CHAPTER I

INTRODUCTION

1.1 Coral reefs, Significance and Threats

Coral reefs are one of the most productive ecosystems of the world. They support the food chains and the food web of the ocean. They are home to representatives of all the phylum of the animal kingdom (Veron, 2000). Reef building corals consist of the accumulation of delicate, coelenterate organisms over many centuries. Coral reefs flourish in tropical and subtropical clear waters within a narrow range of bio-physical environmental parameters (Cumings, 1932). These parameters include temperature, salinity, turbidity, inorganic salts dissolved in surrounding sea water.

Although coral reefs have survived over many centuries, the environmental conditions of recent decades are proving to be highly detrimental for them. For all those involved in the field of ecology and economics of the coastal zone, the health of coral reefs is an important current global issue. Latest research has identified the greenhouse trajectory of planet Earth as disastrous to coral reefs and the millions of people whose livelihood depends on them (Carte, 1996; Schuttenberg and Guldberg, 2007). As a result, it has become essential for reef researchers to concentrate on the causes and consequences of different stress factors affecting this sensitive ecosystem.

1.1.1 Coral Anatomy

Corals belong to the Phylum Coelenterata, Class Anthozoa, and Order Sclerectinia. They have soft bodies with radial symmetry. An individual coral animal is called a polyp and millions of tiny polyps together create a coral colony. A polyp has a sac-like body cavity with one opening, which serves as both the mouth and the anus. The opening is surrounded with tentacles, which are tipped with nematophores. With these tentacles, corals defend themselves and capture live prey. The sac-like body cavity of the polyp is the coelenteron. The coelenterons of one polyp are connected to coelenterons of other adjacent polyps by tubes through which water circulates and nutrients are transported. The coelenterons performs the functions of digestion, respiration, and circulation of fluid and nutrients.

Corals have zooxanthallae, unicellular algae, as a symbiont in their body. In this symbiotic relationship, corals provide a protected environment and the necessary compounds for photosynthesis, including carbon dioxide and inorganic nutrients to zooxanthallae. In return, these algae provide nutrients and help with the removal of wastes. The different colours of live coral tissue are due to these zooxanthallae, and without these algae, survival of polyps is difficult. As zooxanthallae produce nutrients from photosynthesis, they can only survive till the depth of the ocean that is penetrated by sunlight, namely the photic depth.

Corals also form an exoskeleton with the help of calcium carbonate secreted from their ectoderm. This skeleton, known as corallite, provides a protective barrier to the polyp, and acts as a building block of the reef. It has a tube with vertical plates radiating from the centre. The tube itself is a wall of the corallite and the vertical plates are called septo-costae. These tubes are horizontally connected to each other by coenosteum. Classification of the corals is mostly based on their skeletal structure. Therefore, it is important to know the detailed skeletal features of the corallite. The detailed structural diagram of the coral polyp with a cross sectional view is shown in **Figure 1.1**.

1.1.2 Classification of Corals

Generally, corals are classified into two different types – Ahermatypic and Hermatypic.

1.1.2.1 Ahermatypic corals

These corals do not have zooxanthallae in their cells, and most soft corals fall under this class. Most Ahermatypic corals make exoskeleton of proteinaceous rather than calcareous material, and as a result, they are not active reef builders. Examples of such corals include sea whips, sea feathers, and sea pens. Biologically, these corals live in colonies, and are an essential part of the reef ecosystem. As they are independent from zooxanthallae, Ahermatypic corals can also be found at higher depths, and can live at higher latitudes, provided they get planktonic food. Hence, they can also be called cold water reefs.

1.1.2.2 Hermatypic corals

Although Ahermatypic corals are an important part of the reef ecosystem, the majority of reef-building corals are Hermatypic corals. These corals have zooxanthallae inside their cells, and hence can perform photosynthesis. Because of the presence of the symbiotic algae, these corals can only grow till the photic depths. Hermatypic corals contain both hard and soft corals, with the majority being hard corals. These hard corals build a hard exoskeleton made up of calcium carbonate. They can take different growth forms, depending on the species and environmental conditions. The most common forms are massive, branching, encrusting, foliaceous, columnar, and laminar (**Figure 1.2**).

When a coral polyp dies, the skeleton remains, adding new material to the reef framework. It takes thousands of years for reefs to get established, with a yearly growth rate of 2 to 185 millimeters depending upon the species and environmental conditions (Shinn, 1966; Harriott and Banks, 2002). Due to their limited growth rate and the need for a specific range of bio-physical parameters, they are more vulnerable to long term damage and extinction. In fact, reefs around the world are degrading at a rapid rate, and if this continues, there will be no reefs left in the world in 20 years time (Hoegh-Guldberg, 1999). This change may create a significant disturbance in the local and global ecology of oceans. As they are precious and fragile, it is crucial that reefs are conserved well.

1.1.3 Types of Reefs

Coral reefs everywhere grow by the same processes, but their geomorphology is shaped by the foundations on which they grow and the sea level history. Most modern reefs were established less than 10,000 years ago, after a sea level rise associated with the melting of glaciers caused widespread flooding of the continental shelves (Dubinsky, 1990). Once the coral reef communities were established, they began building reefs that grew upwards in conjunction with continued sea level rises. Although, many theories have been proposed for reef formation, Darwin's Subsidence theory, presented in 1842, is accepted worldwide by most researchers (Rosen, 1982; Veron, 2000). According to this theory, all reefs started developing near volcanic islands. A subsequent sea level rise led to submergence of the island, and at the same time, reefs grew upwards with the rising sea level.

Based on this theory, reefs are classified into three major types: fringing reefs, barrier reefs, and atolls (**Figure 1.3**).

1.1.3.1 Fringing reefs

As suggested by their name, these reefs fringe or grow attached to the shoreline (of either continents or islands). They begin growth in shallow water close to shore and tend to accumulate outwards. According to

Darwin's theory, they are the youngest or most primitive type of reef. Examples include the reefs of the Gulf of Kachchh (GoK) and Andaman and Nicobar Islands.

1.1.3.2 Barrier reefs

Darwin proposed that as the island slowly starts sinking, reefs slowly grow upwards. The typical growth along the outer edges of continental shelves, separated from the mainland by a lagoon, forms a Barrier Reef. Barrier reefs are considered a stage in between Fringing and Atoll Reefs. The Great Barrier Reef of Australia is an example of a barrier reef.

1.1.3.3 Atoll Reefs

Atolls are reefs in the final stage of development. They are circular reefs, enclosing lagoons. They have a characteristic ring shape which is formed due to the sea level rise and subsidence of the island completely. They grow upwards with the rise in sea level and can grow till the surface. Atoll reefs grow more towards the seaward side leaving a deep lagoon in the centre. This lagoon is often covered by sand instead of corals. The reefs of Maldives and Lakshadweep island of India are Atoll Reefs.

Apart from these major reef types, there are certain other types of reef structures, including Patch reefs, Platform Reefs and Ribbon reefs.

1.1.3.4 Patch Reefs

Patch reefs are small, isolated reefs that grow up from the open bottom of the island platform or continental shelf. They usually occur in the protected water between fringing reefs and barrier reefs. They vary greatly in size.

1.1.3.5 Platform Reefs

Platform reefs are bigger than patch reefs and have a flat upper surface and sometimes form an island.

1.1.3.6 Ribbon Reefs

Ribbon reefs are linear reefs that have inwardly curved extremities and form a festoon along the precipitous edge of the continental shelf.

1.1.4 Significance of coral reefs

Worldwide, coral reefs cover almost 284,300 square kilometers of ocean floor. Nearly 92% of this is within the Indo Pacific region, including the Red sea, the Indian Ocean, areas of South East Asia, and the Pacific Ocean. Atlantic and Caribbean reefs comprise the other 8% of the coral reef area of the world (Spalding, 2001). A map of the coral reef regions of the world is given in **Figure 1.4.**

There may be upto 1 billion species living in or near coral reefs (Odum and Odum, 1955; Gordon and Kelly, 1962; Lewis, 1977). They are present on earth since the Cambrian period (542 million years ago) and have been protecting shores from many centuries (Dubinsky, 1990; Pratt et al., 2001). Moreover for those people living close to reef colonies, reefs provide food, nutrients, medicine, leisure, and a source of income through tourism.

Biological, geological and economical benefits provided by reefs are described below.

1.1.4.1 Geological importance of coral reefs

Coral reefs are shallow water tropical ecosystems. Around the world, 110 tropical countries have been blessed by the presence of coral reefs near their coast (Spalding, 2001). They are found in a variety of forms including fringing, barrier, atoll, platform, patch, pinnacles, and apron reefs. Variations in their type and location makes them diverse in terms of biology and geology. They are large oceanic structures, which have been studied from spacecrafts and satellites for many years (Lyzenga, 1978, 1981; Biña et al., 1979; Jupp et al., 1985; Jupp, 1986; Kuchler et al., 1988; Bierwirth et al., 1993; Mumby et al., 1998; Green et al., 2000). They are also the oldest and biggest structure composed by living creatures. The geological age of reefs date back to around 2,000 million years (Veron, 2000). The fossil records indicate the presence of rugosa and tabulate corals from Cambrian period (Veron, 2000). Therefore, they are a geologically important source of information for knowing the earth's climate in the past geological eras. They have evolved into massive structures as a result of skeletal deposits of tiny coelenterate organisms over millions of years. Their magnitude means that they act as a shore protector, and save the shore from erosion, storm damage and flooding by reducing strong wave action (Mobers and Folke, 1999). The skeletal deposits are made up of mainly calcium carbonate, which has been a source of limestone formation in the geological past (Dubinsky, 1990). This can thus shed more light on the history of sea level rises and other oceanic changes (Dubinsky, 1990; Veron, 2000)

1.1.4.2 Biological importance of coral reefs

Coral reefs are not only important geologically but also biologically. Despite having low nutrient content, they are home to more than one million species (Odum and Odum, 1955; Gordon and Kelly, 1962; Lewis, 1977; Muscatine and Porter, 1977). Although they cover less than 0.2 % of the coast of 110 tropical countries, they harbor about 25% of all marine species known. This includes almost one third of all marine fishes that are associated with coral reefs at some stage in their life (McAllister, 1991). It is considered that about 45% of commercially important fishes breed in coral reefs (Ryther, 1969). Some experts also believe that coral reefs harbor more phyla than tropical rainforests (Hubbell, 1997; Sale, 1999). The protection offered by corals enables formation of associated ecosystems of seagrass and mangroves, which allows formation of integrated food chains and a food web **(Figure 1.5)** (Moberg and Folke, 1999).

Coral reefs and mangroves are an important nursery ground for the larva and hatchlings of many marine species. The high productivity of these otherwise unproductive waters makes coral reefs critical to the survival of tropical marine ecosystems. Furthermore, recent research shows that corals are an important source of medicines. Many reef dwelling organisms are involved in the production of bio-chemical substances that are crucial for cardiovascular and oncology medications (Hilgemann, 2003; Kockskämper et al., 2004; Chavanich et al., 2005; Simmons et al., 2005).

1.1.4.3 Economical importance of coral reefs

Although coral reefs are biologically and geologically important, an understanding of their direct contribution to human life is imperative. Their conservation is also important because of the annual capita they generate for the economy of a country. They provide a crucial source of income through tourism, fishing, building materials, coastal protection, and diversity of new drugs and biologically active compounds (Smith, 1978; Kühlmann, 1988; Spurgeon, 1992; Carte, 1996; Done et al., 1996; Peterson and Lubchenco, 1997; Moberg and Folke, 1999). Coral reefs contribute an estimated US $ 375 billion to the global economy per year (Costanza et al., 1997, 2006; Troy and Wilson 2006; Turner et al., 2007). Tourism alone generates billions of dollars every year for the countries associated with coral reefs. Fisheries associated with coral reefs are also an important source of income for fishermen and provide employment for millions (Roberts et al., 1998, Wilkinson, 2004). The fish catch yields around 6 million tons per year from reef-related fisheries (Munro, 1996, Hoegh-Guldberg, 1999, Wilkinson, 2004).

1.1.5 Threats to coral reefs

As discussed, coral reefs are extremely important with respect to global ecology, geology and economics, and therefore it is very important that they are conserved. In addition, coral reefs are a fragile ecosystem, putting them at a greater risk of damage, and thus they are in need for extra care. In recent years, various environmental issues have threatened reef survival, and human activities are damaging their delicate ecological balance. Greenhouse gases and global warming are causing major changes in the environment of ecosystems. As corals require a narrow range of parameters for their survival, they are more prone to these environmental changes.

There are a number of threats contributing to the destruction of coral reefs worldwide. Major threats include temperatures anomalies, ocean acidity due to increased carbon dioxide in the atmosphere, salinity, turbidity, nutrient influx, terrestrial runoffs, coastal industries, oil spills, perilous fishing methods, and pressure from recreational activities. Other threats are competition related phase shift, outbreaks of coral disease or predators, algal overgrowth, and loss of associated habitats. These threats vary depending on geographical and temporal aspects, and a combination of two or more, natural or anthropogenic, threats can increase their effect by several folds (Hughes and Connell, 1999).

The damage occurring to coral reefs from human activities may be more severe than the damage from natural causes (Hughes and Connell, 1999).

With increased human activities near coastal areas, a number of anthropogenic threats are putting reefs at risk. Both Edinger and colleagues in 1998, and Fabricius in 2005, gave an example of how land-based pollution, destructive fishing practice, sedimentation, and nutrient enrichment decrease coral cover and colony health when reefs are close to human activity centers.

The main method of destruction of coral reefs is via bleaching. Bleaching refers to the loss of zooxanthallae from coral tissue cells. The colours of coral colonies are due to these symbiotic algae, and they are also an important source of polyp nourishment. When any external or internal stress is applied to coral polyps, they release their symbioant into the surrounding sea water. Upon returning of favorable conditions, zooxanthallae can reoccupy the original space. However, when the stress is prolonged, coral polyps die due to malnourishment. (Brown and Howard, 1985; Hoegh-Guldberg and Smith, 1989).

There are multiple causes of bleaching. They include higher than normal water temperatures, solar radiation, changes in nutrient concentrations, sedimentation regimes, salinity, and hurricanes (Dollar and Grigg, 1981; Jokiel and Coles, 1990; Brown et al., 1994; Brown 1997; West and Salm, 2003). Prolonged and elevated water temperatures have been related to global mass bleaching in 1998 (Winter et al., 1998; Berkelmans and Oliver, 1999; Hoegh-Guldberg, 1999; Wilkinson et al., 1999; Berkelmans et al., 2004). Moreover, higher temperatures favour growth of other harmful organisms, and an increase in the number of such competitors in the reef habitat, adds further pressure on reefs.

Competition between corals and algae is a well known phenomena, and is important in determining the structure and composition of the benthic communities on coral reefs (Lang and Chornesky, 1990; Karlson, 1999). It is crucial to study the competition between hard corals and benthic macro algae during the events of "Phase Shift" – a phenomena that refers to the conversion of coral dominated areas into macro algae dominated areas (Littler and Littler, 1984; Lapointe, 1989; Done, 1992; Hughes, 1994; Miller, 1998). Although there is some controversy over whether phase shift has long-term or permanent effects on coral reefs, there is evidence suggesting the detrimental effects of algae on corals (McCook et al., 2001).

Although the threats to coral reefs vary depending on their geographical location around the world, vast reef damage has already occurred due to a number of reasons.

1) In 1998, due to the extended El Niño effect, temperatures of the oceans of the world increased substantially. This caused large scale mortality of corals of many countries including the Great Barrier Reef of Australia, and the reefs of the Maldives atolls, Seychelles islands, coral triangle, Caribbean, and many other tropical countries (Berkelmans and Oliver, 1999; Arthur, 2000; Goreau et al., 2000; Baird et al., 2009).

2) Coral needs clear waters. However, extremely clear waters can also be detrimental in summer. Increased penetration of sunlight results in higher temperatures, and thus loss of zooxanthallae (Warner et al., 1996; Jones et al., 1998; Warner et al., 1999; Lesser and Farrell, 2004; Takahashi et al., 2004; Smith et al., 2005).
3) Oceanic biota is at risk from oil spills (Boesch and Rabalais, 1987). For example, there was a widely publicized oil spill from the bulk coal carrier, *MV Shen Nang 1*, in April 2010, that occurred near the Great Kappel Island of the Great Barrier Reef, Australia. This oil spill has caused the most damage to the Great Barrier Reef till date (Gelinean, 2010). The oil spill damaged an area of 3 kilometres x 250 metres, with some parts becoming completely devoid of marine life (Purvis, 2011).
4) A combination of different parameters, such as high temperature, reduced salinity, and nutrient enrichment, result in more severe stress to corals and subsequently cause more harm to reefs (Hughes et al., 2003; Humphrey et al., 2008; Faxneld et al., 2010).
5) Corals are often predated by other reef inhabitants. These include fishes, other coelenterates, molluscans and echinoderms. One of the major organisms is the Crown of thorns starfish, *Acanthaster planci*. It is a specialized corallivore which feeds on coral polyps. When they are present in large numbers during outbreaks, they can destroy large areas of hard coral cover. Outbreaks are caused by other abiotic and biotic

parameters such as terrestrial runoff, over-fishing of larvaevorous fishes, and the amount of phytoplankton available as food for the starfish larva (Birkeland, 1982; Houk et al., 2007; Sweatman, 2008).

1.2 Protection methods for Coral Reefs

As discussed above, there are a number of threats prevailing in the reef environment. It is, therefore, important to take measures that can protect corals and reefs. However, this is only possible if the prevailing threats are identified early, and precautionary measures against them are taken. There are a large number of organizations working for the protection of reefs, and their aim is to regularly monitor the health of reefs and minimize the impact of threats.

A number of traditional field-based methods like Self Contained Underwater Breathing Apparatus (SCUBA), snorkeling, transects, quadrants, and video transecting are used to provide useful and real time data on reefs. However, these techniques are site specific and time consuming. Furthermore, coral reefs are present throughout the world, including in remote locations. Hence it is necessary to have a technique which can monitor stressors covering vast areas. This can be facilitated by remotely sensed data (Nalli et al., 2004).

1.2.1 Remote sensing

Remote sensing is defined as the art and science of obtaining information about an object without being in direct physical contact with it. It is scientific technology that can be used to measure and monitor important bio-physical characteristics and human activities on Earth. This technology was developed 150 years ago when the first known aerial photograph was taken from a tethered balloon by Frenchman Gaspard Felix Tournachon. The technique was initially developed for military purposes, and then evolved into the role of monitoring Earth's natural resources. With increasing technological developments, new sensors have replaced old ones, and considerable advances in resolution have been made. Remote sensing integrates all the sciences and simultaneously involves Physics, Mathematics, Botany, Zoology, Geology, Geography, Oceanography, and Space Science.

1.2.1.1 Principles of Remote Sensing

Remote sensing started as a tool when aerial photography first began with the use of balloons. The technique was initially used for military purposes during World War I and II. Later, the technique became an important tool for scientists to further understanding of the Earth's natural resources.

The main tool or instrument used in this technique is the sensor. It is a tool which receives radiation and generates an image in binary format. Initially, radiation used was electromagnetic radiation of the sun. Electromagnetic radiation emitted by the sun has many bands, but only a few have been used for remote sensing. The human eye has limited visibility to this wide range of spectrum. All radiation detected by the sensor is converted into Red Green Blue (RGB) mode. The sensor works on the same principle as the human eye. Objects are seen as a particular colour because some of the radiation is reflected back to the eye, whereas the rest is absorbed.

The sensor needs a platform located at a designated height and location in order to be able to function appropriately. Initial platforms included aerial balloons and airplanes, which have now given way to satellites. These can take photographs at a much higher resolution and can cover a larger area of the earth. Technological advances have revolutionized sensors, with tailor-made sensor designs now available depending on the study being performed. Sensors can be differentiated based on the type of resolution, and there are four major resolutions taken into consideration.

1) Spectral Resolution: This depends on the number and dimension of specific wavelength intervals in the electromagnetic spectrum to which the sensor is sensitive.
2) Spatial Resolution: This depends on the relationship between the size of a feature to be identified and the spatial resolution of the remote sensing system. Spatial resolution is a measure of the smallest angular or linear separation between two objects that can be resolved by the sensor.
3) Temporal Resolution: Temporal resolution of the sensor refers to how often it records the imagery of the same area. In other words, this refers to the repeativity of the sensor when taking images of a particular area.

4) Radiometric Resolution: Radiometric resolution is defined as the sensitivity of a remote sensing detector to differentiate signal strength as it records the radiant flux reflected or emitted from the terrain. It defines the number of just discriminable signal levels; consequently it can have a significant impact on our ability to measure the properties of scene objects.

There are two major types of sensors used for remote sensing: active and passive sensors. Active sensors require a source of light within them and can provide information by detecting how much emitted radiation is reflected after reacting with the substrate. Passive sensors use natural solar radiation as a source of light and thus depend upon electromagnetic waves for the detection of information. Depending on the type of sensor used, remote sensing can be classified as either active or passive.

1.2.1.2 Use and Interpretation of Remote Sensing Data

Remote sensing is a computer-based tool and remotely sensed data is in binary format in most cases. Recently, due to the technological enhancement of sensors and platforms, more efficient and precise digital data has been acquired. Moreover, improved spectral channels have allowed for a deeper exploration of the earth resources. For example, the Hyperspectral remote sensing sensor, Hyperion, divides the electromagnetic spectrum in upto 242 bands, thus giving a greater differentiation of ground imagery.

Although remote sensing provides extensive information about various aspects of the earth's resources, it may sometimes be difficult to interpret remotely sensed data. Remotely sensed data is mostly in the form of False Colour Composite (FCC), and thus does not show the real colours and images of the section of the area. Thus an expert needs to interpret the image and convert it into a format that can be easily understood. This is done with the help of computer aided programs and software such as ARC and ERDAS IMAGINE.

Firstly, and most importantly, the image taken by the sensor needs to have the correct earth geo-location, and thus the raw data needs geo-correction at a first hand. The next step towards better interpretation of data is atmospheric correction. The data read by the sensor is in the form of reflected light rays, and during the travel of electromagnetic radiation to and fro in the atmosphere, atmospheric impurities, gases and many other particles may change the path of this electromagnetic radiation by refraction, diffraction and divergence. Thus data received from the sensor needs to have an atmospheric correction for an accurate interpretation of the image.

The next step is data interpretation. This is done on the basis of colour, tone, texture and location. Based on these four characteristics, the interest area needs to be classified or converted into a map.

1.2.1.3 Environmental Remote Sensing

Remote sensing is extensively used in the field of environmental sciences. Specialized sensors have been specifically tailored for certain environmental conditions. The earth is made up of two main components – land and water. Although land covers only 23% of the earth's surface, it still harbors many small to large ecosystems with diverse biota. The major contribution of environmental remote sensing is land use land cover changes, as well as changes in vegetative species and community, distribution pattern, alteration in vegetative growth cycles, and modification in plant physiology and morphology. These contribute to a greater understanding of the climatic, adaptive, geologic and physiographic conditions of the area (Jones et al., 1998). Scientists have developed various sensors that specially work on capturing data on vegetative and land-based systems (Frohn, 1998). Thus, remote sensing is useful for various aspects of agriculture, forest, rangeland, wetland, urban vegetation and urban development (Danson, 1998; Lyon et al., 1998).

Oceans can be sources of numerous amounts of information. Remote sensing can not only contribute to water body measurement and sustainment, but can also give various environmental parameters of the hydrological cycle. These parameters include precipitation, water depth, temperature, salinity, organic and inorganic water constituents, suspended minerals, chlorophyll, water, snow and ice surface area, and cloud cover.

The sensors designed for detecting water parameters are different from the ones that are used for land and vegetation parameters. As water absorbs the high frequency wavelengths of electromagnetic radiation, sensors need to be able to detect lights of lower wavelength.

1.2.1.4 Remote Sensing in Reef Environments

With the accelerated pace of climate change and global warming, it is important to take steps that prevent reef damage. In order to do this, it has become essential to use techniques that are rapid and frequently provides large-scale data. Remote sensing has proved to be a very useful tool for this purpose. Various sensors designed for reef-based studies help in better understanding and monitoring of reefs (Hochberg and Atkinson, 2000; Palandro et al., 2003; Mumby et al., 1997, 2004). The best example is the NOAA satellite's AVHRR and NESDIS sensors that detect sea surface temperatures. Monitoring of El Niño and La Nina weather patterns and temperature related bleaching events can be studied easily with such images (Carrinquiry et al., 2001). Remote sensing can also detect the amount of nutrients and the sediment load in water, which can help in the identification of various problems in the reef environment (Kleypas, 1996). Furthermore, remote sensing provides a synoptic coverage of the reef which makes it possible to detect a large scale change, in contrast to site-specific data collection by field methods. Therefore, remote sensing can significantly contribute to the monitoring and protection of reefs.

1.3 Literature Review

Coral reefs in tropical and subtropical areas have been extensively studied. These studies have reported data on the biology, geology, geography, and various other environmental phenomena of coral reefs. The impact of climate change can be studied very well on coral reefs (Kleypas et al., 1999; Hughes et al., 2003; Donner et al., 2005). Research has shown that changes in the environment have had a degrading effect on coral reefs. Increased sedimentation can cause detrimental impacts on corals and other reef biota (Hubbard, 1972; Hashimi, 1978; Caroline, 1990). The overgrowth of macro algae on corals is also a limiting factor (Maliao, 2008). There may also be many unknown biological predators in certain areas.

While most of the attention is given to global warming related threats, there are many other prevailing threats in various places which are destroying these fragile ecosystems (please refer section 1.1.4). Moreover latest research is focused on the conservation of coral species genetically and preservation of these samples for future generations (Baums, 2008; Lesser et al., 2010; Combosch and Vollmer, 2011). This conservation and frequent checking is an important aspect of reef research. Data from NOAA and NESDIS provides daily data on Sea Surface Temperature (SST) for all reef regions of the entire globe. Globally, various institutes and Non Government Organisations (NGOs) are working for the conservation and sustainment of coral reefs.

India has four main coral reef regions, namely Andaman and Nicobar Islands, Lakshadweep Islands, Gulf of Mannar, and GoK. Lakshadweep Islands form Atoll reefs, while the other three regions mainly comprise Fringing reefs. Studies of Indian reefs have focused on their extent, management and socio-economic aspects (Hoon, 1997; Arthur, 2000; Muley et al., 2002; Deshmukh et al., 2005; Bahuguna et al., 2010). Early studies analysed the diversity of corals and other reef inhabitants (Pillai, 1969). Recent studies have also addressed the threats and possible actions that may be taken to address them (Venkataraman et al., 2003; Sukumaran et al., 2005; 2007; Patterson et al., 2007; Jasmin et al., 2009). A number of researchers have discussed aspects of monitoring, conservation, and management of reefs. Over exploration of reef resources and Chank fisheries is a threat to Gulf of Mannar reefs (Jagadis et al., 2010; Mohanraj et al., 2011) and efforts to educate the local community on their conservation have been taken by a number of organizations (Patterson et al., 2008). Recent literature has also identified how reef exploration activities are attracting tourists to Lakshadweep and Andaman and Nicobar Islands, and the steps being taken to educate them about preventing damage to reefs (Kokkranikal et al., 2003; Reddy, 2009; Kokkranikal and Baum, 2011). Frequent monitoring of reefs is necessary in order to monitor impacts of threats, and this is often difficult..

GoK has been studied to a lesser extent when compared to other reef regions of India. Various studies have been done to study the faunal and floral assemblage of the GoK (Venkatraman & Wafar, 2005; Dave, 2011). Recent literature has shown that all the prevailing biota are still under threat due to continuous environmental pressures (Vaghela et al., 2010). Coral reef research thus far has been done with conventional field methods. Although they provide a near-perfect picture of biodiversity, these methods are time consuming and site specific. Furthermore, when degradation is occurring rapidly, other options for reef study must be explored. Moreover, coral reefs are marine ecosystems, and so traditional studies can only be done during low tides or with diving facilities. In places like the GoK, where turbidity makes underwater visibility difficult, it is not possible to explore reefs with diving. The only option that would be possible is waiting for low tide conditions for the study of such reefs. However, physical surveys during low tides provide less time for field researchers to work on site, and even to reach the specific site.

In such constraints, remote sensing is considered a boon for the study and assessment of reefs. For example, due to the capacity of current Indian satellites, reef conditions and health can be monitored regularly (Bahuguna et al., 2007; Sharma et al., 2008). Many parts of the world are already using remote sensing to monitor the health of their reef wealth (Andréfouët, 2004). Indian satellites have been used to study reefs for a number of years, and have provided a synoptic view of reefs (Nayak et al., 1997). Evolving technologies have also contributed to more accurate assessments (Elvidge, 2004). With such advances, space research organizations around the world have launched a series of new satellites with improved sensor quality and increased capacity for higher resolutions. As a result, a number of groups have used satellite images for the classification of reef areas (Joyce, 2004; Bello-Pineda, 2005, Deshmukh, 2005).

1.4 Lacuna

Reef research has been given high priority on the global scale, but at a regional level, only a little amount of work has been carried out on the reefs of the GoK. Previous research has been based on the direction of geology and basic biology. However, there has been limited exploration of the integrated study of biology, geology, geography and remote sensing. Even though the reefs of the GoK have been given protection by being declared as the Marine National Park and Sanctuary, previous anthropogenic activities have inflicted considerable damage to the reefs of the GoK. Reef biota was studied many years ago, and there is paucity of research on recent developments. In addition, due to the remote location, tidal fluctuation, and climatic conditions, the scientific community has been reluctant to explore these reefs. Current studies have been limited to biodiversity assessment, impact of industrialization, fisheries, and the geographical setting of the GoK. Furthermore, some biological threats have been wrongly identified as coral colonies. No studies have presented the long-term reef conservation and management practices for the protection and preservation of the reefs of the GoK.

In summary, a search of the literature has revealed the need for directed research on coral reefs of the GoK with the assistance of a remote sensing approach. This will help in understanding the prevailing threats in the region, and ongoing monitoring will help with conservation efforts.

This research work was targeted at bridging this gap, and utilized the latest technology, recent satellite data, and substratum level data analysis. The objectives of this study are described below.

1.5 Aims and Objectives

As discussed in the above mentioned lacuna, this academic study was aimed at understanding the threats to some of the popular reef areas of the Marine National Park and Sanctuary – Pirotan, Bural Chank, Paga, and Dwarka. On the basis of observations made and results obtained, recommendations for better conservation practices in this area will be made.

The following are the specific objectives of this study:

1 To delineate reef habitat structure using remotely sensed data.

2 To study reef geomorphology and its relationship with inhabitants.

3 To study major abiotic threats to coral reefs of the GoK.

4 To study biological threats to coral reefs of the GoK.

5 To make recommendations for conservation and management of these reefs

1.6 Flow of Thesis

This thesis is written in seven chapters. Chapter 1 provides an introduction to corals, coral reefs, threats to reefs, and current study approaches. Chapter 2 introduces the different study areas and prevailing threats. Chapter 3 provides a comprehensive analysis of a major abiotic threat, sedimentation, and, in particular, cites Pirotan reef as a case study. Chapter 4 gives a detailed description of biotic threats, specifically algal overgrowth and *Palythoa*, prevailing in the study area. An analysis of the inter-relations of all the threats is provided in Chapters 5. Recommendations for conservation of reefs are presented in Chapter 6. Finally, Chapter 7 provides an overall conclusion, and is followed by a concise summary.

Figure 1.1 The general structure of a polyp and its underlying skeleton (Adapted from, Veron, 2000)

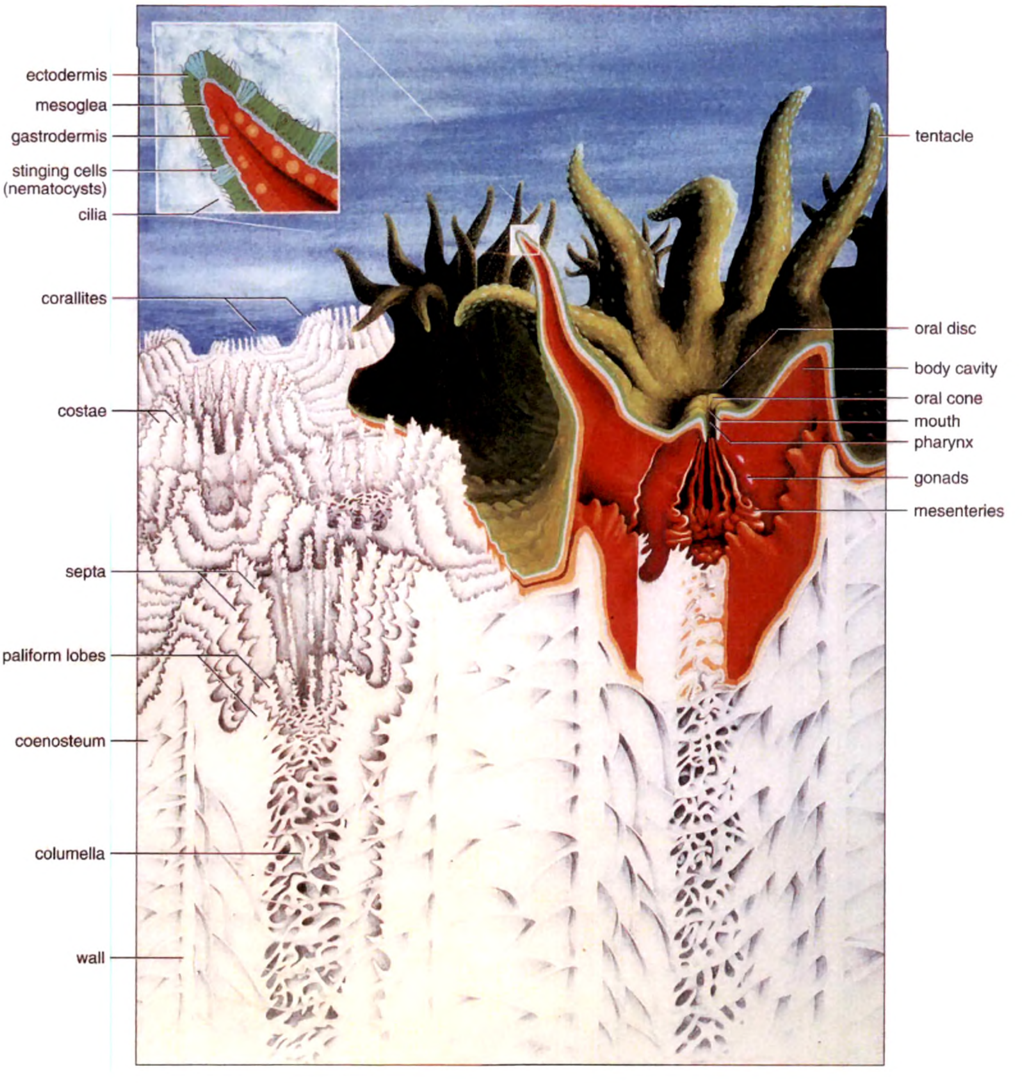

Figure 1.2 Growth forms of Hermatypic corals (Adapted from, Veron, 2000)

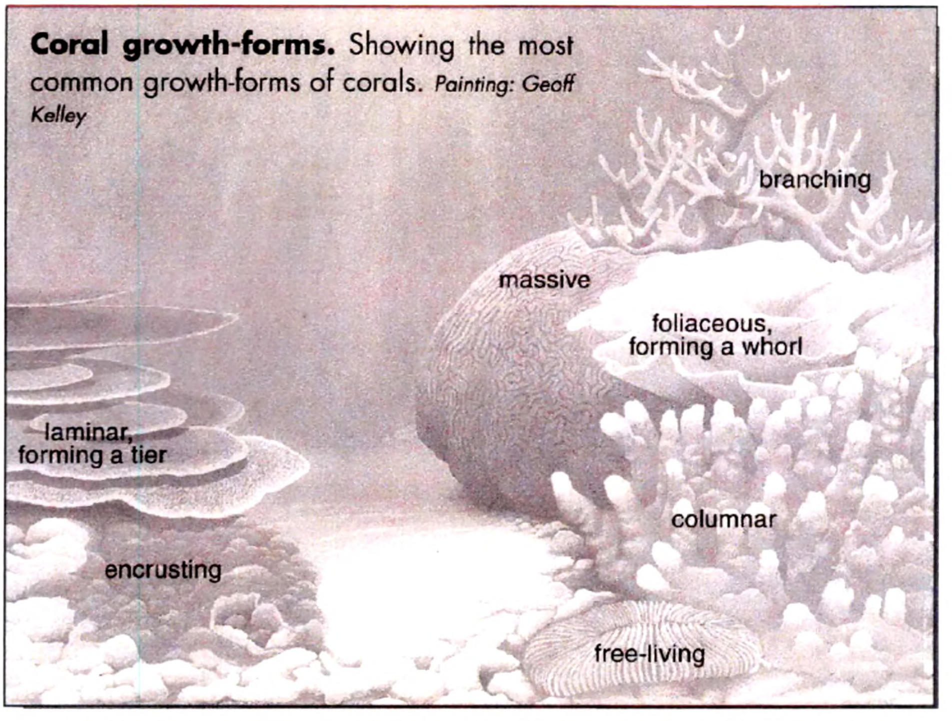

Figure 1.3 Types of Reefs: Fringing, Barrier, and Atoll

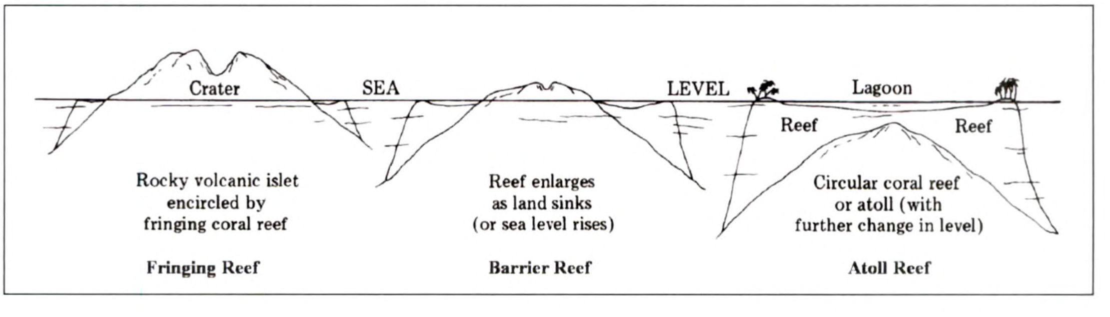

Figure 1.4 Distribution of warm and cold water reefs in the World (Source: UNEP World Conservation Monitoring Centre, 2005)

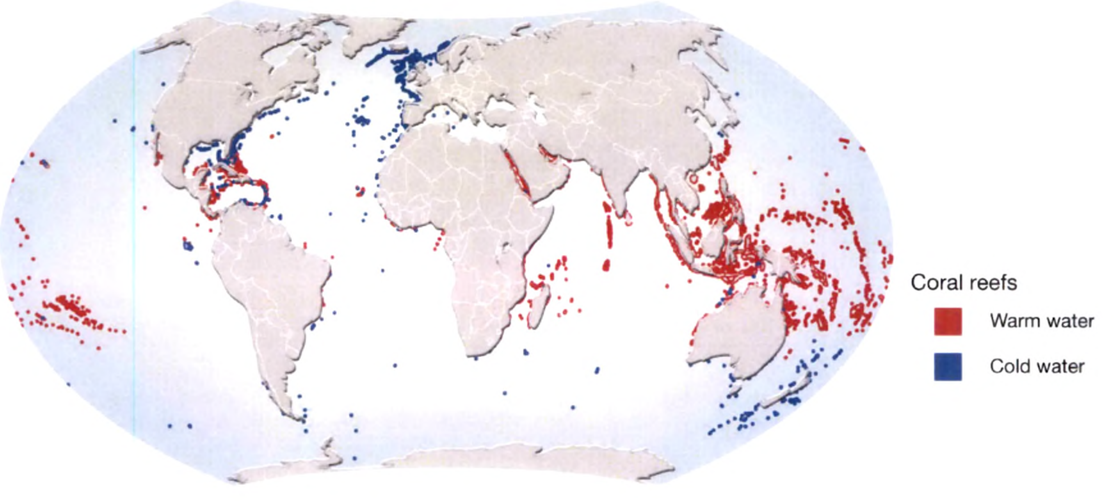

Figure 1.5 Inter-relationships of associated ecosystems (Adapted from, Moberg and Folke, 1999)