77	61.00	2500	0.82	32.05	9.12	7.11	77.88	174	NA	NA	NA	NA	NA	NA
	25	1.10	19.90	21.81	8.25	37.83	2361	0.78	31.82	11.36	8.42	74.15	48	NA	NA	NA	NA	NA	NA

Min=Minimum; Max=Maximum; M=Mean; SD= Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix – III continued

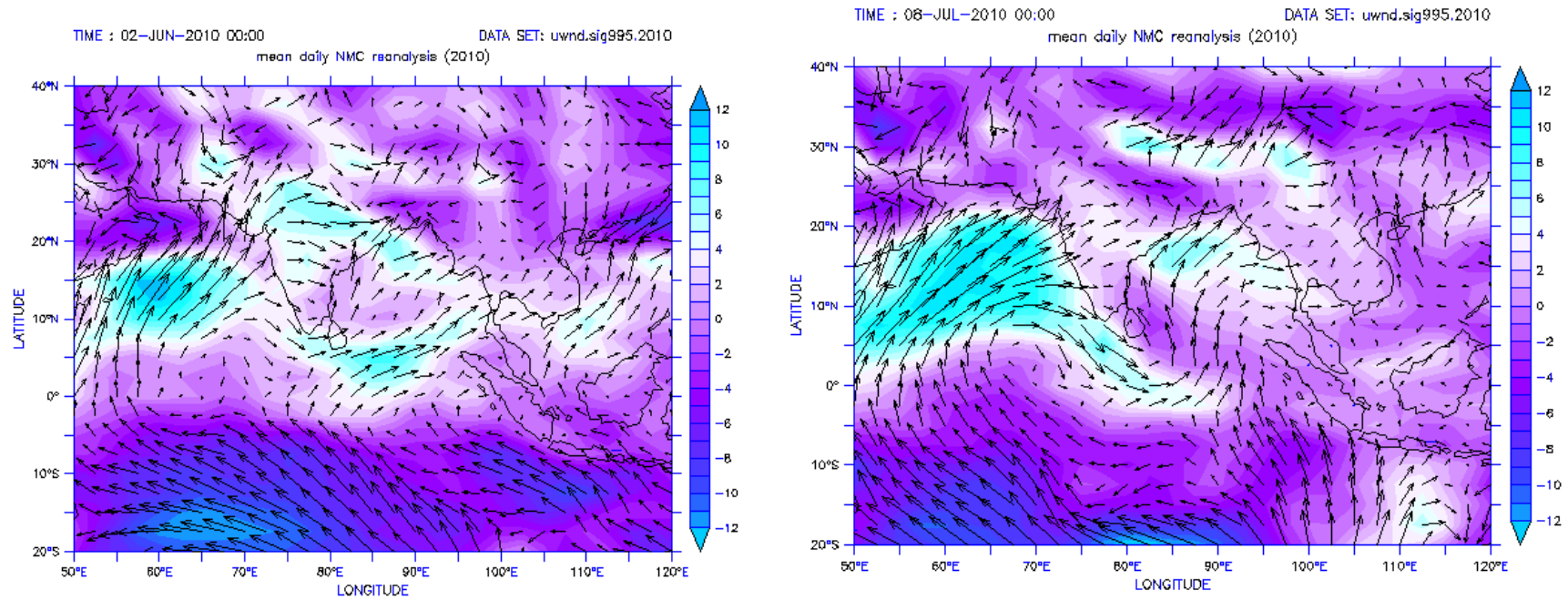
Spatial and temporal distribution of SSCs (mg/l) derived in three sectors from OCM in October, November, and December 2012.

Sector	Subsectors (10' along x 40' across)	October						November						December					
		Min	Max	A	SD	CV(%)	N	Min	Max	A	SD	CV(%)	N	Min	Max	A	SD	CV(%)	N
Southern	1	0.78	13.76	1.34	0.95	70.90	1223	0.66	27.25	5.95	6.00	100.98	4855	1.47	4.17	2.80	0.39	13.84	22276
	2	0.89	12.89	2.3	1.98	86.09	2344	1.11	26.73	3.60	2.35	65.41	11913	0.79	20.03	3.01	1.14	37.80	21558
	3	1.9	14.8	2.89	1.23	42.56	198	0.67	12.58	3.48	2.61	75.12	15389	0.92	24.99	3.11	1.09	35.06	21777
	4	0.89	12	1.34	0.89	66.42	234	1.96	5.38	3.77	3.25	86.24	15675	1.50	6.07	3.36	1.22	36.28	22711
	5	0.61	18.53	1.27	0.56	44.43	2681	2.15	11.16	4.24	3.51	82.93	15811	1.21	13.96	3.39	1.76	51.94	21134
	6	1.62	18.89	0.88	1.15	129.74	1036	2.42	18.54	5.02	4.31	85.88	14904	1.54	13.03	10.78	5.78	53.62	22042
	7	0.91	20.62	0.50	1.16	229.47	464	1.29	28.47	5.82	3.50	60.14	15321	0.73	31.49	4.39	3.14	71.58	19588
Central	8	0.79	30.79	1.30	1.62	124.51	6437	0.67	36.93	5.41	5.39	99.65	15201	0.64	30.02	4.76	3.29	69.14	22003
	9	0.66	29.30	2.32	1.81	78.09	5068	1.76	9.13	5.10	4.99	97.90	16197	0.73	33.28	5.12	4.12	80.43	19445
	10	1.02	38.90	3.51	1.34	38.25	3226	2.25	10.59	5.01	4.99	99.60	16329	0.75	28.28	4.13	3.65	88.28	21126
	11	0.43	29.99	2.24	1.50	67.14	3608	2.35	7.41	4.24	4.21	99.40	16508	1.91	7.00	3.53	3.22	91.22	23942
	12	0.54	18.96	0.92	0.49	53.64	12375	2.72	7.37	4.40	4.39	99.67	16584	1.93	11.78	3.90	3.67	93.99	23628
	13	0.61	34.14	1.09	0.99	90.47	13154	2.21	11.72	5.35	5.30	99.15	17323	2.21	7.83	3.88	2.89	74.66	23561
	14	0.76	31.86	4.03	0.87	21.67	4783	1.91	13.77	6.00	5.98	99.71	15007	2.23	8.78	4.09	3.08	75.46	23455
	15	0.99	26.60	2.16	0.92	42.77	5846	3.07	10.01	5.30	5.29	99.89	16456	1.84	12.11	5.46	4.79	87.70	23582
	16	1.00	29.62	2.45	1.48	60.50	1683	2.93	10.49	5.42	5.33	98.34	16311	1.25	26.16	5.85	4.33	74.07	23125
	17	0.58	20.14	1.76	1.25	70.84	8247	3.27	12.00	6.57	6.49	98.72	16331	2.14	13.01	5.84	4.76	81.48	22088
Northern	18	0.70	32.13	2.69	1.44	53.54	5386	1.70	15.64	6.35	1.95	30.69	16444	1.49	20.33	5.61	1.95	34.74	22356
	19	0.60	23.10	1.45	1.20	82.30	10492	1.83	24.41	5.23	1.96	37.56	16035	0.69	28.88	5.48	3.05	55.54	20075
	20	1.12	32.29	1.63	2.21	135.68	8574	1.14	18.83	5.02	1.23	24.53	16584	1.23	26.35	4.96	2.10	42.27	21291
	21	0.66	23.70	2.42	1.59	65.99	7726	1.65	13.92	4.84	1.46	30.09	16444	2.05	9.49	4.96	1.17	23.65	16189
	22	0.99	18.03	0.74	0.54	72.06	5571	2.06	8.82	4.33	0.91	20.94	15764	1.55	19.92	5.04	1.33	26.47	16628
	23	0.76	31.55	3.19	1.43	44.79	6892	2.06	9.46	4.03	1.17	28.98	11957	1.51	12.07	6.01	1.49	24.75	15741
	24	0.61	28.31	4.61	1.59	34.47	5212	1.79	21.11	5.72	3.02	52.84	6808	1.98	20.56	6.36	2.80	43.95	9784
	25	0.73	34.48	4.52	5.17	114.34	4193	0.81	19.26	4.12	2.10	50.83	7084	0.61	19.46	5.94	2.55	42.87	4299

Min=Minimum; Max=Maximum; M= Mean; SD= Standard Deviation; CV=Coefficient of Variation; N= Number of pixels

Appendix –IV

The daily mean wind speed and direction derived from NMC reanalysis for the period of 2nd June and 8th July 2010.



List of Publications

Research Papers:

1. **N. Sravanthi**, I.V. Ramana, P. Yunus Ali, M. Ashraf, M.M. Ali, and A.C. Narayana. 2013. An algorithm for estimating suspended sediment concentrations in coastal waters of India using remotely sensed reflectance and its application to coastal environments. *International Journal of Environmental Research*, 7(4), 841-850
2. **N. Sravanthi**, R. Ramankrishana, A. S. Rajawat, and A.C. Narayana. 2015. Application of numerical model in suspended sediment transport studies along the central Kerala, west coast of India. *Aquatic Procedia*, 4, 109-116.

Papers presented in seminars/conferences:

1. A.C. Narayana, **N. Sravanthi** and P. Yunus Ali. Suspended sediment concentrations in the coastal waters of north-west India derived from ocean color monitor onboard Oceansat. *International Asia Oceania Geosciences Society conference*, Taipei, Taiwan, 08-12th August, 2011
2. **N. Sravanthi** and A.C. Narayana. Temporal variations of suspended sediment concentrations in the coastal waters of the Bay of Bengal using high resolution ocean colour data. *International Asia Oceania Geosciences Society conference*, Singapore, 13th-17th August, 2012.
3. **N. Sravanthi**, P. Yunus Ali, I.V. Ramana, P. Muhamed Ashraf, T. Srinivas Kumar, M. M. Ali and A.C. Narayana. Validation of suspended sediment concentrations derived from satellite data with *in situ* measurements. *International Pan Ocean Remote Sensing Conference*, Cochin, 05th-09th November, 2012.
4. **N. Sravanthi** and A. C. Narayana. Remotely sensed spatial and temporal distribution of suspended sediment concentrations in coastal waters of southwest of India. *A. P Science congress*, University of Hyderabad, 14th-16th November, 2013.
5. **N. Sravanthi** and A. C. Narayana. Satellite derived suspended sediment concentrations in coastal waters and their simulations with MIKE-21 Model. *International Asia Oceania Geosciences Society conference*, Sapporo, Japan, 28th July to 1st August, 2014.