

Environmental characteristics of tropical coral reef-seagrass dominated lagoons (Lakshadweep, India) and implications to resilience to climate change

E.P. Nobi^{*}, P.K. Dinesh Kumar[†]

^{*}Ministry of Environment and Forests, Paryavaran Bhavan, C.G.O Complex, Lodhi Road, New Delhi

E-mail: nobiep2007@gmail.com, Tele-Fax: +91-11-24362434

[†]CSIR-National Institute of Oceanography, Regional Centre, Dr. Salim Ali Road, Kochi – 682 018, India

Abstract: Environmental characteristics of the coral reef-seagrass ecosystem of selected Lakshadweep Islands (India) were assessed with a view to understanding the future climate change scenario in the region. Images obtained from the Indian Remote Sensing Satellite (IRS P6) were used to identify the different zones such as the corals, the seagrass and the sandy region. The pH (7.6-8.6) of sediment was relatively high in the coral reef compared to the seagrass area, possibly indicating a climate shift -induced coral bleaching. The water quality and sediment texture generally showed marked intra- and inter-island variations illustrating that these coral reef ecosystems are highly vulnerable to climate change brought about by increased human interventions. Future research should therefore explore the habitat and resource connections, to predict their restoring capabilities for a sustainable exploitation. With an alarming increase in the population and associated developmental activities, the island ecosystems are expected to respond severely to the climate change, which may eventually lead to mass mortality of corals due to bleaching.

Keywords: Ecosystem, Atoll, Ocean acidification, sediment pH, IRS P6.

Introduction

Coral reefs, also known as *rainforests of the sea*, are some of the most diverse ecosystems on earth (Davidson 1998). The health, abundance and diversity of organisms of coral reef ecosystems are directly linked to the surrounding marine environment. Seagrass beds are an important facet of the coral reef ecosystem. Tropical seagrass is unique, as it stabilizes the coral environment and also provides support to the biological communities around (Amesbury and Francis 1988). However, it has been recently observed that coral reefs and seagrasses are facing unprecedented pressure on local, regional and global scales (D'Elia et al. 1991). Similarly, the impacts of non climatic anthropogenic disturbances on a global scale have been the subject of discussion for a long time (Smith and Buddemeier 1992). Although the effect of climatic change on coral bleaching has stimulated considerable interest worldwide, very little information is available for the Lakshadweep Islands (Vivekanandan et al. 2009).

The extent to which an ecosystem can withstand climatic disturbance without changing itself was first explained by Holling (1973). Thus, the different ways of ecosystem adaptations were between efficiency and persistence, constancy and change and, predictability and unpredictability. The resilience of an ecosystem generally refers to its capacity to recover or withstand disturbances (McCook et al. 2007; Nystrom et al. 2008). In many ecosystems, resilience is normally maintained by structuring the processes that interfere with multiple sources (Gunderson 2000). An ecosystem's ability to absorb or recover from impacts depends on the ability of existing species or habitats to mitigate the disturbance. Thus, it is apparent that a single mechanism alone cannot bring out resilience to a disturbed ecosystem (Gunderson 2000).

Since the health and growth of coral and seagrass are regulated by several factors, the environmental monitoring of the coral ecosystem is a challenging study (Bulthuis 1983; Haynes et al. 2005; Prange et al. 2007; De'ath and Fabricius 2008; Waycott et al. 2009; Ateweberhan et al. 2013). Water quality parameters are considered as indicators of seagrass and coral sensitivity (Masini et al. 1990; Funderbunk et al. 1991; Dennison et al. 1993). Zonal classification of coral reefs based on the environmental quality will be useful to establish criteria for the survival of seagrasses and corals and predict their probable degradation. Further, it can be used to protect those sensitive communities by implementing appropriate management plans.

Lakshadweep islands are the only island groups in India possessing coral atolls with extensive seagrass meadows. Lakshadweep islands, known for their diverse flora and pristine nature, are

progressively facing serious threats due to various factors (Desai et al. 2003; Arthur et al. 2006; Anu et al. 2004; Thangaradjou et al. 2009). The environmental characteristics of this ecosystem are subjected to severe alterations causing disappearance of seagrass beds (Nobi et al. 2013). In recent years, there has been considerable decline in the live coral reef tract due to coral diseases following bleaching events (Ravindran and Raghukumar 2006; Arthur et al. 2006).

The expanse and density of corals and seagrasses in India have significantly declined over the years (SAC 2006). In order to conserve the islands and their coastal habitats, there is an urgent need for continuous monitoring of the habitats at regular intervals to suggest remedial measures for optimum utilization of resources. In view of the above, the present study investigates the characteristics of the different zones of the coral lagoons of Lakshadweep islands, India based on *in situ* data and satellite images. In addition, an assessment has also been made to forecast the possible impacts of climate change on this fragile island ecosystem.

Study area

The Lakshadweep group of islands are scattered between the latitude 8⁰- 12⁰ N and longitude 71⁰-74⁰ E in the Arabian Sea at about 200 to 400 km off Kerala, the southernmost state of India (Fig. 1). It consists of 36 islands, out of which, only 10 (Minicoy, Kalpeni, Androth, Kavarathi, Agathi, Amini, Kadamath, Kilthan, Chethlath and Bitra) are inhabited. The general topography of the islands is hummocky to flat with steeper shore on the east. The coralline islands are fringed by beach materials all around the islands. They are largely composed of coarse sand, disintegrated corals, shell fragments and uncemented pebbles. The western sides of the islands are fringed with coralline reefs enclosing the lagoon. Erosion is more pronounced towards the eastern side.

The islands in general are narrow, arcuate and are positioned on the eastern rims of the atolls. The lagoon is 3-5 m deep and the outer slopes of the atoll drop steeply to depths of several hundred meters. The islands have a humid, warm and pleasant climate. The temperature ranges from 27⁰ to 33⁰C. Five islands (Kavarathi, Agathi, Kadamath, Thinnakkara and Bangaram) were focused on for the present study (Fig. 1).

Materials and Methods

Indian Remote Sensing Satellite, IRS P6 LISS IV cloud free satellite data of Kavarathi, Agathi, Bangaram, Thinnakkara, and Kadamath islands were selected for the present study (Fig. 1). Satellite

image preprocessing was done with the aid of ERDAS Imagine 9.2, and ArcGIS software was used for spatial analysis of the water and sediment characteristics. An eTrex, Garmin Global Positioning System (GPS) receiver was used to determine the coordinates of the sampling sites in terms of its latitude, longitude, and altitude. All GPS files were downloaded and exported to the GIS platform and were superimposed on the geometrically corrected satellite image.

Sampling sites were chosen depending upon the environmental setting of the lagoon habitats in different islands. Schematic representation of the sampling locations, station numbers, and depth of the water column are given in Fig. 1. Water and sediment samples were collected from the waters adjacent to the five islands mentioned above. Samples were collected from seagrass, coral reef and sandy environments at 25 locations each at Kavarathi, Agathi and Kadamath islands and 15 locations each at Bangaram, and Thinnakkara islands, based on the extent of lagoon area of these islands. Sampling was done during January and February, 2009. Surface water samples were collected in plastic bottles and transported immediately to the shore laboratory. Sediment samples were collected with a stainless steel corer having internal plastic lining. Sub samples were carefully skimmed and kept in ice boxes for analysis.

Surface water temperatures were measured with a LCD portable Digital Multi-Stem thermometer (Mextech multi-thermometer). Soil pH was recorded using a field soil pH pen (Takemura Electric Works Ltd.). Water turbidity was determined using a digital Nephelo turbidity meter (132, Systronics). Electrical conductivity of the sediment samples was recorded using EC-TDS analyzer (CM 183, Elico). Sediment grade analysis was done for soil samples in polythene bags collected from the sampling sites. Samples were air dried and sieved through a mechanical sieve to remove shells, coral pieces etc. and the dried samples were subjected to size fraction analysis following the procedure of Udden modified by Wentworth (1922). Samples (100 g dry wt) were sieved through a mesh (62 μ) for ten minutes in a sieve shaker. The sediment fraction (sand) remain in the sieve was weighed. The sediment fraction passed through the 62 μ sieve was silt and clay and was separated by means of pipette method (Lindholm 1987).

Pearson Correlation Coefficient was employed for a better understanding of the relationship between the physic-chemical parameters in the seagrass and coral reef ecosystems using statistical package of SPSS11.5. A Dendrogram was constructed to trace the relationship of sampling stations with respect to ecosystem.

Results

The satellite imagery clearly depicts the distribution and boundary of seagrasses, coral reefs and sandy zones in different islands studied (Fig. 1). Atoll formation which encircles the islands with a lagoon in between also could be observed. Most of the coral reef formations are found outside the lagoon and seagrasses are found distributed mostly in the areas towards the shoreline. Sandy zones are found in between seagrass meadows and adjunction between coral and seagrass. The satellite data thus provided information of the environmental setting of different habitats of the study area and enabled accurate fixing of the sampling locations.

Of the 25 stations in Agathi, Kavarathi and Kadamath islands, 10 stations each represent the coral reef and seagrass zones and the remaining stations represent sandy areas (Fig. 1). In Bangaram, and Thinnakkara, 8 of the 15 stations fixed represent seagrass, 4 stations represent coral and 3 stations represent sandy zones. Surface water temperature in the five islands varied between 27.8 and 31.5⁰C (Fig. 2a-e). The spatial distribution map of Agathi portrays higher surface water temperature in the coral reef areas which was found to lower toward the northern part of the lagoon and showed an even distribution in the seagrass environment. In the case of Bangaram and Thinnakkara islands, higher temperature was recorded in the north-west part (seagrass zones). The spatial distribution map of Kadamath and Kavarathi showed higher temperature in the southern and middle zones of the lagoon.

Fig. 3a-e represents the spatial distribution map of the Turbidity recorded from the study area. Turbidity ranged from 0.8 to- 3.8 NTU. Turbidity showed clear variation between different habitats with higher value (3.8 NTU) in the seagrass areas and mostly in the northern and southern part of the islands.

Sediment pH showed apparent spatial variation with respect to different habitats viz. the coral reef areas recording higher pH (Fig. 4a-e) compared to the seagrass and sandy regions. Intra-island variation in spatial distribution pattern of sediment pH was clearly visible during the study. The sediment pH at Agathi ranged between 7.6 and 7.9 (Fig. 4a); whereas at Bangaram and Thinnakkara, it ranged from 7.8 to 8.4 (Fig. 4b-c). Kadamath, which has the higher spatial seagrass coverage, recorded lower sediment pH (7-7.4; Fig. 4d) and Kavarathi recorded higher pH ranging from 8.1 to 8.4 (Fig. 4e).

Electrical conductivity (EC) recorded in the present study varied between 3.4 and 5.7 dSm⁻¹ (Fig. 5). Significant positive correlation was obtained between EC and soil pH in Kavarathi and Agathi ($r=0.984$, $P<0.05$) and Thinnakara ($r = 0.999$, $P<0.05$) islands. Lower spatial distribution of EC was found

in the sandy areas of most of the islands. In Kavarathi island (Fig. 5e), higher EC was recorded in the northern and southern part of the lagoon.

Sand (Fig. 6), silt (Fig. 7) and clay (Fig. 8) showed wide fluctuations with respect to the adjacent ecosystem of the islands. During the present investigation, sand was found to be the major component followed by silt and clay in the sedimentary composition. Increase in sand content will normally decrease the percentage of silt in the sediments, as evidenced by the negative correlation obtained between sand and silt {($r = -0.997$, $P < 0.05$ at Kavarathi), ($r = -0.993$, $P < 0.05$ at Agathi), ($r = -0.998$, $P < 0.05$ at Thinnakkara), and ($r = -0.999$, $P < 0.05$ at Kadamath)}. Percentage of clay in the sediments varied from 0.1 to 0.83 % with higher percentage in the coral reef area at Kavarathi.

Along with water quality and substratum characteristics, the amount of light available significantly affects the spatial distribution and growth of seagrass in the coral reef environment. Table 1 presents sampling locations in different islands along with average depth range in different habitats in the study area. In the Lakshadweep islands, seagrasses are generally distributed in the shallow waters towards the shoreline. During the present study, seagrasses are found distributed at depths ranging from 0.1 to 4 m. Seagrasses at Bangaram and Thinnakkara occur in shallow depth (0.1-2.5 m) and are exposed to sunlight during low tide, whereas at Kadamath, seagrasses are distributed in the deeper part of the lagoon. Corals of Lakshadweep are of atoll formation and are distributed at depths ranging from 2 to 5 m in the study area. Sandy bottom is encountered in different depth ranges of 0.1 -6 m and are scattered in between seagrass-coral reef areas and also towards the shoreline. At Kadamath island, the sandy region is visible at a depth of 6 m adjacent to coral patches.

Discussion

The major threat to coral reefs is the global warming as a consequence of climate change, though other factors such as changes in tidal regimes, UV radiation, oxygen depletion etc. also influence their health. It has been observed that Indian Seas were unusually warm during 1998 and 2005, which resulted in large-scale bleaching and mortality of corals (Vivekanandan et al. 2008). There was an increase in the mean sea surface temperature (SST) from 28.5°C to 28.92°C during 1985-, which even increased to 31°C in 1998 causing intense coral bleaching (Vivekanandan et al. 2008). Though this kind of increased sea surface temperature leading to coral bleaching has generated concern (Arthur 2000; Vivekanandan et al. 2009; Sheppard 2003), few studies have been done on the long term impacts of climate changes on the seagrass ecosystems of this region.

Climate change studies of the above magnitude require a dual approach integrating both mitigation and resilience. The resilience is the ability of the coral and seagrass ecosystems to adapt with climate variations without undergoing functional changes. In simple terms, it is the ability to survive, recover, and thrive in changing climatic conditions. It includes the ability to overcome the potential impacts due to events such as increased temperature or environmental quality and maintain its normal functions.

The surface waters during the present study were relatively warmer compared to the previous years (Goswami 1983; Desai et al. 2003). The sensitivity of different species of corals varies widely for temperate and tropical waters. Water temperatures exceeding 25°C in temperate and 43°C in tropical regions respectively, would destroy all the seagrasses (Biebl and McRoy 1971; Campbell et al. 2006; Almela et al. 2007; Ehlers et al. 2008). A warming beyond this threshold limit will affect the entire flora of the coral reef and trigger micro-algal growth.

Increasing trends in the ocean acidification following sea surface warming is also supported by factors operating at regional and local scales such as nutrient enrichment and turbidity (Reopanichkul et al. 2009). The turbidity of the lagoon waters in the present study ranged from 0.8 to 3.8 NTU (Fig. 3a-e), which is very low compared to the turbidity of the Gulf of Mannar (Thangaradjou and Kannan 2007). It is evident that the turbidity was high only in the northern part of Agathi Island (Fig. 3a), while it remained uniformly high in Kavarathi (Fig. 3e) and Kadamath (Fig. 3d) islands. It is well established that growth and productivity of seagrasses are dependent on the availability of light in the water column (Campbell et al. 2008).

Ocean acidification is the most devastating event that can completely destroy marine ecosystems. Coral reefs are very sensitive to lowering of pH (Albright et al. 2013), as it can affect the growth of the delicate calcareous shell forming organisms. In the present study, the sediment pH in the five islands was marginally higher in the coral reefs compared to the seagrass area (Fig. 4a-e). This generally indicates that the coral reefs of this area are not currently under the threat of ocean acidification. However, the El Nino event of 1998 had a disastrous effect on the Lakshadweep Islands, as most of the coral reefs were exposed to bleaching (Arthur 2000; Arthur et al. 2006). This also suggests that the seagrasses are playing a vital role in maintaining the hydrogen ion concentration by consuming more of the CO₂ through photosynthesis (Nobi 2010). The growth of seagrass in turn, largely depends on the sediment characteristics because the roots forming the bulk of their biomass (60-80%), are closely

associated with the sediments (Thangaradjou and Kannan 2007). The low pH of sediments in the region may be due to humic acid produced during the decomposition of seagrasses (Kannan et al. 1998). The lowering of pH may also be due to the low Ca levels in the seagrass sediments compared to that in the coral reefs (Vinithkumar et al. 1999). Further, the alkaline conditions prevailing in the seagrass sediments have increased the electrical conductivity to 3.4-5.7 dSm⁻¹, evidencing the role of sediment metal ions in regulating the EC (Nobi et al. 2010). They have attributed the pH variations to the higher EC values of the seagrass sediments in the Andaman Islands.

The present study observed wide variations in the sediment texture with respect to sand (Fig. 6a-e), silt (Fig. 7a-e) and clay (Fig. 8a-e) of all the islands, whereas an earlier study had reported the sediment texture to be exclusively sandy in the seagrass area of Minicoy, Lakshadweep (Jagtap and Untawale 1984). The quality and texture of sediment are found to be important factors influencing the growth and morphology of seagrass. The cluster analysis could clearly identify the similarity within the respective island in seagrass and coral reef environment. It is also seen that similar zones in different islands are clustered together (Fig. 9), clearly implying that seagrass and coral reef have different environmental settings.

The corals and seagrasses during the present study in the region were found to be well adapted to the warm environment. However, since this temperature falls very close to their lethal limits, they are susceptible to mass mortality if there is any further rise in surface temperature. Responses to global climate change are very slow until it disturbs the system beyond its carrying capacity, and is then followed by shifts in their biotic properties. The present study speculates an increase of 2 °C rise in tropical mean sea surface temperature by 2100.

Coral reefs tend to fringe abundantly along the coasts during winter (>20⁰ C), when the thermocline deepened in the study region. Since coral reefs are calcifying organisms, an increase in the rate of calcification is followed by a corresponding increase in the growth of coral polyps and zooxanthellae. The corals are found to show maximum growth in clear waters because the rate of calcification and the reef accretion is light dependent (Hopley and Kinsey 1988). The impeding factors of coral reefs in the study region are sea surface warming, sea level rise and increase in levels of ultra-violet radiation, although the latter is not strictly due to climate. Changes in winds and currents can induce changes in the rain pattern, sedimentation, salinity and nutrients to influence the coral ecosystem in total. The resource mapping along with geomorphological interpretations (Nayak and Bahuguna

2001; SAC 2003; SAC 2006) has shown that there are only 2.5% of seagrass when compared to corals and other flora in Lakshadweep Islands.

The seagrasses in the Lakshadweep Islands are successfully adapted to the shallow regions of tropical marine environments (Nobi 2010) and can easily trap suspended sediments, resulting in a fall out of sediments over corals causing their mortality (Waycott et al. 2011). Seagrasses are useful for coastal protection functions promoting sediment deposition and reducing sediment loads reaching the coral reefs (Borum et al. 2004; Bjork et al. 2008). However, intertidal and shallow seas seagrasses (<5 m) are most likely to be affected by climate change, which gets subsequently transmitted to the adjacent coral reefs. Prolonged exposures to warm waters as in the shallow lagoons of Lakshadweep can be significantly reduce the seagrass productivity due to nutrient depletion and thermal stress, leading to extensive mortality. Seagrass communities that rely on coral reefs for protection from strong wave actions would suffer if the reefs are impacted. The present analysis illustrates the potential vulnerability of seagrass to climate change and its threat to the ecological stability of the coral reef-seagrass dominated lagoon of Lakshadweep. Future research should therefore explore the habitat and resource connections to predict their restoring capabilities for a sustainable exploitation. There are many such small islands globally facing multiple challenges to protect their natural resources and restore the coastal habitats. The findings from the present study can be used to develop conservation and management plans with immediate controls on waste disposal to these lagoons which cause eutrophication.

Conclusion

The ecological status of the coral reef-seagrass ecosystems in the five Lakshadweep Islands showed wide intra- and inter-island variations in water and sediment quality. The factors causing most concern were the increased sea surface temperature and ocean acidification initiating bleaching of coral reefs. This is an indication of the vulnerability of coral reefs to climate change and will be a threat to the ecological stability of the lagoons of Lakshadweep. The climate change events, mainly caused by the developmental pressures following the explosive increase in the population, are likely to bring severe damage to these sensitive coral islands in the coming decades. A dual approach integrating both mitigation and resilience is required to restore these ecosystems. The corals and seagrasses of the Lakshadweep Islands are presently found to live at temperatures close to their lethal limits, during the summer months; however, they are prone to destruction at any stage of rise in sea water temperature. With an alarming increase in the population and associated developmental activities, the island

ecosystems are expected to respond severely to the climate change, which may eventually lead to mass mortality of corals due to bleaching.

Acknowledgements

We thank Dr. T. Balasubramanian, former Dean, Centre of Advanced Study in Marine Biology, Annamalai University and Dr. S.W.A. Naqvi, Director, CSIR-National Institute of Oceanography, India for the encouragement and support. We also Thank Dr. C.T. Achuthankutty, Visiting Scientist, National Centre for Antarctic and Ocean Research (NCAOR), MoES, Goa for the critical reading of an earlier version of this manuscript. We thank Prof. Ramola Antao, consultant, Senior Cambridge English examinations in India, for editing the manuscript. The first author is thankful to the Ministry of Environment and Forests, New Delhi for the financial support and Department of Environment and Forests, Lakshadweep islands for the logistic support provided during the field investigations.

References

- Albright R, Langdon C, Anthony KRN (2013) Dynamics of seawater carbonate chemistry, production, and calcification of a coral reef flat, central Great Barrier Reef. *Biogeosciences* 10: 6747-6758
- Almela ED, Marba N, Duarte CM (2007) Consequences of Mediterranean warming events in seagrass (*Posidonia oceanica*) flowering records. *Global Change Biol* 13: 224-235
- Amesbury SS, Francis JH (1988) The role of seagrass communities in the biology of coral reef fishes: Experiments with artificial seagrass beds. *Sea Grant Quarterly* 10 (1): 1-6
- Anu G, Kumar NC, Padmalal D, Nair SM (2004) Speciation of nitrogen in the coral reef sedimentary environment of Lakshadweep archipelago, Indian Ocean. *Chem Ecol* 20 (4): 267-278
- Arthur R (2000) Coral bleaching and mortality in three Indian reef regions during an El Niño southern oscillation event. *Curr Sci India* 79: 1723-1729
- Arthur R, Done TJ, Marsh H, Harriott V (2006) Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep Islands. *Coral Reefs* 25: 427-440.
- Atweberhan M, Feary DA, Keshavmurthy S, Chen A, Schleyer MH, Sheppard CRC (2013) Climate change impacts on coral reefs: synergies with local effects, possibilities for acclimation, and management implications. *Mar Pollut Bull* 74: 526-539
- Biebl R, McRoy CP (1971) Plasmatic resistance of respiration and photosynthesis of *Zostera marina* at different salinities and temperatures. *Mar Biol* 8: 48-56

- Bjork M, Short F, Mcleod E, Beer S (2008) Managing seagrasses for resilience to climate change. IUCN Switzerland
- Borum J, Duarte CM, Krause-Jensen D, Greve TM (2004) European seagrasses: an introduction to monitoring and management. EU project Monitoring and Managing of European Seagrasses.
- Bulthuis DA (1983) Effect of in situ light reduction of density of the seagrass *Heterozostera tasmanica* (Martens ex Aschers) den Hartog in Western Port, Victoria, Australia. *J Exp Biol Ecol* 67:91-103
- Campbell SJ, Kerville SP, Coles RG, Short F (2008) Photosynthetic responses of subtidal seagrasses to a daily light cycle in Torres Strait: A comparative study. *Cont Shelf Res* 28(16): 2275-2281
- Campbell SJ, McKenzie LJ, Kerville SP (2006) Photosynthetic responses of seven tropical seagrasses to elevated seawater temperature. *J Exp Mar Biol Ecol* 330: 455-468
- D'Elia CF, Buddemeier RW, Smith SV (1991) A workshop on coral bleaching, coral reef ecosystems and global change: report of proceedings. Maryland Sea Grant College Publication no. UM-SG-TS-91-03, University of Maryland, College Park
- Davidson OG (1998) Once more to the Keys. In *The Enchanted Braid-Come to Terms with Nature on the Coral Reefs*. John Wiley & Sons, New York
- De'ath G, Fabricius KE (2008) Water quality of the Great Barrier Reef: distributions, effects on reef biota and trigger values for the protection of ecosystem health. Final Report to the Great Barrier Reef Marine Park Authority. Australian Institute of Marine Science, Townsville.
- Dennison WC, Orth RJ, Moore KA, Stevenson JC, Carter V, Kollar S, Bergstrom PW, Batiuk RA (1993) Assessing water quality with submersed aquatic vegetation. *BioScience* 43: 86-94
- Desai VV, Komarpant DS, Jagtap TG (2003) Distribution and diversity of marine flora in coral reef ecosystems of Kadamat island in Lakshadweep archipelago, Arabian Sea, India. *Atoll Research Bulletin* 506: 1-23
- Ehlers A, Worm B, Reutsch BH (2008) Importance of genetic diversity in eelgrass *Zostera marina* for its resilience to global warming. *Mar Ecol Prog Ser* 355: 1-7
- Funderbunk SL, Jordan SJ, Mihursky JA, Riley D (1991) *Habitat Requirements for Chesapeake Bay Living Resources*. 2nd edition, Chesapeake Research Consortium, Inc., Solomons, Maryland.
- Goswami SC (1983) Production & Zooplankton community structure in the lagoon & surrounding sea at Kavaratti atoll (Lakshadweep). *Indian J Mar Sci* 12: 31-35
- Gunderson LH (2000) Ecological Resilience- In theory and practice. *Ann Rev Eco1* 31: 425-439
- Haynes D, Waterhouse J, Innes J, Vella K, Furnas M, Schaffelke B (2005) Great Barrier Reef Water Quality Protection Plan (Reef Plan): First Annual Marine Monitoring Programme Report, Great Barrier Reef Marine Park Authority.

- Holling CS (1973) Resilience and stability of ecological systems. *Ann Rev Ecol* 4:1-23
- Hopley D, Kinsey DW (1988) The effects of a rapid short-term sea level rise on the Great Barrier Reef. In: Pearman GI (ed) *Greenhouse: Planning for Climate Change*, CSIRO Publications, Australia 189-201
- Jagtap TG, Untawale AG (1984) Chemical composition of marine macrophytes & their surrounding water & sediments, from Minicoy, Lakshadweep. *Indian J Mar Sci* 13:123-125
- Kannan L, Veluswamy K, Thangaradjou T (1998) Seagrass of the Portonovo marine environment: 1. Morphological diversity in *Halophila ovalis* (R.Br.) Hook, with reference to depth and substratum. *Seaweed Research and Utilization* 20 (1&2): 107-113
- Lindholm R (1987) *A Practical approach to sedimentology*. Allen and Unwin, London.
- Masini RJ, Cary JL, Simpson CJ, McComb AJ (1990) Effects of light and temperature on the photosynthesis of seagrasses, epiphytes and macroalgae and implications for management of the Albany Harbours. Environmental Protection Authority. Technical Series 32. Perth, Western Australia.
- McCook LJ, Folke C, Hughes T, Nystrom M, Obura D, Salm R (2007) Ecological resilience, climate change and the Great Barrier Reef. In: Johnson JE, Marshall PA (ed) *Climate Change and the Great Barrier Reef*. Great Barrier Reef Marine Park Authority, Townsville, Australia.
- Nayak S, Bahuguna A (2001) Application of remote sensing data to monitor mangroves and other coastal vegetation of India. *Indian J Mar Sci* 30 (4): 195-213
- Nobi EP (2010) Assessment and Evaluation of the seagrass resources of Lakshadweep Islands (India): A Remote Sensing and GIS approach. Ph.D. thesis, Annamalai University, India
- Nobi EP, Dilipan E, Thangaradjou T, Dinesh Kumar PK (2013) Restoration scaling of seagrass habitats in the oceanic islands of Lakshadweep, India using geospatial technology. *Applied Geomatics* 5(2): 167-175
- Nobi EP, Dilipan E, Thangaradjou T, Sivakumar K, Kannan L (2010). Geochemical and geo-statistical assessment of heavy metal concentration in the sediments of different coastal ecosystems of Andaman Islands, India. *Estuar Coast Shelf S* 87 (2): 253-264
- Nystrom M, Graham NAJ, Lokrantz J, Norstrom A (2008) Capturing the cornerstones of coral reef resilience: linking theory to practice. *Coral Reefs* 27: 795-809
- Prange J, Haynes D, Schaffelke B, Waterhouse J (2007) Great Barrier Reef Water Quality Protection Plan, Annual Marine Monitoring Report. Great Barrier Reef Marine Park Authority, Townsville.
- Ravindran J, Raghukumar C (2006) Pink-line syndrome, a physiological crisis in the scleractinian coral *Porites lutea*. *Mar Biol* 149:347-356
- Reopanichkul P, Schlacher TA, Carter RW, Worachananant S (2009) Sewage impacts coral reefs at multiple levels of ecological organization. *Mar Pollut Bull* 58: 1356-1362

SAC (2003) Community Zonation of selected mangrove habitats of India using satellite data. Scientific Note, RESIPA/MWRG/MSCED/TR/50/2006: 67

SAC (2006) National (natural) resources information system (NRIS) for Lakshadweep island. Technical note, SAC/SAC/RESIPA/MWRG/MSCED/SN/17: 92

Sheppard CRC (2003) Predicted recurrences of mass mortality in the India Ocean. *Nature* 425: 294-297

Smith SV, Buddemeier RW (1992) Global change and coral reef ecosystems. *Ann Rev Eco1* 23: 89-118

Thangaradjou T, Kannan L (2007). Nutrient characteristics and sediment texture of the seagrass beds of the Gulf of Mannar. *J Environ Biol* 28(1): 29-33

Thangaradjou T, Nobi EP, Dilipan E, Sivakumar K, Kannan L (2009) Seagrasses under threat. *Seagrass Watch*, 39: 20-21

Vinithkumar NV, Kumeresan S, Manjusha M, Balasubramanian T (1999) Organic matter, nutrients and major ions in the sediments of coral reefs and seagrass beds of Gulf of Mannar Biosphere Reserve, southeast coast of India. *Indian J Mar Sci* 28: 383-393

Vivekanandan E, Hussain Ali M, Jasper B, Rajagopalan M (2008) Thermal thresholds for coral bleaching in the Indian Seas. *J Mar Biol Assoc India* 50:209-214

Vivekanandan E, Hussain Ali M, Jasper B, Rajagopalan M (2009) Vulnerability of corals to warming of the Indian seas: a projection for the 21st century. *Curr Sci India* 97 (11): 1654-1658

Waycott M, Duarte CM, Carruthers T, Orth R, Dennison WC, Olyarnik S, Calladine A, Fourqurean J, Heck K, Hughes R, Kendrick G, Kenworthy W, Short F, Williams S (2009) Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *P Natl Acad Sci USA* 106: 12377-12381

Waycott M, McKenzie LJ, Mellors JE, Ellison JC, Sheaves MT, Collier C, Schwarz AM, Webb A, Johnson JE, Payri CE (2011) Vulnerability of mangroves, sea grasses and intertidal flats in the tropical Pacific to climate change. In: Bell JD, Johnson JE, Hobday AJ (ed) *Vulnerability of fisheries and aquaculture in the Pacific to climate change*. Secretariat of the Pacific Community, Noumea, pp 297-368

Wentworth CK (1922) A scale of grade and class terms for clastic sediments. *J Geol* 30: 377-392

Table 1 Depth range of Seagrass, Coral Reef and Sandy areas in the study region

Island/Habitat	Seagrass	Average Depth (m)	Coral reef (m)	Average Depth (m)	Sandy bottom (m)	Average Depth (m)
Kavarathi	1-10	0.5-2	11-20	2-5	21-25	2-6
Agathi	1-10	0.5-2	11-20	2-4	21-25	1-3
Kadamath	1-10	0.2-4	11-20	2-4	21-25	2-3
Bangaram	1-8	0.1-2.5	9-12	3-5	13-15	0.1-1
Thinnakkara	1-8	0.1-1.5	9-12	2-4	13-15	0.1-0.5

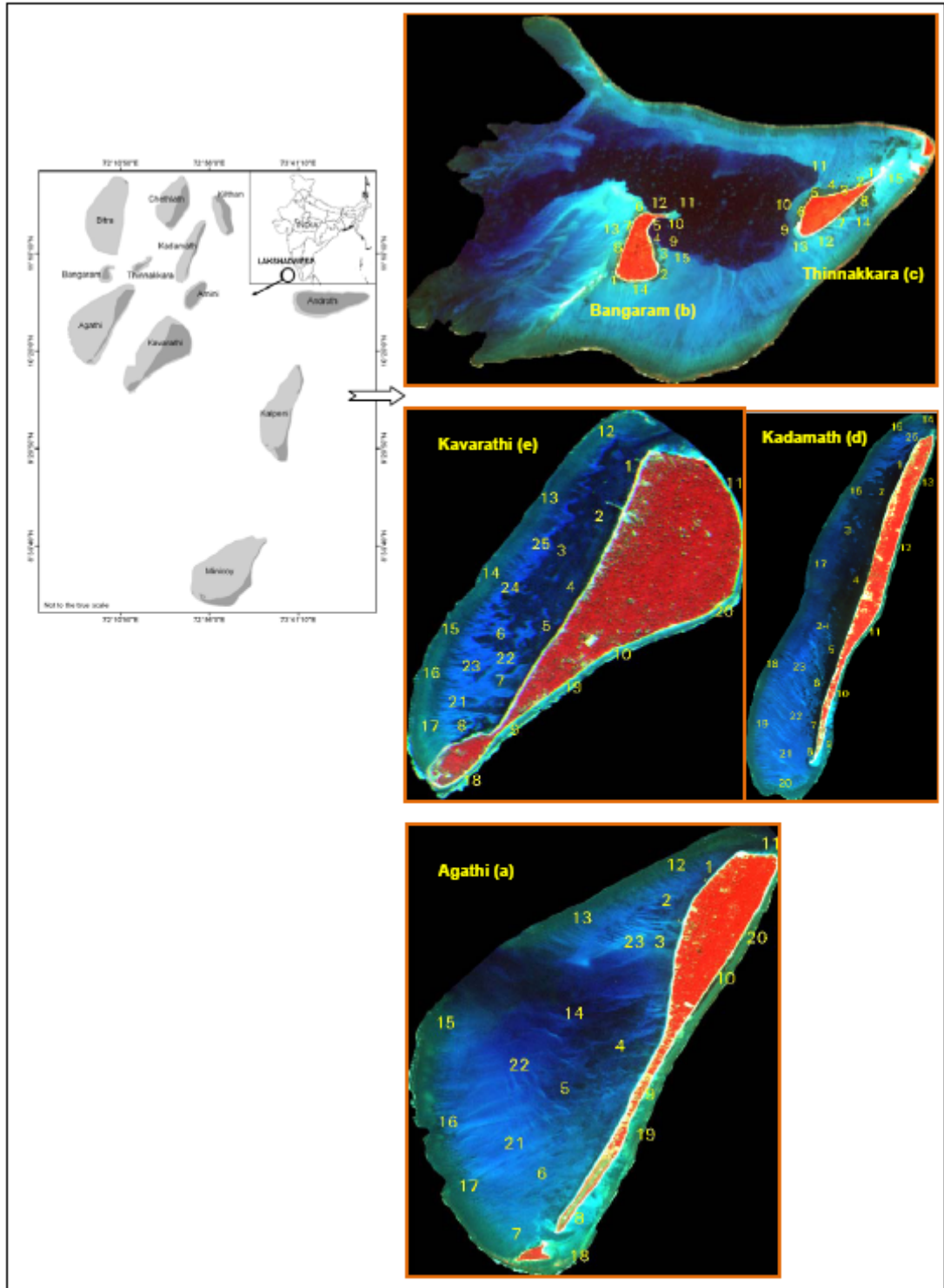


Fig. 1 Location map of the study area

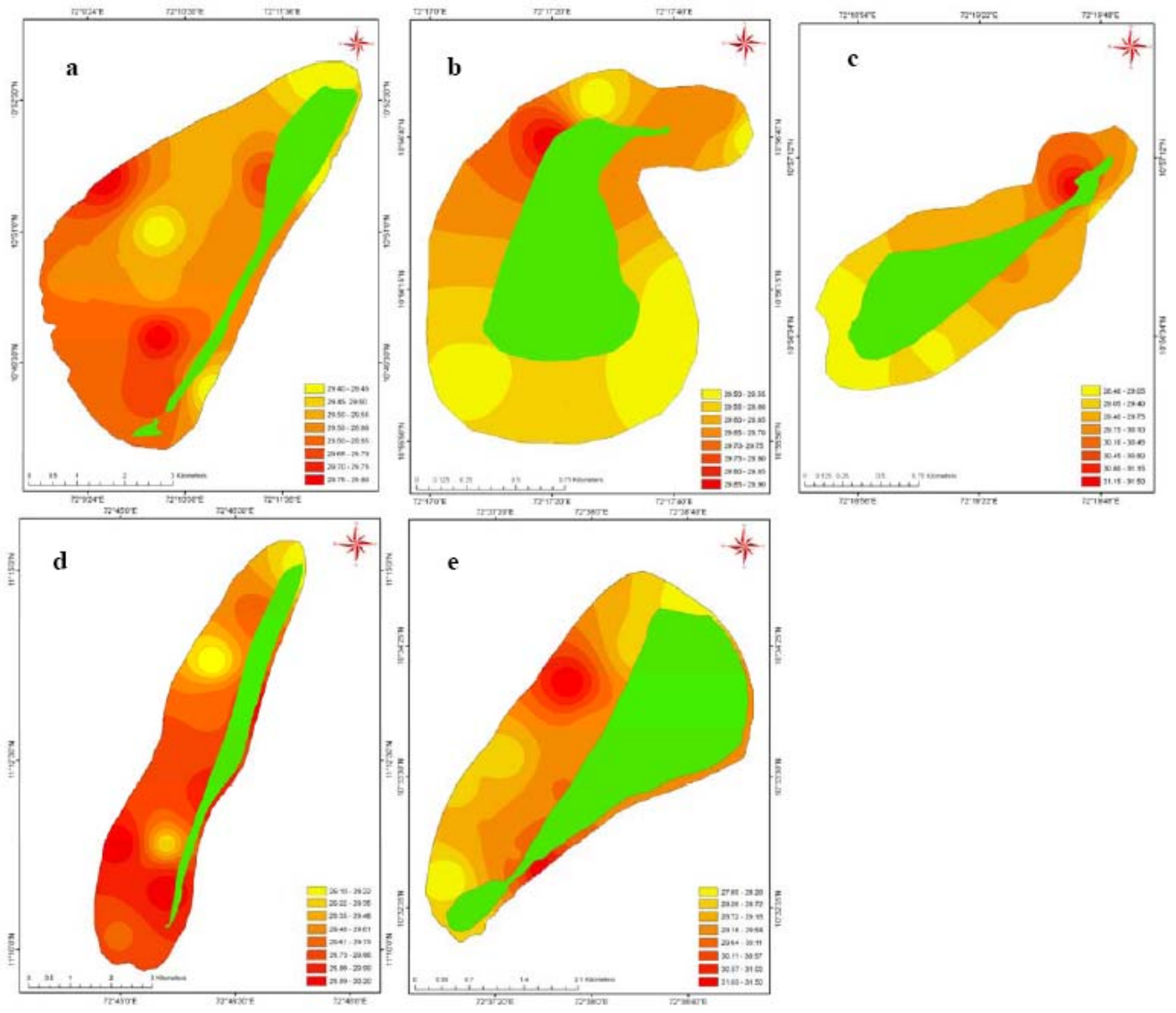


Fig. 2 Spatial distribution of temperature in the study area ($^{\circ}\text{C}$)

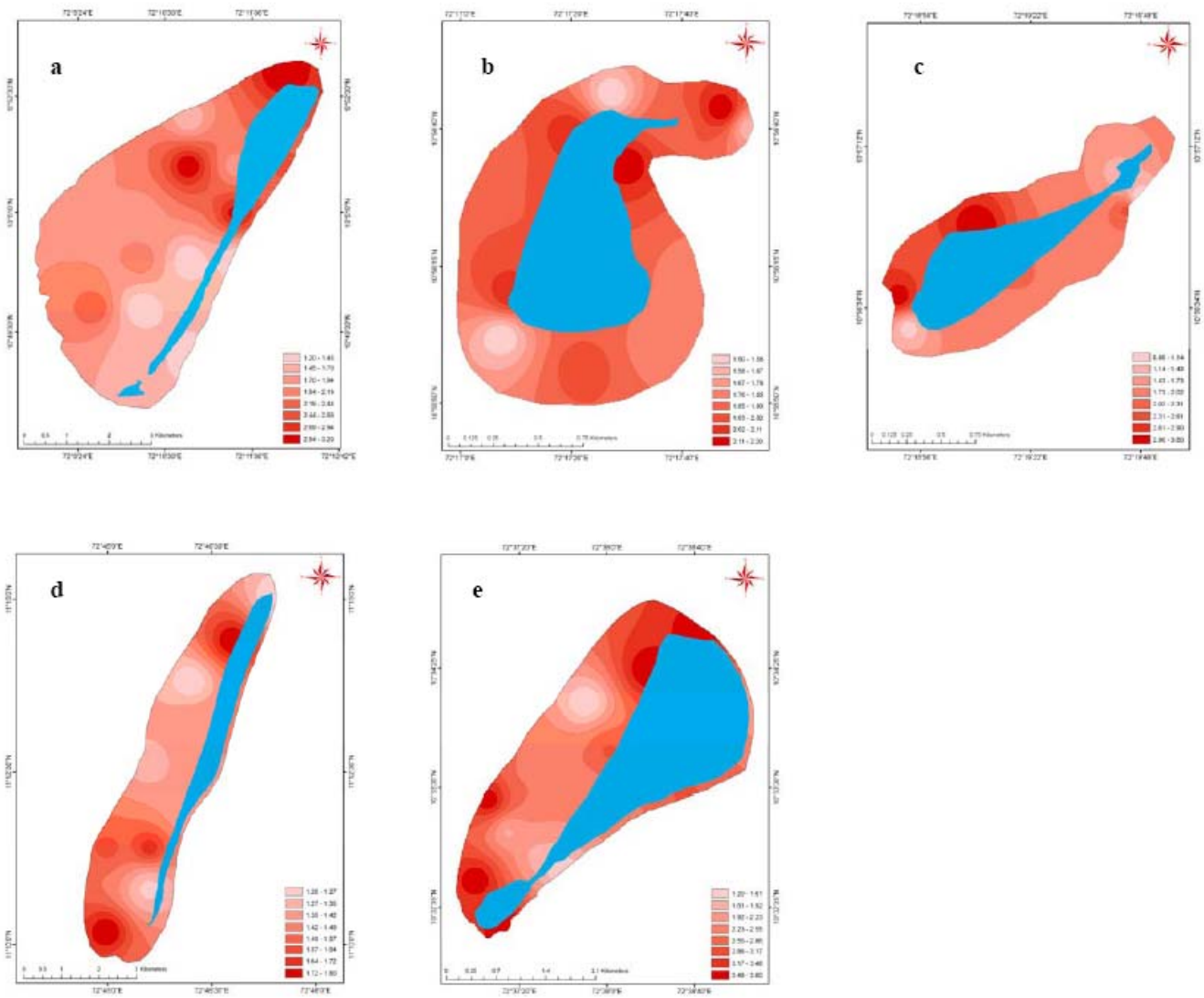


Fig. 3 Spatial distribution of Turbidity (NTU)

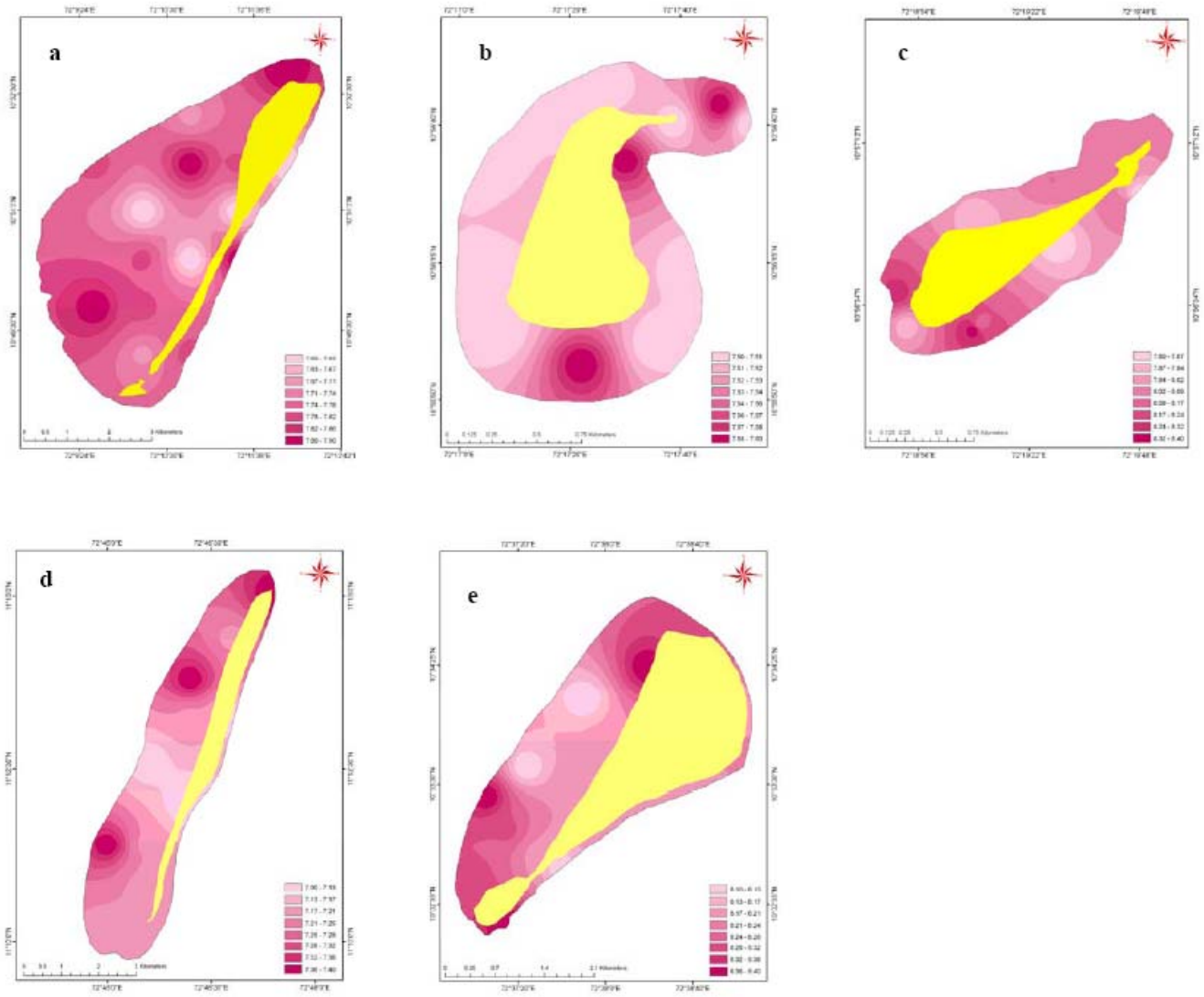


Fig. 4 Spatial distribution of sediment pH

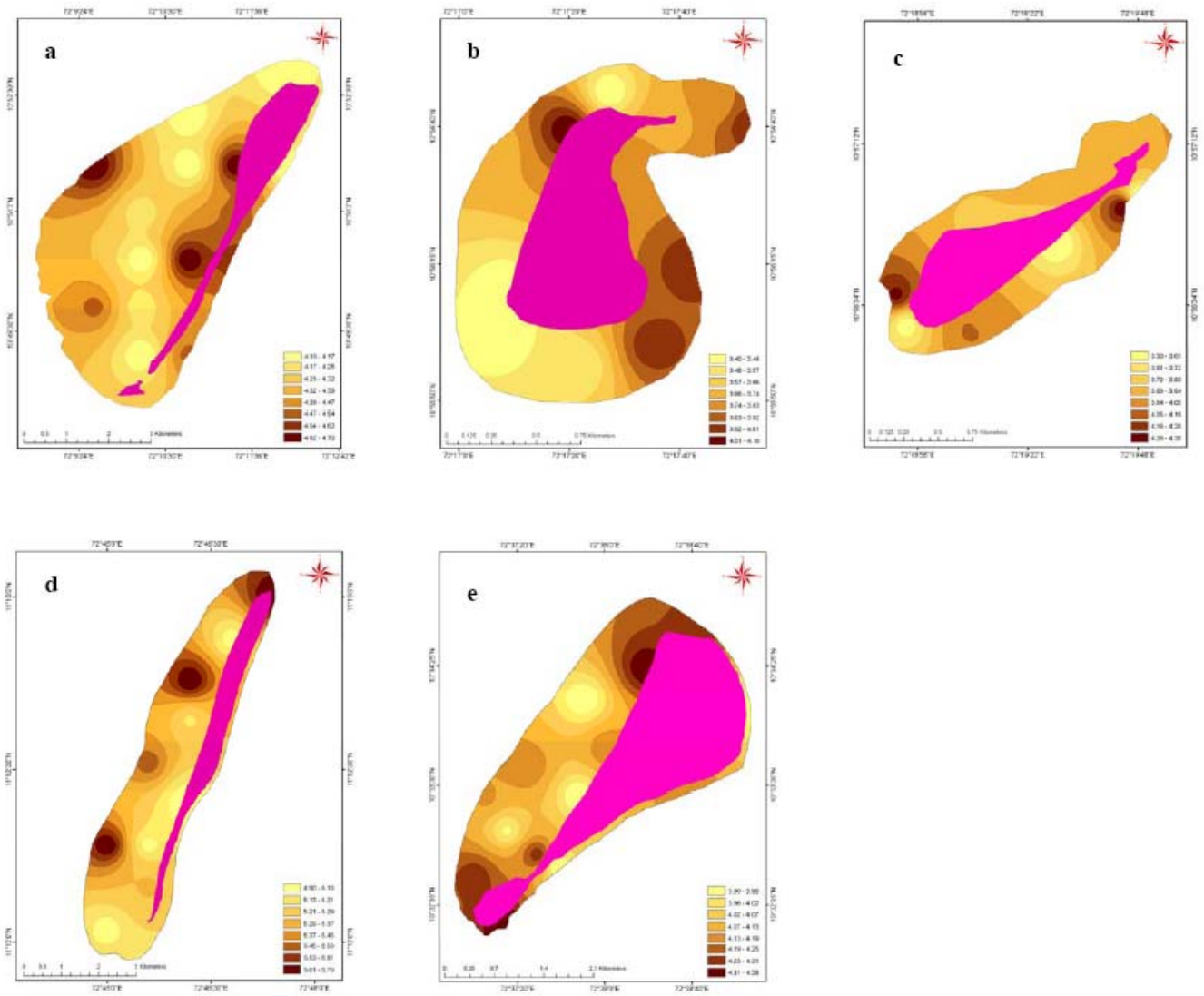


Fig. 5 Spatial distribution of electrical conductivity in the study area (dSm^{-1})

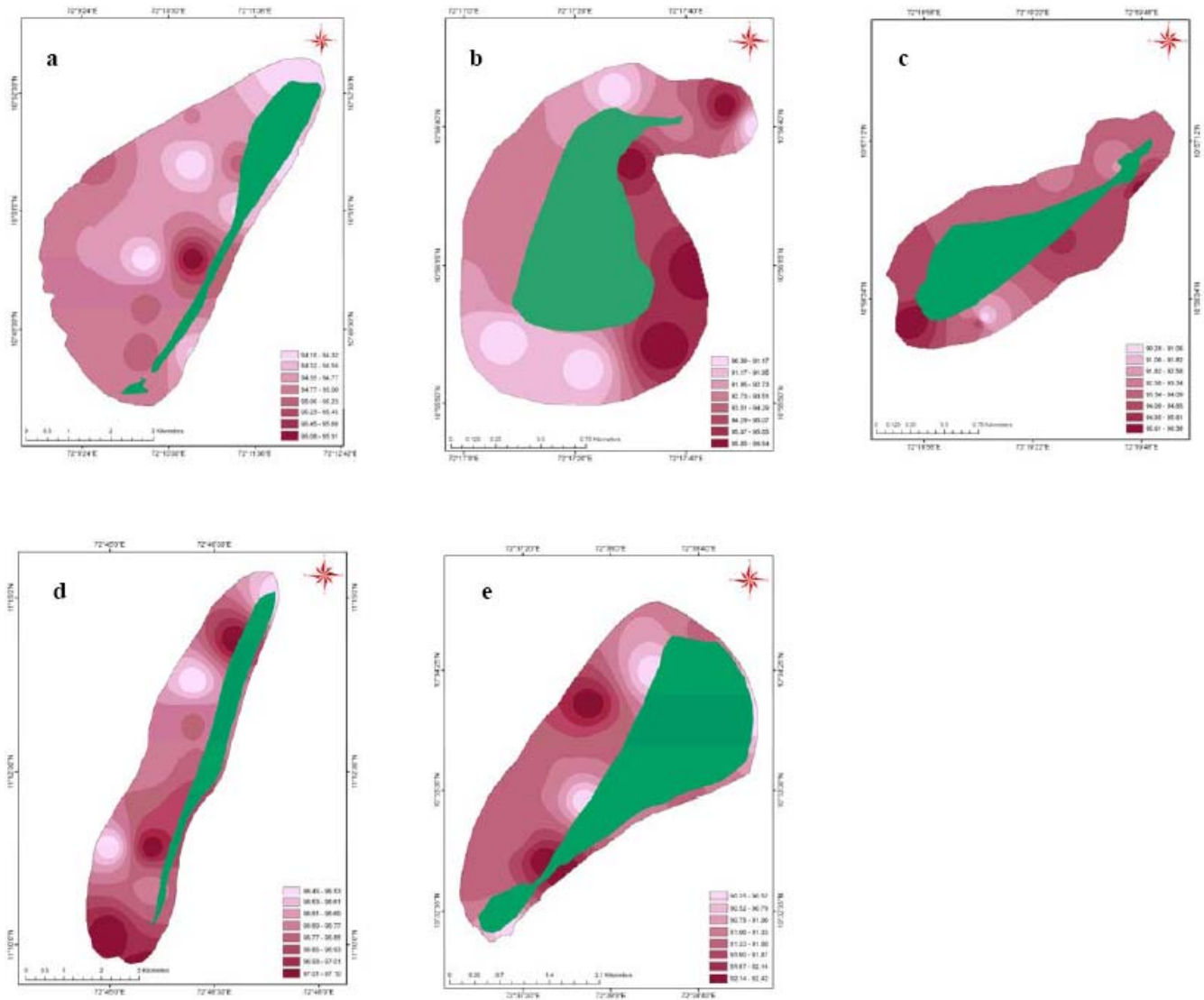


Fig. 6 Spatial distribution map of sand composition (%) in the study area

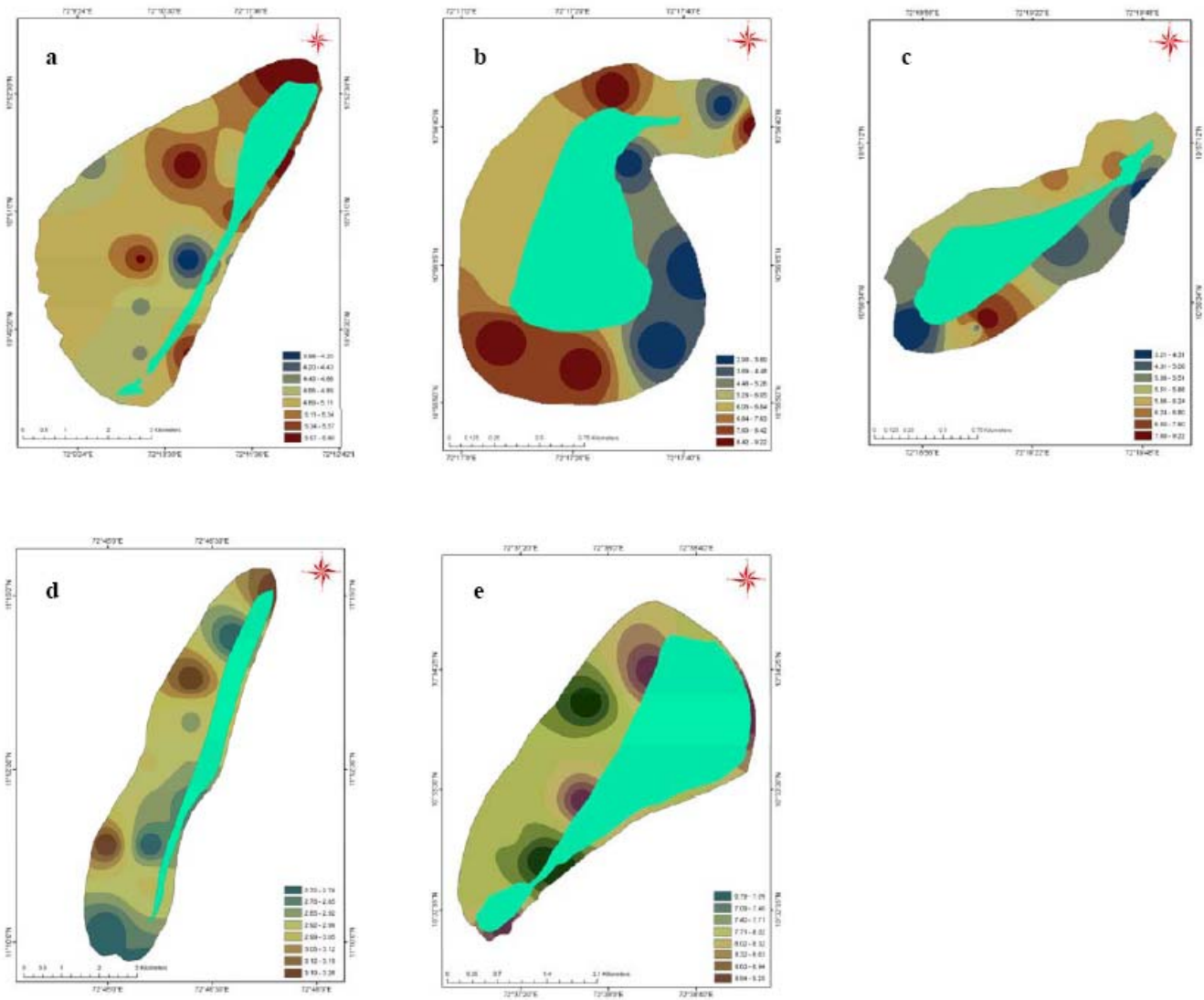


Fig. 7 Spatial distribution map of silt composition (%) in the study area

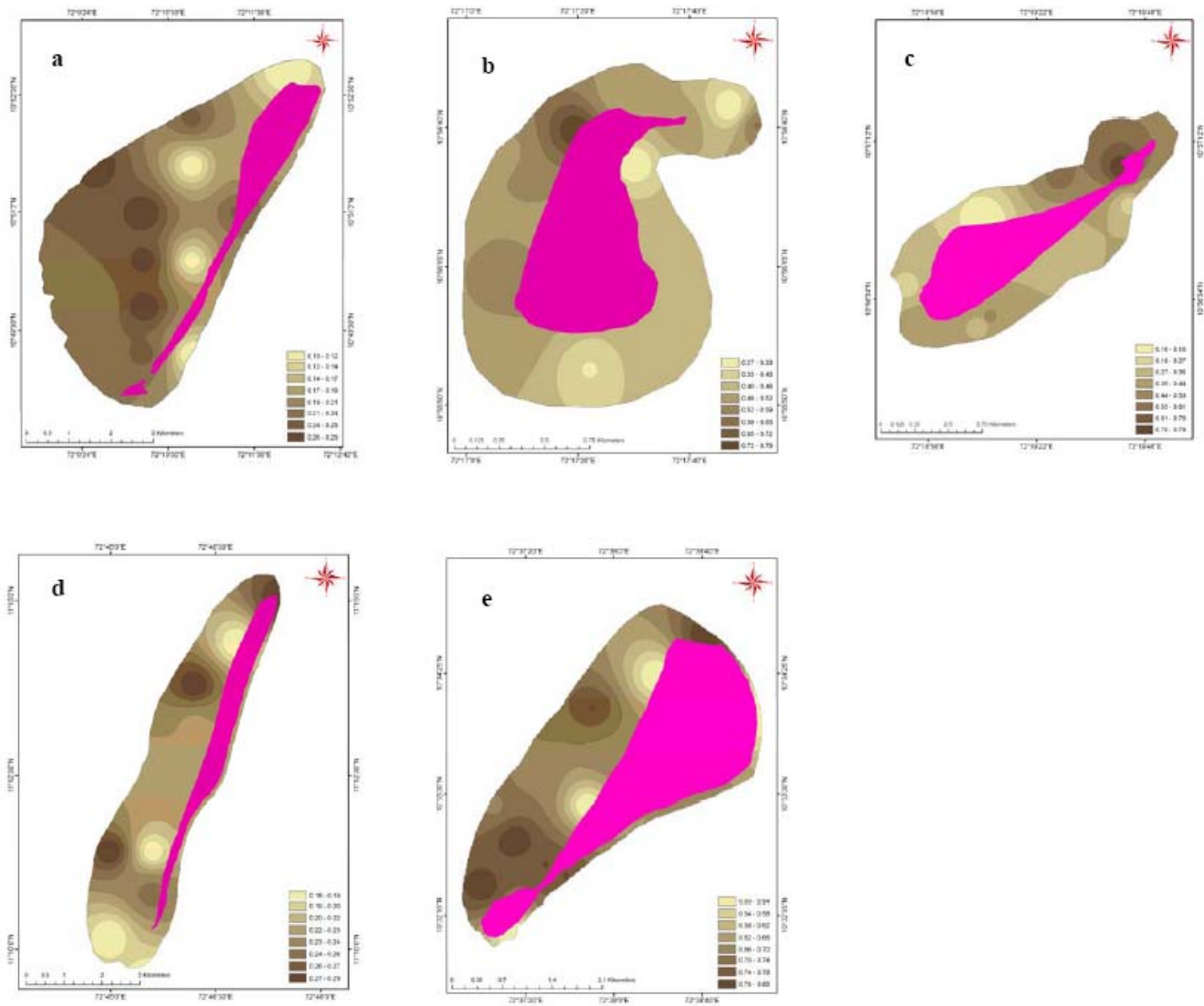


Fig. 8 Spatial distribution map of clay composition (%) in the study area

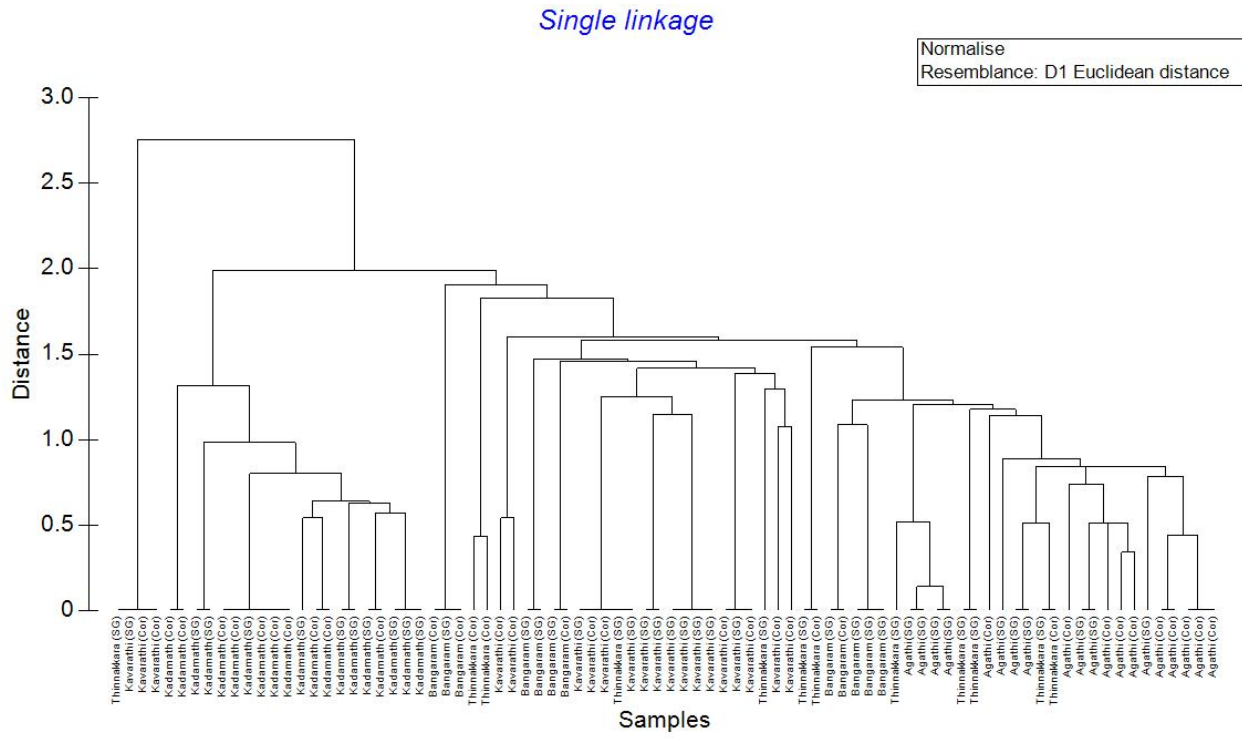


Fig. 9 Dendrogram showing the interrelationship among Coral reef-seagrass areas (Cluster analysis)