Review of the Sethusamduram Ship Canal Project – Mitigation and monitoring measures as a management strategy for the Gulf of Mannar

Commissioned by
Gulf of Mannar Biosphere Reserve Trust

Prepared by
Sudarshan Rodriguez, Jacob John, Rohan Arthur, Kartik Shanker and Aarthi Sridhar

For
Ashoka Trust for Research in Ecology and the Environment, Bangalore
November 2007

Project Team Contact Details:

Sudarshan Rodriguez
Ashoka Trust for Research in Ecology and the Environment (ATREE)
659, 5th Main Road, Hebbal,
Bangalore 560092. India
Phone: +91 9840680127
E-mail: sudarshanr@yahoo.com

Jacob John
1, 3rd Cross,
Vivekananda Nagar
Bangalore 560033
Phone: +91 9944712266
E-mail: j.t.john@gmail.com

Dr. Rohan Arthur
Nature Conservation Foundation
3076/5, 4th Cross, Gokulam Park
Mysore 570002. India.
Ph: +91-821-2515601
E-mail: rohan@ncf-india.org

Dr. Kartik Shanker
Assistant Professor, Centre for Ecological Sciences
Indian Institute of Science,
Bangalore 560012
Ph: +-80-22933104
E-mail: kshanker@ces.iisc.ernet.in

Aarthi Sridhar
Ashoka Trust for Research in Ecology and the Environment (ATREE)
659, 5th Main Road, Hebbal,
Bangalore 560092. India
Ph: +91-80-23533942
E-mail: aarthisridhar@yahoo.co.uk

Table of Contents

List of Abbreviations

DPR	Detailed Project Report
DMP	Disaster Management Plan
EIA	Environment Impact Assessment
EMP	Environment Management Plan
GoM	Gulf of Mannar
NEERI	National Environmental Engineering Research Institute
NIOT	National Institute of Ocean Technology
NHO	National Hydrographic Office
NSDRC	National Ship Design and Research Centre
MoEF	Ministry of Environment & Forest
L& T Ramboll	Larson & Toubro - Ramboll
MoST	Ministry of Surface Transport
SSCP	Sethusamudram Ship Canal Project
TFEAR	Technical Feasibility and Economic Analysis Report
TOR	Terms of Reference

Acknowledgement

Dr. R. Ramesh from the Doctors for a Safe Environment, Coimbatore is acknowledged in this report for sharing all his work, including an unpublished report for this review. His website www.sethusamudram.in is a storehouse of literature, interviews and documents on the project area and was extensively referred to in compiling this report.

I. Introduction to the Review

The GEF-UNDP assisted project on "Conservation and Sustainable Use of Gulf of Manner Biosphere Reserve's Coastal Biodiversity" is the first initiative in India to develop a multi-sectoral, management and conservation programme for a part of India's coastline which is unique and harbours globally significant marine biodiversity. The establishment of a statutory body - the Gulf of Mannar Biosphere Reserve Trust (GOMBRT) for co-ordination the implementation of the project activity is a unique and first initiative of its kind in India. The GOMBRT is a statutory Trust established by the Government of Tamil Nadu in 2001. The Chief Secretary to the Government of Tamil Nadu is the Chairperson of the Trust. The Trust has to play more than an advisory role and has to have a flexible, transparent and innovative approach to ensure appropriate integrated coastal development actions in the Reserve. During the fourth meeting of the Board of Trustees on 15.07.2005, the issue of the Sethusamudram Ship Canal Project (SSCP) was discussed. The Chairman suggested that the Trust undertake an impact assessment study about the SSCP & further that the Trust may collect details from TNPCB, NIOT, Tuticorin Port Trust and collate the relevant data on the subject. The GoMBRT thought it appropriate to engage an expert agency / institution to undertake this task, as it did not possess the required expertise to critically examine and collate the information and data. It is in this light that the GOMBRT commissioned ATREE to assist it in critically reviewing various reports and literature available on the impacts of the SSCP on the Gulf of Mannar Biosphere Reserve's biodiversity and in developing recommendations related to its conservation in light of SSCP activity.

1. Scope of the Review

It is important to place at the outset the limitations of this report. The Terms of Reference limited the scope of this review this. Some of these limitations are explicated below:

1. The Palk Bay and Gulf of Mannar are considered as distinct water bodies with very different conditions, seasonal cycles and ocean-met parameters, although they are inextricably linked to each other via Adams Bridge and the Pamban pass. Though there are sea grasses and corals in the Palk Bay making it an equally fragile & important ecosystem as the Gulf of Mannar, it was considered outside the scope of this review to examine the implications of the project on this ecosystem. It must be noted that a large part of the canal/project is in the Palk Bay. Critical aspects for the project design and sustainability such as the state of knowledge of bathymetry, sub-surface geology and sedimentation transport dynamics were examined for the Gulf of Mannar and Adams Bridge area alone as specified in the Terms of Reference.

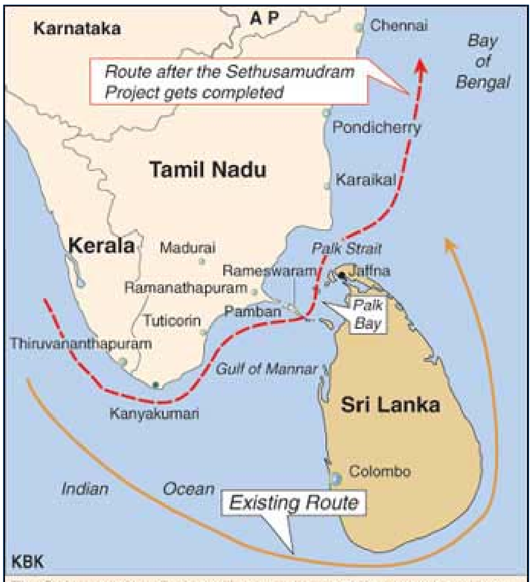
2. The implications of the December 2004 Indian Ocean Tsunami and any future possibilities of a tsunami to the stability and environment of the canal was also not examined.

3. The review also does not attempt to examine or analyse the economic and financial viability of the project and focuses on environmental and ecological aspects of the project in the given area.
4. Compliance of project and project documents with various legislation and prescribed guidelines was examined only in context of future monitoring and the environment management plan. Post-project committees and other intuitional mechanisms vis a vis environmental aspects of the project have not been commented on.
5. The main focus of the review was on reviewing literature and experiences from around the world on dredging and its possible impacts to the marine environment in general and specifically for sea grasses and coral reefs. Based on this, the main mandate of the review was to outline recommendations for mitigation and monitoring measures as management strategies in the wake of the SSCP project.

2. Project Area of the SSCP

The SSCP is a 167 km. long shipping canal, which is to pass through the Gulf of Mannar, the Palk Strait and the Palk Bay. It involves dredging in an 89-kilometer stretch for a width of 300 meters and for a depth of 12 meters for ships less than 30, 000 DWT with draft restricted to 10m. The project is said to have been conceived in 1860 by Commander Taylor and the project has been subject to several reviews in the 20th century. The project route is shown below[1]:

Figure 1.1: Showing the route of the SSCP



The Sethusamudram Project will reduce distance between east and west coasts by up to 424 nautical miles and sailing time of up to 30 hours.

[1] Source: http://sethusamudram.tamilar.org/

Gulf of Mannar[2]

The Gulf of Mannar falls in the Indo-Pacific region, considered to be one of world's richest marine biological resources. The proposed SSCP site is located in a globally significant ecologically sensitive marine ecosystem – the Gulf of Mannar Biosphere Reserve. It is one of the four major coral reef ecosystems of India. The reefs in Gulf of Mannar are around a chain of 21 uninhabited islands that lie along the 140 km stretch between Tuticorin and Rameswaram of Tamil Nadu, on the southeast coast of India. These islands are located between latitude 8° 47' N and 9° 15'N and longitude 78° 12'E and 79° 14'E. The average distance of these islands from mainland is about 8 km. The islands in the Gulf of Mannar can be classified into four major groups:

1. Mandapam Group (7 islands): Musal, Manoli, Manoliputti, and Poomarichan, Pullivasal. Krusadai and Shingle.
2. Keezhakkarai group (7 islands): Yaanaipar, Pallimunai, Poovarasanputti, Appa, Thalaiyari, Vaalai and Mulli.
3. Vembar Group (3 islands): Upputhanni, Pulivinichalli and Nallathanni.
4. Tuticorin Group (4 islands): Vaan, Koswari, Kariachalli and Velanguchalli (submerged)

The GoM has chains of shoal, nearly seven in all, 30 km long called the Adam's Bridge. It is an inlet of the Indian Ocean, between southeastern India and western Sri Lanka. It is through this area (Adam's Bridge) that the SSCP will run through, which will be pathway connecting the Gulf of Mannar to the Palk Bay. During high tide, the seawater is known to rise more than 1.2 meters above the mean sea level. Full of beach ridges, the GoM can be grouped into: (i) Beach ridges south of Vaigai River; (ii) Beach ridges between Kotangudi River and Palar River; (iii) Beach ridges between Palar River and Gundar River system; (iv) Beach ridges between Gundar River and Vaippar River; and (v) Beach ridges south of Vaippar River. The total water logged land has been calculated to be 5.96 km^2. Eight series of Strand Lines can also be observed, apart from the sea cliff and caves.

Pillai provided a comprehensive account of coral fauna of Gulf of Mannar and the diversity includes 94 species of 37 genera with most common being Acropora sp, Montipora sp and Porites sp. (Pillai,1986) Patterson et al., have subsequently updated the species list to 104 species of 38 genera (Patterson et al, 2004).

The coastal waters of the Gulf of Mannar harbour a remarkable variety of Scleractinian coral species. A widespread family, the Acroporidae, has two common genera, *Montipora* and *Acropora. Acropora* is the dominating genera in Gulf of Mannar. *Acropora* characteristically forms large circular colonies with a branching network. *Montipora* has growth forms commonly referred to as "foliose" or "encrusting", "branching" and forms flats of dense stands. Another large family, the Faviidae, with 22 species, includes genera *Favia*, *Favites*, *Goniastrea*, *Platygyra*,

[2] Some sections adapted from (Venkatraman, 2006)

Leptoria, *Leptastrea*, *Cyphastrea*, *Echinopora*, *Hydnophora*, which mostly are of massive forms. The Poritidae family, with 9 species includes the genera *Porites* and *Goniopora*. It includes the common massive brown "hump coral" which looks like small mountings (Venkatraman, 2006).

It is also well known for its diversity of sea grasses. Out of the fourteen species of seagrasses under 6 genera known from Indian seas, thirteen species occur in the Gulf of Mannar Biosphere Reserve, with *Halophila, Halodule, Enhalus* and *Cymodocea* being common among them (Venkataraman & Wafar, 2005).

The Gulf of Mannar is predominantly a high biodiversity reef ecosystem with 147 species of seaweeds (Kaliyaperumal 1998), 17 species of sea cucumbers (James 2001), 510 species of finfishes (Durairaj 1998) 106 species of shellfishes such as crabs (Jeyabaskaran and Ajmal Khan, 1998), 4 species of shrimps (Ramaiyan *et al.,* 1996) and 4 species of lobsters (Susheelan 1993). During recent survey on mollusk, 5 species of polyplacophorans, 174 species of bivalves, 271 species of gastropods, 5 species of scaphopods and 16 species of cephalopods (Scaphopods added for the first time) were recorded (Deepak and Patterson, 2004). In addition, a total of 10 true mangrove and 24 mangrove associated species were recorded from the islands in the Biosphere Reserve (Jeganathan, et al, 2006).

In recognition of its global significance and rich biodiversity, on May 7, 1999 the Global Environmental Facility (GEF), the official financial mechanism for the Convention on Biological Diversity (CBD) approved the funding of the project proposed by the Government of India titled "Conservation and Sustainable Use of the Gulf of Mannar Biosphere Reserve's Coastal Biodiversity " for US $ 7.868 million[3]. The GEF only funds projects and conservation in areas that are globally significant[4]. The project document states "*The overall objective of this project is to conserve the Gulf of Mannar's globally significant assemblage of coastal and marine biodiversity and to demonstrate, in a large biosphere reserve with various multiple uses, how to integrate biodiversity conservation into coastal zone management plans".* Thus the Gulf of Mannar in addition to being a national priority site also assumes global significance and priority. The Gulf has been chosen as a biosphere reserve primarily because of its biological and ecological uniqueness (MoEF, 2002)[5]. The region has a distinctive socio-economic and cultural profile shaped by its geography. It has an ancient maritime history and was famous for the production of pearls. Pearl has been an important item of trade with the Roman Empire as early as the first century A.D., while Rameswaram, with its links in legend to the Ramayana epic, has been an important pilgrim centre. The region has been and continues to be famous for its production of chank (Indian conch). The GoM thus constitutes a live scientific laboratory of national and international value. It has 3,600 species of plants and animals that make it India's biologically richest coastal region (Global Environment Facility, 1999).

---

3 Also available at http://www.gefonline.org/projectDetails.cfm?projID=634

4 GEF Operational Strategy Document, see http://www.gefonline.org/projectDetails.cfm?projID=634

5 See http://www.envfor.nic.in/report/0102/chap03.html and http://www.indian-ocean.org/bioinformatics/mangrove/MANGCD/bios1.htm

3. Structure of this Review

The proposed Sethusamudram Shipping Canal Project (SSCP) canal between India and Sri Lanka across the Adam's Bridge connecting the Arabian Sea with the Bay of Bengal has the potential to effect very significant consequences on this globally significant marine biodiversity area. The construction and maintenance of the canal will involve a range of coastal and marine engineering activities, and when completed will be the largest such undertaking of its kind for India. In a broad sense, this review aimed at understanding how project planning considered the biological diversity of the region.

This review involved an analysis of all the SSCP documents and relevant literature to arrive at a multi-pronged assessment of the implications of the SSCP particularly its implications for the biodiversity of Gulf of Mannar and Palk Bay regions. The literature reviewed includes published articles and papers in peer reviewed journals, expert reports pertaining to the economic, ecological and social impacts of the project. Other relevant background literature pertaining to the project area and specifically, literature pertaining to dredging and its implications to sea grasses and coral reefs were also examined and the findings are presented in this report.

Section 1 of the report reviews the technical aspects in the project documents referring to critiques of these as well as other relevant background literature on the project area. The state of knowledge of four aspects of the project is reviewed, namely subsurface geology, bathymetry, sedimentation process and dynamics. The implications of all of the above on dredge disposal are also analysed.

Section 2 looks at aspects related to post-project clearance namely the conditions of environment clearance, environment monitoring requirements and the Environmental Management Plan (EMP).

Section 3 is authored by **Dr. Rohan Arthur** and looks at the implications of dredging, sedimentation, and its impacts on coral reefs and seagrass meadows. This section reviews literature on dredging, dredging related sedimentation and its impacts on corals and sea grasses to draw conclusions for impacts of the project on the same. This section also provides a detailed bibliography on effects of dredging on sedimentation, and on coral reefs and seagrass ecosystems in particular.

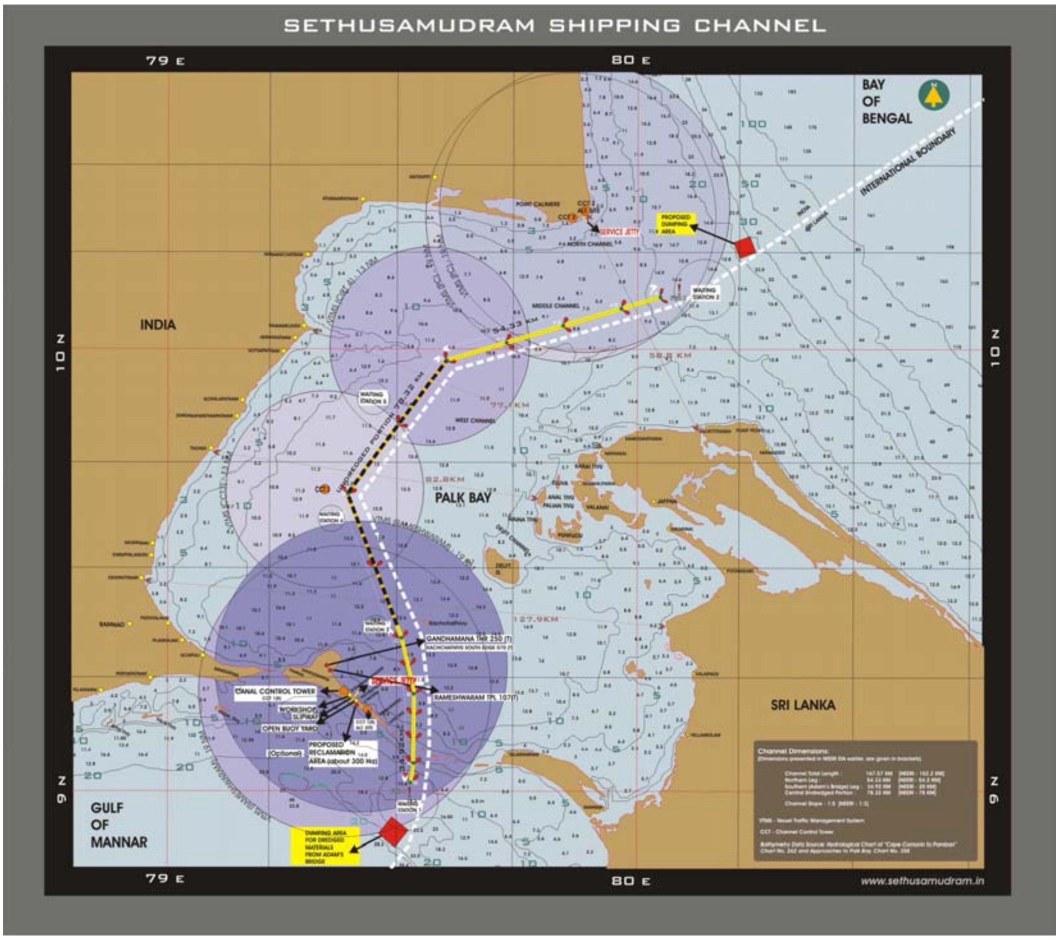
Section 4, the last section, summarises the findings of the above sections and analyses their implications and provides recommendations based on this review.

Sections 1, 2, and 4 were authored by **Sudarshan Rodriguez.**

Section 1: Issues Relating to Technical Aspects in Project Design, EIA and Related Studies

For a project such as the Sethusamudram Ship Canal Project (SSCP), to be environmentally sound and well designed, a full understanding of the project area, its ecology, its environmental processes, the project activities – namely dredging and waste disposal and movement of ships in the region is a must. It has been stated that the navigation channels of ports on the East Coast of India face three major and persistent problems - (1) problems due to sedimentation, (2) problems due to tropical cyclonic disturbances, and (3) issues related to dumping of dredged material (Ramesh, 2005a).

Figure 1.2: Showing the area of the Gulf of Mannar[6]



Thus the Sethusamudram Ship Canal Project should have been backed by a complete scientific understanding of the following parameters and factors in the project area:

---

[6] Source www.sethusamudram.in

1. Sub-surface geology
2. Bathymetry
3. Sedimentation process and transport regime in the project
4. Any element/factor that impacts and influences the above such as monsoons, storm surges, cyclones, tsunamis, land-use etc.
5. Assessment of the implications of the loss of bottom fauna along dredged area
6. Assessment of the implications of dredge disposal on the ecosystem
7. Assessment of the implications/impact of the channel on the existing sediment transport regime/process of the Palk Bay and Gulf of Mannar.
8. Assessment of the implications/impact of the previous three points on biodiversity and fisheries.
9. Assessment of the implications/impact of the operational phase of the project on biodiversity and fisheries in the region.

The sub-surface geology and the bathymetry help determine the alignment of the canal and the type of dredging required. Once this is known, the sedimentation from the dredging activity as well as dredge disposal can be ascertained. This also determines the amount of capital dredging and its costs. This sediment dispersion can be predicted by knowing the sediment quality (from the surface-geology studies) coupled with the modelling of various scenarios of ocean-met and physico-chemical parameters. The scenarios should be based on primary data as well as past historical data. Once this is done the impact of the sedimentation on biodiversity especially reefs can be extrapolated.

Sedimentation and transport regimes and factors affecting these, determine the level of maintenance dredging required as well as the possible sites for disposal of dredged material and the environmental impacts of this activity. Only after full information and data on the above is obtained can the details of points 5-9 be derived. Points 8 and 9 would come under an ecological risk assessment report. It should be pointed here that other than the NEERI report stating that all bottom fauna and flora in the dredged part of the canal will be lost, no impact study using primary data on the biodiversity is available. The quantum and details of the loss of bottom flora and fauna along the canal is also not detailed in the literature and documents.

Table 1.1 Chronological Timeline of Project

Dec 1998	NEERI Initial Environmental Examination (IEE)
May 2003 & Feb 2004	NEERI-NSDRC Sea Geo Survey in the Pamban Pass Area
Jan-Feb 2004	NHO Bathymetry survey (25 January – 18 February 2004)
May 2004	NEERI EIA (this version titled 'Rapid EIA' was circulated for the public hearings)[7]
July 2004	NEERI's TFEAR Report[8] (incorporates NHO Bathymetry survey)
August 2004	NEERI EIA (Final Version appears online without the words 'Rapid EIA')[9] (incorporates NHO Bathymetry survey)[10]
August 2004	L&T- Ramboll was entrusted with preparing the Detailed Project Report in August 2004
Nov-Dec 2004	NIOT Bathymetry Survey (6-23 November 2004 and 16-17 December 2004)[11]
February 2005	L&T-Ramboll DPR[12]
February 2005	Indomer-Alkyon, Hydrodynamic Modelling Sedimentation Studies and Ship Manoeuvring Study for Sethusamudram Ship Canal[13]
31 March 2005	Ministry of Environment grants Environment Clearance to SSCP[14]

The above table will assist in following information flow of the various SSCP project documents. This is explained in the following sections.

[7] The authors had procured copies of the May 2004 NEERI EIA report at the time of its release.
[8] (NEERI, 2004b) Available at http://sethusamudram.gov.in/Images/TechnoEconomicReport.pdf
[9] (NEERI, 2004a)This version is available online at http://sethusamudram.gov.in/images/eia_fullversion.pdf
[10] A reading of both versions shows that the August 2004 version only contains additional information on the Adam's bridge region.
[11] (NIOT, 2004) Available on http://sethusamudram.gov.in/BathyStudy.asp
[12] (L&T-Ramboll, 2005) Available on http://sethusamudram.gov.in/Images/Sethusamudram%20Final%20DPR-%20Rev.A%20-%20Feb%202005%20-%20Print.pdf
[13] (Indomer-Alkyon, 2005) Available on http://www.sethusamudram.in/pdfdocs/HydroStudy.pdf
[14] Available on http://sethusamudram.gov.in/EnvMinistry.asp

1. Sub-Surface Geology

In order to identify the method of dredging for the various sections of the canal, the knowledge of sub-surface geology is absolutely essential. As mentioned earlier, this knowledge is also essential, to identify the potential impacts of the dredging on the environment. Dr. R. Ramesh points out that the EIA and other investigations conducted by the project authorities contain very scanty information on the sub-surface geology of the channel's alignment (Ramesh, 2006). This has also been admitted in the L& T Ramboll Detailed Project Report (DPR) and in the Technical Feasibility and Economic Analysis Report (TFEAR) prepared by the National Environmental Engineering Research Institute (NEERI). The relevant sections of the respective reports are quoted below:

The NEERI TFEAR (in section 5.1.1.1, page 5.1-65 & 5.1-66) mentions that the National Hydrographic Office, Dehradun had collected bathymetry data and also carried out a sub-bottom seismic survey for the Palk Strait area and NSDRC carried out a similar exercise for the Adam's bridge area and that recent drilling data (bore holes) in the Palk Bay is not available (Ramesh, 2006). The NEERI TFEAR further points out (on page 5.1-66) that 'detailed sub-soil investigation must be carried out as it is essential" and also that "any short cut will be a disaster for the project". Dr. Ramesh suggests that, as the NEERI EIA did not have a full knowledge base of the sub-surface geology, the L&T Ramboll DPR recommended "Marine boreholes up to -16 m, suitably staggered covering the width of 1 km of alignment in suitable numbers so as to collect all information for full understanding of the dredged area" (L&T Ramboll DPR 2005: pages 5-6 and 5-7) (Ramesh, 2006).

Krishnaswamy[15] in his article states that the L&T-Ramboll DPR considers the soil to be mostly dregdeable but in some reaches, blasting may be required before dredging, due to the hard nature of the sandstone that may be encountered in drilling (Krishnaswamy, 2005)[16]. He has also based this on the 44 vibro-coring operations done by National Institute of Ocean Technology (NIOT) during January – February 2005 (NIOT, 2004). This view is also held by Seshagiri[17] in his assessment of the same investigations and his conclusion is that "the vibro-core data had indicated harder strata at depth. The amenability of this medium to conventional dredging is to be ascertained" (Seshagiri, 2005). The project documents such as the DPR and the EIA directly do not envisage blasting but the NEERI TFEAR does state (section 5.1.1.1, page 5.1-65), "In the event that hard strata comprising rock is encountered, the dimension of dredging costs will drastically change as blasting might be required." The project documents do not assess impacts in the event of blasting being required.

[15] Dr.V.S. Krishnasamy is a renowned expert Engineering Geologist and was the Former Director General of Geological Survey of India. He was personally involved in the Sub Surface Geological Studies for the construction of the Pamban Bridge Project (also located in the Project Area).

[16] Also available on http://neelankrisna.blogspot.com/2006/02/sethusamudram-dredging-technical.html

[17] Dr. Seshagiri was the Former Director, Geological Survey of India

On NIOT's Geological & Geo-technical Assessment of the sub-sea region, Krishnaswamy states that in order to correctly ascertain the nature of the formations to be excavated and to decide whether they are dregdable, or if blasting will be required in specified sections, vibro *coring or the jet coring methods may not provide fully satisfactory information* (Krishnaswamy, 2006). He is of the view that rotary drilling is required using "large diameter bits and barrels with stipulation of short runs and double tube core barrel and the usage of dry drilling techniques to the maximum extent possible.". He also points out that the costs of blasting has not been taken into account while estimating the cost of capital dredging and more importantly, the ***impact of blasting on the marine environment, ecology and fisheries has not been taken into account in the NEERI EIA***.

The lack of knowledge on the nature of the substratum of the region is also pointed by Rajendran (Rajendran, 2005a; Rajendran, 2005b). He adds that the impact of the bottom topography as a result of possible blasting especially on the movement of currents **is not known or studied.** Ramesh cautions that as a result of the gaps in the sub-surface geology, the nature of the dredged spoil is currently known only for about 38.5 to 40.5% of the total dredged spoil (Ramesh, 2005a; Ramesh, 2005b).

From the above it is clear that the all project documents had a poor understanding and information of the sub-surface geology. Consequently the kind of dredging that is required in this region and its impacts on the environment were not estimated accurately. Thus the present views of project documents on environmental impacts of the dredging and disposal of dredge material in this region are incomplete are informed.

2. Bathymetry

Precise data on bathymetry is essential to estimate the amount of capital dredging required (along with sub-surface geology data). From this information, the quantum of dredging required using various techniques (based on sub-surface geology data) in different sections of the canal can be ascertained to arrive at an accurate estimation of capital dredging costs. The bathymetry, sub-surface geology and the type of dredging determine the total sediment that may be dispersed and hence are also relevant inputs for dredge management programme which can based on the above information can mitigate and reduce the environmental impact and sediment dispersal.

A bathymetric survey was done by NEERI (along with the National Ship Design and Research Centre) in the Pamban Pass area of the Adam's Bridge in May 2003 and February 2004. In addition to this, the National Hyrdographic Office (NHO) had done a survey in January-February 2004 for the channel alignment proposed by NEERI earlier, starting from the north side of the Adam's Bridge area. The L&T-Ramboll DPR suggested that a fresh Bathymetry Survey with much finer resolutions than the one presented by NHO would be necessary to arrive at reasonably accurate estimates of capital dredging (L& T DPR, section 5.2.4, page 5.6). It has been stated that this new Bathymetric Survey was carried out by NIOT, Chennai in the periods 6-23 November 2004 and 16-17 December 2004 The environmental implications of this new data was not ascertained and never incorporated into the EIA (Ramesh, 2006).

It is quite clear from the above that there were gaps in the knowledge of bathymetry along the sections of the channel, especially the Adam's bridge. The revised information was not incorporated into the environmental assessments of the channel.

3. Prediction of Sediment Dispersal and Environmental Impact

This sediment dispersion can be predicted by knowing the sediment quality (from the surface-geology studies) coupled with the modelling of various scenarios of ocean-met and physico-chemical parameters. The scenarios should be based on primary data as well as past historical data. Once this is done the impact of the sedimentation on biodiversity especially reefs can be extrapolated. The bathymetry, sub-surface geology, type of dredging and the sediment dispersal modeling determine the total sediment that may be dispersed and hence are also relevant inputs for dredge management programme/protocol which can mitigate and reduce the environmental impact and sediment dispersal. No literature on this was available prior to the project clearance or even till date.

4. Information base and Data on Sedimentation

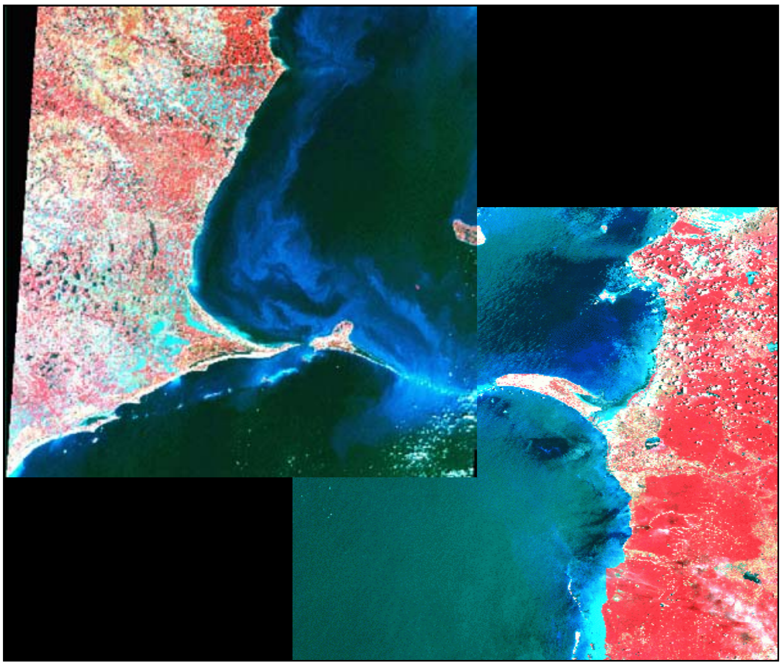
As stated earlier, one of the three major persistent problems that navigation channels of ports on the East Coast have been facing is sedimentation (Ramesh, 2005a; Ramesh 2005b). The lack of studies and data in the EIA and other documents on the littoral processes and flow characteristics that will affect the channel in the Palk Straits region has been highlighted (Rajendran 2005a; Rajendran, 2005b; Ramesh, 2004; Ramesh, 2005a; Ramesh 2005b) and further stresses that this area (the Palk Bay/Straits) is noted for unusually high sedimentation rate and is one of the five permanent sediment sinks of India. Rajendran also points out that the EIA has looked at the sedimentation dynamic of very few areas of the canal and not studied the adjacent portions of Palk Strait, which is noted for its unusually high sedimentation rate (Rajendran, 2005b).

The sediment sink and transport mechanism in the region (both Palk Bay and Gulf of Mannar) is yet to be fully understood. In fact, there is evidence to suggest that there is an annual seasonally cycle that allows sediment flow from the Palk Bay into the Gulf of Mannar along the Adam's bridge (Dwivedi, 2006). Thus, the canal through the Adam's Bridge might increase this sediment flow into the Gulf of Mannar from the Palk Bay thus impacting and affecting its sensitive ecosystem. This literature on this dimension and impact is **not available.**

Critics have stated that the NEERI EIA needs to incorporate the information and data from the most important research papers on sedimentation process in the project area that had been published in peer reviewed science journals after the year

1989 (Ramesh 2004b; Ramesh, 2005a; Ramesh, 2005b; Rajendran, 2005a). Some of these are Sanil Kumar et al. (2002), Ramasamy et al. (1998), and Chandramohan *et al* (2001). Furthermore, whether the operational phase of the canal will have any implications to the sediment transport **has not been ascertained** by any of the literature. A satellite picture illustrates this in the adjoining pages.

Figure 1.2: Satellite image showing sediment dispersal patterns from Palk Bay to Gulf of Mannar through the Adams bridge area.[18]



5. Dredge Disposal

The NEERI TFEAR states, "It is very necessary to carry out a Radio Active Tracer Study to optimise the dredge disposal areas as 80% of the cost of the project is on dredging and disposal of dredged spoil" (NEERI TFEAR, page 5.1.65). It is re-stated here that the NEERI EIA had not carried not any studies on this aspect and the NEERI EIA itself mentions (in section 6.4.1.2, page 318), "tracer studies have been initiated for further studies to select suitable locations. In no case will dredged spoil be allowed to be dispersed in the Palk Bay." The SSCP's EIA should have included information on suitable disposal sites, since the project is located in an ecologically sensitive area and this activity involves obvious environmental implications.

Krishnaswamy is of the view that it is very premature to come to any conclusion on the suitability or otherwise of the proposed dredge disposal areas (Krishnaswamy, 2006). He states that opinion of specialists in oceanographic studies/with regard to the disposal of the dredged material is that it is better to dispose the dredged waste in waters 50-60m deep instead of the current proposal of

[18] Source: Dwivedi, 2006

25-30m. This view is also held by Prof. G.Victor Rajamanickam who mentions in his interview to www.sethusamudram.in that the present chosen depths of 25-30m for the dumping sites would be disturbed by any monsoon (leave alone cyclones or a tsunami). Rajendran further states that the EIA is ambivalent on the identification of sites for environmentally safe disposal of dredged material thus posing an environmental hazard to marine organisms (Rajendran, 2005a; Rajendran, 2005b).

6. Ecological Risk Assessment

NEERI's Terms of Reference (ToR) for the EIA also specifies the need for an ecological risk assessment. This is also mentioned in the section 1.5.4.6 in the EIA which is given below:

- Quantification of ecological risks and delineation of ecological risk mitigation measures
- Analysis of information with regard to environmental impact (direct, synergistic and cumulative) and associated navigational and landward activities in and around the project region
- Quantification of ecological risks with recourse to appropriate ecosystem models

Section 6.6 in the NEERI EIA, which is "Impacts on Productivity and Ecology in GoM/Palk Bay" only very briefly and qualitatively, lists the impacts and risks with no quantification of the same as suggested by the ToRs and introduction of the EIA. It should be pointed here that, other than stating that all bottom fauna and flora in the dredged part of the canal will be lost[19], there is no impact study on the biodiversity is available. The quantum and description of the bottom flora and fauna lost due to dredging along the canal is also not detailed in the documents or any other literature.

7. Distance from Islands

There are no details of the distance of the islands from the navigational route of the canal or the canal itself except for a mention in the EIA that "a navigational route keeping a minimum 6-8 km distance from Van Tiu near Tuticorin and more than 20 km from Shingle Island in Adams Bridge approach area has been suggested." in Section 1.0 para 3, executive summary of the EIA. There is also no information on coordinates of the navigation route up to the canal from Tuticorin or Kanyakumari. However, a possible route is illustrated below by ATREE's GIS team and the distances from the islands have been shown in the table below:

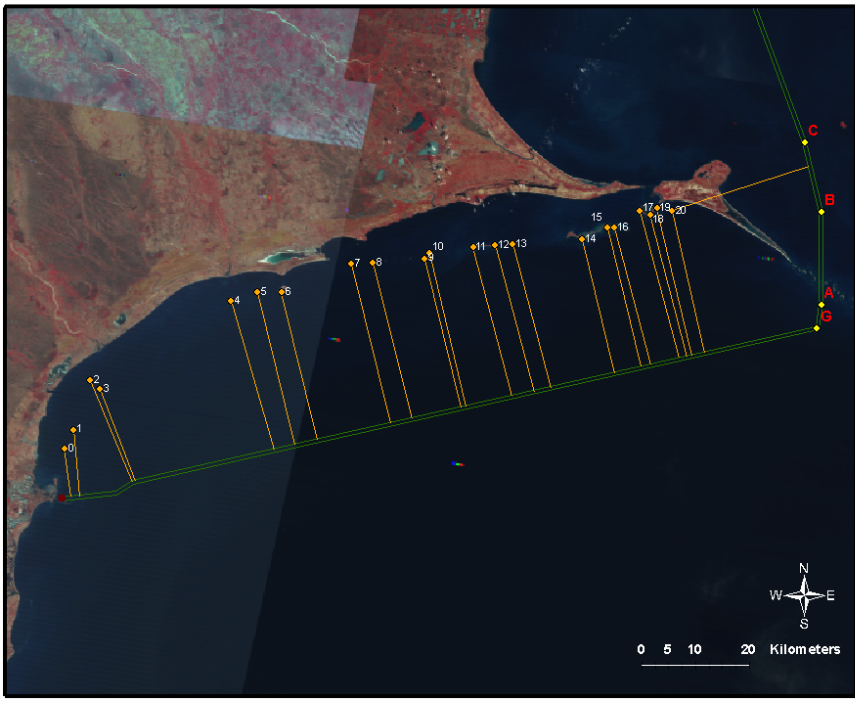
Table 1.2: Distances of Islands to possible navigational route of canal

Code on map	Name of island	Distance from route (km)
0	Van Tivu	9.20
1	Kasuvar Island	12.50
2	Karaichalli Island	20.50

[19] NEERI EIA, see section 6.4.1.2 and 6.6, L&T Ramboll DPR, see page 12-4 section 12.6.2.3, 2nd paragraph

3	Villanguchalli Island	18.37
4	Upputhanni Island	29.06
5	Pulvinichalli Island	29.10
6	Nallathanni Island	28.30
7	Appa Island	30.50
8	Valimunai Island	30.00
9	Adda Island	28.50
10	Poovarasanpatti Island	29.30
11	Talairi Island	28.50
12	Valai Island	28.30
13	Mulli Island	28.40
14	Hare / Musal Island	25.60
15	Manoli Island	26.60
16	Manoliputtu Island	26.30
17	Poomarichan Island	28.30
18	Pullivasal Island	27.30
19	Krusadai Island	28.30
20	Shingle Island *	27.10
	Shingle Island *	27.80
Average distance of possible Navigational Route		27.04
*	(island to pt on route)	
**	(island to pt on canal)	

Figure 1.4: Distances of Islands to possible navigational route of canal



The above suggest a distance more than 20 km and are in line with the above statement in the EIA.

Section 2. Issues Related to Environmental Management Plan (EMP) & Environment Monitoring

1. Environment monitoring program

The NEERI EIA does not have an environmental monitoring program despite the ToR for NEERI's EIA clearly stating that the Environmental Management Plan (EMP) will "essentially consist of details of work proposed under mitigative measures, implementation schedule of such measures, fund and manpower requirements and arrangements for ***monitoring on a long-term basis***." In fact, the NEERI EIA itself further states in section 1.5.2, the Scope of the Study, "Formulation of an environmental quality monitoring programme for various phases of the project to be pursued as per the requirements of statutory authorities."

This lacuna, indeed omission in the EMP of the EIA is pointed out by L&T-Ramboll in their DPR in section 2.5.4 on page 2-12. It states, "The Environment Management Plan reported is well presented but **does not cover pre and post project monitoring requirements and mechanisms for environmental management.**" In fact, it is the L&T-Ramboll DPR that lays down the detailed environmental monitoring requirements for the implementation & operational phase in appendix A.12.2 on page 2-1 and appendix A.12.2.1 on page 2-3 respectively. This includes monitoring of marine water and sediment quality. This has been adopted by the SSCP and is also on their website on environmental monitoring.[20] However, a closer look at the details of environmental monitoring as updated on the website implies that the following parameters are either **not being followed or not being posted** on the website:

Chemical Properties: DO, BOD, COD, Oil & Grease, Nutrients, Sulphates, Chlorides

Heavy Metals: Fe,Zn,Mg,Mn,Cd,Cr,Hg

Bacteriological parameters: Coliform count

Marine Biology: Phytoplankton and Zooplankton.

Thus only physical properties - pH, EC (electrical conductivity), salinity, temperature, turbidity, TSS (Total Suspended Solids) is being monitored. It also seems that it is **being done only for marine water quality and not for sediment quality.** The SSCP had earlier publicly announced that results of all the environmental monitoring would be updated everyday on the website (Anon, 2005).[21]

2. Monitoring of Sub-Marine Conditions

The L&T-Ramboll DPR in section 12.9.2 page 12-11 bullet point 5 states, "The submarine conditions during the dredging activity should be inspected by divers and photographic and video records should be maintained. This activity should also

[20] See http://sethusamudram.gov.in/Monitor.asp

[21] Also available on http://www.hindu.com/2005/07/01/stories/2005070105760400.htm

cover the disposal grounds (at sea)". This is evidently not being done as seen from the information on the SSCP website where the entire environment monitoring detail is being maintained.[22]

3. Monitoring of other parameters

Prof. Rajamanickam stresses that currently important factors like hydrography, bathymetry, current dynamics, total suspension load, climate changes, sea level alterations etc., that have the ability to affect the Project and the Bay are not being monitored either (Rajamanickam, 2005).

Seralathan highlights that other conditions from the MoEF's clearance letter, such as the stoppage of dredging during the fish breeding & spawning periods, and the condition that suspended matter at the dredging sites should not spread more than a kilometer on either side of the channel route have been disregarded by project authorities (Seralathan, 2006). None of the project documents or the MoEF clearance conditions refers to this.

[22] http://sethusamudram.gov.in/Monitor.asp

Section 3: Dredging, Sedimentation, and its Impacts on Coral Reefs and Seagrass Meadows: Implications for the Gulf of Mannar

1. Introduction

The proposed canal between India and Sri Lanka across the Adam's bridge connecting the Arabian Sea with the Bay of Bengal has the potential to have very significant consequences on some of the most important marine biodiversity areas of mainland India. The Gulf of Mannar regions have some of India's richest coral reef ecosystems and are also home to some of the most extensive and diverse seagrass meadows in the country. Apart from being ecosystems of high productivity and diversity, they perform vital ecosystem functions, protecting coastal systems, and serving as nursery grounds for fish stocks that sustain local fishing communities (Moberg and Folke 1999; Harborne et al., 2006). The seagrasses of the Gulf of Mannar is additionally important as they represent the last refuge of the globally threatened dugong (*Dugong dugon*) in mainland India.

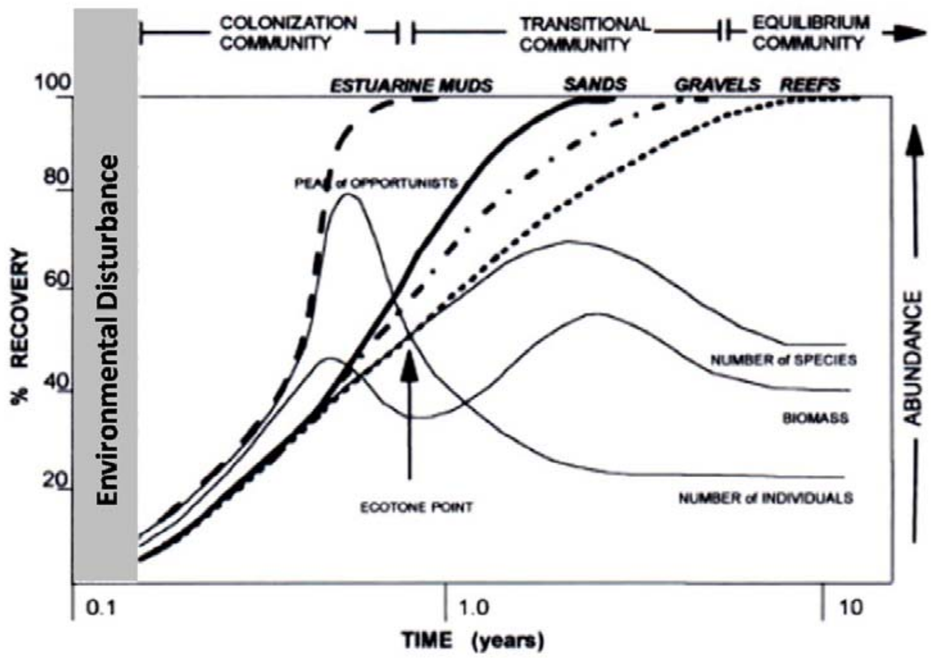
Given the shallow nature of the Palk Bay and the Adam's Bridge area, it will require considerable dredging of the sea floor to attain this depth (Ramesh, 2005). These activities, along with the increased coastal development that will doubtless result with the establishment of the canal will introduce dramatic changes in the marine environment of the Gulf of Mannar. This section examines these potential impacts to seagrasses and coral reefs, and discusses the implications of these impacts for marine biosphere managers concerned with maximising the resilience of these systems as well the livelihoods of local communities. It should be mentioned here that there is no data and literature on the impact of the project on fish and soft bottom communities in the literature and project documents. However, it should be pointed here that project does state that all bottom fauna and flora in the dredged part of the canal will be lost (which is currently located outside the GoMNP)

2. Consequences of Dredging Activity on Marine Environments

Marine dredging, by its very nature, is an earth-moving exercise of immense proportions. The SSCP canal proposes to dredge up regions of the Adam's bridge to between 9m and 12 m depth, from its current 3m to 5m depth as stated in Section E.7 and E.8, page 5 of the Executive Summary of the L&T-Ramboll DPR. The L&T-Ramboll DPR states that the expected dredging amount is 0.1 x 106 $m^{3.}$ (See Section 2 of this review for details). The dredging itself will result in large-scale benthic scarring and removal of all sedentary organisms on the ocean floor. The specific kind of dredging used will eventually determine the nature of the impact on the benthic floor, but the commonly used forms of dredging – anchor dredging and trailer dredging both cause considerable damage (Newell et al. 1998). The project documents refer to trailer suction dredgers are being used for most areas of the dredging of the canal. However, for the Adam's bridge the documents state that cutter section dredgers will be being used.[23].

This direct habitat destruction will result in losses of marine benthic environments along the course of the canal, and can also lead to significant alterations in the characteristics of the sea bed, which may make benthic recovery a protracted process. Recolonisation could begin as early as a year after the event in the case of early successional species, but in the case of more slow-growing, long-lived marine organisms, the recovery could be considerably slower (Newell et al. 1998, also see Figure 2.1.). Large-scale changes in bathymetry will also result in alterations in local flow patterns that could change patterns of sediment flux in these waters, and potentially affect dispersal and settlement of benthic organisms. In areas of high flow, recovery could be relatively rapid, in areas where flow rates are much reduced, recovery could take as long as 5-10 years (Van Der Veer et al. 1985).

Figure 2.1. Schematic showing the potential recovery paths of benthic communities after disturbances such as dredging. Early r-selected species lead the succession, followed by longer-lived, K-selected species, leading eventually to an equilibrium community. Estuarine muds and sandy bottoms are subject to constant natural disturbance as well and may never reach an equilibrium community, quickly regain a transitional state. In contrast, coral reef systems will eventually reach an equilibrium state, but may need between 8-10 years of complete cessation of the disturbance to recover completely. From Newell et al. 1998



[23] Page 5.1-64 of the TFEAR

Dredging activity associated with the construction of the canal will result in large quantities of dredge spoils, which will have to be efficiently disposed. Generally, dredging operations retain a proportion of the dredge materials on board for potential mineral exploitation or as landfill, while the rest is released back into the sea via the reject chute. Although the project proponents propose to dispose the spoils in deep waters 25-30m offshore (Section 12.6.3.1, pg 12-5 m, of the L&T-Ramboll DPR), the dumping of dredge materials could result in a range of deleterious consequences for ecosystems, from burial of the ecosystem to changing sedimentation regimes. This is particularly important given the fact that dredge spoils will be generated not merely during the construction phase of the canal, but throughout the operational phase as well, as maintenance dredging will need to continue through the life of the project (See Section 8.3 page 8-2 and 8-3 of the L&T-Ramboll DPR and Section 2 and 3 of this Review). One of the fallouts of this is that we should expect a marked increase in fine sediment suspension in the waters around the Gulf of Mannar, and will result in increasing sediment deposits in marine habitats, and a lowering of light conditions. Although only a very small percentage of dredge spoils are represented by fine silty particles, these are generated in sufficiently large amounts to considerably increase sedimentation levels in dredged areas, sometimes for up to 4 years of the dredging activity (Newell et al. 1998). In one estimate of spoils released from the reject screening chutes and from overspill, a typical dredging operation could result in 334 kg.s-1 of fine sand, 19.4 kg.s-1 of silt, and a further 12.2 kg.s-1 of muddy sediment (Hitchcock and Drucker 1996). The spread of these sediments is likely dependent on a combination of particle size, local current patterns and weather conditions. The penumbra of influence of the dredging operations is likely to extend far beyond the dredging zone itself, and may increase the sediment and nutrient loads in nearby marine systems, potentially impacting the region's coral reefs and seagrasses. The rest of the report attempts to clarify these impacts and its implications for the environmental management of the region.

3. Dredging, Sedimentation and Marine Systems: Coral Reefs

As mentioned in the earlier section, apart from the actual physical removal of benthic habitat as a result of dredging, the construction of the canal could have significant flow-on consequences for marine ecosystems in the Gulf of Mannar by increasing sediment loads. However, specific to the SSCP project, its documents and other relevant literature, there is very little information on this aspect. Changed sediment conditions have a range of effects on corals growing on reefs, affecting their basic physiology, reproduction, recruitment, population and community structure. In addition, by potentially favouring other opportunistic species, sediments and the nutrients they bring in, could also work to reduce the overall resilience of coral reef systems.

Perhaps the most direct consequence of dredging is the physical removal of coral and other benthic organisms as a result of dredge operations (Newell et al. 1998). A review of the project documents reveal that no direct physical removal of corals or sea grasses is being envisaged within the National Park. This, in effect, resets the ecosystem to a post-disturbance condition, and recovery has to begin from a virtual zero-point. In these cases, the recovery of the reef is likely dependent on a suite of local and landscape-level factors. At the local level, the quality of the dredge-modified will be paramount, particularly if the benthos has been changed so dramatically as to preclude any further recruitment and growth. Depending on how patchy the initial habitat destruction caused by the dredging was, the reef will be reliant to different degrees on external recruitment, and much depends on the integrity of upstream recruitment sources. In the best of all scenarios, after a major disturbance of this nature, reefs are likely to recover as quickly as 5 years after the initial disturbance event, as was documented after a major lava flow killed off virtually all coral in reefs of Banda Island in Indonesia (Tomasik et al. 1996). In the Lakshadweep, after a near complete mortality of coral after a major bleaching event, recovery at some sites was very rapid after 4 years (Arthur et al. 2005). The pattern of recovery in the Lakshadweep was revealing, because other monitored locations showed negligible recovery, driven by recruit survival and hydrodynamic influences (Arthur et al. 2006). In many instances, recovery from dramatic declines or chronic losses can be protracted, and the prospects for regaining the full complement of species in the reef very bleak (Hughes and Tanner, 2000; Lourey et al., 2000; Pandolfi et al., 2003; Lambo and Ormond, 2006).

Apart from physical removal, dredging can also result of smothering of corals as a result of releases of dredge spoils drifting into reef areas. The canal is more than 20 km from the nearest island of the National Park namely, Shingle Island, and the above must only be stated as a possibility in current scenario as there are no studies and literature to suggest reefs of the national park directly being smothered as a result of releases of dredge spoils The health of the coral is highly dependent on its ability to deal quickly and effectively with sediment loads if it has to avoid being buried under them, and different coral species have different tolerances to sediment loads (Bak and Elgershuizen, 1976; Stafford-Smith, 1993). This tolerance is linked closely with growth form, with branching or vertically plating coral best able to resist sediments through passive transport. Corals also actively reject sediments through mucus formation, and through active ciliary transport of sediments away from their skeleton (Stafford-Smith, 1993; Brown and Bythell, 2005). However, active sediment transport is an energetically costly activity, and places a large physiological demand on corals. This can lead to an eventual decline in calcification abilities and growth rates (Bak, 1978; Edinger et al., 2000; Crabbe and David, 2005).

Scleractinian corals are the main structural element of reefs, and depend heavily on the photosynthetic potential of their symbiont zooxanthellae for growth. Under conditions of increased sedimentation that is often the result of sustained maintenance dredging, this could result in serious physiological consequences for coral, including a shift towards increasing heterotrophy, decreased photosynthetic quantum yields, increased mucus production and respiration, and an overall decline in vitality (Riegl and Branch, 1995; Philipp and Fabricius, 2003; Weber et al., 2006). When these conditions become chronic, it can lead to a gradual reduction of coral cover in the area, and an eventual decline of reef health, and its consequences can often be traced long after the dredging events (Esslemont et al., 2004).

Sedimentation as a consequence of dredging has other population-level impacts on corals on reefs. Several studies have shown a connection between increased sedimentation and decreased juveniles in reefs (see Fabricius, 2005 for a synthesis). The mechanisms of this shift in population structure have been linked to decreased settlement of recruits on silty or muddy substrates, and reduced survivorship of young settlers in highly sedimented reefs (Gilmour, 1999; Fabricius, 2005; Flood et al., 2005). These changes can have long-term consequences for coral population structure, and can lead to heavily skewed populations (Bak and Meesters, 1999).

Dredge sediments and the nutrients they often carry may lead to more subtle changes in reef communities. At one level, this could lead to a gradual shift in communities towards coral species more tolerant of sediment loads, and a gradual change in reef zonation, often coupled with a loss in reef diversity (Acevedo et al., 1989; Clarke et al., 1993; McCook, 2001; Brown et al., 2002). More dramatic are the often rapid shifts in ecosystem states that coral reefs sometimes undergo under conditions of stress, sediments and nutrient loads. These switches in state are termed 'phase shifts', and have been reported to occur when nutrient conditions increase (as it often does close to dredged environments), favouring the growth of macroalgae (Done, 1992; Umar et al., 1998). When herbivore numbers cannot keep up with the increased macroalgae in these reefs (often because of over-fishing), this can lead to a state where macroalgae rapidly take over the reef, out-competing coral and transforming the reef environment (for examples of phase shifts see Hughes, 1994; Hughes et al., 1999; Bellwood et al., 2004). Recovery from a macroalgae-dominated state is often a very difficult process, and requires a large amount of management input (Carpenter et al., 2001; Scheffer et al., 2001; Peterson et al., 2003). In perhaps the best-documented case of a coral reef phase shift in Jamaica, after more than 30 years of the initial change in state, there has been very little recovery back to a healthy reef (Hughes and Tanner, 2000; Gardner et al., 2003). For a detailed position paper on the impacts of sedimentation and nutrients on coral reef systems see the briefing document compiled by the International Society for Reef Studies (attached Appendix 1).

4. Dredging, Sedimentation and Marine Systems: Seagrasses

While seagrass ecosystems are not as diverse and complex as tropical coral reef systems, they are vital ecosystems for coastlines. Important among their functions is their role in regulating erosional and depositional processes, in stabilising beaches and coasts, and in trapping sediments (Fonseca, 1989; Gacia and Duarte, 2001; Duarte, 2002; Harborne et al., 2006). They also serve as nurseries for fish stocks, and are essential grazing areas for turtles and dugongs (Duarte, 2002; Waycott et al., 2005; Sheppard et al., 2007). Seagrasses grow on sandy bottoms which are particularly attractive for easy dredging, making them perhaps even more susceptible to dredging and its related impacts than coral reefs. Additionally, seagrasses do not receive the same attention and protection in Indian waters as coral reefs. The Palk Bay, where most of the capital dredging is being conducted, has extensive seagrass meadows, distributed in very shallow waters, and these meadows are at highest risk from dredging and its fallouts. The importance of the extensive seagrass meadows of the Gulf of Mannar cannot be overstated, as they are a conservation hotspot of regional and global relevance. They represent the most significant meadow system in mainland India, and, with a seagrass diversity of 14 species, are among the most diverse seagrass systems anywhere in the world (Jagtap 2003).

As with coral reefs, the most direct impact of dredging on seagrass meadows will be caused by direct removal of seagrass habitats by the dredge. For instance, in the case of Florida's Tampa Bay, the combined effects of dredging and land-based influences resulted in a loss of more than 80% of its seagrass meadows (Lewis, 1976). The most likely result of dredging is the fragmentation of the meadow, an alteration in habitat arrangement, an increase in gaps and habitat edges, and a change in the transport of nutrients through the meadow (Robbins and Bell, 1994; Bell et al., 1999). The recovery potential of seagrasses after such events is highly variable, dependent on the intensity of disturbance, and the natural history characteristics of the seagrass species that formed the intact community before the disturbance event. While in some cases recovery can be very rapid, in the case of very long-lived, slow-growing species, it may take at least a century for effective recovery to take place (Meinesz and Lefevre, 1984). Apart from direct removal and fragmentation of contiguous meadows, the decreased water transparency, and increased rates of sedimentation caused as a result of the dredging and disposal of dredge materials can severely reduce seagrass habitat quality in a variety of ways. Major changes in benthic topography caused through the construction of canals and other marine constructions can result in significant modifications in sediment flows regimes. This could have important lethal and sub-lethal consequences for seagrass meadows, particularly if these changes result in modifications of the patterns of erosion and deposition that seagrasses are dependent on (Marbà and Duarte, 1995). Sub-lethally, increasing sediment loads can result in changes in rates of vertical elongation and growth as seagrasses struggle to keep up with the increase (Gacia et al., 2003). Additionally, light attenuation as a result of increased turbidity can reduce the photosynthetic potential of seagrasses, one of the key resources necessary for seagrass growth and survival (Hemminga and Duarte, 2000). The insidious impacts of turbidity have been implicated as the major cause of seagrass decline worldwide (Shepherd, 1989; Duarte, 2002). Prolonged exposure to changed turbidity conditions may result in a range of effects, from decreases in below-ground biomass and nutrient contents in tissues, the chlorophyll contents of leaves, and changes in above-ground growth parameters (Gacia et al., 2005; Zimmerman 2006). Every species of seagrass has a different tolerance to turbidity conditions, but it is clear that when these thresholds are crossed, a range of flow-on growth and decline consequences can result (Erftemeijer and Lewis, 2006). As light conditions change as a result of turbidity, seagrass communities may show population and community-level shifts towards species and communities that are more tolerant of the changed conditions, profoundly altering the functional values of the system (Waycott et al., 2005).

Beyond chronic insidious processes, increased sedimentation can also result in complete burial of plants. When sediment loads increase beyond the ability of the seagrass to compensate with increased growth, the vital apical sections of the plant are stifled with sand deposition, and the plant will die. When dredging or similar habitat modification exercises result in widespread sudden widespread increases in sedimentation, entire meadows can be destroyed by burial, often well outside the area of primary impact (Marbà and Duarte, 1995; Duarte et al., 1997; Erftemeijer and Lewis, 2006). Dredging can also often cause an increase in nutrients entering seagrass systems, either through the dredge spoils themselves, or through re-suspension of nutrients from the benthic floor as a result of dredging activity (Newell et al., 1998). Declining water quality can often be detected as changes in heavy metal concentrations that accumulate directly in seagrasses (Filho et al., 2004), suggesting that seagrasses may be a good indicator of changes in water quality. As nutrients increase in the water column, this can result in serious eutrophication impacts on seagrasses, and a suite of fallout consequences. The mechanism of eutrophication and seagrass decline is a complex one, mediated by two main processes. The first is the preferential growth of macroalgae in seagrass meadows as a result of increased nutrient conditions – this can result in an out-competition of seagrass by space acquisition and shading, resulting in its eventual decline (Peralta et al., 2002). Increased nutrients also often lead to increases in epiphytes growing on seagrass leaves, which can reduce light levels reaching the plant, and all the consequences of light attenuation mentioned above (Wear et al., 1999).

5. Management Strategies in the Gulf of Mannar Biosphere Reserve in Response to the Proposed Canal Building Activity

There is little doubt that the construction of the Sethusamudram canal will result in some consequences for important marine ecosystems in the region of its construction. What is less clear is how far the influence of the canal building will spread to the surrounding waters. Much of this will be dependent to a large extent on how sensitively the construction effort is managed and controlled, and whether adequate precautions are taken to ensure that surrounding ecosystems do not decline below previously determined thresholds of acceptable loss. Given time, and with adequate protection from other pressures, many marine systems show remarkable resilience, and may recover fairly quickly from even the worst disturbances, but ensuring that this resilience is not compromised because of developmental pressures is often a huge task.

This section attempts to give an overview of the potential consequences and responses of coral reefs and seagrass beds to the canal development activity. This is based completely on a reasoned assessment of the secondary literature available from other areas and other developmental projects. If the section is circumspect in its conclusions, it reflects the natural circumspection that any scientist must maintain in the absence of primary data. The list of scientific documents available in the peer-reviewed literature on the potential effects of sedimentation on the Gulf of Mannar is, to this author's knowledge, practically non-existent, necessitating the largely derivative approach taken here. Having said that, it is not an unreasonable best practice to use experiences elsewhere to prepare for the range of potential scenarios that the construction of the canal can throw up.

A large proportion of any possible impacts to marine ecosystems is likely to be felt by seagrasses in the Palk Bay, since that is where most of the capital dredging is focused. However, it is not possible to discount changes to sediment regimes, turbidity and nutrient increases within the Gulf of Mannar Biosphere Reserve jurisdiction as a direct result of this activity. As stated earlier, there is no direct physical removal of corals or sea grasses being envisaged within the National Park. While jurisdictional boundaries may certainly restrict what marine managers can do outside their administrative limits, it must be understood that the particularly fluid environments of coral reefs and seagrasses are strongly influenced by forces often well outside the protected area. Management needs to constantly keep an eye on these factors and be aware of any potential impacts and subsequent changes in parameters (ocean-met, ecological, physico- chemical, or biological). Given the fact that many marine ecosystems also show sudden shifts in their functioning, a fire fighting approach may not be of much use if the system is tipped over the cusp of its resilience potential. It has also been pointed earlier in this section as well as previous sections that there is inadequate literature and data on the environmental impacts especially on the Gulf of Mannar ecosystem in terms of its ecology, biodiversity, and fisheries. Hence in the light of this, developing and adopting a strong monitoring programme is the most prudent approach to be followed by the GOMBRT. The following are a series of small but essential measures that can be undertaken by the GoMBRT in the light of these potential impacts on the ecological systems of the Gulf:

1. Mapping the distribution of corals and seagrasses in the Gulf of Mannar Biosphere reserve. This community cartographic exercise is absolutely essential to get an idea of what species of seagrass and coral are present in what locations. Apart from being a useful baseline from which ecologically-relevant ecosystem management can proceed, this will give Biosphere managers a good sense of which species and communities are most at risk from sedimentation impacts. Different species of seagrass and corals respond very differently to near and distant sedimentation impact, but it is impossible to determine the long-term consequences to community composition, population numbers and diversity, unless distributional information is available at a fairly detailed level for the Gulf. A well-planned exercise of this nature can be conducted within 12-18 months, and will be an invaluable resource for the Biosphere Reserve.

2. Establish a monitoring protocol for seagrasses and coral reefs that directly address the issues of sedimentation, eutrophication and turbidity impacts. As global best practice, most impact assessments will standardly be based on a BACI (Before-After-Control-Impact) design. In the absence of this best practice being employed in the current EIA notification, it may be imperative for the Trust to enforce it at the local level at least to document any potential impacts of the dredging activity. This will serve as an early warning system to alert the manager on remedial action

to be taken. Using a functional indicator system approach is ideal for such a monitoring programme, and it could potentially include measures of nutrient and heavy metal accumulation directly in seagrasses. While there are a few monitoring programmes already designed that can be used, most are not geared to dealing with specific functional aspects that may be important in the Gulf and therefore cannot be applied without considerable modification. To be adequate, a monitoring programme needs to prove its sensitivity to changes in sedimentation regimes at sub-lethal levels. To do this, detailed standardisation studies are required for coral reefs as well as for seagrasses. These studies should be designed to examine the efficacy of a whole range of ecological parameters, to determine which of them, when combined, allow the most sensitive assessment of ecological change in relation to the developmental activities in the Gulf. Ideally, these studies should be conducted over an annual cycle, and will eventually lead to the development of a comprehensive protocol for monitoring.

3. Establishing tight controls over the treatment and deposition of dredge spoils in relation to the reserve boundaries. This should ideally extend well beyond the limits of the boundary, given the inherent connectivity of marine systems.

References to Section 3

Acevedo, R., J. Morelock, and R. A. Olivieri. 1989. Modification of Coral Reef Zonation by Terrigenous Sediment Stress. PALAIOS 4:92-100.

Arthur, R., T. J. Done, H. Marsh, and V. Harriott. 2006. Local processes strongly influence post-bleaching benthic recovery in the Lakshadweep islands. Coral Reefs 25:427-440.

Arthur, R., T. J. Done, H. Marsh, and V. J. Harriott. 2005. Benthic recovery four years after an El Niño-induced coral mass mortality in the Lakshadweep atolls. Current Science 89:694-699.

Bak, R. P. M. 1978. Lethal and Sublethal Effects of Dredging on Reef Corals. Marine Pollution Bulletin 9.

Bak, R. P. M., and J. Elgershuizen. 1976. Patterns of Oil-Sediment rejection in corals. Marine Biology 37:105-113.

Bak, R. P. M., and E. H. Meesters. 1999. Population structure as a response of coral communities to global change. American Zoologist 39 56-65.

Bell, S. S., B. D. Robbins, and S. L. Jensen. 1999. Gap dynamics in a seagrass landscape. Ecosystems 2:493-504.

Bellwood, D. R., T. P. Hughes, C. Folke, and M. Nyström. 2004. Confronting the coral reef crisis. Nature 429 827-833.

Brown, B. E., and J. C. Bythell. 2005. Perspectives on mucus secretion in reef corals. Marine Ecology Progress Series 296:291-309.

Brown, B. E., K. R. Clarke, and R. M. Warwick. 2002. Serial patterns of biodiversity change in corals across shallow reef flats in Ko Phuket, Thailand, due to the effects of local (sedimentation) and regional (climatic) perturbations. Marine Biology 141:21-29.

Carpenter, S. R., M. C. Press, N. J. Huntley, and S. A. Levin. 2001. Alternate states of ecosystem: evidence and some implications. Pages 357-383 Ecology: Achievement and challenge. Blackwell, London.

Chandramohan, P., B. K. Jena, and V. S. Kumar. 2001. Littoral drift sources and sinks along the Indian coast. Current Science 81:292-296.

Clarke, K. R., R. M. Warwick, and B. E. Brown. 1993. An index showing breakdown of seriation, related to disturbance, in a coral-reef assemblage. Marine Ecology Progress Series 102:153-160.

Crabbe, M. J. C., and J. S. David. 2005. Sediment impacts on growth rates of Acropora and Porites corals from fringing reefs of Sulawesi, Indonesia. Coral Reefs V24:437-441.

Done, T. J. 1992. Phase shifts in coral reef communities and their ecological significance. Hydrobiologia 247:121-132.

Duarte, C. M. 2002. The future of seagrass meadows. Environmental Conservation 29 192-206.

Duarte, C. M., J. Terrados, N. S. R. Agawin, M. D. Fortes, S. Bach, and W. J. Kenworthy. 1997. Response of a mixed Philippine seagrass meadow to experimental burial. Marine Ecology Progress Series 147:285-294.

Edinger, E. N., G. V. Limmon, J. Jompa, W. Widjatmoko, J. M. Heikoop, and M. J. Risk. 2000. Normal Coral Growth Rates on Dying Reefs: Are Coral Growth Rates Good Indicators of Reef Health? Marine Pollution Bulletin 40:404-425.

Erftemeijer, P. L. A., and R. R. Lewis. 2006. Environmental impacts of dredging on seagrasses: A review. Marine Pollution Bulletin 52:1553-1572.

Esslemont, G., R. A. Russell, and W. A. Maher. 2004. Coral record of harbour dredging: Townsville, Australia. Journal of Marine Systems 52:51-64.

Fabricius, K. E. 2005. Effects of terrestrial runoff on the ecology of corals and coral reefs: review and synthesis. Marine Pollution Bulletin 50:125-146.

Filho, G. M. A., J. C. Creed, L. R. Andrade, and W. C. Pfeiffer. 2004. Metal accumulation by Halodule wrightii populations. Aquatic Botany 80:241-251.

Flood, V. S., J. M. Pitt, and S. R. Smith. 2005. Historical and ecological analysis of coral communities in Castle Harbour (Bermuda) after more than a century of environmental perturbation. Marine Pollution Bulletin 51:545-557.

Fonseca, M. S. 1989. Sediment stablisation by Halophila decipiens in comparison with other seagrasses. Estuarine, Coastal and Shelf Science 17.

Gacia, E., and C. M. Duarte. 2001. Sediment retention by a Mediterranean Posidonia oceanica meadow: The balance between deposition and resuspension. Estuarine, Coastal and Shelf Science 52:505-514.

Gacia, E., C. M. Duarte, N. Marbà, J. Terrados, H. Kennedy, M. D. Fortes, and N. H. Tri. 2003. Sediment deposition and production in SE-Asia seagrass meadows. Estuarine, Coastal and Shelf Science 56:909-919.

Gacia, E., H. Kennedy, C. M. Duarte, J. Terrados, N. Marba, S. Papadimitriou, and M. D. Fortes. 2005. Light-dependence of the metabolic balance of a highly productive Philippine seagrass community. Journal of Experimental Marine Biology and Ecology 316:55-67.

Gardner, T. A., I. M. Cote, J. A. Gill, A. Grant, and A. R. Watkinson. 2003. Long-term region-wide declines in Caribbean corals. Science 301:958-960.

Gilmour, J. 1999. Experimental investigation into the effects of suspended sediment on fertilisation, larval survival and settlement in a scleractinian coral. Marine Biology 135:451-462.

Harborne, A. R., P. J. Mumby, F. Micheli, C. T. Perry, C. P. Dahlgren, K. E. Holmes, and D. R. Brumbaugh. 2006. The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. Adv Mar Biol 50:57-189.

Hemminga, M., and C. M. Duarte. 2000. Seagrass Ecology. Cambridge University Press, Cambridge.

Hitchcock, D. R., and B. R. Drucker. 1996. Investigation of benthic and surface plumes associated with marine aggregates mining in the United Kingdom. Pages 221-284 The Global Ocean-Towards Operational Oceanography: Conference of Oceanology International. Spearhead Publications, Surrey.

Hughes, T. P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. Science 265:1547-1551.

Hughes, T. P., A. M. Szmant, R. Steneck, R. C. Carpenter, and S. Miller. 1999. Algal blooms on coral reefs: What are the causes? Limnology and Oceanography 44(6):1583-1586.

Hughes, T. P., and J. E. Tanner. 2000. Recruitment failure, life histories, and long-term decline of caribbean corals. Ecology 81:2250-2263.

Jagtap, T. G., Komarpant, D.G, Rodrigues, R. 2003. The seagrasses of India. Page 310 in E. P. S. Green, F.T., editor. World Atlas of Seagrasses. University of California Press.

Lambo, A. L., and R. F. G. Ormond. 2006. Continued post-bleaching decline and changed benthic community of a Kenyan coral reef. Marine Pollution Bulletin 52:1617-1624.

Lewis, R. R. 1976. Impact of dredging in the Tampa Bay estuary, 1876-1976. Pages 31-55 in E. L. Pruitt, editor. Time-stressed coastal environments: Assessment and future action. The Coastal Society, Arlington, Virginia.

Lourey, M. J., D. A. J. Ryan, and I. R. Miller. 2000. Rates of decline and recovery of coral cover on reefs impacted by, recovering from and unaffected by crown-of-thorns starfish Acanthaster planci : a regional perspective of the Great Barrier Reef. Marine Ecology Progress Series 196:179-186.

Marbà, N., and C. M. Duarte. 1995. Coupling of seagrass (Cymodocea nodosa) patch dynamics to subaqueous dune migration. Journal of Ecology 83:381-389.

McCook, L. J. 2001. Competition between corals and algal turfs along a gradient of terrestrial influence in the nearshore central Great Barrier Reef. Coral Reefs 19:419-425.

Meinesz, A., and J. R. Lefevre. 1984. Régénération d'un herbier de Posidonia oceanica quarante années après sa destruction par une bombe dans la rade de Villefranche (Alpes-Maritimes, France). Pages 39–44 International Workshop on Posidonia oceanica beds. Posidonie, Gis France.

Moberg, F., and C. Folke. 1999. Ecological goods and services of coral reef ecosytems. Ecological Economics 29 215-233.

Newell, R. C., L. J. Seiderer, and D. R. Hitchcock. 1998. The impact of dredging works in coastal waters: a review of the sensitivity to disturbance and subsequent recovery of biological resources on the sea bed. Oceanography and Marine Biology: An Annual Review 36:127-178.

Pandolfi, J. M., R. H. Bradbury, E. Sala, T. P. Hughes, K. A. Bjorndal, R. G. Cooke, D. McArdle, L. McClenachan, M. J. H. Newman, G. Paredes, R. R. Warner, and J. B. C. Jackson. 2003. Global trajectories of the long-term decline of coral reef ecosystems. Science 301:955-958.

Peralta, G., J. L. Perez-Llorens, I. Hernandez, and J. J. Vergara. 2002. Effects of light availability on growth, architecture and nutrient content of the seagrass Zostera noltii Hornem. Journal of Experimental Marine Biology and Ecology 269:9-26.

Peterson, G. D., S. R. Carpenter, and W. A. Brock. 2003. Uncertainty and the management of multistate ecosytems: an apparently rational route to collapse. Ecology 84 1403-1411.

Philipp, E., and K. Fabricius. 2003. Photophysiological stress in scleractinian corals in response to short-term sedimentation. Journal of Experimental Marine Biology and Ecology 287:57-78.

Ramesh, R. 2005. Sethusamudram Shipping Canal Project. Current Science 88:536-537.

Riegl, B., and G. M. Branch. 1995. Effects of sediment on the energy budgets of four scleractinian (Bourne 1900) and five alcyonacean (Lamouroux 1816) corals. Journal of Experimental Marine Biology and Ecology 186:259-275.

Robbins, B. D., and S. S. Bell. 1994. Seagrass landscapes: a terrestrial approach to the marine subtidal environment. Trends in Ecology and Evolution 9:301-304.

Scheffer, M., R. C. Carpenter, J. A. Foley, C. Folke, and B. Walker. 2001. Catastrophic shifts in ecosystems. Nature 413 591-596.

Shepherd, S. A. 1989. Decline of seagrass.in A. W. D. Larkum, A. J. McComb, and S. A. Shepherd, editors. Biology of Seagrasses. Elsevier: New York., New York.

Sheppard, J. K., I. R. Lawler, and H. Marsh. 2007. Seagrass as pasture for seacows: Landscape-level dugong habitat evaluation. Estuarine, Coastal and Shelf Science 71:117-132.

Stafford-Smith, M. G. 1993. Sediment-rejection efficiency of 22 species of Australian scleractinian corals. Marine Biology 115:229-243.

Tomasik, T., R. van Woesik, and A. J. Mah. 1996. Rapid coral colonization of a recent lava flow following a volcanic eruption, Banda Islands, Indonesia. Coral Reefs 15 169-175.

Umar, M. J., L. J. McCook, and I. R. Price. 1998. Effects of sediment deposition on the seaweed Sargassum on a fringing coral reef. Coral Reefs 17:169-177.

Van Der Veer, H. W., M. J. N. Bergman, and J. J. Beukema. 1985. Dredging Activities in the Dutch Wadden Sea: Effects on Macrobenthic Infauna. Netherlands Journal of Sea Research 19.

Waycott, M., B. J. Longstaff, and J. Mellors. 2005. Seagrass population dynamics and water quality in the Great Barrier Reef region: A review and future research directions. Marine Pollution Bulletin 51:343-350.

Wear, D. J., M. J. Sullivan, A. D. Moore, and D. F. Millie. 1999. Effects of water-column enrichment on the production dynamics of three seagrass species and their epiphytic algae. Marine Ecology Progress Series 179:201-213.

Weber, M., C. Lott, and K. E. Fabricius. 2006. Sedimentation stress in a scleractinian coral exposed to terrestrial and marine sediments with contrasting physical, organic and geochemical properties. Journal of Experimental Marine Biology and Ecology 336:18-32.

Zimmerman, R. C. 2006. Light and photosynthesis in seagrass meadows. Pages 303-321 in A. W. D. Larkum, R. J. Orth, and C. M. Duarte, editors. Seagrasses: Biology, ecology and conservation. Springer, Dordrecht, The Netherlands.

Section 4: Findings and Recommendations of the Review

1. Findings

The first two sections of this review reveal short-comings in the literature and other related documents of the SSCP project in terms of adequacy and methods used to assess environmental impacts, but more importantly, in terms of data on basic parameters such as sub-surface geology, bathymetry, and sedimentation process in the project area. These data gaps result in the inability to assess and review the risks, hazards and environmental impact of the project on the ecosystem.

As result of the poor understanding of the sub-surface geology and the bathymetry, the type of dredging required and the characteristics of the dredged sediments are not known. This means the exact impact while dredging as well as dredge disposal **cannot be ascertained** and so also the impacts on the environment.

.

The poor knowledge base of the sedimentation process and dynamics of the project area across all the documents implies that there is a likelihood of the instability of the dredging dump sites and in turn environmental impacts as a result of this instability.

A summary of these gaps is presented below:

Geology and Bathymetry

- Bathymetry survey by NEERI in the Pamban Pass area of the Adam's Bridge and National Hyrdographic Officer (NHO) starting from the north-side of the Adam's Bridge area is inadequate
- Lack of full knowledge base of the sub-surface geology along canal
- Bathymetric Survey data was carried out by NIOT (6-23 November 2004 and 16-17 December 2004) not incorporated into NEERI EIA
- Non inclusion of vital studies in EIA -NIOT's Geological & Geo-technical Assessment, Indomer's Hydrodynamic Modelling (both of which have), Radio Active Tracer Study

Dredge Spoil and Dumping

- Nature of the dredged spoil is currently known only for about 38.5 to 40.5% of the total dredged spoil.
- No Radio Active Tracer Study to optimise the dredge disposal in dredge dumping sites

Environment Monitoring & Environmental Clearance

- No monitoring of heavy metals, bacteriological parameters, and marine biology: phytoplankton and zooplankton, only physical properties are being monitored.
- It also seems that it is being done only for marine water quality and NOT for sediment quality.

- No monitoring of the submarine conditions during the dredging by divers and photographic and video records
- No monitoring of important factors like hydrography, bathymetry, current dynamics, total suspension load, climate changes, sea level alterations.

Miscellaneous

- Not taken into account impacts of blasting (as a possible activity that might be required later) on the ecosystem.
- Inadequate Ecological Risk Assessment

In light of all the above, we conclude that is not possible to adequately assess the exact environmental impacts to the biodiversity and habitat of the Gulf of Mannar from all the available literature and more detailed studies may be required for the same. Reviewing the current status of the implementation phase of the project, it prudent to undertake a strong long-term monitoring programme in the GOMBR area.

2. Recommendations

In light of the above the reviewers have specific recommendations, which are listed below:

- Based on the dredge spoil characteristics, quantum and sedimentation of the region identify suitable sites for dredge disposal after assessing their stability using a full year's primary data (for normal and cyclonic conditions). The disposal sites should be in waters at least 50-60m deep instead of the current proposal. Establish tight controls over the treatment and deposition of dredge spoils in relation to the reserve boundaries. This should ideally extend well beyond the limits of the boundary, given the inherent connectivity of marine systems.

- Ensure monitoring of all the parameters suggested in the DPR and MoEF clearance conditions are being carried out and is fully published on the project website regularly.

- The environmental factors and parameters that have the ability to affect the project need to be expanded to include other aspects such as hydrography, bathymetry, current dynamics, total suspension load, etc., should be monitored in the GOMBR and GOMNP. Specifically the following ocean-met parameters should also be monitored: a) wind speed & direction b) wave height, period & direction c) current speed & direction d) tide &water level. This could be funded and undertaken by the SSCP jointly with the GOMBR and be incorporated into EMP and post-project environmental monitoring.

- Studies on other factors such as implications of climate change and sea level alterations for the GOMBRR and project area based on modeling studies should be explored and developed.

- Seralathan highlights that other conditions from the MoEF's clearance letter, such as the stoppage of dredging during the fish breeding & spawning periods, and the condition that suspended matter at the dredging sites should not spread more than a kilometer on either side of the channel route have been disregarded by project authorities (Seralathan, 2006).

- Map the distribution of corals and seagrasses in the Gulf of Mannar Biosphere reserve. Apart from being a useful baseline from which ecologically-relevant ecosystem management can proceed, this will give Biosphere managers a good sense of which species and communities are most at risk from sedimentation impacts. As different species of seagrass and corals respond very differently to near and distant sedimentation impact, distributional information will need to be available at a fairly detailed level for the Gulf in order to determine the long-term consequences to community composition, population numbers and diversity. A well-planned exercise of this nature can be conducted within 12-18 months, and will be an invaluable resource for the Biosphere Reserve.

- Establish a monitoring protocol for seagrasses and coral reefs that directly address the issues of sedimentation, eutrophication and turbidity impacts. This will serve as an early warning system to alert the manager on remedial action to be taken. Using a functional indicator system approach is ideal for such a monitoring programme, and it could potentially include measures of nutrient and heavy metal accumulation directly in seagrasses.

- Divers should inspect the submarine conditions during the dredging activity and photographic and video records should be maintained. This activity should also cover the dredge disposal sites. This should be incorporated into EMP and post-project environmental monitoring.

- All of the above monitoring recommendations and the existing the SSCP monitoring should be linked up and synergized with all the research projects of the GOMBRT such as the recently commissioned study by Suganthi Devadason Marine Research Institute (SDMRI) which includes mapping of corals and sea grasses in the GOMBR that aims to establish some baselines and rigorous monitoring. A suitable coordinating mechanism would need to be established for all such projects, monitoring and studies in the GOMBR. The GOMBRT and its scientific advisory committee could function as the lead agency for this mechanism.

- The GOMBRT Trust Director and the Chief Wildlife Warden should be made members of the monitoring committee on environmental issues on

SSCP. This will enable a closer monitoring of activities towards achieving the objectives of the Trust.

- The GOMBRT Trust Director and the Chief Wildlife Warden should also be made members of the recently formed Committee of Eminent Persons constituted by the Government of India on the SSCP. [24]

- The SSCP should proactively support and assist the monitoring programmes undertaken by the GOMBRT and Forest Department official in the Gulf of Mannar in the form of human, financial resources as well as logistical support. This could be done under a Corporate Social Responsibility (CSR) programme by the SSCP. The GOMBRT Trust Director and the Chief Wildlife Warden may be made members of the body that will develop the CSR the activities of SSCP.

[24] http://pib.nic. in/release/release.asp? relid=31845
http://pib.nic.in/release/release.asp?relid=31845

References

Anonymous. 2005. Website launched. *The Hindu* Friday, Jul 01, 2005

Chandramohan, P., B. K. Jena and V. Sanil Kumar. 2001. Littoral Drift Sources and Sinks along the Indian Coast, *Current Science*, Vol. 81, No. 3. pp 295.

Deepak, S.V. and Patterson, J., 2004. *Reef associated molluscs of Gulf of Mannar Marine Biosphere Reserve, Southeast coast of India - Diversity, threats and management practices*, paper presented in the 10th International Coral Reef Symposium, Okinawa, Japan, 28 June-02 July 2004.

DoD. 2005. *Preliminary Assessment of Impact of Tsunami in Selected Coastal Areas of India*. Department of Ocean Development, Integrated Coastal and Marine Area Management Project Directorate, Chennai.

Durairaj, K., 1998. *Economic and ecological diversity of marine fish resources*. Pp 129-149. In: Biodiversity of Gulf of Mannar Marine Biosphere Reserve –Proceedings of the technical workshopheld at Chennai, 10-11 February 1998.

Dwivedi, R.M. 2006. *Coral reefs of Tamil Nadu.* presentation at the workshop on development of management plan for the Gulf of Mannar Marine Biosphere Reserve, 26-27th September 2006, Ramand.

Global Environment Facility. 1999. *Conservation and Sustainable Use of the Gulf of Mannar Biosphere Reserve's Coastal Biodiversity,* Project Document, GEF Project ID 634, GEF Secretariat, Washington.

Indomer-Alkyon. 2005. *Hydrodynamic Modelling Sedimentation Studies and Ship Manoeuvring Study for Sethusamudram Shipping Channel*. Indomer-Alkyon, Chennai.

James, D. B.2001. Twenty sea cucumbers from seas around India. *Naga.* 24(1&2):4-8.

Jeganathan, S., K. R. Saravanan, B.C. Choudhury, and K. Sivakumar. 2006. *Vegetation Status in the Offshore Islands of Gulf of Mannar Marine National Park, Tamil Nadu*. National Institute for Coastal and Marine Biodiversity (NICMB), WII, Dehradhun.

Jeyabaskaran, R. and S. Ajmal Khan, 1998. Biodiversity of brachyuran crab resources. pp 150-155. In: Biodiversity of Gulf of Mannar Marine Biosphere Reserve – Proceedings of the technical workshop held at Chennai, 10-11 February 1998.

Jeyanthi, N. 2002. *Cyclone Disaster Management.* National Interactive Workshop held at Tamil Nadu Agricultural University, February 25-26, 2002.

Kathal, P.K. 2005. Sethusamudram Ship Canal Project: oceanographic/geological and ecological impact on marine life in the Gulf of Mannar and Palk Bay, South-eastern coast of India. *Current Science*, Vol. 89, No. 7.

Kaliyaperumal, 1998. *Seaweed resources and biodiversity*, pp 92-97. In: Biodiversity of Gulf of Mannar Marine Biosphere Reserve – Proceedings of the technical workshop held at Chennai, 10-11 February 1998.

Kelleher G, C. Bleakley, and S. Wells. 1995. *A Global Representative System of Marine Protected Areas. Volume 3: Central Indian Ocean, Arabian Seas, East Africa and East Asian Seas.* The Great Barrier Reef Marine Park Authority, The World Bank and the World Conservation Union (IUCN), Washington, D.C. pp 146.

Krishnaswamy, V.S 2006. Sethusamudram Dredging Technical Issues, Dated the18th October'05, White Plains, New York.

Kumaraguru, A. K., K. Jayakumar, J. J. Wilson and C. M. Ramakritinan. 2005. Impact of the tsunami of 26 December 2004 on the coral reef environment of Gulf of Mannar and Palk Bay in the southeast coast of India. *Current Science*, Vol. 89, No. 10.

L&T-Ramboll. 2005. *Detailed Project Report and Evaluation of EIA Study for Sethusamudram Ship Channel Project*. Larson & Toubro –Ramboll Consulting Engineers Limited.

McCloskey, J., S. Nalbant, S. and S. Steacy. 2005. Earthquake risk from co-seismic stress. *Nature*, Vol. 434.

MoEF. 1998. Chapter 3: Conservation Of Natural Resources Including Forestry and Wildlife in *MoEF Annual Report 1997-98*. Ministry of Environment & Forests, New Delhi.

MoEF. 2002. Chapter 3: Conservation Of Natural Resources Including Forestry And Wildlife in *MoEF Annual Report 2001-02.* Ministry of Environment & Forests, New Delhi.

MoEF. 2005. *Letter No.J-16011/6/99-IA-III, Sethusamudram Shipping Channel Project by M/s Tuticorin Port Trust, Tuticorin, Tamil Nadu - Environmental Clearance, Letter dated 31st March,2005.* Ministry of Environment and Forests, New Delhi.

Natesan, U. 1993. Seasonal Shoreline Oscillation of Tamil Nadu Coast, *Current Science*, Vol 65, No 9. pp 667-68.

NEERI. 2004a. *Environmental Impact Assessment for Proposed Sethusamudram Ship Channel Project*, National Environmental Engineering Research Institute, Nagpur. August 2004. pp 427.

NEERI. 2004b. *Technical Feasibility and Economic Analysis of Proposed Sethusamudram Channel*, National Environmental Engineering Research Institute Nagpur, July 2004. pp330.

NIOT. 2004. *Geological & Geo-technical Assessment of the Subsea, Chennai - Executive Summary.* Sethusamudram Project Website, http://www.sethusamudram.gov.in/Geotech.asp

Pillai C.S.G. 1986. Recent corals from the south east coast of India. *Recent advances in marine biology*. New Delhi: 107-201.

Patterson Edward, J.K., Jamila Patterson, M. Venkatesh, G. Mathews, C. Chellaram and Dan Wilhelmsson, 2004. *A field guide to stony corals (Scleractinia) of Tuticorin in Gulf of Mannar, Southeast India*, 80 pp.

Patterson , J.K. 2005. Rapid assessment of status of corals in Gulf of Mannar after tsunami. See http://www.sethusamudram.gov.in/PeterArticle.asp

Rajamanickam, V. G. 2004. Sethusamudram Canal: The Life of Tamil Nadu in Abstracts of the
proceedings of the *National Seminar on Ecological Balance and Sethusamudram Canal* held on October 1-3, 2004 at Alagappa University, Thondi Campus,. pp 29-30.

Rajendran, C.P. 2005a. Assessing the Stability of the Sethusamudram Shipping Canal, *Jounal of Geol.Soc.India*, Vol. 66, No.3. pp. 367-370.

Rajendran, C.P. 2005b. Sethusamudram shipping canal project and the eternal silence of the
Indian earth scientists. *Current Science*, Vol. 89, No. 2.

Ramasamy, S. M., D. Ramesh, M. A. Paul, S. Kusumgar, M. A. Yadava, A. R. Nair, U. K. Sinha and
T. B. Joseph.,1998. Land Building Activity along Vedaranniyam Coast and its Possible Implications, *Current Science,* Vol 75, No 9. pp 884-86.

Ramaiyan, V., Kasinathan R., Ajmal Khan, S., Patterson Edward, J.K., and Rajagopal, S., 1996. Studies on the biodiversity of invertebrates (Annelids, turbellarians, bivalves, gastropods and crustaceans) and vertebrate (fishes) in the Gulf of Mannar. A monograph submitted to MoEn, Govt. of India, pp 133.

Ramesh, A. and T. Kannupandi. 1997. Recent Changes in the Coral Reef Ecosystem of Palk Bay: A Comparative Status of Previous Reports and Researches in *Hoon, V. (ed), Proceedings of the Regional Workshop on the Conservation and Sustainable Management of Coral Reefs. Proceedings No.22*. CRSARD, Chennai.

Ramesh, R. 2004a.*Critique on the Methodology of NEERI EIA for the Proposed Sethusamudram Ship Canal Project*. Doctors for Safer Environment (DOSE), Coimbatore. pp23.

Ramesh, R. 2004b. *Sethusamudram Shipping Canal Project and the unconsidered high risk factors: Can it withstand them?* Doctors for Safer Environment, Coimbatore. pp73.

Ramesh, R. 2005a. Is the Sethusamudram Shipping Canal Project Technically Feasible?, *Economic and Political Weekly,* January 22, 2005.

Ramesh, R. 2005b. Sethusamudram Shipping Canal Project, *Current Science*, Vol. 88, No. 4.

Ramesh, R. 2006. Sethusamudram Ship Canal Project - Further Inputs, *Unpublished.*

Sanil Kumar, V., N. M. Anand, and R. Gowthaman. 2002. Variations in Nearshore Processes
along Nagapattinam Coast, India, *Current Science*, Vol 82, No 11. pp 1381-89.

Seralathan, P. 2006. Disposal of dredge spoil from Sethusamudram Ship Channel Project, Current Science, Vol. 90, No. 2.

Seshagiri, D.N. 2005. *Assessment of the Results of the Geotechnical Study by NIOT for Sethusamudram Shipping Canal Project.* Uploaded on 9th September 2005. www.sethusamudram.in.

Susheelan, C., 1993. Hand book on seafarming – Shrimp, lobster and mud crab. MPEDA, pp 47-54.

Venkataraman K and M. Waffar. 2005. Coastal and Marine Biodiversity of India. *Indian Journal of Marine Sciences*. Vol 34(1).pp 57-75.

Venkatraman, K. 2006. Conservation of Coral Reefs in Gulf of Mannar. Green Coast Project Report. pp 2-4.

ISRS BRIEFING PAPER 3

THE EFFECTS OF TERRESTRIAL RUNOFF OF SEDIMENTS, NUTRIENTS AND OTHER POLLUTANTS ON CORAL REEFS[1]

SYNOPSIS

Increasing terrestrial runoff of sediments, nutrients and other pollutants into the sea is a growing concern for many of the over 100 nations endowed with coral reefs. This document provides a brief overview of the known effects of exposure to terrestrial runoff on the health of corals and of coral reef ecosystems. It also describes measures some countries have started taking, as there are considerable economic net benefits gained from an investment into reducing the loss of sediments, nutrients and other pollutants into the sea.

- The main reasons for deteriorating water quality in coastal and inshore marine systems are land-based activities including vegetation removal, soil erosion and fertilizer loss from expanding agriculture, expanding coastal urbanization and the associated discharge of insufficiently treated sewage, and industrial pollution.
- The main direct effects of terrestrial runoff on coral populations are: reduced recruitment, decreased calcification, shallower depth distribution limits, altered species composition (shifting from a more phototrophic to a more heterotrophic fauna), and the loss of biodiversity.
- A number of effects on the wider coral reef ecosystem are also observed and/or discussed, although their links to water quality are more difficult to test. Particularly relevant are: (1) the proliferation of algae that compete with corals for space; (2) increasing rates of internal bioerosion making corals less resistant to storm impacts; (3) increased susceptibility of corals to some diseases; and (5) more frequent outbreaks of the coral-eating starfish *Acanthaster planci*.
- Because terrestrial runoff directly affects coral recruitment, runoff-exposed coastal and inshore coral reefs will take longer to recover from disturbances by storms, coral bleaching and outbreaks of coral predators than reefs in cleaner water. Coral reefs in well-flushed locations are at lower risk of being degraded by terrestrial runoff than regions where the retention of pollutants is high.

The economic costs of failing to control land-based activities are high. However, no universal measures to combat terrestrial runoff exist, instead regions have to develop and costs evaluate separate solutions for each situation. Measures to consider are to (1) raise awareness how actions on land negatively impact the adjacent marine environment; (2) carefully plan land use, and use self-regulation and regulatory frameworks to implement these plans; (3) prevent habitat destruction through education and enforcement; (4) protect riparian and coastal vegetation and wetlands that actively filter out pollutants, (5) implement advanced waste water treatment, (6) monitor and scientifically evaluate the ecological status of riparian, coastal and marine habitats, and (7) develop national and international policies that take into account the economic value of environmental goods and services.

---

[1] Cite as: 'ISRS (2004) The effects of terrestrial runoff of sediments, nutrients and other pollutants on coral reefs. Briefing Paper 3, International Society for Reef Studies, pp: 18'

Links between Land and Sea

Coastal seas are under growing pressure from land-based sources of pollution as the result of increasing deforestation and associated soil loss, escalating use of fertilizers and pesticides, and discharges of other effluents including domestic and industrial sewage (GESAMP 2001). Model estimates indicate that soil erosion and land-based pollution represents a medium to high threat to 22% of the world's coral reefs (Bryant *et al.* 1998). The percentage of reefs threatened by terrestrial runoff is up to 50% in countries with widespread land clearing (Bourke *et al.* 2002). Other forms of deteriorating water quality further add pressure to coral reefs: the models classify 12% and 30% of reefs under threat from marine pollution and coastal development, respectively (Bryant *et al.* 1998). At global scales, pollution, together with coral bleaching, destructive fishing and overfishing, is rated as one of the main threats to coral reefs (Spalding *et al.* 2001). At local scales, it can be the single most dominating pressure on the ecological balance in particular of inshore coral reefs.

Coral reefs are most commonly found in clear oceanic tropical waters where they can grow to depths of >40 m. However, coral reefs can also flourish in naturally turbid waters to at least 10 m depth (Yentsch *et al.* 2002), supporting unique and diverse communities that are not found in clearer offshore waters. Reefs in coastal and inshore waters experience naturally more variable conditions, including higher levels of dissolved and particulate nutrients and siltation and hence reduced water clarity, and more fluctuating salinity, than reefs in oceanic waters, where water clarity is high, siltation is low, and nutrient levels are generally low except during periods of upwelling (Furnas 2003). Coral reef communities naturally change along gradients from terrestrially influenced to oceanic conditions. These natural gradients contribute to the diversity of types of coral reefs found. Large volumes of freshwater and sediment discharges kill corals and prevent coral reef growth, even when systems are unaltered by humans; hence no coral reefs are found tens to hundreds of kilometres downstream of large rivers such as the Amazon (Brazil) or Fly River (Papua New Guinea). Smaller streams can alter reef communities at the scale of hundreds of meters to a few kilometres downstream of their mouths (West and Van Woesik 2001). When watersheds (catchments) from larger landmasses are heavily altered, runoff pathways change, with rapid overland flow over compacted, often bare surfaces replacing slower through flow pathways through vegetation, leaf litter and soil profiles. As a result, their discharges into the sea are intensified and/or spatially extended, enhancing near shore siltation, nutrient concentrations and water turbidity, and adding pollutants such as pesticides, fertilizers, and heavy metals to the coastal zone. Similar processes occur at smaller scales around islands, through alteration of coastal zone vegetation and hydrodynamics, and the increased import of sewage and industrial pollutants associated with urban development.

WATER QUALITY EFFECTS ON CORAL POPULATIONS

The responses of coral populations to sedimentation, turbidity, nutrients and pesticides are reasonably well understood from controlled experiments, and from observations around point sources.

Sedimentation

Direct effects of sedimentation include smothering, energy expenditure for surface cleaning by ciliary action, abrasion and shading of adult corals (Rogers 1990, van Katwijk *et al.* 1993, West and Van Woesik 2001), and reduced depth ranges (Edinger *et al.* 2000, Anthony and Fabricius 2000). Thresholds to recover from sedimentation vary between species (Stafford-Smith and Ormond 1992), and increase with organic loads and microbial activities in sediments. They are an order of magnitude lower for coral recruits than for adult corals (Fabricius *et al.* 2003). Probably the most severe effect of sedimentation is the inhibition of recruitment (Tomascik and Sander 1987b, Babcock and Davies 1991, Wittenberg and Hunte 1992, Gilmour 1999, Ward and Harrison 2000, Harrison and Ward 2001, Babcock and Smith 2002, Cox and Ward 2002). Sedimentation is therefore considered one of the most widespread contemporary, human-induced perturbations on reefs.

Turbidity

Turbidity that reduces light penetration is often associated with resuspension of sediments, or with enhanced water column productivity. Although corals are animals, they garden within their tissues a large number of single-celled micro algae (called zooxanthellae) that greatly contribute to the corals' nutrition through photosynthesis. For this reason, corals depend on light and clear water to gain energy. Direct effects of enhanced turbidity and chronic siltation on corals are a reduction in photosynthesis and growth, and increase in metabolic costs (Rogers 1979, Rogers 1983; Telesnicki and

Goldberg 1995). Consequently, the depth range within which corals can survive or maintain active reef growth diminishes (Yentsch *et al.* 2002).

Nutrients

Experimental studies and work in areas of nutrient upwelling has shown that dissolved inorganic nutrients negatively affect coral fertilization rates (Harrison and Ward 2001) and rates of coral calcification (Kinsey and Davies 1979, Marubini and Davies 1996). Studies to investigate the effects of elevated dissolved inorganic nutrients on coral growth have yielded inconsistent responses, possibly because many responses are non-linear (Tomascik and Sander 1985): although slightly enhanced concentrations of nutrients may stimulate coral growth (while reducing skeletal density), high concentrations can have the opposite effect (stunting coral growth). This is because high nutrient concentrations increase the density of zooxanthellae in the tissue, hence altering the balance of energy, CO_2 and nutrients transferred between zooxanthellae and host (Muscatine *et al.* 1989, Marubini and Davies 1996). Many species of coral can however gain nutrients from suspended particulate matter, partly compensating for reduced phototrophy in turbid waters (Anthony and Fabricius 2000).

Other pollutants

Due to the great diversity of contaminants and exposure levels in different areas, it is difficult to adequately summarize the effects of agrochemicals, petrochemicals, heavy metals and other industrial pollutants from mine tailings, refineries, smelters, port operations etc on coral reefs. For example, low concentrations (a few parts per billion) of some widely applied photosynthesis-inhibiting herbicides effectively suppress photosynthesis in corals, seagrass, and other photosynthetic organisms (Scarlett *et al.* 1999, Jones *et al.* 2003). Cyanide severely damages or kills corals after a few minutes exposure (Cervino *et al.* 2003). Heavy metals such as copper suppress coral fertilization at concentrations of a few tens of parts per billion (Reichelt-Brushett and Harrison 1999). Effects of many of the numerous existing pollutants (PAH, PCB, persistent organic pollutants, endocrine disruptors, insecticides, fungicides etc) on corals and coral reef organisms are presently largely unknown, but some of these substances are known to accumulate in the food web and have toxic effects above certain concentrations.

WATER QUALITY EFFECTS ON THE WIDER CORAL REEF ECOSYSTEM

The studies listed above document that the reproduction, growth rates and mortality of corals is strongly affected by deteriorating water quality. High turbidity, shading and high particle loads also lead to reduced biodiversity in hard corals and octocorals, due to their differences in tolerance levels (Fig. 1; Tomascik and Sander 1987a, Edinger *et al.* 1998, van Woesik *et al.* 1999).

Terrestrial runoff not only affects coral populations directly, but can also have profound effects on other key groups of reef organisms. Establishing causal relationships between ecological responses and environmental conditions is often difficult. Nevertheless, strong circumstantial evidence exists for the existence of links between water quality and the following ecosystem responses (Fabricius, in review): increasing macroalgal abundances; increased internal bioerosion; increased susceptibility to some diseases in corals and octocorals; and changes in the abundance of coral predators.

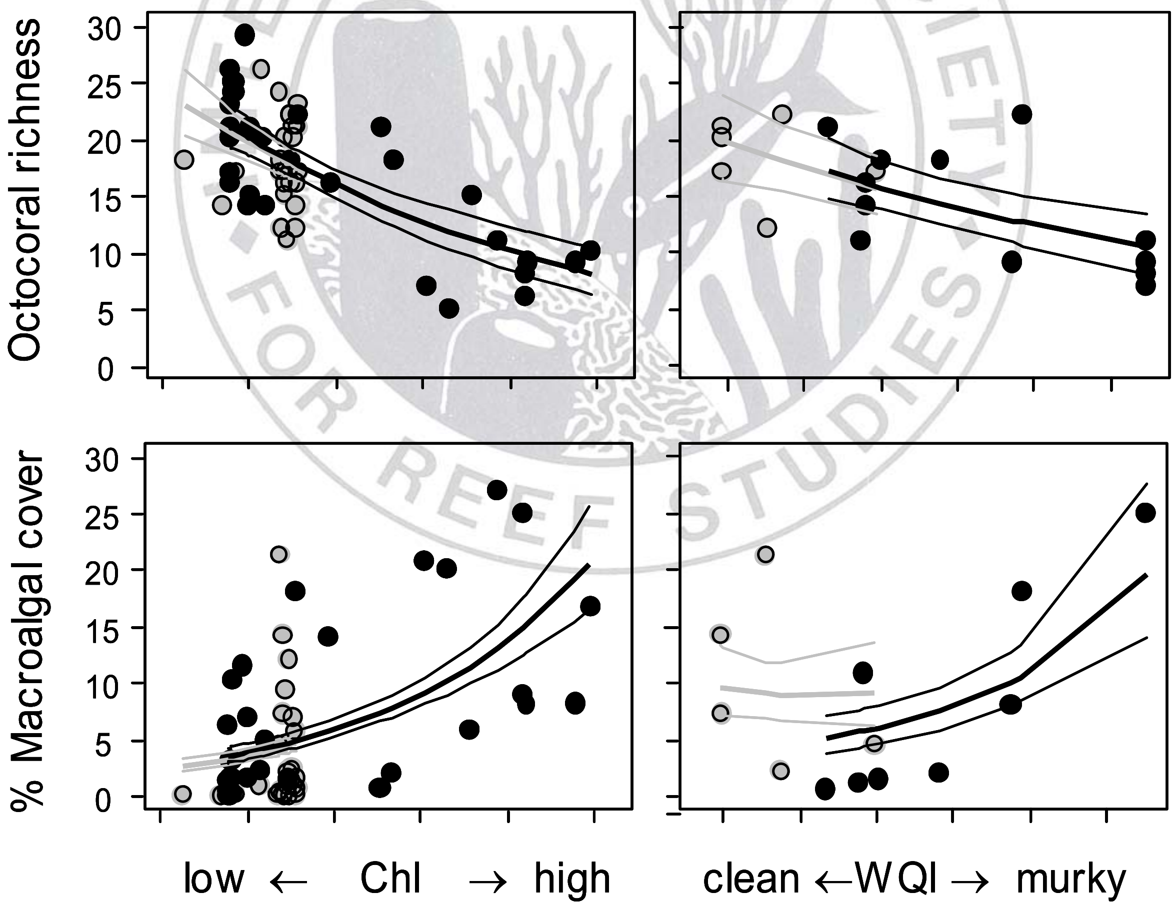


Figure 1: *Changes in the taxonomic richness of octocorals and in macroalgal cover along water quality gradients in the Great Barrier Reef; black points represent reefs exposed to runoff from agriculturally used watersheds, gray points are reefs exposed to runoff from watersheds with little agriculture. The chlorophyll data (Chl, left panel) are based on 10-years chlorophyll monitoring by the Great Barrier Reef Marine Park Authority. The inshore water quality index (WQI, right panel) is based on a composite index of concentrations of nutrients, chlorophyll and suspended solids on inshore reefs over 3 years. Adapted from Fabricius and De'ath (2004).*

Shifts from coral to macroalgal dominance

After disturbance such as storms, benthic algae settle on the dead corals and obtain space dominance. Environmental conditions determine whether they continue to dominate space and inhibit coral recovery, or whether corals are able to settle amongst these macroalgae, eventually outcompeting them and regaining space dominance. Under experimental conditions, some macroalgae are nutrient-limited and have a direct growth advantage at slightly enhanced levels of inorganic nutrients (Lapointe 1997, Schaffelke 1999b). Some coral reef inhabiting macroalgae can also grow faster by trapping particulate organic matter in their fine hair-like structures on their surface and using associate nutrients (Schaffelke 1999a). On the Great Barrier Reef, macroalgal abundances increase along two water quality gradients from low to higher nutrient levels (Fig. 1). However, the relationship between macroalgal cover and nutrient status is complicated by the fact that in many areas, macroalgal standing stocks are co-limited by grazing (Hughes *et al.* 1999, McCook 1999, Szmant 2002, Diaz-Pulido and McCook 2003, McClanahan *et al.* 2002, McClanahan *et al.* 2003): hence, macroalgal cover may not respond to nutrients if grazing is intense, or, in reverse, algal carpets can establish even without higher nutrient availability if grazing is low (either naturally or due to overfishing or disease).

Internal bioerosion

Some filter feeders and microalgae bore into the skeletons of live corals and the underlying inorganic reef substratum; these organisms are called internal bioeroders. While some bioeroders are sensitive to sedimentation, the rate of internal bioerosion is higher in areas of high loads of nutrients and particulate matter than in nutrient-poor clear oceanic waters (Rose and Risk 1985, Sammarco and Risk 1990, Edinger and Risk 1996, Holmes 2000). Intense internal bioerosion can reduce the resistance of reefs to storm damage. Some researchers therefore suggest that enhanced nutrient levels may affect overall reef growth not just be reducing coral calcification, but also by increasing reef erosion (Hallock 1988).

Increased susceptibility to diseases in corals

Both prevalence and virulence of certain coral diseases increase when levels of dissolved inorganic nutrients are experimentally enhanced (Bruno *et al.* 2003). Airborne or waterborne microbes from eroding soils such as Saharan dust have also been linked to greater disease prevalence in corals (Shinn *et al.* 2000, Jolles *et al.* 2002). It is however not yet clear to which extent the high levels of disease found in the Caribbean corals and sea fans are affected by water quality, and how big a problem the coral diseases are in other geographic regions.

Changes in the abundance of coral predators

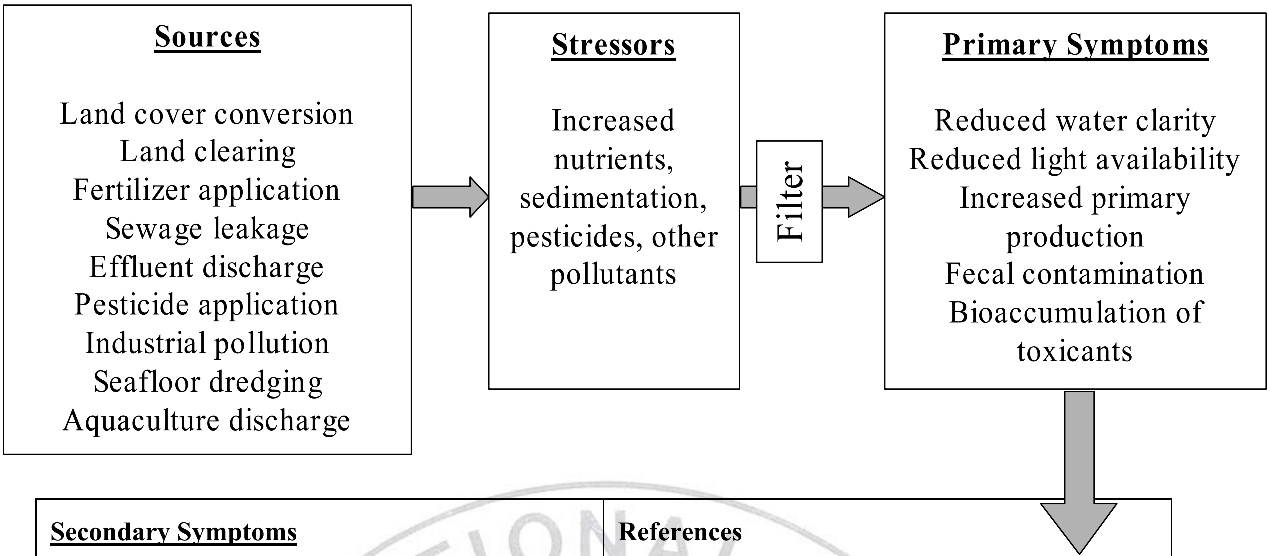
The potential increase in the frequency of population outbreaks of the crown-of-thorns seastar *Acanthaster planci* through terrestrial runoff (Birkeland 1982, Brodie 1992) represents another indirect effect, and particularly severe effect of water quality on the status of the wider coral reef ecosystem. There is a strong spatial and temporal association between drought-breaking floods from high continental Indo-Pacific islands and outbreaks of *A. planci* (Birkeland 1982). More *A. planci* larvae complete their development at slightly increased concentrations of large planktonic algae (Okaji *et al.* 1997), algae that tend to bloom when nutrient limitation is released. While overfishing of predators of juvenile *A. planci* can also contribute to higher seastar survival, evidence is strong that nutrification leads to increased frequencies or intensities of crown-of-thorns outbreaks.

Examples of coral reefs exposed to terrestrial runoff

Field studies on the effects of terrestrial runoff from all oceans have provided compelling evidence of long-term ecological changes in coastal and inshore reefs at local scales in response to excess sedimentation, turbidity and nutrients (Table 1, Fig. 2). At regional scales, causal links between reef degradation and the diffuse pollution from broad-scale land use practices have often been more difficult to demonstrate, because of a lack of historic data to distinguish anthropogenic impact from natural gradients and succession cycles. Regional-scale effects of terrestrial runoff are also often difficult to separate from the effects of other forms of reef use.

Well-studied cases from Kaneohe Bay in Hawaii and from Barbados demonstrate the deleterious effects of chronic eutrophication on coral reefs, and the mechanisms that led to changes. In most cases, factors other than eutrophication were the proximate causes of coral mortality. Thereafter, hard corals failed to re-establish on the affected sites. Only a few cases are described where differential post-settlement survival, selecting for more resistant or adaptive coral species, appeared to be responsible for shaping the coral communities (Wittenberg and Hunte 1992, van Woesik *et al.* 1999). In Kaneohe Bay, a sewage outfall pipe had caused local severe eutrophication for two decades, however a diversion of the outfall site to an offshore location locally improved the water quality and initiated reef recovery within a few years (Hunter and Evans 1995). Recovery has remained incomplete, possibly because nutrients in sediments are still high and because diffuse discharges from the increasing human population continue to discharge nutrients into the bay (Stimson *et al.* 2001). In Barbados, sewage discharge and industrial pollution changed the water chemistry along the coast sufficiently to reduce growth and recruitment of some of the main reef building corals (Tomascik and Sander 1985, Tomascik and Sander 1987b). On inshore reefs of the central part of the Great Barrier Reef, coral cover has declined to low levels from a series of unrelated disturbances since 1986, and reef building capacity on some reefs is reduced compared to pre-European settlement times (van Woesik *et al.* 1999). In two inshore regions, coral cover, hard coral and octocoral coral species richness decrease, and macroalgal cover increases along water quality gradients (Fig. 1; van Woesik *et al.* 1999, Fabricius and De'ath 2004). Similar studies exist from Indonesia, where coral biodiversity decrease and bioerosion rates increase with increasing water pollution (Edinger *et al.* 1998, Holmes *et al.* 2000), and Okinawa, Japan, where coral cover declines along gradients of eutrophication or river influences (Shimoda *et al.* 1998, West and Van Woesik 2001). These and many other case studies suggest that enhanced sedimentation or eutrophication alter the community composition and slow the recovery of hard coral communities after disturbance events, by substantially affecting coral recruitment. They also demonstrate cases of enhanced bioerosion, reduced coral growth and calcification rates, and hence reefs that erode faster than accrete.

Reefs vary greatly in their susceptibility to damage by poor water quality. Existing field observations from around the world indicate that reefs in poorly flushed semi-enclosed bays or lagoons, and reefs surrounded by a shallow sea floor, are at greatest risk of degradation, probably because materials are retained for prolonged periods of time, extending the period of exposure to more ‘chronic’ conditions. In contrast, reefs along well-flushed coastlines surrounded by deep water, where terrestrial pollutants are washed out within days to weeks, appear more resistant and resilient against degradation by exposure to high sediment and nutrient loads.



Secondary Symptoms	**References**
Lower larval production	Tomascik and Sander 1987b, Cox and Ward 2002.
Lower coral recruitment	Smith *et al.* 1981, Hunte and Wittenberg 1992.
Higher incidence of some coral diseases	Bruno *et al.* 2003, Shinn *et al.* 2000.
Lower skeletal density	Kinsey and Davies 1979, Lough and Barnes 1992.
Higher coral mortality	Wittenberg and Hunte 1992, Wesseling *et al.* 2001, Cortes 1994.
Reduced coral diversity, community phase shift	Smith *et al.* 1981, Pastorak and Bilyard 1985, Tomascik and Sander 1987a, Acevedo and Morelock 1988, Edinger *et al.* 1998, Fabricius and De'ath 2001, Fabricius and De'ath 2004.
Enhanced bioerosion	Rose and Risk 1985, Hallock and Schlager 1986, Hallock 1988, Holmes 2000, Chazottes *et al.* 2002.
Enhanced macroalgal growth and biomass	Smith *et al.* 1981, Lapointe 1997, Costa Jr *et al.* 2000, Lapointe *et al.* 2004.
Higher frequency of outbreaks of *Acanthaster planci*	Birkeland 1982, Brodie 1992.

Figure 2: *Schema of potential sources, stressors, primary symptoms, and secondary symptoms directly affecting hard corals and coral reef ecosystems (adapted from Sullivan Sealey 2004). The "filter" represents local conditions that determine the resistance and resilience of a reef to being affected by terrestrial runoff, such as flushing rates, depth of the surrounding sea floor etc (Cloern 2001).*

WHAT NEEDS TO BE DONE?

Coastal and inshore reefs are of high economic and ecological value. They supply food and wave protection for coastal settlements, they are popular destinations for the growing dive tourism industry, and they are unique habitats for a vast number of coral reef associated plants and animals that are not found on offshore reefs. Despite a growing understanding of the effects of terrestrial runoff on coral reefs, there are often uncertainties in the interpretation of field studies of terrestrial runoff, as a result of paucity of proper river monitoring programs in the Tropics, the under-sampling of extreme runoff events, and the co-occurrence of runoff with other forms of human reef usage. Notwithstanding these uncertainties, governments of many nations have begun to recognize the seriousness of the problem of enhanced discharge of sediments, nutrients and other pollutants into the coastal waters, and accept the existing evidence that sedimentation and excess nutrients harm coral reefs. For example, an extensive review of the current scientific evidence of the effects of runoff on the Great Barrier Reef and the economic implications has now lead to a plan to "halt or reverse the decline in water quality entering the reef" (The State of Queensland and Commonwealth of Australia 2003).

The increase in agricultural production and associated loss of terrestrial, freshwater and marine biodiversity and reduced ecosystem services represents a global problem that deserves urgent attention (Tilman et al., 2001). The problem of terrestrial runoff of soils and nutrients into coastal areas will continue to worsen unless the government, agricultural groups and coastal residents put measures in place to ameliorate this problem: tropical forests are lost at a rate of about 0.8% (15.2 million hectares) per year, mostly due to conversion to agriculture, timber harvest and fires (FAO 2000). Global fertilizer application has increased five-fold since 1960 to 150 million tonnes in 1990 and will continue to increase to an estimated 220 million tones in 2020, especially in less developed countries (Bumb and Baanante 1996). Hence, nitrogen and phosphorus-driven eutrophication of freshwater and near-shore marine systems and exposure to pesticides are estimated to increase 2.4 to 2.7-fold by 2050 (Tilman and others 2001). Similarly, the number of coastal residents without access to sewage treatment will continue to increase with increasing human population density and growing urbanization. Decisive actions are therefore urgently needed to combat the associated losses of terrestrial and marine biodiversity. Government plans should aim at setting targets to halt and reverse the decline in water quality discharged from the land within a set period of time, by reducing discharges from point sources and diffuse sources. The necessary actions required are (modified from GESAMP 2001):

1. To raise awareness how land-based activities can negatively impact adjacent marine environments;
2. To design national and international policies for integrated coastal and watershed management, carefully planning the sustainable use and management of natural resources, and using community-based voluntary self-regulatory and regulatory frameworks to implement these plans;
3. To prevent habitat destruction and the loss of biodiversity through education as well as legal, institutional and economic enforcement measures;
4. To rehabilitate, restore and protect riparian and coastal vegetation, wetlands, and other areas of the watersheds that actively filter out suspended sediments and nutrients; to minimize physical restructuring of the shoreline and to maintain coastal set-backs as defined by UNESCO;
5. To develop options for advanced waste water treatment – this is especially critical for growing cities and on small islands; and
6. To monitor and scientifically evaluate the ecological status and functions of riparian, coastal and marine habitats.
7. To design national and international policies that account for the economic value of environmental goods and services, and to provide for the internalisation of environmental costs.

Unlike global climate change, water pollution can be successfully managed by actions taken at local to regional scale. While most action has to take place on land, some management action in the sea can also enhance the resistance and resilience of coral reefs exposed to runoff. In particular, healthy populations of herbivores and predators will help maintaining control of algal or prey populations that may be nutrient limited; hence good fisheries management and the establishment of fish refuges ("no-take zones") may partly ameliorate some of the effects of deteriorating water quality. In return, coral reefs protected from terrestrial runoff will support higher yields of reef fishes than degraded coral communities with little structural complexity, and may even show higher level of resistance and resilience against pressure from global climate change.

Scientists should be involved in establishing integrated monitoring programs, characterizing water and sediment quality, determining contaminant releases, and quantifying environmental impacts in coral reefs. It is important to note that the information already available often provides a sufficient basis for action, and that action should not be postponed pending additional information (GESAMP 2001). However, monitoring data will help assessing and prioritizing management options, and are essential to test the effectiveness of management actions. An integrated monitoring program should therefore aim at resolving (1) sources of pollutants, (2) rates of transport to the reef, and (3) effects on the reef ecosystem. Detailed guidelines explaining the elements of effective water quality monitoring programs, from the initial design over field and laboratory methods to data analyses and interpretation are available free of charge (e.g., Australian and New Zealand Environment and Conservation Council 2000), and coral reef survey methods are well described (English *et al.* 2002, Wilkinson 2002). It is important to note that many traditional indicators such as coral cover and fish counts are too unspecific to be useful in detecting water quality impacts. Instead, reef monitoring must focus on early indicators of ecosystem change that are relatively specific to water quality impacts (Jameson *et al.* 2001), including coral recruitment, recruit survivorship, and abundance and dynamics of algae.

Threshold values of nutrients and sediments are usually not applicable, as responses tend to be dose-dependent or specific to local conditions. Therefore acceptable concentrations of "water quality" parameters and ecosystem properties require careful local definition before guidelines can be set at local or regional scales. However, some tentative sedimentation tolerance limits of 10 - 30 mg dry weight sediments deposited cm^{-2} day^{-1} have been proposed (Rogers 1990, Pastorok and Bilyard 1985, Hawker and Connell 1989), but as acceptable levels will depend on hydrodynamic conditions, organic loading, and background turbidity, thresholds need to be adjusted to local conditions. In contrast, general water quality guidelines for pesticides and heavy metals may eventually be established since the understanding of ecotoxicological effects of these substances on corals and reef-associated organisms is now beginning to emerge.

To conclude, terrestrial runoff can and will seriously alter and degrade inshore coral reefs. It is possible to successfully control water pollution at local to regional scales; however this requires a long-term commitment by governments and the public. Management solutions must be tailored to local circumstances, and each country needs to develop their own strategies to best combat pollution (GESAMP 2001). Most of the solutions will be on the land, and will include adhering to best management practices to retain topsoil, by protection or replanting of vegetation on steep slopes and along waterways, adequate waste water treatment, and spatial and temporal matching of fertilizer and pesticide application with actual crop demands. Socioeconomic studies unequivocally conclude that the costs of failing to control land-based pollution are enormous (GESAMP 2001); therefore considerable economic incentives exist to halt or reverse pollution of coral reefs from terrestrial runoff.

REFERENCES

Acevedo R, Morelock J (1988) Effects of terrigenous sediment influx on coral reef zonation in southwestern Puerto Rico. Proceedings of the Sixth International Coral Reef Symposium, Townsville, Australia. Vol. 2:189-194

Anthony KRN, Fabricius KE (2000) Shifting roles of heterotrophy and autotrophy in coral energetics under varying turbidity. Journal of Experimental Marine Biology and Ecology 252: 221-253

Australian and New Zealand Environment and Conservation Council (2000) Australian Guidelines for Water Quality Monitoring and Reporting. ANZECC, Canberra

Babcock R, Davies P (1991) Effects of sedimentation on settlement of *Acropora millepora*. Coral Reefs 9: 205-208

Babcock RC, Smith L (2002) Effects of sedimentation on coral settlement and survivorship. Proceedings of the Ninth International Coral Reef Symposium, Bali. Bali, Indonesia, October 23-27 2000 pp 245-248

Birkeland C (1982) Terrestrial runoff as a cause of outbreaks of *Acanthaster planci* (Echinodermata: Asteroidea). Marine Biology 69: 175-185

Bourke L, Selig E, Spalding M (2002) Reefs at risk in Southeast Asia. World Resources Institute, Cambridge, pp 72

Brodie J (1992) Enhancement of larval and juvenile survival and recruitment in *Acanthaster planci* from the effects of terrestrial runoff: a review. Australian Journal of Marine and Freshwater Research 43: 539-554

Bruno J, Petes LE, Harvell D, Hettinger A (2003) Nutrient enrichment can increase the severity of coral diseases. Ecology Letters 6: 1056-1061

Bryant DG, Burke L, McManus J, Spalding M (1998) Reefs at risk: a map-based indicator of threats to the world's coral reefs. World Resources Institute, Washington DC

Bumb B, Baanante C (1996) World trends in fertilizer use and projections to 2020. International Food Policy Research Institute, Washington, DC

Cervino JM, Hayes RL, Honovitch M, Goreau TJ, Jones S, Rubec PJ (2003) Changes in zooxanthellae density, morphology, and mitotic index in hermatypic corals and anemones exposed to cyanide. Marine Pollution Bulletin 46: 573-586

Chazottes V, Le Campion-Alsumard T, Peyrot-Clausade M, Cuet P (2002) The effects of eutrophication-related alterations to coral reef communities on agents and rates of bioerosion (Reunion Island, Indian Ocean). Coral Reefs 21: 375-390

Cloern JE (2001) Our evolving conceptual model of the coastal eutrophication problem. Marine Ecology Progress Series 210: 223-253

Cortes J (1994) A reef under siltation stress: a decade of degradation. Colloquium and Forum on Global Aspects of Coral Reef Health: Health, Hazards and History. Miami:240-246

Costa Jr OS, Leao ZM, Nimmo M, Attrill MJ (2000) Nutrification impacts on coral reefs from northern Bahia, Brazil. Hydrobiologia 440: 370-415

Cox EF, Ward S (2002) Impact of elevated ammonium on reproduction in two Hawaiian scleractinian corals with different life history patterns. Marine Pollution Bulletin 44: 1230-1235

Diaz-Pulido G, McCook LJ (2003) Relative roles of herbivory and nutrients in the recruitment of coral-reef seaweeds. Ecology 84: 2026-2033

Edinger EN, Jompa J, Limmon GV, Widjatmoko W, Risk MJ (1998) Reef degradation and coral biodiversity in Indonesia: Effects of land-based pollution, destructive fishing practices and changes over time. Marine Pollution Bulletin 36: 617-630

Edinger EN, Limmon GV, Jompa J, Widjatmoko W, Heikoop JM, Risk MJ (2000) Normal coral growth rates on dying reefs: Are coral growth rates good indicators of reef health? Marine Pollution Bulletin 5: 404-425

Edinger EN, Risk MJ (1996) Sponge borehole size as a relative measure of bioerosion and paleoproductivity. Lethaia 29: 275-286

English S, Wilkinson C, Baker V (2002) Survey Manual for Tropical Marine Resources. 2nd Edition. Australian Institute of Marine Science, Townsville

Fabricius K, Wild C, Wolanski E, Abele D (2003) Effects of transparent exopolymer particles (TEP) and muddy terrigenous sediments on the survival of hard coral recruits. Estuarine, Coastal and Shelf Science 57: 613-621

Fabricius KE, De'ath G (2001) Biodiversity on the Great Barrier Reef: Large-scale patterns and turbidity-related local loss of soft coral taxa. In: Wolanski E (ed) Oceanographic processes of coral reefs: physical and biological links in the Great Barrier Reef. CRC Press, London, pp 127 - 144

Fabricius KE, De'ath G (2004) Identifying ecological change and its causes: A case study on coral reefs. Ecological Applications: in press

FAO (2000) State of the World's Forests 2001. Food and Agriculture Organization of the United Nations, Rome

Furnas MJ (2003) Catchments and Corals: Terrestrial Runoff to the Great Barrier Reef. Australian Institute of Marine Science, CRC Reef. Townsville, Australia.

GESAMP (2001) Protecting the oceans from land-based activities. Land-based sources and activities affecting the quality and uses of the marine, coastal and associated freshwater environment. United Nations Environment Program, Nairobi

Gilmour J (1999) Experimental investigation into the effects of suspended sediment on fertilisation, larval survival and settlement in a scleractinian coral. Marine Biology 135: 451-462

Hallock P (1988) The role of nutrient availability in bioerosion: Consequences to carbonate buildups. Palaeogeography, Palaeoclimatology, Palaeoecology 63: 275-291

Hallock P, Schlager W (1986) Nutrient excess and the demise of coral reefs and carbonate platforms. Palaios 1: 389-398

Harrison PL, Ward S (2001) Elevated levels of nitrogen and phosphorus reduce fertilisation success of gametes from scleractinian reef corals. Marine Biology 139: 1057-1068

Hawker DW, Connell DW (1989) An evaluation of the tolerance of corals to nutrients and related water quality characteristics. International Journal of Environmental Studies A & B 34: 179-188

Holmes KE (2000) Effects of eutrophication on bioeroding sponge communities with the description of new West Indian sponges, *Cliona* spp. (Porifera: Hadromerida: Clionidae). Invertebrate Biology 119: 125-138

Holmes KE, Edinger EN, Hariyadi, Limmon GV, Risk MJ (2000) Bioerosion of live massive corals and branching coral rubble on Indonesian coral reefs. Marine Pollution Bulletin 7: 606-617

Hughes T, Szmant AM, Steneck R, Carpenter R, Miller S (1999) Algal blooms on coral reefs: What are the causes? Limnology and Oceanography 6: 1583-1586

Hunte W, Wittenberg M (1992) Effects of eutrophication and sedimentation on juvenile corals. 2. Settlement. Marine Biology 114: 625-631

Hunter CL, Evans CW (1995) Coral reefs in Kaneohe Bay, Hawaii: Two centuries of western influence and two decades of data. Bulletin of Marine Science 57: 501-515

Jameson SC, Erdmann MV, Karr JR, Potts KW (2001) Charting a course toward diagnostic monitoring: A continuing review of coral reef attributes and a research strategy for creating coral reef indexes of biotic integrity. Rosenstiel School of Marine and Atmospheric Science, [URL http //www.rsmas.miami.edu/bms/]

Jolles AE, Sullivan P, Alker AP, Harvell CD (2002) Disease transmission of aspergillosis in sea fans: Inferring process from spatial pattern. Ecology 83: 2373-2378

Jones RJ, Muller J, Haynes D, Schreiber U (2003) Effects of herbicides diuron and atrazine on corals of the Great Barrier Reef, Australia. Marine Ecology Progress Series 251: 153-167

Kinsey DW, Davies PJ (1979) Effects of elevated nitrogen and phosphorus on coral reef growth. Limnology and Oceanography 24: 935-940

Lapointe BE (1997) Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnology and Oceanography 42: 1119-1131

Lapointe BE, Barile PJ, Yentsch CS, Littler MM, Littler DS, Kakuk B (2004) The relative importance of nutrient enrichment and herbivory on macroalgal communities near Norman's Pond Cay, Exumas Cays, Bahamas: a 'natural' enrichment experiment. Journal of Experimental Marine Biology and Ecology 298: 275-301

Lough JM, Barnes DJ (1992) Comparisons of skeletal density variations in *Porites* from the central Great Barrier Reef. Journal of Experimental Marine Biology and Ecology 155: 1-25

Marubini F, Davies PS (1996) Nitrate increases zooxanthellae population density and reduces skeletogenesis in corals. Marine Biology 127: 319-328

McClanahan TR, Cokos BA, Sala E (2002) Algal growth and species composition under experimental control of herbivory, phosphorus and coral abundance in Glovers Reef, Belize. Marine Pollution Bulletin 44: 441-451

McClanahan TR, Sala E, Stickels PA, Cokos BA, Baker AC, Starger CJ, Jones SI (2003) Interaction between nutrients and herbivory in controlling algal communities and coral condition on Glover's Reef, Belize. Marine Ecology Progress Series 261: 135-147

McCook LJ (1999) Macroalgae, nutrients and phase shifts on coral reefs: scientific issues and management consequences for the Great Barrier Reef. Coral Reefs 18: 357-367

Muscatine L, Falkowski PG, Dubinsky Z, Cook PA, McCloskey LR (1989) The effect of external nutrient resources on the population dynamics of zooxanthellae in a reef coral. Proceedings of the Royal Society of London, Series B 236: 311-324

Okaji K, Ayukai T, Lucas JS (1997) Selective feeding by larvae of the crown-of-thorns starfish, *Acanthaster planci* (L.). Coral Reefs 16: 47-50

Pastorok RA, Bilyard GR (1985) Effects of sewage pollution on coral-reef communities. Marine Ecology Progress Series 21: 175-189

Reichelt-Brushett AJ, Harrison PL (1999) The effect of copper, zinc and cadmium on fertilization success of gametes from scleractinian reef corals. Marine Pollution Bulletin 38: 182-187

Rogers CS (1979) The effect of shading on coral reef structure and function. Journal of Experimental Marine Biology and Ecology 41: 269-288

Rogers CS (1983) Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. Marine Pollution Bulletin 14: 378-382

Rogers CS (1990) Responses of coral reefs and reef organisms to sedimentation. Marine Ecology Progress Series 62: 185-202

Rose CS, Risk MJ (1985) Increase in *Cliona delitrix* infestation of *Montastrea cavernosa* heads on an organically polluted portion of the Grand Cayman fringing reef. Pubblicazioni della Stazione Zoologica di Napoli I: Marine Ecology 6: 345-362

Sammarco PW, Risk MJ (1990) Large-scale patterns in internal bioerosion of *Porites*: Cross continental shelf trends on the Great Barrier Reef. Marine Ecology Progress Series 59: 145-156

Scarlett A, Donkin P, Fileman T, Morris R (1999) Occurrence of the antifouling herbicide, Irgarol 1051, within coastal-water seagrasses from Queensland, Australia. Marine Pollution Bulletin 38: 687-691

Schaffelke B (1999a) Particulate organic matter as an alternative nutrient source for tropical *Sargassum* species (Fucales, Phaeophyceae). Journal of Phycology 35: 1150-1157

Schaffelke B (1999b) Short-term nutrient pulses as tools to assess responses of coral reef macroalgae to enhanced nutrient availability. Marine Ecology Progress Series 182: 305-310

Shimoda T, Ichikawa T, Matsukawa Y (1998) Nutrient conditions and their effects on coral growth in reefs around Ryukyu Islands. Bulletin of the National Research Institute of Fisheries Science 12: 71-80

Shinn EA, Smith GW, Prospero JM, Betzer P, Hayes ML, Garrison V, Barber RT (2000) African dust and the demise of Caribbean coral reefs. Geophysical Research Letters 27: 3029-3032

Smith SV, Kimmener WJ, Laws EA, Brock RE, Walsh TW (1981) Kaneohe Bay sewerage diversion experiment: perspectives on ecosystem response to nutritional perturbation. Pacific Science 35: 279 -395

Spalding MD, Ravilious C, Green EP (2001) World Atlas of Coral Reefs. University of California Press, Berkeley

Stafford-Smith MG, Ormond RFG (1992) Sediment-rejection mechanisms of 42 species of Australian scleractinian corals. Australian Journal of Marine and Freshwater Research 43: 683-705

Stimson J, Larned ST, Conklin E (2001) Effects of herbivory, nutrient levels, and introduced algae on the distribution and abundance of the invasive macroalga *Dictyosphaeria cavernosa* in Kaneohe Bay, Hawaii. Coral Reefs 19: 343-357

Sullivan Sealey KM (2004) Large-scale ecological impacts of development on tropical islands systems: Comparison of developed and undeveloped islands in the Central Bahamas. Bulletin of Marine Science: in press

Szmant AM (2002) Nutrient enrichment on coral reefs: is it a major cause of coral reef decline? Estuaries 25: 743-766

Telesnicki GJ, Goldberg WM (1995) Effects of turbidity on the photosynthesis and respiration of two south Florida reef coral species. Bulletin of Marine Science 57: 527-539

The State of Queensland and Commonwealth of Australia (2003) Reef Water Quality Protection Plan; for catchments adjacent to the Great Barrier Reef World Heritage Area. Queensland Department of Premier and Cabinet, Brisbane

Tilman D, others (2001) Forecasting agriculturally driven global environmental change. Science 292: 281-284

Tomascik T, Sander F (1985) Effects of eutrophication on reef-building corals. 1. Growth rate of the reef-building coral *Montastrea annularis*. Marine Biology 87: 143-155

Tomascik T, Sander F (1987a) Effects of eutrophication on reef-building corals. 2. Structure of scleractinian coral communities on fringing reefs, Barbados, West Indies. Marine Biology 94: 53-75

Tomascik T, Sander F (1987b) Effects of eutrophication on reef-building corals. 3. Reproduction of the reef-building coral *Porites porites*. Marine Biology 94: 77-94

van Katwijk MM, Meier NF, van Loon R, van Howe EM, Giesen WBJT, van der Velde G (1993) Sabaki River sediment loading and coral stress: correlation between sediments and condition of the Malindi-Watamu reefs in Kenya (Indian Ocean). Marine Biology 117: 675-683

van Woesik R, Tomascik T, Blake S (1999) Coral assemblages and physico-chemical characteristics of the Whitsunday Islands: evidence of recent community changes. Marine and Freshwater Research 50: 427-440

Ward S, Harrison P (2000) Changes in gametogenesis and fecundity of acroporid corals that were exposed to elevated nitrogen and phosphorus during the ENCORE experiment. Journal of Experimental Marine Biology and Ecology 246: 179-221

Wesseling I, Uychiaoco AJ, Alino PM, Vermaat JE (2001) Partial mortality in *Porites* corals: variation among Philippine reefs. International Review of Hydrobiology 86: 77-85

West K, Van Woesik R (2001) Spatial and temporal variance of river discharge on Okinawa (Japan): Inferring the temporal impact on adjacent coral reefs. Marine Pollution Bulletin 42: 864-872

Wilkinson C (2002) Status of Coral Reefs of the World: 2002. Australian Institute of Marine Science, Townsville (Australia)

Wittenberg M, Hunte W (1992) Effects of eutrophication and sedimentation on juvenile corals. 1. Abundance, mortality and community structure. Marine Biology 116: 131-138

Yentsch CS, Yentsch CM, Cullen JJ, Lapointe B, Phinney DA, Yentsch SW (2002) Sunlight and water transparency: cornerstones in coral research. Journal of Experimental Marine Biology and Ecology 268: 171-183