Available online at www.sciencedirect.com
ScienceDirect
Marine Pollution Bulletin 56 (2008) 170–186
MARINE POLLUTION BULLETIN
www.elsevier.com/locate/marpolbul

Viewpoint

Possible ecological consequences from the Sethu Samudram Canal Project, India

D.V. Subba Rao [a,*], K. Srinivasa Rao [b], C.S.P. Iyer [c], P. Chittibabu [d]

[a] *Bedford Institute of Oceanography, Habitat Ecology Division, Department of Fisheries and Oceans, P.O. Box 1006, Dartmouth, NS, Canada B2Y 4A2*
[b] *815 Rainier Court, Allen 75002, Texas, USA*
[c] *Indian Institute of Information Technology & Management Kerala, Thiruvananthapuram, Kerala, India*
[d] *Baird and Associates Coastal Engineers, Suite 500, 1145 Hunt Club Road, Ottawa, Ontario, Canada K1V 0Y3*

Abstract

The Sethu Samudram Canal Project (SSCP), considered as a harbinger of economic growth in India, is a mega engineering project being developed to provide a 260 km long, 300 m wide and 12 m deep shipping channel between the Arabian Sea and the Bay of Bengal. This project impacts the unique biota and biodiversity of a 10,500 km^2 Marine Biosphere Reserve. This man-made link facilitates exchange of water masses between the less saline Bay of Bengal and the more saline Arabian Sea. Initial construction, subsequent dredging for channel maintenance, and the associated ship traffic would result in irreversible changes to the already over-exploited and stressed environment. Additionally, the channel would form a deep ocean route for future tsunamis. However, to provide assurance to the public, particularly the 50,000 fishing folk, in 47 villages in this area, it would be crucial that a long-term environmental monitoring program is instituted. A thorough evaluation of the impending environmental impacts, similar to those addressed by a Before/After and Control/Impact (BACI model) is recommended.

Keywords: Mega-engineering shipping channel; Environmental impacts; Tsunamis; India–Sri Lanka region

Introduction

The Sethu Samudram Canal Project (SSCP) is a 144-year proposal conceived originally in 1860 by Mr. A.D. Taylor, a British Naval Commander; subsequently there were eight more proposals. It has a current price tag of US $300 million. There is no navigable sea route, at present, around the Indian Peninsula, between the Gulf of Mannar and the Bay of Bengal due to the presence of a shallow ridge, Adam's Bridge, between India and Sri Lanka. Further, at Palk Strait, connecting Palk Bay and Bay of Bengal, the waters are shallow in some places. The SSCP is an undertaking by the Government of India to provide a shipping channel (Fig. 1) between the Arabian Sea (A.S) and the Bay of Bengal (B.B) with the hope it will in turn foster coastal trade and industries.

The Sethu Samudram Canal (SSC) will originate at Tuticorin Port, the southern tip of India and runs through the Gulf of Mannar (G.M), Palk Bay (P.B) and the Palk Strait (P.S) in a north–north-easterly direction to the northern part of Sri Lanka (S.L.) (Fig. 1).

Advantages resulting from SSC include: (1) Passage of ships with 10–12 m draft between the Arabian Sea and the Bay of Bengal through Indian territorial waters without circumnavigating Sri Lanka. (2) Reduction of sailing distance to about 750 km, the steaming time to 21–36 h. (3) Provides quicker and easier access to Indian Coast Guard and Naval ships which is an asset for the national defence and security. (4) Substantial increase in India's export–import trade and national economy, and savings in bunkering costs that would benefit the shipping industry.

* Corresponding author. Present address: 12 The Horseshoe, Manor Park, Dartmouth, Nova Scotia, Canada, B2Y 4E5. Tel./fax: +1 902 463 7804.
E-mail address: onyx@accesswave.ca (D.V.S. Rao).

0025-326X/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.marpolbul.2007.10.018

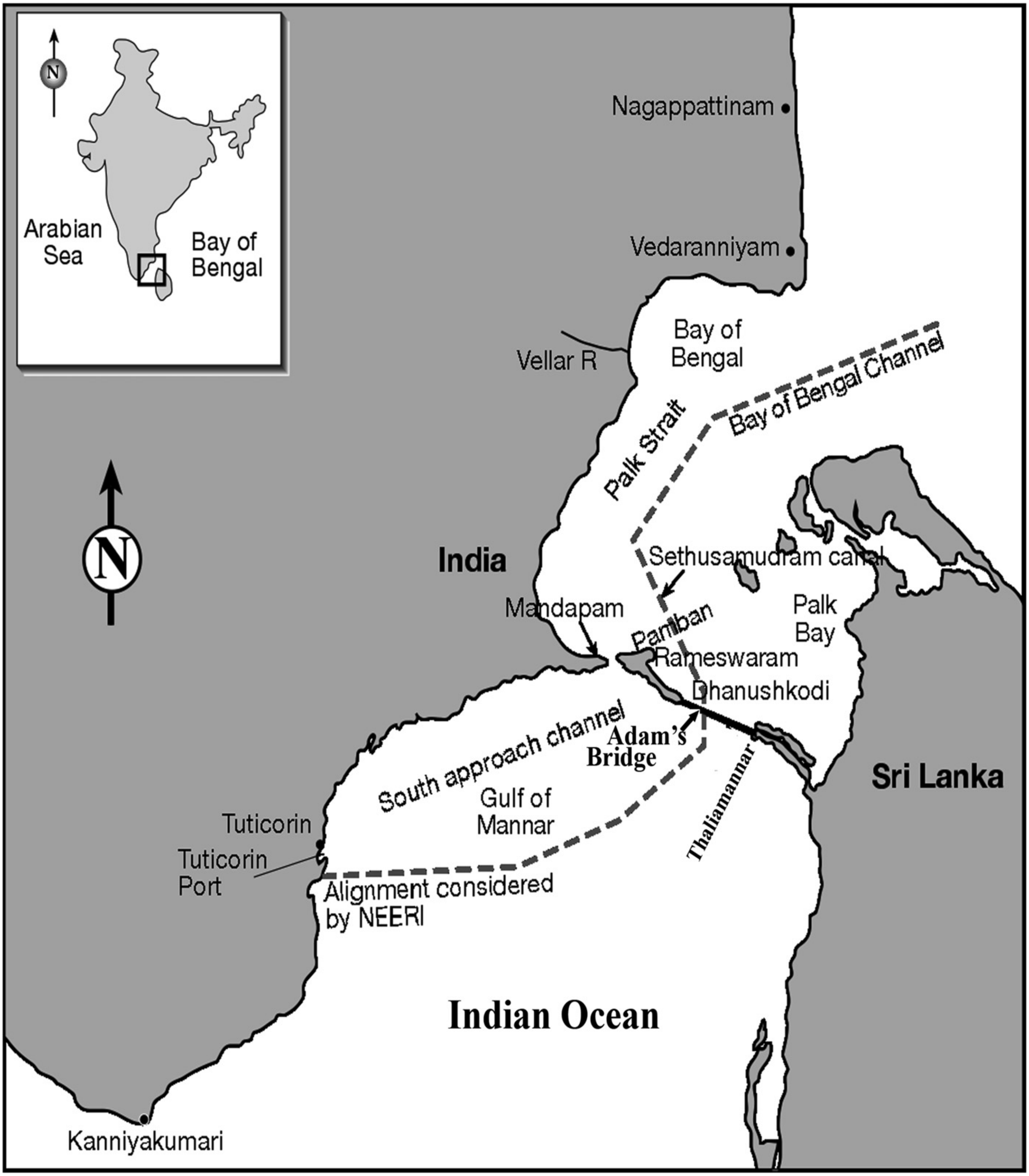

Fig. 1. A geographical map showing the location of SSCP.

The Sethu Samudram Canal with a total length of 152.2 km comprises of a 20 km southern leg in the Adam's Bridge area, a 54.2 km northern leg in the Palk Strait and a central 78 km leg. This necessitates dredging a 83 km channel through the Rameswaram Island and the shallow waters of Adam's Bridge and Palk Bay. Specifically, it is planned to connect the Gulf of Mannar with Palk Straits through a 260 km long, 300 m wide and 12 m deep ship channel. It is estimated that more than 2000 vessels will use the canal annually.

A rapid Environmental Impact Assessment for the SSCP was done by the National Environmental Engineering Research Institute (NEERI, 2004) and their findings are incorporated in eight Sethusamudram Corporation Limited Reports (SCL) available from the Nodal Agency the Tuticorin Port Trust. Coastal Action Network pointed out, however, that the NEERI reports (2004) are not comprehensive and distribution of SCL reports is strictly limited.

Most of these reports however debated mainly the pros and cons of the implementation of the SSCP and discuss more the physical aspects of sediment dynamics and the associated coastal erosion than the ecology unique to this region. We emphasize here that considerable changes in the geomorphology and habitat could take place. Because of their interdependency on sediment dynamics, the unique fauna and flora of this region would undergo drastic irreversible changes and so the potential impacts of SSCP should be of grave concern.

The course we will follow in our analysis of the proposed SSCP is to describe the SSC region regarded as nature's paradise which rebounds with marine life, and followed by an account on the four kinds of major changes that potentially could take place with the implementation of the SSCP (Fig. 2). The first category of changes are associated with sediment dynamics caused by dredging operations that could have an impact on the coastline and structures; these could provide new areas for settlement of benthic and fouling organisms qualitatively and also cause changes in quantitative abundance of species which in turn will impact the structure and functioning of the ecosystem (Emmerson et al., 2005). The second are perturbations associated with the actual shipping traffic, and the third includes impacts of tunneling caused by deepening the straits in this area prone to cyclones and tsunamis, and finally the fourth is about changes in the socio-economics caused by dislocation of fishing folk and increased maritime trade.

The region: a marine biosphere reserve

The SSC is located off the south-eastern coast of India in the Gulf of Mannar and its ocean floor has a broad trough, probably resulting from earthquake activity. This region consists of a chain of 21 islands lying between 8°49′N and 9°15′N and 78°11′E and 79°15′E and covers approximately 10,500 km^2. It has been declared a Marine Biosphere Reserve (MBR) which serves as a confluence of the Bay of Bengal, the Arabian Sea and the Indian Ocean (Fig. 1). This MBR, a highly productive area, in the Indo-Pacific region, provides a rich habitat with a great biodiversity of 5896 species of plants and animals ranging from bacteria to dugongs (Table 1). It includes 450 species of fishes, 731 species of molluscs including 110 species of gastropods (Samuel and Patterson, 2000), 77 species of bivalves (Jayaseeli and Murugan, 2003), 53 species of Scleratinia corals (Edward et al., 2004), 110 species of hermatypic and ahermatypic corals (Gopinadha Pillai, 1971), 100 species of echinoderms, 54 species of benthic foraminiferans (Jayaraju and Reddi, 1999), 47 species of marine algae, 100 species of sea grasses (Kallaperumal et al., 1998), 17 mangrove species, 52 species of Ostracods (Hussain et al., 1996), and 42 species of fouling organisms (Chidambaram, 1990) live. Of these 377 species are endemic. However, besides bivalves and gastropods, about 0.12×10^6 million tons fish including commercially important cephalopods are harvested by fishing folk in this area (Kumaraguru et al., 2000; Kannan et al., 2001).

Characteristics of the Bay of Bengal and the Arabian Sea

A broad comparison of the Bay of Bengal with the Arabian Sea reveals existence of large differences in their physical, chemical and biological characteristics (Table 1). The Bay of Bengal is more cyclone prone and has experienced 1500 cyclonic depressions and 500 major storms over the past 100 years. The eight Himalayan and peninsular rivers discharge 1283 km^3 annually into the Bay of Bengal which in turn influence temperature, salinity, Ekman transport, and turbidity. In contrast, 5 rivers empty 162 km^3 into the Arabian Sea and as a result its surface waters are more saline than those of the Bay of Bengal. Formation of oxygen deficient layer, denitrification layer and mud banks are exclusive to the Arabian Sea.

Phytoplankton characteristics also differ between these two bodies of water (Table 1). While 32 algal species contribute to the blooms in the Bay of Bengal, 37 altogether different species constitute the blooms of the Arabian Sea. The algal biomass measured as chlorophyll *a* is higher in the Bay of Bengal (30–200 mg m^2) than in the Arabian Sea (Pant, 1992); that also results in a high primary production ($0.3\ g\ Cm^2\ d^{-1}$) (Qasim, 1977). But the total annual column production ($394 \times 10^6\ t\ C\ y^{-1}$) is lower than that of the Arabian Sea $1084 \times 10^6\ t\ C\ y^{-1}$, probably due to limitations of light essential for photosynthetic growth (Qasim, 1977). Algal blooms of *Dinophysis* sp. *Prorocentrum* sp. causing Diarhetic Shellfish Poisoning (DSP), *Alexandrium* sp. causing Paralytic Shellfish Poisoning (PSP) episodes, and of *Gymnodinium nagasakiense* resulting in fish kills are limited to the Arabian Sea.

The fish yield and total potential pelagic, demersal, crustacean, fish stocks, the benthic macro and meiofaunal production and the benthic biomass in the EEZ are lower in the Bay of Bengal than in the Arabian Sea (Table 1). The fisheries in the Bay of Bengal are based on elasmobranchs, croaker, tuna, bill fish, pomfrets, prawns and squid while on the west coast the main species are *Sardinella longiceps*, *Rastrilliger kanagurta*, and *Harpadon nehereus*. *Sardinella aurita* is absent in the Bay of Bengal.

Comparison of Palk Bay with the Gulf of Mannar

The waters in the Gulf of Mannar are rendered intermediate between the oceanic conditions of the Indian Ocean

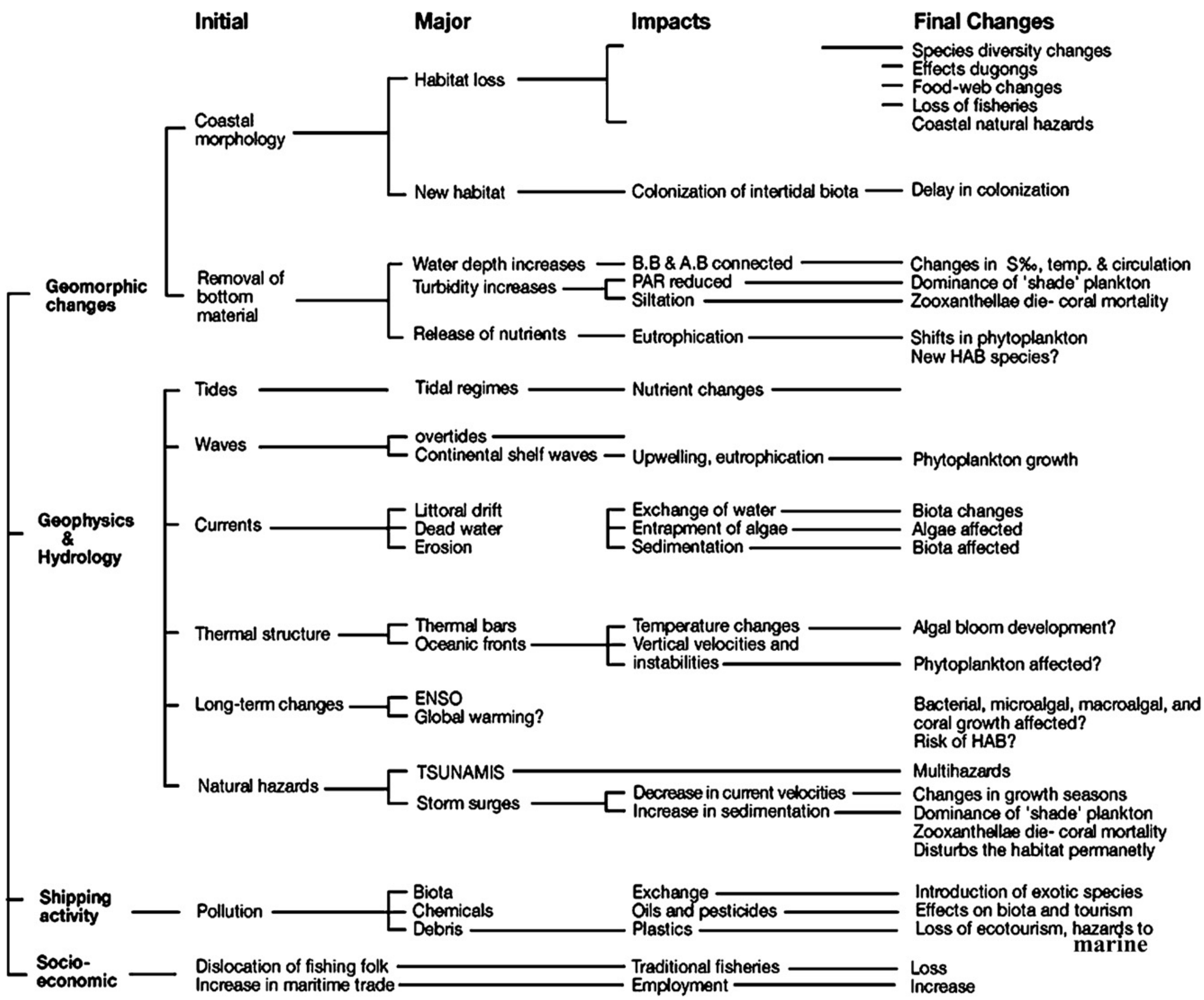

Fig. 2. Schematic representation of possible environmental changes due to SSCP implementation.

and coastal conditions of Palk Bay. The submerged island chain (Adam's Bridge) acts as a subsurface physical barrier, between Rameswaram Island and Mannar Island. Indian Ocean waters enter the Gulf, and the water at the head of the Gulf under the influence of the southwest monsoon is piled up like a cushion (Silas, 1968). The Bay of Bengal waters entering through Palk Strait have a major influence on the hydrographic conditions of Palk Bay, while the Gulf waters influence Palk Bay to a minor extent only (Murty and Varma, 1964). The differences in the ecological regimes of the Bay and Gulf waters seem to have a profound influence on the distribution and biology of the marine biota in this region.

A comparison of the Palk Bay with the Gulf of Mannar (Table 2) suggests the Palk Bay waters resemble more those of the Bay of Bengal with respect to their lower salinity and higher nutrients. The annual phytoplankton cycle in the Palk Bay showed three peaks constituted mostly of diatom species with marked differences in the constituents between the Palk Bay and the Gulf of Mannar. Monospecific blooms of *Rhizosolenia alata* and *R. imbricata* were present only in the Palk Bay. The Palk Bay waters were productive and the zooplankton had unimodel peak distribution. The meroplankton species diversity index, evenness of species, and richness of dominance index were lower in the Palk Bay than in the Gulf of Mannar.

Fish spawning grounds

The shallow bays and coves of the Gulf of Mannar – adjacent to Palk Bay, where the depth is not more than 25 m are the favourite spawning grounds of the streaked seer (*Scomberomorus lineolatus*) and king seer (*S. commerson*), while the spawning of the relatively small spotted seer (*S. guttatus*) takes place around the islands in the northern Gulf of Mannar, on the Palk Bay side of Adam's bridge (Devaraj, 1986). *Chirocentrus nudus* and *C. dorab*, which constitute a fishery unique to the region, also have their main spawning ground in The Gulf of Mannar, and it was suggested that these fish move from Palk Bay to the

Table 1
Broad comparisons between Bay of Bengal and the Arabian Sea

Feature	Bay of Bengal	Arabian Sea	Reference
Depressions in 100 years	1500		Mani (1997)
Storms	500		Mani (1997)
Annual river discharge km^3	1283	162	CPCB (2005)
Low temperature anomaly	Influenced by freshwater discharge	Wind driven	Naidu et al. (1999)
Ekman transport	Influenced by freshwater discharge	Wind driven	Naidu et al. (1999)
Paleo-upwelling indicators	*Globigerinoides bulloides*	*Neogloboquadrina dutertrei*	Naidu et al. (1999)
Sediment shifted to sea 10^{12} kg y^{-1}	1.139	0.061	Chandramohan et al. (2001)
Shallow mixed layer	Shallow	Deep	Naidu and Lakshmana Rao (1990)
Thermocline (m)	100–125 but raises to 50–55	Usually 100–125 but raises to 20–30	Panickkar and Jayaraman (1966)
Upwelling isotherm 28.5 °C	49 m	36 m	Mohan and Ali (1995)
Surface salinity PSU	30–33	34-37-	Panickkar and Jayaraman (1966)
Surface temperature (°C)	27–29	23–29	Panickkar and Jayaraman (1966)
Oxygen deficient and denitrification layers	Absent	Present	Sarin et al. (1994)
PO_4–P 100 m integrated (μg at l^{-1})	30–60	20–40	Qasim (1977)
NO_3–N (μg at l^{-1})	1000–1500	100–200	Qasim (1977)
Surface Chlorophyll-*a* (mg m^3)	0.30	0.35–0.85	Chauhan et al. (2001)
Chlorophyll-*a* (mg m^2)	30–200	2–25	Pant (1992)
		28–60	Prasanna Kumar et al. (2001)
Average production tonnes (carbon km^2 y^{-1})	4.9	3.9	Qasim (1977)
Primary production (g C m^2 d^{-1})	0.3	0.076	Pant (1992)
		0.77–1.782	Prasanna Kumar et al. (2001)
Total column production (10^6 tons C m^2 y^{-1})	394	1064	Qasim (1977)
Blooming species	@*Bacteriastrum varians*, *Coscinodiscus centralis*, *Lauderai borealis*, *Guinardia flaccida*, *Rhizosolenia setigera*, *R. stolterfothii*, *R. setigera*, *R. styliformis*, *R. crassispina*, *R. alata*, *Bacteriastrum hyalinum*, *B. delicatulum*, *B. comosum*, *Chaetoceros diversus*, *C. curvisetus*, *C. compressus*, *C. lorenzianus*, *C. indicus*, *Hemidiscus hardmannianus*, *Thalassionema nitzschioides*, *Thlassithrix frauenfeldii*, *Ditylum sol*, *Biddulphia sinensis*, *B. mobiliensis*, *Nitzschia seraita*, *Peridinium depressum*, *P. oceanicum*, *Gymnodinium* sp. *Trichodesmium erythraeum*, *Stephanopyxis palmeriana* *Thalassiosira subtilis*, *Streptortheca indica*	#*Asterionella japonica*, *Bacteriastrum hyalinum* var. *princes*, *Odontella heteroceros*, *O. mobiliensis*, *Chaetoceros affinis*, *C. brevis*, *C. compressus*, *C. contortum*, *C. curvisetus*, *C. lascinosus*, *C. lauderii*, *C. lorenzianus*, *C. pelagicus*, *C. socialis*, *Coscinodiscus asteromphalus*, *C. oculus-iridis*, *Fragilaria oceanica*, *Guinardia flaccida*, *Lauderia annulata*, *Leptocylindrus danicus*, *Nitzschia seriata*, *N. sigma* var. *indica*, *Rhizosolenia alata*, *R. robusta*, *R. stolterfothii*, *Schroderella delicatula*, *Skeletonema costatum*, *Thalassiothrix frauenfeldii*, *T. longissima*, *Ceratium fusus*, *C. macroceros*, *C. tripos*, *Dinophysis caudata*, *Glenodinium lenticula* f. *asymmetrica*, *Noctiluca miliaris*, *Peridinium depressum*, *Trichodesmium erythraeum*	# Subramanyan and Viswanatha Sarma (1961) @ Subba Rao (1970, 2000)

Table 1 (*continued*)

Feature	Bay of Bengal	Arabian Sea	Reference
Fish yield (10^6 tons per year)	1.85	6.51	Goswami et al. (1992)
Total potential fish stocks in the EEZ (10^6 tons)	1.09	2.357	Somvanshi (1998)
Major fisheries	Elasmobranchs, Croaker, Tunas and bill fishes, pomfrets, prawns, Squid	*Sardinella longiceps*, *Rastrilliger kanagurta*, *Harpadon nehereus*	Rao and Griffitths (1998)
Mass mortality due to		Trichodesmium erythraeum Noctiluca miliaris	Bhimachar et al. (1950)
Sardinella aurita	Absent	Present	Dutt and Raju (1983)
Toxigenic episodes		DSP- *Dinophysis* sp. *Prorocentrum* sp.	Karunasagar et al. (1989)
		PSP, *Alexandrium* sp.	Karunasagar et al. (1990)
		Fish kill, *Gymnodinium nagasakiense*	Karunasagar and Karunasagar (1992)
Marine benthic faunal biomass (g m^2)	10	35	Dalal and Parulekar (1992)
Benthic macro + meio production (g m^2) 0–300 m zone	1.4–12.08	5.13–20.41	Rao and Griffitths (1998)
Exploited marine resources[a]	220944 P, 101786 D, 40611C	627452 P, 133243 D, 219386 C	Qasim (1977)

[a] P = pelagic fish including tuna, D = demersal, C = crustaceans.

adjacent Gulf of Mannar for spawning (Luther, 1986). Clupeoid fish in general and *Chanos chanos* (milk fish) in particular, also seem to prefer the Gulf waters for spawning. An unique phenomenon of the Gulf waters is the appearance of swarms of milkfish fry on the shores at the head of the Gulf, towards the end of the southwest monsoon (personal communication, Dr. G. Luther). Sea horses (genus *Hippocampus*) are a target fishery in the Gulf of Mannar and constitute most of India's 3.6 tons exported annually; this is an endangered species (Sreepada et al., 2001).

Ecotones and hybrid fishes

Intermediacy of the Gulf of Mannar waters has a far reaching significance, by way of formation of an ecotone (a transitional zone between two communities containing the characteristic species of each) between oceanic waters of the Indian Ocean and coastal waters of the Bay of Bengal. Ecotonal waters are ideal for the survival of hybrid derivations, because of hybrid superiority in Narrow Hybrid Zones (NHZ). In the NHZ, the hybrids are usually at a selective advantage over their putative parents of widely distributed fisheries of importance in their respective habitats (Srinivasa Rao and Lakshmi, 1993, 1999). Further the hybrids in the NHZ are usually predominant forming a stable hybrid fishery population, thereby giving scope for their misidentification as valid species. For example in the SSCP region the nominal species *Scomberomorus lineolatus* (Cuv.) and *S. koreanus* (Kishinouye) are confined to the Gulf of Mannar and Palk Bay respectively, where they form a fishery of some magnitude (Jones, 1968; Silas, 1968; Collette and Russo, 1984; Devaraj, 1977, 1986 and personal observations of Srinivasa Rao). But otherwise in the Indian waters *S. lineolatus* was identified as a natural hybrid between the coastal *S. guttatus* (Bloch & Schneider) and oceanic *S. commerson* (Lacépède) (Srinivasa Rao and Lakshmi, 1993, 1999). Presumably *S. koreanus* is also of hybrid origin. They are distinct from their putative parents when they are fully grown; otherwise they can be mistaken for *S. guttatus* with which *S. koreanus* bears very close resemblance in juvenile stages (Srinivasa Rao and Lakshmi, 1993, 1999). As full grown adults – at a size larger than 70 cm furcal length, *S. lineolatus* is abundant in the Gulf of Mannar and *S. koreanus* in Palk Bay. Another nominal species, identified as a hybrid derivative is the catfish *Arius dussumieri* (*A. tenuispinis* × *A. bilineatus*) which appears occasionally as swarms in the different parts of the east and west coasts of India, but forms a regular fishery around Rameswaram island, forms a stable hybrid population constituting around 30% of the catfish catches in that area (Lakshmi and Srinivasa Rao, 1992). Otherwise, it appears sporadically elsewhere. Thus, Palk and the Gulf of Mannar constitute a potential narrow hybrid zone, that could harbour many more unidentified stable hybrid populations. With the implementation of the SSCP the ecotonal quality of the narrow hybrid zone (Palk Bay and Gulf of Mannar) will be destroyed.

Unique biota

Traditionally, the Gulf of Mannar regarded as biologist's paradise, harboured unique biota of value, not only for the fisheries, but also from the educational point of view and attracted students of biology for field studies. The Gulf of Mannar is world famous for its pearl oyster (*Pinctada fucata*) found at deeper levels off Tuticorin. From the beginning of 20th century the British naturalists

Table 2
Comparison between Gulf of Mannar and Palk Bay

Feature	Gulf of Mannar	Palk Bay	Reference
Temperature °C	∼24–33		Raghu Prasad (1956)
Salinity PSU	∼27.2–36.0	∼25.5–36.0	Raghu Prasad (1956)
Oxygen saturation %	59–89	52–86	Raghu Prasad (1956)
Phosphate (μg at l^{-1})	0.09–0.30	0.14–0.25	Raghu Prasad (1956)
Silicate (μg at l^{-1})	3.3–14.8	5.3–17.9	Raghu Prasad (1956)
Nitrate (μg at l^{-1})	1.9–4.7	1.6–5.0	Raghu Prasad (1956)
Phytoplankton peaks	January; April–May; October–November	May–June; October–November	Raghu Prasad (1956)
Dominant diatom species	*Chaetoceros coarctatus*, *Ditylum brightwelli*, *Odontella sinensis*, *Hemidiscus hardmannianus*	*Thalassiosira coramandeliana*, *Guinardia* sp. *Rhizosolenia styliformis*, *R. calcaravis*, *R. casracanei*, *Hemiaulus sinensis*, *Bacteriastrum varians*, *Chaetoceros denticulatum*, *Climacosphenia elongate*, *Asterionella japonica*	Raghu Prasad (1956)
Single species blooms	Absent	*Rhizosolenia alata*, *R. imbricata*	Raghu Prasad (1956)
Cyanophyte *Trichodesmium erythraeum*	Large quantities during summer ∼1300 filaments ml^{-1}	April 600 filaments ml^{-1}	Raghu Prasad (1956)
Dinoflagellates	*Ceratium trichoceros*, *C. massiliense*	*C. fusus*, *C. furca*	Raghu Prasad (1956)
Noctiluca sp.	Few	≫more	Raghu Prasad (1956)
Copepod peaks	Dicyclic-January; September–October	Unimodel-September or October	Raghu Prasad (1956)
Primary production (mg C m^3 d^{-1})	*18–298	#1.8–2342	*Raghu Prasad and Nair (1963) # Nair (1970)
	114–1600, average 350		Gopinathan and Rodrigo (1991)
Meroplankton species diversity index	2.18	1.19	Krishnamoorthy and Subramaniam (1999)
Species evenness	1.5	1.3	
Species richness	3.13	3.0	
Dominance index	74.6	71.6	

(Hornell, 1906, 1914, see also Kunz and Davidson, 1993) investigated the natural oyster beds and made several suggestions for their conservation. The Fisheries Department of the former Madras Government used to harvest the pearls of great value once in five years. This practice is no longer in vogue because of the depletion of the oyster beds, as a result of human intervention. In the shallow waters, another molluscan resource of great reputation is the sacred chank (*Xancus pyrum*), a resource much sought after as a fishery. The rare dextral aberration of this mollusk is sacred to the Hindus and therefore much sought after at any price. The shore of Rameswaram at the head of the Gulf was noted for patches of the burrowing "living fossil"*Ptychodera flava* that links vertebrates (Hemichordata) and invertebrates. The shallow waters in the vicinity were thickly populated with a variety of sea cucumbers (Holothuroidea) *Holothuria scabra*, *H. spinifera* and *Actinopyga echinites* of which *H. spinifera* is endemic to these waters. Biotic uniqueness of the area is further augmented by the richness and variety of macroalgae, particularly the Indo-Pacific, *Enhalus acoroides*, that supports the sea cow, *Dugong dugong* (Coastal Action Network Report, 2004). All five known species of marine turtles (Green, Hawksbill, Olive ridley, Leatherback and Logger head turtles),10 species of whales including the toothed whale, the baleen whale, the blue whale, the sie whale, the fin whale and the pilot whale occur in this region (Coastal Action Network Report, 2004).

Bathymetry

The bathymetric data (Fig. 3) show that across Adam's Bridge between Arippumunai (India) and Thaliamannar (Sri Lanka), the water depths vary from 1 to 3 m. Similarly between Kodikarai (India) and Kenagesan Thurai (Sri Lanka), known as Palk Strait, the depth ranges from 2 to 10 m (ETOPV2 http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html). Over major part of the Palk Bay the depth is around 12 m. Hence, for making a navigable route around India on the East side, dredging will be needed for 20 km at Adam's Bridge and 36 km at Palk Strait. To evaluate the quantum of dredging, both capital and maintenance, sedimentation in the area has to be taken into account (NEERI, 2004; Ramesh, 2004, 2005).

Sedimentation in Palk Bay

Palk Bay covers an area of 12,285 km^2 with the Bay of Bengal to the north and Gulf of Mannar to the south. Sediments are brought into the Bay by: (1) Rivers, mainly

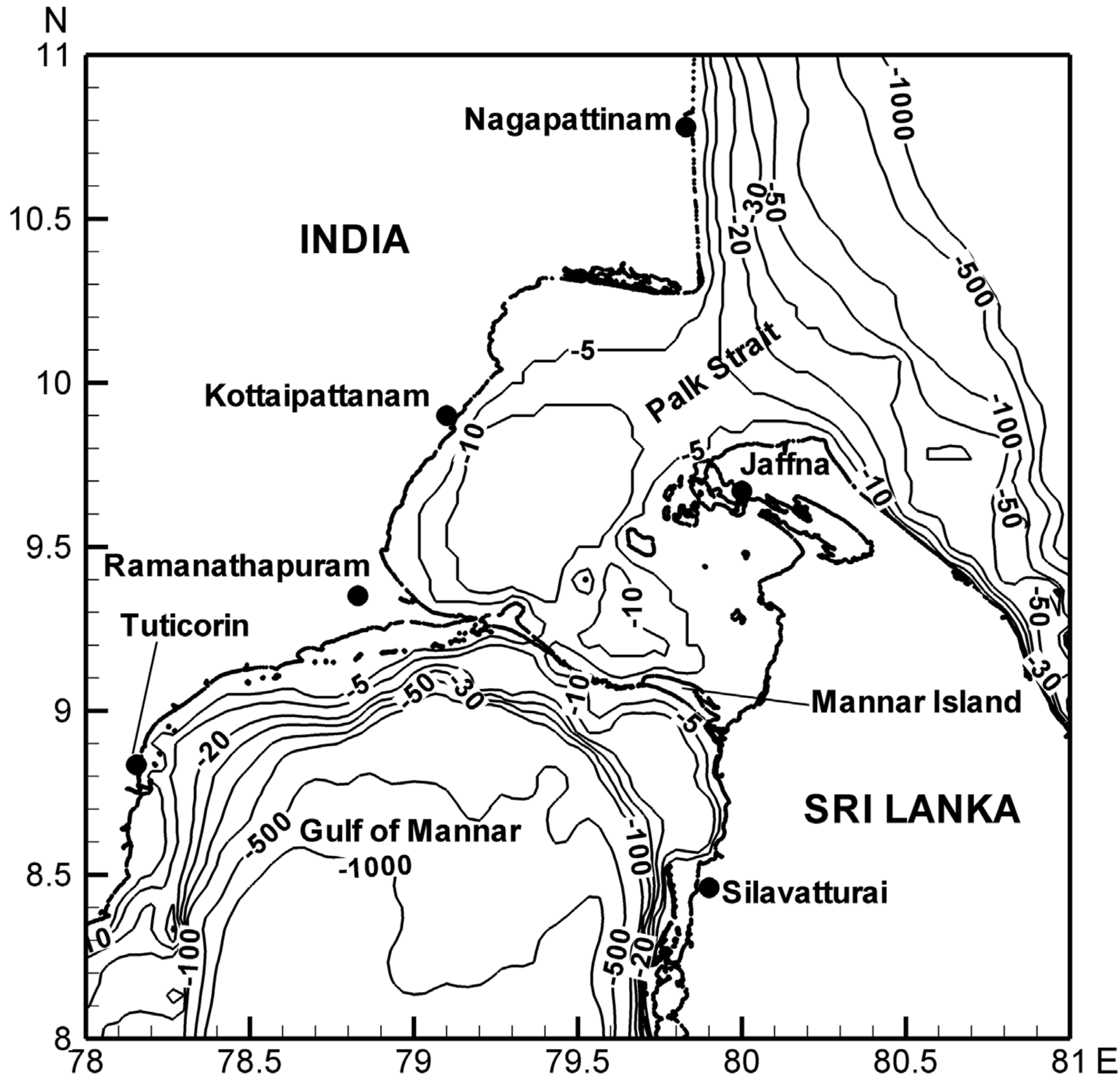

Fig. 3. Bathymetry of the SSCP area based on ETOPO version 2 data from NGDC.

Vaigai, Vaishali, and Variyar on the east coast of Tamil Nadu. (2) Littoral transport from the northern parts of Tamil Nadu. (3) Littoral transport from the Gulf of Mannar through Pamban Pass and Adam's Bridge. (4) Cyclones that occur, especially in the Nagapattinam – Poomphur region. (5) Rivers flowing into the Bay from Sri Lanka, and (6) Currents from the Bay of Bengal.

Palk Bay on the S.E. Coast of India is considered as one of the five major sinks for sediments along with Gulf of Mannar, Sandheads, Gulf of Khambhat, Gulf of Kutch (Chandramohan et al., 2001) The sediments discharged by the rivers and transported by the surf currents as littoral drift, settle in permanent, semi permanent and temporary sinks.

Low wave action and protection from southerly waves encourage deposition of transported material in the Bay. This is evident from the emergence of sand banks between Point Calimere and Point Pedro (in Sri Lanka) and accretion at Ammanipattinam, Mandapam and Ramesawaram (Natesan and Subramanian, 1993). The sediment suspension and movement in the Bay has been assessed from satellite data of the Tamil Nadu Coast (Chauhan et al., 1996; Natesan, 2004). Sediments move towards south during the N.E. Monsoon and north in the S.W. Monsoon .The annual long shore sediment transport along Nagapattinam Coast, during October to February (N.E. Monsoon) is around $0.273 \times 10^6\,m^3$ towards south and $0.175 \times 10^6\,m^3$ towards north during the rest of the year. The gross sediment transport is around $0.448 \times 10^6\,m^3$ in the Bay. The net long shore sediment transport is between $0.098 \times 10^6\,m^3$ towards south, in the Bay (Sanil Kumar et al., 2002).

Sediment exchange between Palk Bay and Gulf of Mannar

Rameswaram, the geological formation of coral atoll with huge sand cover between India and Sri Lanka plays a vital role on the processes of exchange of littoral drift between east and west coast of India. The wave sheltering effect due to Sri Lanka Island, the presence of numerous off shore islands in Gulf of Mannar, the growing sand spit along Dhanushkodi and the Adam's Bridge largely modify the sediment movement.

The Gulf of Mannar covers an area of $263.2\,km^2$ and receives sediments from the rivers Tambraparni, Vembar and Vaipar flowing from the east coast of Tamil Nadu. It also receives sediments brought from the western coast of India via Kanniyakumari and from the Palk Bay. Chandramohan et al. (2001) estimated nearly $200 \times 10^6\,m^3$ of deposition over a period of 75 years, 1906–1981 leading to a reduction in depth of 0.72 m. Thus, on the average annually $2.6 \times 10^6\,m^3$ sedimentation has occurred (Chandramohan et al., 2001).

Long shore sediment transportation

During South-west monsoon, the long shore sediment transport was considerable along the spit facing Gulf of Mannar and negligible in Palk Bay. The movement of the sediments was from Gulf of Mannar to Palk Bay through Adam's Bridge. During North-east monsoon, the long shore transport was relatively low along the spit facing Gulf of Mannar and negligible in Palk Bay. In fair weather period, the sediment transport was low along the spit and Palk Bay. Thus, during the months of March, June, July, August and September, $0.058 \times 10^6\,m^3$ sediment moves from Gulf of Mannar to Palk Bay. For the rest of the year, $0.034 \times 10^6\,m^3$ sediment is transported in the reverse direction. Thus, the net annual sediment of $0.024 \times 10^6\,m^3$ is transported from Gulf of Mannar into Palk Bay (NEERI, 2004).

Sediment transport by tidal currents

Due to tidal currents, during N.E. Monsoon, $0.015 \times 10^6\,m^3$ sediments move from Palk Bay to Gulf of Mannar through Pamban pass and $0.021 \times 10^6\,m^3$ through Adam's Bridge. During S.W. Monsoon, sediment transport is $0.006 \times 10^6\,m^3$ through Pamban Pass and $0.030 \times 10^6\,m^3$ through Adam's Bridge, moving from Gulf of Mannar to Palk Bay. In the fair weather period, $0.003 \times 10^6\,m^3$ sediments pass through Pamban Pass and $0.0165 \times 10^6\,m^3$ through Adam's Bridge, from Gulf of Mannar to Palk Bay. The net annual quantity of sediment transported from Gulf of Mannar into the Bay through Pamban Pass and Adam's Bridge by tidal waves is assessed at $0.0195 \times 10^6\,m^3$ (NEERI, 2004).

Break in the chain of littoral drift on the East Coast

During south west monsoon, a sizable portion of littoral drift from west coast to east coast is getting deposited before reaching Tuticorin. This deposited sediment is transported back during north east monsoon. Such deposition has led to the occurrence of large beach deposits along Tiruchendur – Manapad Region. Similarly, the southerly transport of sediments along the east coast during north-east monsoon gets deposited between Vedaranniam and Manmelkudi in Park Bay which is reversed during south west monsoon. Thus there is a break in the chain of littoral drift at Tuticorin, leading to limited exchange through Pamban Pass and Adam's Bridge. It signifies that Adam's Bridge is a major sink for the littoral drift.

Dredging

It is to be noted that the SSC dredging area coincides with zones of such high sedimentation rates. Data are not available on the quantity of sediments into the Palk Bay due to cyclonic storms, rivers from Sri Lanka and currents from Bay of Bengal. The SCL hydrographic study (2007) reports that the capital dredging needed to form the navigational channel and for its maintenance would be of the order of $90 \times 10^6\,m^3$ covering the regions of Adam's Bridge and Palk Strait. Based on UNIBEST – LT model the report has projected the quantum of maintenance dredging. It was theoretically calculated that $23.1 \times 10^3\,m^3\,y^{-1}$ sediment is brought into 4000 m long channel due to long shore transport. The sediment rate per metre is thus insignificant. For Adam's Bridge, on the northern side, the model gives sedimentation of $0.0315 \times 10^6\,m^3$ during the north-east monsoon and $1.375 \times 10^3\,m^3$ for the south west monsoon. On the southern side of Adam's Bridge, $3.5 \times 10^3\,m^3$ is deposited for the north east season and $0.165 \times 10^6\,m^3$ for the south west monsoon. This works out to a total quantity of $201.375 \times 10^3\,m^3$ per year. This volume of sediment gets deposited along the channel section which crosses the Adam's Bridge. These are not the main sources of sedimentation in the channel at Adam's Bridge. Computations yielded transportation of $2 \times 10^6\,m^3$ sediment parallel to the ship channel during the monsoon periods. (SCL Hydrographic Study Report, 2007).

The net annual quantity of sediment transported into the Bay by littoral currents from the Nagapattinam Coast is $0.098 \times 10^6\,m^3$. From the Gulf of Mannar, the net quantity of sediment brought into the Bay by littoral and tidal currents is of the order of 0.0435×10^6 m^3. The total quantity is thus of the order of 0.14×10^6 m^3 annually. On the other hand, Chandramohan et al. (2001) reported 3000×10^6 m^3 sediment deposition in the bay, over a period of 51 years, from 1931 to 1982, which has lead to a reduction in water depth of 0.32 m. Assuming a uniform rate of deposition, 58.8 million cubic meters of sediment get deposited in the Bay per year (Ramesh, 2004) This leaves a major gap in the quantity of deposition, which is to be accounted for. There is the possibility that the water depth reduction has been carried out only in a few places and an assumption has been made that it will hold for the entire area. There are other sedimentation transportation routes to be assessed as the contribution from cyclonic storms, the Bay of Bengal and from Sri Lankan rivers. There are other observations, which have indicated high sedimentation in the area. Thus, Agarwal (1998) noted a significant change in the bathymetry of Palk Bay. The 10 m contour line in 1920 chart has disappeared by 1986 (Agarwal, 1998). Due to certain geomorphological features, deposition of sediments is more in certain areas. Thus, in Vedaranniam, the sediment building activity is as high as 29 m y^{-1} (Ramasamy et al., 1998).

With the implementation of this project, the sedimentation in the channel (4000 m long) at Palk Strait would be 23,100 m^3 per annum (SCL Hydrographic Report, 2007). This is not significant compared to the nearly 2×10^6 m^3 sediment deposited in the channel at Adam's Bridge (SCL Hydrographic Report, 2007).

With the implementation of the SSC, the UNIBEST-LT model also predicted 2-fold increase in current velocities along the dredged channel from 0.8 m s^{-1} to 1.2 m s^{-1} under moderate winds, and to 1.8–2.2 m s^{-1} under strong winds (SCL Hydrographic Study Report, 2007). Also the model predicted a reversal in the direction of flow for every tidal cycle; during the NE monsoon it will be consistently unidirectional from Palk Bay to Gulf of Mannar while during SW monsoon period, the flow will be from Gulf of Mannar to Palk Bay (SCL Hydrographic Study Report, 2007). Due to ongoing human land building activity in this region, the coastline is being pushed seaward by as much as 29 m y^{-1} (Kumaraguru, 1991). Additionally, offshore growth of bars through natural causes is occurring at the rate of 10 m y^{-1} (Kumaraguru, 1991). The most serious physical consequence of the SSP could be complete changes in sedimentation patterns, erosion of nearby coastlines, changes in accretion patterns on the local scale close to the channel. This could have severe ecological consequences as discussed in later sections.

Shipping traffic

Since 1960 there has been a steady increase in maritime traffic in the Indian Seas. It is important to consider that annually in India's Exclusive Economic Zone (EEZ) about 3500 tankers including very large crude carriers carry about 500×10^6 tons. In this EEZ, there were six oil spills and the largest 18,500 tons was in Kutch area (Table 3). There were also 65 minor and major oil spills in Indian coastal waters including 692 tons from "MV Jayabola" on 7 September 1991 in the Gulf of Mannar (Directorate of Fisheries and Environment 2007). Besides 58.44 tons diesel, off Haldia Port, Sagar Island, "MV Lucnam" sank and released 11,000 tons ammonium phosphate and 2200 tons di-ammonium phosphate. It is estimated that every day about 30 ships sail between Tuticorin, Colombo and Singapore and if these used the SSC it would cause an increase in maritime traffic. Associated with this traffic the estimated spilled fuel oil at the SSC would be ~230 tons y^{-1} (Coastal Action Network Report, 2004).

Discussion

To assess the ecological consequences of the SSCP, we have assumed that all physical processes are in a state of equilibrium and may be disturbed as a result of the construction of SSC. Deepening the channel and its orientation significantly effect the currents, tidal regime, waves, sediment transport, storm surge and tsunami. Thus the belief behind a critical examination of the physical processes is that any possible increase in water level due to any physical parameter could pose a threat to navigation and also cause coastal erosion and undermine the stability of the banks of the ship canal. The man-made waterways such as the Suez, Panama and Kiel Canals are dug by cutting an isthmus and not a strait. Only long-term studies as in the Baltic would demonstrate the impact of SSCP on the ecology of this region. In the Baltic, anthropogenic loading has caused changes in the dissolved inorganic nitrogen: dissolved inorganic phosphorus and silicate dynamics which in the long term (1979–2003) have resulted in a shift in

Table 3
Oil spills in India's exclusive economic zone

Date	Name of the vessel	Region	Tons spilled
December 6, 2006	Ocean Soraya	Karwar	12
August 19th, 2006	Japanese tanker a small Indian vessel	Nicobar and Andaman Archipelago	4500
July 1982	Sagar Vikas fire	Bombay	Considerable
September 26 1974	Transhuron	Lakshadweep	3325
June 18, 1973	Cosmos Pioneer	Kutch Area	18,500
August 4, 1970	Ampunia	Kutch	3500

the phytoplankton community structure leading to dominance of cyanobacteria and dinophytes (Wasmund and Uhlig, 2003; Yurkovskis, 2004; Suikkanen et al., 2007). Based on 150 years historical ecology of Elkhorn Slough watershed in central California estuary, Van Dyke and Wasson (2005) concluded that dramatic shifts resulted from anthropogenic modifications and recolonization of former wet lands and mud flats may not reach an equilibrium for many decades. In this region accompanying changes in salinity and mixing patterns contributed to even higher stress factor for sessile organisms (Schumann et al., 2006).

Turbidity: biota

Activities such as canal widening and deepening for maintenance could affect the soil sedimentation, and may cause or accelerate erosion. Disposal of dredged spoil will have serious impacts on the fauna and flora and these need be assessed first. Additionally, changes in sea bed and long-term dispersal patterns of sediment are possible as in the Suez Canal (Stanley et al., 1982; Frihy and Dewidar, 2003) and in the Panama Canal (Sivakumaran et al., 1996). If the canal is dredged, the huge quantities of excavated sand will muddy the waters and block sunlight from reaching the sea bottom, killing coral reefs, pearl banks, sea grass, sea weeds, bottle-nosed dolphins, prawns, lobsters, dugongs and a variety of edible fish of the Gulf of Mannar region. This may lead to unpredictable changes in the biota particularly the coral reef community sensitive to turbidity and siltation as in Panama (Guzman and Holst, 1994). Alterations to coastal morphology and removal of bottom materials will cause loss of habitat which in turn results in the loss of benthic algae essential for the dugong populations that are unique to this region. Intertidal invertebrates contribute nitrogen and phosphorus that fuel prime primary production (Pfiester, 2007), their loss resulting from dredging operations could have a negative effect on primary production in the SSCP region.

Dredging and maintenance of the channel may reduce the photosynthetically active radiation to 90% (Fig. 2). Release of nutrients from the sediments will cause shifts in phytoplankton species composition and only those 'shade populations' adapted to reduced submarine light would grow. If seed populations are present red-tide algae may bloom in this region. This high turbidity may promote nanoplankton growth which may become photoadapted to 'intermittent sun' conditions as has occurred in the Gulf of St. Lawrence (Vincent et al., 1994). In a tropical estuary on the north-eastern coast of Singapore, a shift in the size of dominant phytoplankton cells was associated with reduction in photosynthetically available radiation (PAR) resulting from dredging operations (Nayar et al., 2005). Surface waters under the influence of dredging had smaller size phytoplankton (2–20 μm) with high biomass and production rates while in the subsurface waters larger cells of 20–200 μm size class dominated. Cells of the diatom *Skeletonema costatum* were larger in the dredged subsurface waters than in the surface layers (Nayar et al., 2005). Turbidity may also affect the benthic macro algae.

The Palk Bay–Gulf of Mannar region is highly stressed. In the Tuticorin region sewage alone contributes to a BOD load of 57×10^3 kg d^{-1}, eight times more than cleaner areas in the vicinity (Ramachandran et al., 1989). Rapid industrialization in the Tuticorin region is already affecting the fauna and flora. For example annually 10,000 tons of coral lime is produced by burning *Acropora* corals and this species is being overexploited (Venkataramanujam et al., 1981). This area receives ash and effluents from thermal power plants, chemical effluents from chemical and mining industries operated by multinational corporations. As a consequence, these wastes contribute to high levels (>100 ppb) of zinc, iron, copper and lead in some of the edible gastropods (Patterson et al., 1997). Besides pollution, building activity with an average 29 m y^{-1} land and an offshore growth of bars at the rate of 10 m y^{-1} will further impact the environment (Kumaraguru, 1991). For industrial purposes coral reefs are quarried at an estimate of 80,000 tons y^{-1} (Gopinath Pillai, 1986), and quarrying resulted in a submergence of the islands Vilanguchalli and Poovarasanpatti. Coral mortality in the Indian Ocean is of concern (Sheppard, 2003) and Pet-Soede et al. (2001). In the Indian Ocean region Andaman and Nicobar Islands suffered up to 80% mortality of coral, the reefs of the Gulf of Mannar on the average 60%, followed by the Lakshadweep (43–87%); anthropogenic stressors contributing to this mortality include high sedimentation, high levels of pollution and high fishing pressure (Pet-Soede et al., 2001). Also fishing for crabs, deployment of fish traps, weighing the anchors, siltation, agricultural run off, and sewage discharges compound the stress.

Shipping traffic: exotic biota

Increase in traffic resulting from the SSCP may amount to waiting for biological invasions. Besides the increase in oil spills and bilge water, the ecological damage associated with discharge of ballast water could be considerable and include introduction of exotic species, bioaccumulation of contaminants, biotic impoverishment, altered biotic composition and impaired production. The oil spills in turn would damage corals, mangroves, fish spawning grounds, and nursery areas. The SSC a man-made link may facilitate greater exchange of water masses between the dilute Bay of Bengal waters with the more saline Arabian Sea. This would be expected to facilitate migration of microscopic plankton and larger forms of life like fish as occurred in the Suez Canal. From a review of 100 years of Lessepsian (Canal) migrations associated with the Suez Canal (Por, 1971; Aron and Smith, 1971; Ben-Tuvia, 1978, 1985) the migration of a variety of planktonic groups is well documented. The Gulf of Mannar (Arabian Sea) with its high temperature and salinity may be more conducive to receive more immigrants, similar to the Levant Basin of the

Mediterranean (Por, 1971), than the dilute and less warm Bay of Bengal waters. Studies should be carried out to determine the likely changes in the benthic environment, nature of its substrate, its availability for the growth and colonization of the newly introduced species, and their tolerance capacity to changes in salinity and temperature. It is possible such migrations may not be as pronounced initially, but ultimately may lead to great changes. Successful colonization of the newly introduced species depends on their growth rate, and the carrying capacity (Safriel and Ritte, 1977).

Ships' ballast water could act as a vector in the introduction of pathogens, harmful algae, and several non-indigenous species of fouling and wood destroying organisms. That the Indian coastal waters have already received 205 non-indigenous species including a number of pests, a few harmful toxigenic algae, as well as foulers and wood borers have been discussed (Subba Rao, 2005). In the long run changes in the biodiversity of the biota may take place and this needs be investigated.

Oil pollution

Problems associated with ship's activities, particularly deballasting could be a source of increase in tar balls and oil pollution as on the Oman coast (Burns et al., 1982), the Algerian and Moroccon Coasts (Morris et al. (1975) and along the Cape Agulhas, particularly between Arniston and Mossel Bay (Shannon and Chapman, 1983). It should be noted that compared with the Arabian Sea with 0–6.0 mg m^2, the Bay of Bengal tanker route is already more polluted having floating petroleum residues that varied 0–69.75 mg m^2 (Gupta and Kureishy, 1981). An accumulation of petroleum hydrocarbons among the benthic fauna is a possibility as observed in the rock oysters *Crassostrea margaritacea* on the Oman coast (Burns et al., 1982) Turtles are especially sensitive to oil pollution; NEERI in its Environmental Impact Study acknowledged that dredging and the blasting associated with it would have adverse impact on the sea bottom fauna.

Natural hazards

The SSC is located in an area vulnerable to natural hazards such as cyclones (Kathal, 2005) and tsunamis (Fig. 4). Cyclones and severe storms hit this area annually and major events are the 1964 Rameswaram Cyclone, the 1978 Batticoloa Cyclone, the 1992 Tuticorin Cyclone, the 1993 Karaikal Cyclone and the 1994 Madras (Chittibabu et al., 2002). For example, the cyclone 01-B (17 October 2000) was the worst disaster in 50 years and caused extensive damage to South-Western Sri Lanka (IRI, 2003). A tropical storm (11th to the 19th of May 2003) in the Bay of Bengal caused 300 deaths, displaced 200,000 persons, and damaged heavily the infrastructure, economy and livelihoods of southwestern Sri Lanka (Fig. 4). The hurricanes and storms damage coral reefs of Florida Keys is documented well (Gleason et al., 2007); for example the recent tsunami (December, 2004) caused enormous damage to this area. Although tsunamis are short lived the damage caused by their impact is long-lasting and vast (Subba Rao et al., 2007). Compared to the Hiroshima–Nagasaki atomic blast of August 6, 1945 with an energy equivalent of 32,500 tons TNT, or the Orissa Super Cyclone of 29–30 October 1999 with 32–40 tons explosion of TNT, the Indian Ocean Tsunami of 26 December 2004 is equivalent to 190 million tons explosion of TNT. One specific concern we have with SSC is it provides another deeper ocean route for tsunami to travel and this could have serious implications for the southern Kerala coast. Murty and Rafiq (1991) have provided a tentative list of tsunamis in the marginal seas of the North Indian Ocean, and Murty and Bapat (1999) have provided a shorter list of tsunamis on the coastlines of India. Though tsunamis are not frequent in the Bay of Bengal and Arabian Sea, there is always a potential for a major tsunami with far reaching, devastating effects along peninsular India. For any tsunami generated in the Indian Ocean its travel time for a location off the coast of Sri Lanka, Bay of Bengal, Andaman Sea is <3 h (Bhaskaran et al., 2007). Impacts of a tsunami on marine life are devastating (Subba Rao et al., 2007). When the SSCP is executed and in the event of tsunamis in future, waves would approach the south Kerala coast from two different directions, one from south of Sri Lanka and the other SSC from the Bay of Bengal. There is a strong probability that these two sets of waves could be subjected to constructive interference and grow to very large amplitudes. This is precisely what had happened to Sri Lanka during the 26th December 2004 Tsunami when the waves approached from the eastern and western sides of the island; the resultant convergence created very large amplitudes. In a way this is comparable to the quarter-wave resonance amplification caused during the 1964 Alaska earthquake during which tsunami energy was funneled into the Alberni Inlet, Vancouver Island. Tsunami inundation took place in the canals along the Pacific coast of British Columbia, Oregon, and Puget Sound area of Washington (Hemphill-Haley, 1996). During the 2004 Indian Ocean Tsunami the Adam's Bridge acted as a natural breakwater and considerably diminished the impact while Nagapattinam and Kanniakumari were severely damaged. Removal of this natural breakwater by execution of the SSC would cause a tunneling effect and provide an easy passage leading to a greater devastation in the event of a natural disaster such as a tsunami.

A word of caution

Besides the SSCP, mention should be made of two more anthropogenic projects that would cause dramatic shifts in the distribution of the habitat types. We assume these projects are frivolous futuristic speculations. The first is the establishment of a land connection between Danushkodi (India) and Thaliamannar (Sri Lanka) by uplift of Adam's

Fig. 4. Tsunami genesis areas in the Bay of Bengal, the Arabian Sea and in the northern part of the Indian Ocean (modified from Murty and Bapat, 1999), with a storm track for 11–19 May 2003.

Bridge- a submerged atoll barrier (Schuiling, 2004) which is similar to the ocean sequestration of CO_2 experiment (Johnston et al., 1999). It is a macroscale biogeochemical experiment and involves injection of 1 million m^3 of sulfuric acid at a depth of 100 m in the limestone bedrock to "burp" CO_2 that would in turn uplift the Adam's Bridge.

One should be extremely concerned about its potential effects on this unique marine ecosystem as this could further endanger endangered species. Probably such technology may be successful under controlled laboratory conditions and in an abandoned limestone quarry elsewhere, but must not be attempted in the Palk Bay – a natural paradise. Equally disturbing is another project to convert Palk Bay into a future industrial complex site with a "base seaport servicing a funicular space elevator anchored to a floating passenger and freight station" or a "Palk Strait Power Station" (Cathcart, 2004). That corals in this region are sensitive to sea surface temperature rise has been documented (Kumaraguru et al., 2003). It would be absolutely necessary to characterize the functioning of the ecosystem first and then address how the impending perturbations could cause short-term and long-term effects on the health and functioning of this fragile already stressed ecosystem. This being a tropical coralline ecosystem where the wheels turn faster than elsewhere, the implementation of SSCP may cause several irreversible environmental changes.

Societal impacts

Although the SSCP acts as a catalyst and promises a sub-regional economic integration that could change the economic map of Tuticorin area, we must pay attention to its several societal impacts. There are 140 coastal villages in Ramanathapuram and Tuticorin districts and the Gulf of Mannar has 12 fishing villages with 40 fish landing stations providing livelihood for several thousands of fishermen. Nearly, 20 million people live along the coast of Gulf of Mannar and in Palk Strait whose lives depend on the sea. Recent surveys by the Central Marine Fisheries Research Institute and Central Salt and Marine Chemical Research Institute, Mandapam show a potential harvest of 75,300 tons of sea weed from the Gulf of Mannar which could create employment to several hundreds.

The Port of Tuticorin and 13 associated minor ports will be the greatest beneficiary and transformed into a transshipment hub. Once viewed by the fishermen as "a dream project", they now fear the SSCP will rob them of their traditional livelihood while environmentalists say the project could turn the Gulf of Mannar, a biologist's paradise, into an environmental catastrophe. The associated socio-economic changes such as the dislocation and relocation of the 50,000 fisher folk who live in the 47 villages live along this 180 km coastline need to be addressed. In this Marine Biosphere Reserve (MBR) before a mega project such as SSCP is implemented urgent research is required to evaluate its benefits, risks and uncertainties.

Based on lessons learned from studies elsewhere, we provide here our perception of several potential environmental impacts that could result from SSCP – a major human alteration; any assurances to the public should be based on appropriate sound scientific basis. In this context, it would be particularly useful to utilize a BACI model (Before/After and Control/Impact) to investigate the impacts of anthropogenic perturbations on ecosystems (Underwood, 1992). Further improvements of the BACI model by Hewitt et al. (2001) utilize simulated impacts of different sizes and types and therefore may find application in the SSCP to infer changes over different temporal and spatial scales and to establish what changes can be expected that would be over and above those attributable to natural variability. We recommend an institutionalized long-term environmental monitoring program aimed at effective prognostication based on a thorough evaluation of the impending environmental impacts and the institution of a multi-hazard tsunami warning system.

Acknowledgements

We are grateful to Dr. James E. Stewart, Bedford Institute of Oceanography for constructive comments on the manuscript and for advice and help at various stages of this work. We thank Dr. G. Luther (former Principal Scientist, Central Marine Research Institute, CMFRI, Mandapam, India) for information on the fisheries. Our thanks are due to Mr. Art Cosgrove, Technographics, Bedford Inst. Oceanography for the illustrations and to Bala T. Durvasula for formatting the text. The views expressed here are those of the contributors and do not reflect those of their employers or institutions.

References

Agarwal, J.M., 1998. Manamelkudi sand split and thrust to Palk Bay. Proc. First Indian Geomorphic Conference, Waltair, 1998.

Aron, W.I., Smith, S.H., 1971. Ship canals and aquatic ecosystems. Science 174, 13–20.

Ben-Tuvia, A., 1978. Immigration of fishes through the Suez Canal. Fisheries Bulletin 76, 249–255.

Ben-Tuvia, A., 1985. The impact of the Lessepsian (Suez Canal) fish migration on the Eastern Mediterranean ecosystem. Mediterranean marine ecosystems. 1985, NATO Conference Series. 1. Ecology 8, 367-376.

Bhaskaran, P.K., Dube, S.K., Murty, T.S.,Gangopadhyay, A., Chaudhuri, A., Rao, A.D., 2007. Tsunami travel time Atlas for the Indian Ocean. pp 273-291, Ch 31 'The Indian Ocean Tsunami', edited by Tad S Murty, U. Aswathanarayana, Niru Nirupama , 528pages, Taylor & Francis The Netherlands (incorporating A.A. Balkema Publishers) Leiden, The Netherlands.

Bhimachar, B.S., Bhimachar, B.S., George, PC., 1950. Abrupt set-back on the fisheries of the Malabar and Kanara coasts and 'red water' phenomena and probable cause. Proceedings of the Indian Academy of Sciences 31, 339–350.

Burns, K.A., Villeneuve, J.P., Anderlin, V.C., Flowler, S.W., 1982. Survey of tar, hydrocarbon and metal pollution in the coastal waters of Oman. Marine Pollution Bulletin 13, 240–247.

Cathcart, R.B., 2004. Palk Bay: A future industrial complex site? Current Science 87, 849–850.

Chandramohan, P., Jena, B, K., Sanil Kumar, V., 2001. Littoral drift and sinks along the Indian Coast. Curr. Sci. 81, 292–297.

Chauhan, P., Nagur, C.R.C., Mohan, M., Nayak, S.R., Navalgund, R.R., 2001. Surface chlorophyll-a distribution in Arabian Sea and Bay of Bengal using IRS-P4 Ocean Colour Monitor satellite data. Current Science 80, 127–129.

Chauhan, P., Nayak, S., Ramesh, R., Krishnamoorthy, R., Ramachandran, S., 1996. Remote sensing of suspended sediments along the Tamil Nadu coastal waters. Photonirvachak 24, 105–114.

Chidambaram, K., 1990. Biofouling and corrosion in the coastal waters of Mandapam and Tuticorin. Marine biofouling and power plants. Proceedings of the specialists' meeting on marine biodeterioration with reference to power plant cooling systems held at IGCAR, Kalpakkam on 26-28 April, 1989.90-91.

Chittibabu, P., Dube, S.K., Sinha, P.C., Rao, A.D., Murty, T.S., 2002. Numerical Simulation of Extreme Sea Levels for the Tamila Nadu (India) and Sri Lankan Coasts. Marine Geodesy, 25, 235-244.

Coastal Action Network Report, 2004. Impacts of the proposed Sethusamudram Ship Canal Project (An alternative Report) . Contact Jesu Rethinam, Nagapattinam-611001, 43pp. e mail: coastalactionnetwork @rediffmail.com.

Collette, B.B., Russo, J.L., 1984. Morphology, Systematics, and Biology of the Spanish mackerels (*Scomberomorus*, Scombridae). Fishery Bulletin 82, 545–692.

CPCB, 2005. Assessment and development study of river basin, Central Pollution Control Board, India.

Dalal, S.G., Parulekar, A.H., 1992. Oceanography of the Indian Ocean. In: Desai, B.N. (Ed.), Trophic dynamics and fishery potentials of the Indian Ocean- critical assessment. Oxford and IBH, New Delhi.

Devaraj, M., 1977. Osteology and relationships of the Spanish mackerels and seerfishes of the tribe Scomberomornii. Indian Journal of Fisheries 22, 1–67.

Devaraj, M., 1986. Maturity, spawning and fecunbdity of the streaked seer, *Scomberomorus lineolatus* (Cuvier & Valenciennes) in the Gulf of Mannar and Palk Bay. Indian Journal of Fisheries 33, 293–319.

Dutt, S., Raju, K.V., 1983. A new record of *Sardinella aurita* Valenciennes, 1847 (Teleostei: Clupeidae) from the eastern part of the Arabian Sea: A possible migrant through the Red Sea? Bulletin of the Institute of Oceanography and Fisheries Cairo 9, 264–270.

Edward, J.K.P., Patterson, J., Venkatesh, M., Mathews, G., Chellaram, C., Wilhelmsson, D., 2004. A field guide to stony corals (Scleractinia) of Tuticorin in Gulf of Mannar, southeast coast of India SDMRI Research Publication 4, 89 pp. ETOPOV2 http://www.ngdc.noaa.gov/mgg/fliers/06mgg01.html.

Emmerson, M., Bezemer, M., Hunter, M.D., Joness, T.H., 2005. Global change alters the stability of food webs. Global Change Biology 11, 490–501.

Frihy, O.E., Dewidar, K.M., 2003. Patterns of erosion/sedimentation, heavy mineral concentration and grain size to interpret boundaries of littoral sub-cells of the Nile Delta, Egypt. Marine Geology 199, 27–43.

Gleason, ACR., Lirman, D., Williams, D., Gracias, N.R., Gintert, B.E., Madjidi, H., Reid, R.P., Boynton, G.C., Naghadaripour, S., Miller, M., Kramer, P., 2007. Documenting hurricane impacts on coral reefs using two-dimnsional video-mosaic technology. Marine Ecology 28, 254–258.

Gopinadha Pillai, C.S., 1971. Composition of the coral fauna of the southeastern coast of India and the Laccadives. Symposium of the Zoological Society of London 28, 301–327.

Gopinath Pillai, C.S., 1986. Recent corals from the southeast coast of India. In: James, P.S.B.R. (Ed.), Recent Advances in Marine Biology. Today and Tomorrow's Printers and Publishers, New Delhi, pp. 107–121.

Gopinathan, C.P., Rodrigo, J.X., 1991. Investigations on primary production and related parameters in the inshore waters of Tuticorin. Journal of the Marine Biological Association of India 33, 33–39.

Goswami, S.C., Sarupria, J.S., Bhargava, R.M.S., 1992. Zooplankton standing stock assessment and fishery resources in the Indian Seas. In: Desai, B.N. (Ed.), Oceanography of the Indian Ocean. Oxford and IBH, New Delhi, pp. 217–225.

Gupta, R.S., Kureishy, Y.W., 1981. Present state of oil pollution in the northern Indian Ocean. Marine Pollution Bulletin 12, 295–301.

Guzman, H., Holst, I., 1994. Biological inventory and current state of the coral reefs on both sides of the Panama Canal. Revista de Biologia Tropical 42, 493–514.

Hewitt, J.E., Thrush, S.E., Cummings, V.J., 2001. Assessing environmental impacts: Effects of spatial and temporal variability at likely impact scales. Ecological Applications 11, 1502–1516.

Hemphill-Haley, E., 1996. Diatoms as an aid in identifying late-holocene tsunami deposits. Holocene 6, 439–448.

Hornell, J., 1906. Report on the operations on the pearl banks during the fishery of 1905. Reports from the Ceylon Marine Biological Laboratory 1, 55–80.

Hornell, J., 1914. The sacred chank of India: A monograph of the Indian conch (*Turbinella pyrum*). Madras Fisheries Bulletin 7, 181.

Hussain, S.M., Ragothaman, V., Manivannan, V., 1996. Distribution and species diversity of recent benthic ostracoda from the Gulf of Mannar, off Tuticorin, Tamil Nadu. Journal of Paleontological Society of India 41, 17–20.

IRI, 2003. Climatic impacts May. IRI Climate Digest June 2003. The international Research institute for Climate and Society.

Jayaraju, N., Reddi, K.R., 1999. Benthic foraminifera – Substrate relationship at the southernmost coast of India. Indian Journal of Earth Sciences 26, 25–36.

Jayaseeli, A.A., Murugan, A., 2003. Diversity of bivalve in Tuticorin coast of Gulf of Mannar: Resources status and exploitation. Proceedings of the National Seminar on Marine Biodiversity as a Source of Food and Medicine. SDMRI Research Publication 3, 137–141.

Johnston, P., Santillo, D., Stringer, R., Parmentier, R., Hare, B., Krueger, M., 1999. Sequestration of carbon dioxide from fossil fuel production and use: an overview of rationale, techniques and implications. Environmental Science and Pollution Research 6, 245–246.

Jones, S., 1968. The scombroid fishery of India- present and future. Proceedings of the Symposium on Scombroid fishes. Marine Biological Association of India Symposium Series 1, 1–105.

Kallaperumal, N., Chennubhotla, V.S.K., Kalimuthu, S., Ramalingam, J.R., Pillai, S.K., Muniyandi, K., Rao, K.R., Rao, P.V.S., Thomas, P.C., Zaidi, S.H., Subbaramaiah, K., 1998. Seaweed resources and distribution in deep waters from Dhanushkodi to Kanniakumari, Tamilnadu. Seaweed Research Utility. 20, 141–151.

Kannan, R., Kumaraguru, A.K., Sundaramahalingam, A., Ramakrishnan, M., Rajee, M., 2001. Socioeconomic status of coral reefs resource users of Pamban Region, Gulf of Mannar, South India. Man in Sea 81, 103–121.

Karunasagar, I., Karunasagar, I., 1992. *Gymnodinium nagasakiense* red tide off Someshwar, west coast of India and mussel toxicity. Journal of Shellfish Research 11, 477–478.

Karunasagar, I., Karunasagar, I., Oshima, Y., Yasumoto, T., 1990. A toxin profile for shellfish involved in an outbreak of paralytic shellfish poisoning in India. Toxicon 28, 868–870.

Karunasagar, I., Segar, K., Karunasagar, I., Anderson, D.M., 1989. Potentially toxic dinoflagellates in shellfish harvesting areas along the coast of Karnataka State (India). Red tides: biology, environmental science, and toxicology. Proceedings of the First International Symposium on red tides held November 10–14, 1987, in Takamatsu, Kagawa Prefecture, Japan, 65–68.

Kathal, P.K., 2005. Sethusamudram Ship Canal Project: oceanographic/geological and ecological impact on marine life in the Gulf of Mannar and Palk Bay, southeastern coast of India. Current Science 89, 1082–1083.

Krishnamoorthy, P., Subramaniam, P., 1999. Organization of commercially supporting meroplankton in Palk Bay and Gulf of Mannar biosphere reserve areas, southeast coast of India. Indian Journal of Marine Sciences 28, 211–215.

Kumaraguru, A.K, Kannan, R, Sundaramahalingam, A. 2000. Studies on socioeconomics of coral reef resource users in the Gulf of Mannar Coast, South India. Final Report Ref. No. 015012/29/98 SER Dt.7/30 2000, 163 pp. Centre for Marine Coastal Studies, Madhurai Kamaraj University, Madhurai, India.

Kumaraguru, A.K. 1991. Indian coral reefs and the need for their conservation. Proceedings of the Annual Academy of Environmental Biology, Dec. 21–23, 1990. Marathwada University, Aurangabad, India. Environmental Pollution & Resources of Land & Water, 73–81.

Kumaraguru, A.K., Jayakumar, K., Ramakrishnan, C.M., 2003. Coral bleaching 2002 in the Palk Bay, southeast coast of India. Current Science 85, 1787–1793.

Kunz, G.F., Davidson, C.H., 1993. The book of the pearl: the history, art, science and industry of the queen of gems. Dover Publication, New York, 548 pp.

Lakshmi, K., Srinivasa Rao, K., 1992. Taxonomical and geographical implications in the frequent appearance of swarms of the nominal *Arius dussumeri*, a natural marine catfish hybrid (*A. tennispinus* x *A. bileneatus*) and the possible catfish hybrids in the context of increasing pollution in the seas around India. In: Agarwal, V.P., Rana, S.V.S. (Eds.), Environment and biodegradation. Society of Biosciences, Muzaffarnagar, pp. 293–334.

Luther, G., 1986. Studies on the biology of the fishes of the genus *Chirocentrus* (Cuvier). Part IV. Reproduction. In: James, P.S.B.R. (Ed.), Recent advances in marine biology. Today and Tomorrow Printers and Publishers, Berlin, pp. 439–514.

Mani, J.S., 1997. Report: Coastal zone management plans and policies in India. Coastal Management 25, 93–108.

Mohan, M., Ali, M.M., 1995. Estimation of wind induced offshore upwelling. Continental Shelf Research 15, 757–762.

Morris, B.F., Butle, r J.N., Zsolnay, A., 1975. Pelagic tar in the Mediterranean Sea, 1974-75. Environmental Conservation 2, 275–281.

Murty, A.V.S., Varma, P.U., 1964. The hydrographical features of Palk Bay during March 1963. Journal of the Marine Biological Association of India 6, 207–216.

Murty, T.S., Rafiq, M., 1991. A Tentative list of Tsunamis in the Marginal Seas of the North Indian Ocean. Natural Hazards 4, 81–83.

Murty, T.S., Bapat, A., 1999. Tsunamis on the Coastlines of India. Science of Tsunami Hazards 17, 167–171.

Naidu, V.S., Lakshmana Rao, V.R., 1990. Ekman pumping velocity and depth of surface mixed layer of the north Indian Ocean during southwest monsoon. Indian Journal of Marine Sciences 19, 257–260.

Naidu, P.D., Ramesh Kumar, M.R., Ramesh Babu, V., 1999. Time and space variations of monsoonal upwelling along the west and east coasts of India. Continental Shelf Research 19, 59–572.

Nair, P.V.R., 1970. Primary productivity in the Indian Seas. Bulletin of the Central Marine Fisheries Research Institute 22, 56.

Natesan, U., 2004. Role of satellites in monitoring sediment dynamics. Curr. Sci. 86, 1068–1069.

Natesan, U., Subramanian, S.P., 1993. Seasonal shoreline oscillation of Tamil Nadu coast. Curr. Sci. 65, 667–668.

Nayar, S., Goh, B.P.L., Chou, L.M., 2005. Dynamics in the size structure of *Skeletonema costatum* (Greville) Cleve under conditions of reduced photosynthetically available radiation in a dredged tropical estuary. Journal of Experimental Marine Biology and Ecology 118, 163–182.

NEERI, 2004. Environmental Impact Assessment for proposed Sethusamudram Ship Canal Project. National Environmental Engineering Institute, Nehru Marg, Nagpur, 440 020, May 2004, Sponsored by Tuticorin Port Trust, Tuticorin, 144 pages.

Panickkar, N.K., Jayaraman, R., 1966. Biological and oceanographic differences between the Arabian Sea and the Bay of Bengal as observed from the Indian region. Proceedings of the Indian Academy of Sciences 64B, 31–240.

Pant, A., 1992. Primary productivity in coastal and offshore waters of India during two southwest monsoons, 1987 and 1989. In: Desai, B.N. (Ed.), Oceanography of the Indian Ocean. Oxford and IBH, New Delhi, pp. 81–90.

Patterson, J., Benny, A., Ayyakannu, K., 1997. Distribution of zinc, manganese, iron and copper in edible marine gastropods along the southeast coast of India. Special publication. Phuket Marine Biological Center 17, 127–134.

Pet-Soede, L., Wafar, M., Venkataraman, K., Rajan, P.T., Wilhelmsson, D., 2001. The status of the coral reefs of India following the bleaching event of 1998. Coral reef degradation in the Indian Ocean: Status reports and project presentations 2000. pp. 69–74. 2001.

Pfiester, C.A., 2007. Intertidal invertebrates locally enhance primary production. Ecology 88, 1647–1653.

Por, F.D., 1971. One hundred years of Suez Canal – a century of Lessepsian migration: retrospect and viewpoint. Systematic Zoology 20, 138–159.

Prasanna Kumar, S., Madhupratap, M., Dileep Kumar, M., Muraleedharan, P.M., de Souza, S.N., Gauns, M., Sarma, V.V.S.S., 2001. High biological productivity in the central Arabian Sea during the summer monsoon driven by Ekman pumping and lateral advection. Current Science 81, 1633–1638.

Qasim, S.Z., 1977. Biological productivity of the Indian Ocean. Indian Journal of Marine Sciences 6, 122–137.

Raghu Prasad, R., 1956. Further studies on the plankton of the inshore waters off Mandapam. Indian Journal of Fisheries 3, 1–42.

Raghu Prasad, R., Nair, P.V.R., 1963. Studies on organic production –I. Gulf of Mannar. Journal of the Marine Biological Association of India 5, 1–26.

Ramachandran , S., Sundaramoorthy, S., Natarajan, R., 1989. Status of coastal marine pollution in Tamil Nadu. In: Coastal zone of Tamil Nadu Status reports vol III. Ed. R. Natarajan. Institute of Ocean Management – Center for water resources, Anna University, Madras-25.

Ramesh, R., 2005. Sethusamudram Shipping Canal Project. Curr. Sci. 88, 536–537.

Ramesh, R., 2004. Sethusamudram Shipping Canal Project and the unconditional risk factors: can it withstand them? Published by Doctors for safer environment, Coimbatore, India, 1–71.

Ramasamy, S.M., Ramesh, D., Paul, M.A., Sheela Kusumgar, S., Yadava, M.G., Nair, A.R., Sinha, U.K., Joseph, T.B., 1998. Rapid land building activity along Vedaranniyam coast and its possible implications. Curr.Sci 75, 884–886.

Rao, T.S.S., Griffitths, R., 1998. Understanding the Indian Ocean – Perspectives on Oceanography. UNESCO, Paris.

Safriel, U.N., Ritte, U., 1977. Indices for identifying potential colonizers and their relevance to the colonization of Red Sea organisms in the Mediterranean through the Suez Canal. Israel Journal of Zoology 26, 257.

Samuel, V.D., Patterson, J., 2000. Gastropods and bivalves exploited at Koswari Island, Gulf of Mannar, India. Special publication. Phuket Marine Biological Center 25, 111–112.

Sanil Kumar, V., Ananad, N.M., Gowthaman, R., 2002. Variations in near shore processes along Nagapattinam coast, India. Curr. Sci. 82, 1381–1389.

Sarin, M.M., Krishnaswami, S., Ramesh, R., Somayajulu, B.L.K., 1994. ^{238}U decay series in the northeastern Arabian Sea. Continental Shelf Research 14, 251–265.

Schuiling, RD., 2004. Palk Strait: repairing Adam's Bridge with gypsum? Curr. Sci. 86, 1351–1352.

Schumann, R., Baudler, H., Glass, A., Dümcke, K., Karsten, U., 2006. Long-term observations on salinity dynamics in a tideless shallow coastal lagoon of the Southern Baltic Sea coast and their biological relevance. Journal of Marine Systems 60, 330–344.

SCL, 2007. Sethusamudram Corporation Limited – Hydrographic study http://sethusamudram.gov.in/HydroStudy.asp, 56pp.

Shannon, L.V., Chapman, P., 1983. An explanation for the vulnerability of the Arniston – Mossel Bay region to pollution by oil and tar balls. Fifth National Oceanographic Symposium. 24-28 January 1983. Rhodes University, Grahamstown. Abstracts., (198, pp. E 15).

Sheppard, C., 2003. Predicted recurrences of mass coral mortality in the Indian Ocean. Nature 425, 294–297.

Silas, E.G., 1968. Tuna fishery of the Tinnevelly coast, Gulf of Mannar. Proc. Symposium on Scombroid Fishes. Marine Biological Association of India Symposium Series 1, 1083–1118.

Sivakumaran, K., Rosselli, A.T,, Balloffet, A., 1996. Particulate matter transport in the proposed Sea Level Canal, Panama. Suspended particulate matter in rivers and estuaries. proceeding of an international symposium.Schweizerbart'sche verlagsbuchhandlung, Stuttgart (FRG), 1996, Advances in Limnology 47, 421–438.

Somvanshi, V.S., 1998. Fishery resources in the Indian EEZ: recommendations for deep-sea fisheries development. Indian Journal of Marine Sciences 27, 457–462.

Sreepada, R.A., Desai, U.M., Naik, S., 2001. The plight of Indian Sea horses: need for conservation and management. Current Science 82, 377–378.

Srinivasa Rao, K., Lakshmi, K., 1993. *Scomberomorous lineolatus* (Cuvier), an interspecific natural hybrid (*S. commerson* (Lacépède) x *S. guttatus* (Bloch & Scneider)) off Visakhapatnam, India. Journal of Natural History 27, 471–491.

Srinivasa Rao, K., Lakshmi, K., 1999. Cryptic hybridization in marine fishes: significance of narrow hybrid zones in identifying stable hybrid populations. Journal of Natural History 33, 1237–1259.

Stanley, D.J., Freeland, G.L., Sheng, H., 1982. Dispersal of Mediterranean and Suez Bay sediments in the Suez Canal. Marine Geology 49, 61–79.

Subba Rao, D.V., 1970. The phytoplankton off Lawson's Bay, Waltair, Bay of Bengal. Prof. Ganapati Shastiabdipoorthi Commemoration volume, Andhra University, Waltair, pp. 1–28.

Subba Rao, D.V., 2000. The Bay of Bengal Ch. 71. In: Seas at the Millennium: An Environmental Evaluation, Vol. 2. Elsevier Science Ltd., pp. 269–284.

Subba Rao, D.V., 2005. Comprehensive review of the records of the biota of the Indian Seas and the possible transport of novel species. Aquatic Conservation 15, 117–146.

Subba Rao, D.V., Ingole, B., Tang, D., Satyanarayana, B., Zhao, H., 2007. Tsunamis and marine life, pp. 373–391, Ch 31 'The Indian Ocean Tsunami', edited by Tad S Murty, U. Aswathanarayana, Niru Nirupama, 528pages, Taylor & Francis The Netherlands (incorporating A.A. Balkema Publishers) Leiden, The Netherlands.

Subramanyan, R., Viswanatha Sarma, A.H., 1961. Studies on the phytoplankton of the west coast of India. Indian Journal of Fisheries 7, 307–336.

Suikkanen, S., Laamanen, M., Huttunen, M., 2007. Long-term changes in summer phytoplankton communities of the open northern Baltic Sea. Estuarine, Coastal and Shelf Science. 71, 580–592.

Underwood, A.J., 1992. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. Journal of Experimental Marine Biology and Ecology 161, 145–178.

Van Dyke, E., Wasson, K., 2005. Historical ecology of a central California estuary: 150 years of habitat change. Estuaries 28, 173–189.

Venkataramanujam, K., Santhanam, R., Sukumaran, N., 1981. Coral resources of Tuticorin (S. India) and methods of their conservation. The reef and man. Proceedings of the Fourth International Coral Reef Symposium.1, 259–262.

Vincent, W.F., Bertrand, N., Frenette, J.J., 1994. Photoadaptation to intermittent light across the St. Lawrence Estuary freshwater-saltwater. Marine Ecology Progress Series 110, 283–292.

Wasmund, N., Uhlig, S., 2003. Phytoplankton trends in the Baltic Sea. ICES Journal of Marine Science 60, 177–186.

Yurkovskis, A., 2004. Long-term land-based and internal forcing of the nutrient state of the Gulf of Riga (Baltic Sea). Journal of Marine Systems 50, 181–197.

Further reading

Black, K., Hume, T., Green, M., Bell, R., Healy, T., Mathew, J., 1997. Numerical models depicting hydrodynamic and sediment transport processes at scales from single bedforms to the continental shelf. In: Proceedings of the Second Indian National Conference on Harbour and Ocean Engineering (Inchoe-97), Thiruvananthapuram, vol. 1., December 7–10, 1997. pp. 13–37.

Chandramohan, P., Kumar, V.S., Nayak, B.U., 1991. Wave statistics around the Indian coast based on ship observed data. Ind.J.Mar.Sci. 20, 87–92.

Jena, B.K., Chandramohan, P., Kumar, V.S., 2001. Longshore Transport Based on Directional Waves Along North Tamilnadu Coast, India. J. Coast. Res. 17, 322–327.

Radhakrishna, K., 1978. Primary productivity of the Bay of Bengal during March-April. Indian Journal of Marine Sciences 7, 58–60.

Sanil Kumar, V., Anand, N.M., Chandramohan, P., Naik, G.N., 2003. Longshore sediment transport rate measurement and estimation, central west coast of India. Coastal Engineering 48, 95–109.

Sanil Kumar, V., Pathak, K.C., Pednekar, P., Raju, N.S.N., Gowthaman, R., 2006. Coastal processes along the Indian coastline. Curr. Sci. 91, 530–536.

Subramanian, S.K., Krishnamurthi, M.S., 1997. Studies on the species composition of neritic diatoms in the aquatic realm off Tuticorin Coast in the Gulf of Mannar – Bay of Bengal. Seaweed Research Utilisation 19, 1–11.

Zubair, R.L., Rao, S.C., Yamagatam, T.M., 2003. Modulation of Sri Lanka Rainfall by the Indian Ocean Dipole. Geophysical Research Letters 10, 1063–1066.

Zubair, L., 2004. May 2003 Disaster in Sri Lanka and Cyclone 01-B in the Bay of Bengal, natural hazards. Journal of the International Society for the Prevention and Mitigation of Natural Hazards 33, 303–318.