

ENVIRONMENTAL FACTORS INFLUENCING THE HEALTH AND PRODUCTIVITY OF PHANG-NGA BAY

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ABSTRACT

The Andaman Sea of Thailand borders the west coast of southern Thailand. The sea venues runoff and offshore upwelling supporting rich fisheries habitats. The richness is further enhanced by environmental regimes both in the northern and southern Andaman Sea. Phang-nga Bay is a rich ecosystem, located in between these regimes of the Andaman Sea. The Bay is one of Southeast Asia's most valuable assets, characterized by its extensive estuarine ecosystem and dense mangrove forests. It is blessed with a pleasant tropical climate and high rainfall. The rainfall enriches the Bay's nutrients to support extensive aquaculture and a wide diversity of marine life. The high potential for economic benefits from these resources has led to heavy exploitation and stresses on the Bay's ecosystem.

This paper reviews the status of Phang-nga Bay's environmental resources and ecosystem processes that help determine its health and productivity. These include bed-deposited sediment, distribution of grain size and sorting in relation to its coexisting trace element and CaCO_3 as well as mangrove progradation. Water quality characteristics and their seasonal variations are highlighted together with the application of a two-dimensional, vertically averaged tidal circulation-dispersion model. The model/simulation showed residual tidal eddies in relation to wind-driven circulation vis-a-vis seasonal change. The residence time of both seawater and runoff water in the Bay were estimated to gain insight into the accumulation and dilution of wasteloads in the Bay.

1. INTRODUCTION

The Andaman Sea of Thailand has a coastline of about 700 km (Fig. I), covering a coastal area of approximately 100,000 square km. The sea constitutes a narrow sea shelf, about 108 km wide in the north (Ranong Province), narrowing down to 27 km in the middle (Phuket Province) and widens again to about 130 km in the south (Satun Province). The water characteristics have been summarized by Limpsaichol, et al. (1987). The northern Andaman Sea, from Ranong to Phuket Province, is influenced by an upwelling process that brings in high saline waters. Consequently, salinity of the northern Sea ranges between 32.9-33.4 ppt. The southern Andaman Sea, from Phuket to Satun Province, also experiences strong offshore upwelling (Khokiattiwong and Limpsaichol, 1996), but is mainly influenced

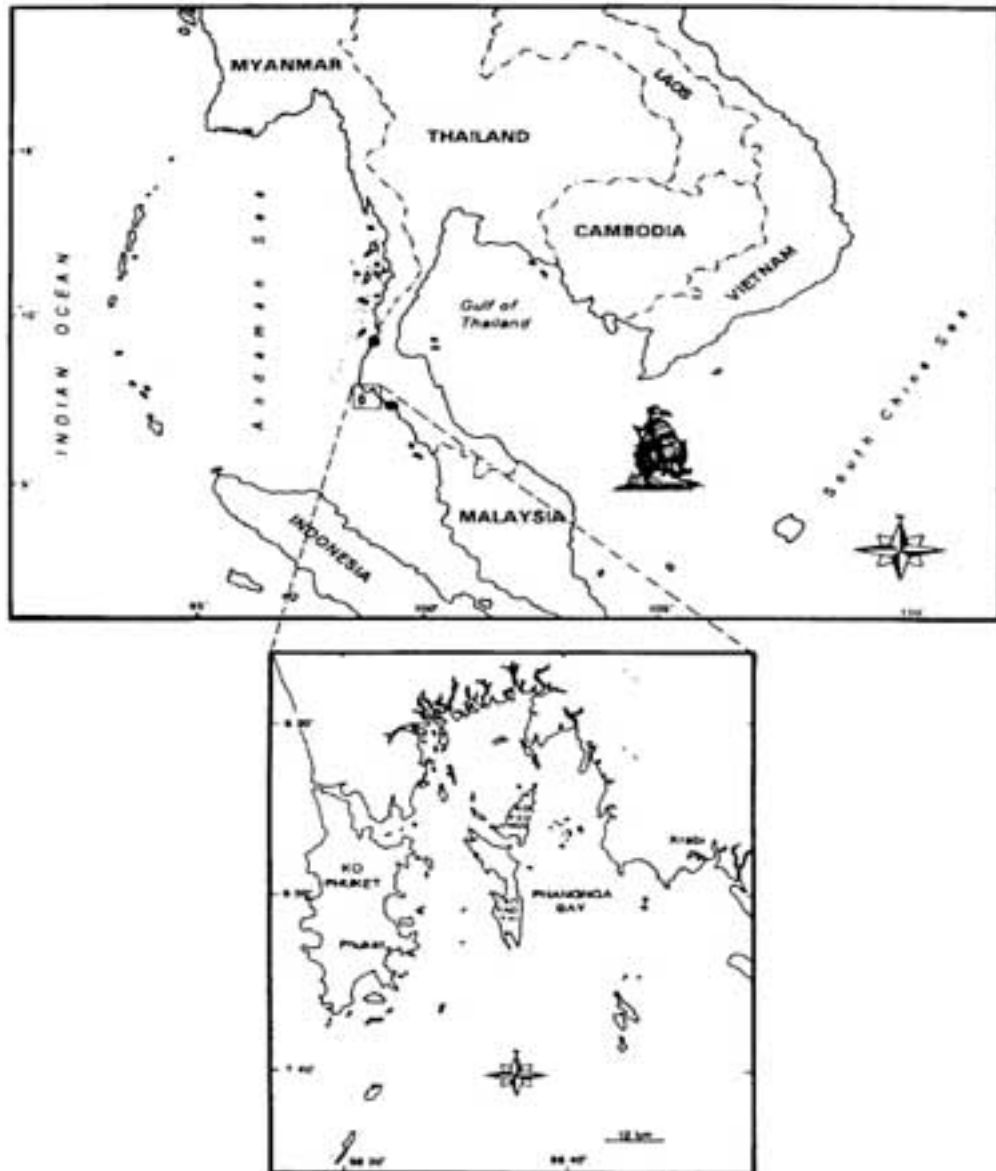


Fig. 1. Andarnan Sea coast and Phang-nga Bay, the upper south of Thailand.

by surface runoff water and water from the Malacca Straits. Consequently, relatively lower salinity of 32.6-32.8 ppt can be found in the southern Sea. The dissolved oxygen, pH and temperature values are fairly uniform along the coast.

The coastlines of Southeast Asia are among the richest in the world in terms of both renewable and non-renewable resources. Phang-nga Bay is not an exception, and is an economically important resource of Thailand. This is one reason it has been chosen as the site for the Department of Fisheries/FAO Bay of Bengal Programme (BOBP) Community-based Fisheries Management (CBFM) project. In previous phases, BOBP initiated a Socio-Economic Development Programme in the area. The current follow up programme on coastal zone management and CBFM builds on other programmes in the area undertaken by local and regional organizations, including the ASEAN/US Coastal Management Project coordinated by ICLARM.

The Bay has a triangular shape covering an area of about 3000 square km, situated at latitude 7° 30' N- 8° 30' N and longitude 98°15'E - 99°15° E.

The Bay is located on the west coast of southern Thailand and is 68 km long, from head to mouth. It is 82 km wide at the mouth in the south which is open to the Andaman Sea. In the northwest, it includes Pak Pra Inlet that separates Phuket Island from the mainland (Fig. 1). Nearshore areas in the north have a water depth generally less than 5 m and cover an area of approximately 700 square km. The northern shores are covered by a fringing mangrove forest with an area approximately 1,900 square km (Aksornkeoa, 1988). Estuarine conditions dominate in the north while marine conditions dominate in the south.

The Bay is under the influence of two tropical monsoonal systems; the northeast monsoon (NE) and southwest monsoon (SW). The NE monsoon is active during November to April, bringing dry weather which originates from the northern continental pressure system. The SW monsoon prevails during May-October and generates wet humid weather and storms which originate from monsoonal regimes in the Indian Ocean. An average annual rainfall of about 290 mm and over 2000 mm characterized the NE and SW monsoon respectively. The hydrodynamics of the Bay is mainly governed by semidiurnal tides with spring tides of up to 2.45 m. and neap tides of about 0.87 m (Khokiattiwong, et al., 1991).

Several environmental factors make Phang-nga Bay a good nursery ground. These include: (1) a great number of islands which provide a variety of coastal habitats used by both juveniles and adults of important marine and estuarine species; (2) nutrient-rich water outflows from the mangrove areas; and (3) favorable hydrodynamic regimes.

The Bay also provides excellent tourism activities that help to generate revenue for the local government and public sectors. Previously, tin mining was the top revenue earner,

but has declined over the past few decades due to the collapse of the world tin market. Most recently, the coastal Bay has faced a new threat; the rapid expansion of shrimp farms has increased the pond effluent or wasteloads entering the Bay. Industrialization, urbanization and upland activities have worsened the situation. Several rivers are contaminated with ~~sewage~~ discharge organic waste, mine tailings and agricultural runoff. However, the Bay's hydrodynamic regime is like a natural cleansing process that has helped to delay environmental deterioration of the Bay's resources.

2. OBJECTIVES

The purpose of this paper is to review various research activities related to fisheries habitats and environmental status of the ~~Andaman~~ Sea and Phang-nga Bay and integrate the results into a more comprehensive view of the environments that support the rich ecosystem of the Bay. The paper will highlight the factors of the Bay ecosystem, including characteristics of bed sediments, water quality and pollution vis-a-vis seasonal dynamic regimes as well as residence times of runoff water and sea water in the Bay.

3. FINDINGS OF VARIOUS INVESTIGATIONS AND DISCUSSIONS

The Andaman Sea of Thailand has been recognized for its high fisheries and economical potential. The Sea composes the northern and southern Andaman Seas - each having different water characteristics (Limpsaichol and Khokiattiwong, 1991).

In the northern Andaman Sea, the offshore area of Ban Kampuan accommodates a major fishery habitat where the southward flow of mangral runoff from the upper north emerges with the shoreward flow of fertile offshore upwelling water. Shelter from predators is provided by the many islands in the northern Sea. High biological productivity characterizes the northern Sea (Limpsaichol, et al. 1994). Such a highly productive habitat supports a rich dwelling of migratory species. Such a richness of sea life was further enhanced when the Department of Fisheries deployed a large number of artificial reefs in 1983. This fishery habitat enhancement method has mostly benefited the bio-economics of the small-scale fisheries of the northern Andaman Sea region (Yodee, 1994).

In the southern Andaman Sea, regimes of tidal currents are an influencing factor on fishery habitats. The southward flow of water from Lanta Island meets the northward flow from Tarutao Island and leads to a zone of low water movement around Liang Island. These waters emerge into the shoreward flow of subsurface water, creating numerous eddies. It was found that this area is highly productive and fertile.

The water patterns coincide with a productive mollusk bed of economically important species existing within this area. The area is a spawning and nursery ground for snails; *Chicoreus ramosus* (Khokiattiwong, 1332). This zone is also related to the abundance of chub-mackerel (*Rastrellinger* spp.) and supports their spawning and nursery grounds (Sutthakorn and Snranakomkut, 1386). Furthermore, the nearshore areas support mangrove and seagrass beds, and coral reefs are located around offshore islands within the Bay. Tuna fishing dominates in the offshore areas.

The status of Phang-nga Bay's important environmental features that support the fisheries production is discussed below.

3.1 Bed Sediment Characteristics of Phang-nga Bay

The Bay lies in a rich tin-bearing granite plane that intrudes folded sedimentary rocks along the length of upper Malay Peninsula. These extensive sedimentary limestone rocks form steep hillsides and ridges which influence the topography of the Bay. Lowland areas along the coast and the central basin of the Bay are composed of alluvial deposits which contain economically important minerals such as tin, rare-earth minerals and quartz. Marine sediments are composed of mud, silt, sand and gravel.

Geological investigations in Phang-nga Bay were conducted by Garson, *et al.* (1975) and reported that the bed sediment of Phang-nga Bay consists of a considerable thickness of arenaceous sediments. Post-Triassic marine bivalves were found in a thin bed of limestone adjacent to arenaceous beds. The sandstone outcrops have always been confined to Phang-nga, and conglomerate sandstone was found in the mangrove areas of the inner Bay.

3.2 Coastal Deposits

The eroded surface of sedimentary rock is overlain by alluvium which comprises poorly-consolidated and considerable thick mud. Sand and gravel beach deposits around the Bay were less extensive and restricted generally to small Bayhead deposits. The typical sediment was a dark gray mud or silt.

The coast of Ko Boi Yai is comprised of a bed of highly impure limestone about 5 m thick, containing abundant fragments of oysters and thick-shelled modioliform bivalves, overlain by massive calcareous sandstone. In the inner Bay (mangrove areas), the sandstone sediments are overlain unconformably by 1.5 m of steeply dipping calcareous sandstone, followed by 4 m of black shale with thin bands of bituminous shale.

The extent of mangral swamp and creeks are related to the rise in sea level during the geologic evolution of the area, approximately one million years ago. This elevation in base level had resulted in a reduction in the power of rivers to rework material already

deposited and thus accounted for the extent of river gravel and alluvium which were overlain by estuarine muds. The alluvial deposit included a wide range of unconsolidated river-deposited sediment, ranging from coarse boulders and gravel to fine silt and clay.

Trace minerals including arsenopyrite (Fe, As) and scorodite (Fe, As, $\text{AsO}_4 \cdot 2\text{H}_2\text{O}$) were commonly minor constituents of granitic areas. A Pb content of 830 ppm was observed in hornfels, and 0-10 ppm Cu in drainage samples with higher values (10-20 ppm) in granitic mass and adamellitic rock. However, drainage samples that derived from the coarse-grained biotite-granites contained Cu 20-160 ppm. Relatively lower values of 10-60 ppm Cu and 0-10 ppm were observed in the fine to medium-grained biotite-granites.

In sedimentary areas, values of 0-20 ppm Cu were reported on Ko Yao and in similar Mesozoic sandstone in Krabi. Values of more than 30 ppm Cu were recorded on the Ko Tang Li granitic areas. Only 5 ppm Cu was found in Ko Yao sandstone. Zn values in granitic areas were less than 80 ppm while they ranged from 10-130 ppm in the drainage samples.

The trace metal concentrations in the sediments showed large variations because of complexation with varying organic fractions. However, the organogenic process in the sediment plays an important role on the quantity of sorbent as does the solubility of the sorbable element.

Various studies have observed the ratio between heavy metal (mg) and organic compound (kg). Findings revealed that the ratio was fairly constant in the Bay sediment and reflected normal background levels. The contents of sorbents and sorbable substances were linearly related and sorbable substances could be significantly disturbed and deviated in case of pollution (Edgren, 1977). Studies of sorption relations of trace metals in the Bay (Khokiattiwong, et al., 1989) led to valuable interpretation of the potential pollution problem.

Trace metals were at a level expected from data on the geochemical composition of the sediments. The level of Cu, Zn in samples of drainage and fine grained biotite-granite were 0-10, 10-130 and 0-10 mg kg^{-1} dry wt sediment respectively (Garson, *et al.*, 1975). It was noted that higher metal fractions were recorded in the deeper bedrock of main granite mass (adamellitic rock) in the Bay.

A more recent study conducted by Carr, et al. (1991) described the nature, grain size and calcium carbonate distribution of surface sediment in the Bay. Late holocene sediment accumulation and mangrove progradation rate were also estimated. Two major findings were clearly delineated:

1. Distribution of CaCO_3 in surface sediment.

Most of the CaCO_3 contribution of the surface sediment originated from whole and fragmented skeletal remains of bivalves, gastropods and other CaCO_3 containing shell fragments (Fig. 2). However CaCO_3 tended to increase from the inner Bay to the seaward areas. Local variation in CaCO_3 was also noted in the inner Bay (<10%->30% CaCO_3) while an elevated content of more than 30% of CaCO_3 was concentrated in the outer Bay, particularly around beach and reef environments.

2. Grain size characteristics of surface sediment.

The inner Bay is dominated by coarse quartz silts (4-6 phi) while the central and outer Bay are dominated by fine quartz sand (2-4 phi) and coarse quartz sand (2 to -2 phi). The grain size distribution tends to increase from the inner Bay seawards, similar to that of the CaCO_3 distribution (Fig.3).

Around the inner Bay, relatively coarser sediment of quartz and occasional feldspar grains were found in channels within the mangrove swamps. It was found that coarse sediments on the northern tip of Ko Yao Noi and other patches of coarse sediments coincided with areas of high CaCO_3 (Fig. 3). In the seaward area, coarse sediments (0 to-2 phi) were related to strong currents.

Poor sorting of sediment occurred in the inner Bay and was rather more complicated than the outer Bay (Fig. 4). However, patches of poorly sorted sediment (> 2.5 phi standard deviation) coincide with areas of coarse sediment and were related to high CaCO_3 . Nevertheless, in the mangrove channels, coarse grain size and poor sorting did not relate to high

Relationships among mean grain size, standard deviation and deposition environments, like intertidal zones, mangrove channels and mangrove swamps, were also studied. Results are shown in Fig. 5.

The intertidal sediments ranged from muds typical of sediments found in mangrove swamp environments with fine grain size and generally good sorting, to poorly sorted sand, typical of sediments found in mangrove channel environments (Fig. 5).

The outer Bay sediments are composed of fine and medium sand (0-4 phi) with relatively small variation. Shallow marine sediments can be clustered into two groups, one of coarse poorly sorted sand and the other of better sorted fine sand similar to that of mangrove swamp sediments.

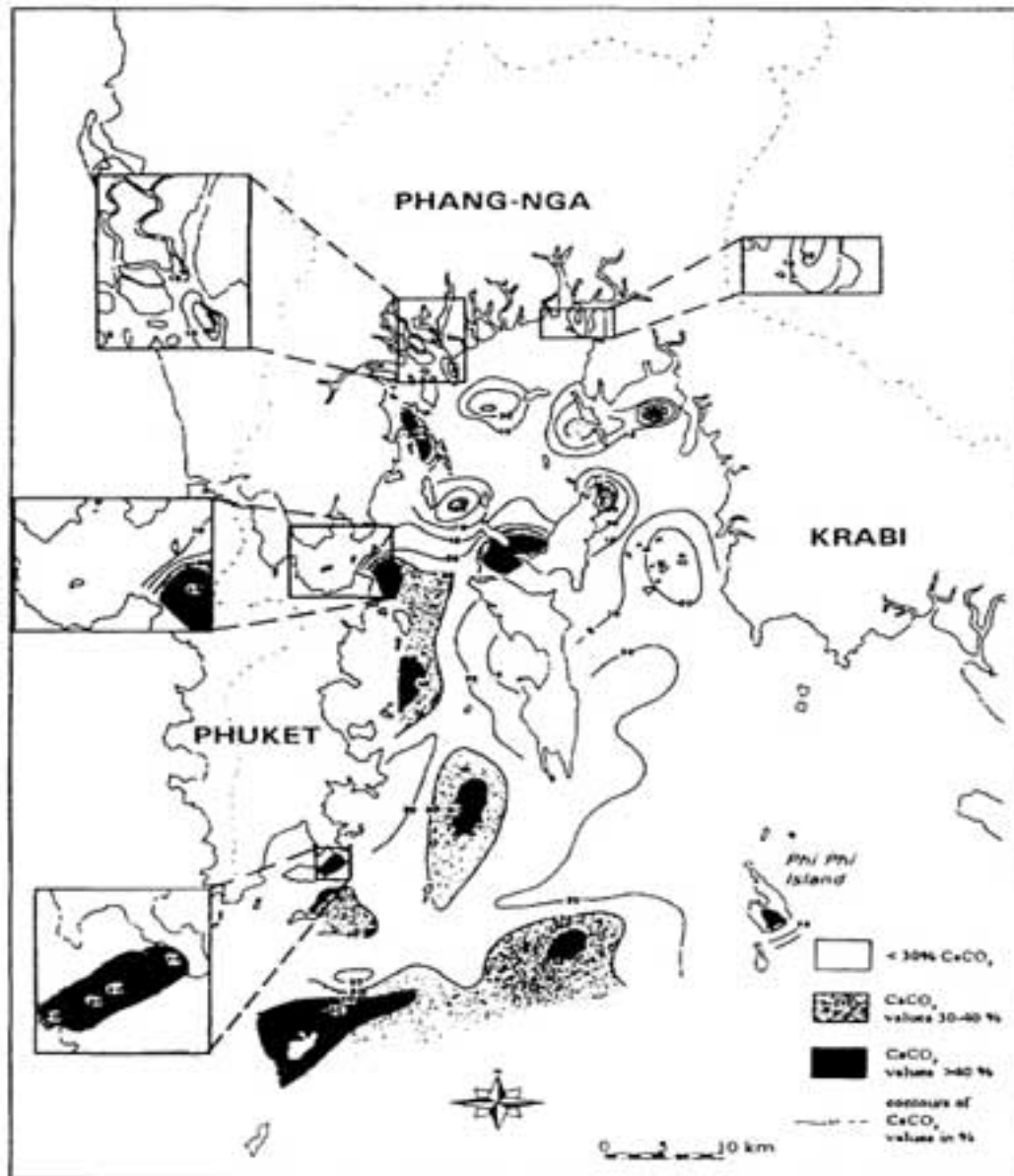


Fig. 2. Distribution of calcium carbonate percent values (after Carr. et. al., 1991).

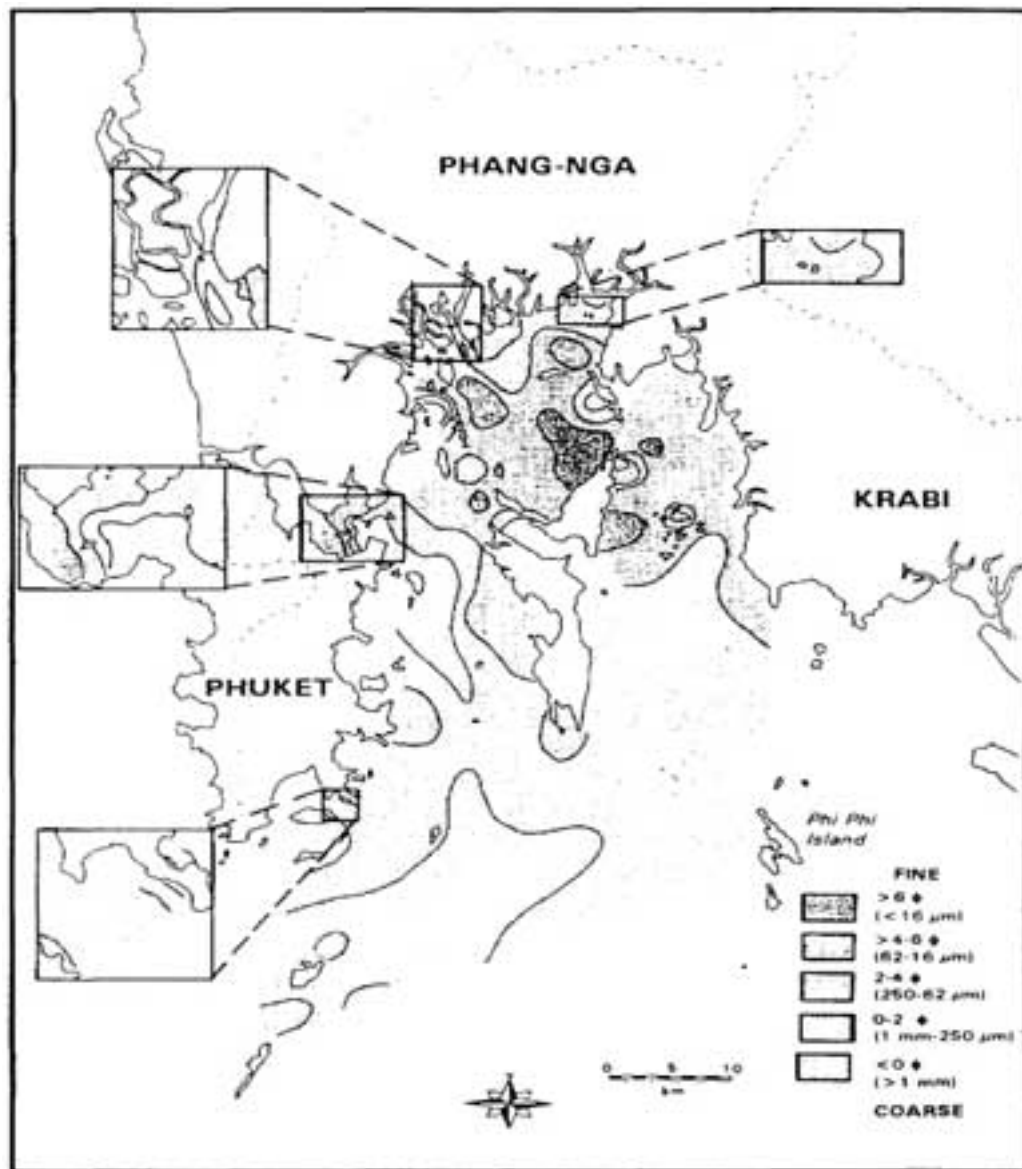


Fig. 3. Distribution of mean grain size values in phi (φ) units (after Carr. *etal.*, 1991).

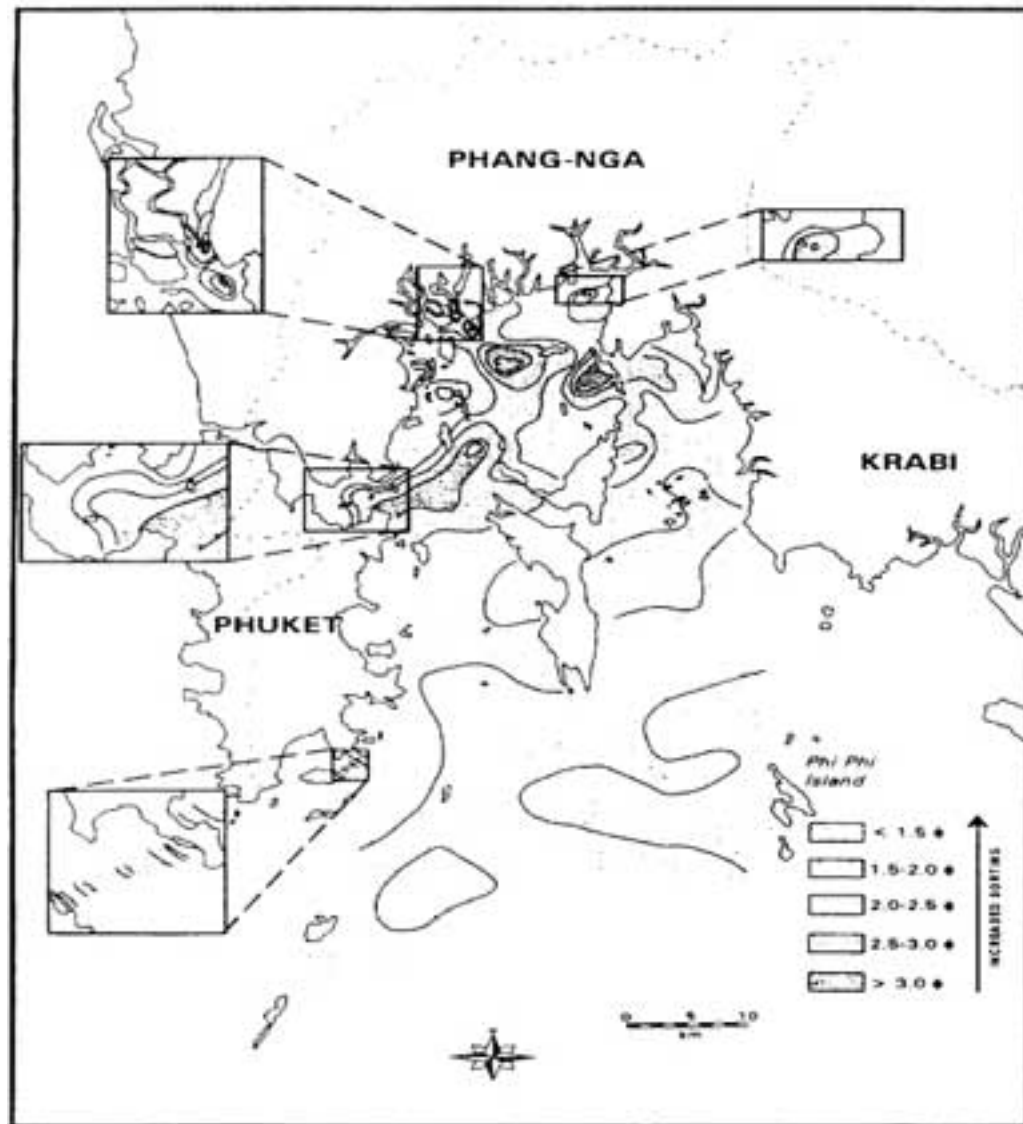


Fig. 4. Distribution of standard deviation (sorting) values in $\phi(\emptyset)$ unit (after Carr, *et al.*, 1991).

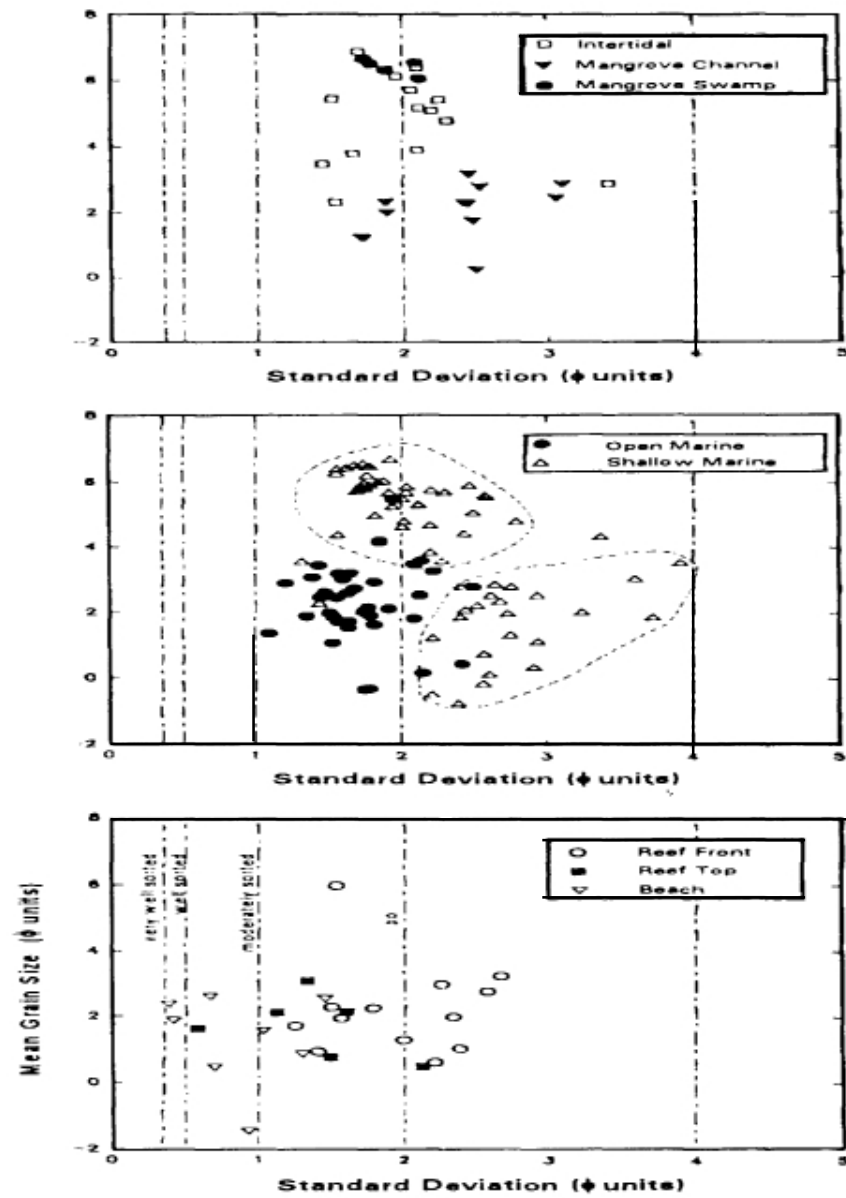


Fig. 5. Graphs of mean grain size versus standard deviation for individual depositional environments (after Carr, *et al.*, 1991).

The beach, reef top and reef front sediments were also studied and showed that they were generally coarse grain by nature. However, comparatively, the best sorted sediments were in the beaches, and the reef top sediments were better sorted than the reef front sediments.

3.3 Accumulation and Progradation Rate of Sediments

In the inner Bay mangrove area, radiocarbon dating was performed on the vertical sediment accumulation and progradation of mangrove swamp. The method observed the bathymetry of sea bed (i.e., present mangrove) and associated vertical sediment accumulation rates. Mangrove progradation was then estimated to be about **1.5** m.year⁻¹ (Fig. 6). A second method used in the study applied the Holocene transgression rate during the past **6000** years up to the present sea level. The progradation was estimated similarly at 1.67 m year⁻¹.

Results indicated that the Phang-nga Bay mangrove areas would prograde at a distance of 3 km into the Bay every 2000 years (Fig. 6).

The organic content in the top sediment was subjected to monsoonal influences while the values of the lower sediment were uniform, regardless of monsoons. Organic compounds were deposited by runoff and tidal flow which were believed to be of mangral origin (Rusnak, 1967). Intensive deposition occurred on the west coast during the counter clockwise circulation of northeast monsoon and visa-versa on the east coast during the southwest monsoon.

Schlegel (1987) reported that undissociated H₂S concentrations below 50 mg. l⁻¹ corresponds to 2% of free H₂S which is toxic to many aerobic organisms. (Toxicity occurs when H₂S inhibits the normal organogenic process in the breakdown of organic materials.) During the northeast monsoon, free H₂S was noted and a strong smell was observed in newly taken sediment cores. However, the sulfide toxicity reduced when pH level increases to 7.5-8.0 (Kroiss and Plahl-wabnegg, 1988). This indicated that the subsurface water of the Bay was not subject to sulfide toxicity of the sediments.

Adverse effects of H₂S on mussel beds have been observed in Limfjorden, Denmark (Jorgensen, 1980). Jorgensen reported that the anoxic bottom water first appeared in the large and dense mussel beds. Oxygen depletion increased relative to the size of the mussel beds. Bacterial metabolism was then stimulated in the upper few cm and as a result, hydrogen sulfide accumulated in the surrounding sediment.

In relation to anoxic sediments, some benthic infauna which were most markedly seen (such as the deep burrowing polychaete *N. virens* and *C. volutator*) bring oxic water

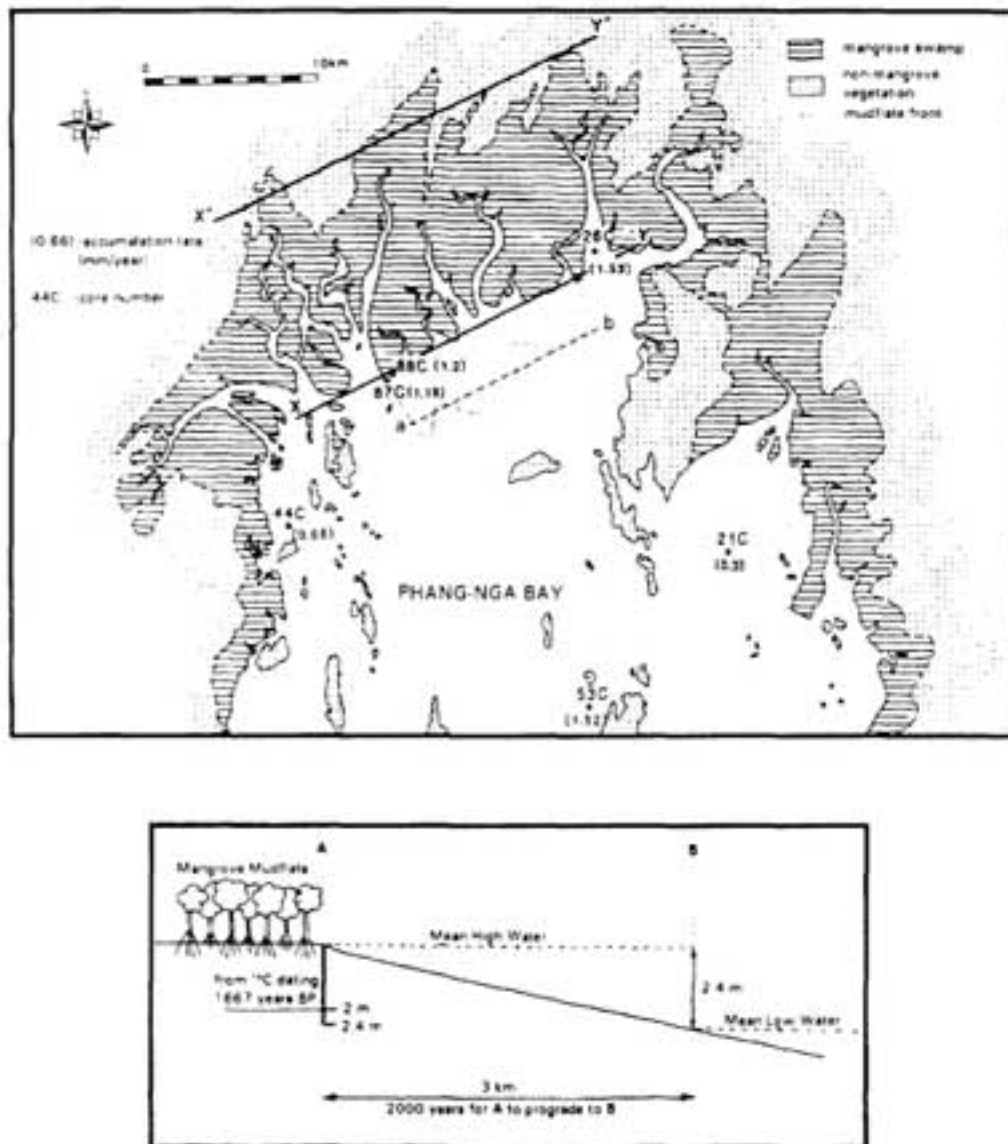


Fig. 6. Location of cores in northern Phang—nga Bay for which radio carbon dates and hence accumulation rates are available. X—Y : present day coastline. X¹—Y¹ postulated coastline 6000 ya. a—h: average position of exposed mudflat extent (above). Model for calculating future progradation of mangrove coastline (after Carr, et al., 1991) (below).

into the anoxic sediments and removed toxic products from the sediments (Henriksen, *et al.*, 1980). They further showed that benthic infauna and microalgae were factors regulating the exchange of waste products at the sediment-water interface in coastal marine sediments.

3.4 Water Quality Characteristics

An investigation of the coastal environment of Phang-nga Bay was undertaken by Limpsaichol and Bussarawit (1991). They discovered that water quality characteristics showed different regimes in three areas of the Bay: the east coast, the west coast and the inner Bay area (Table 1-2).

Table 1 presents the hydrological conditions observed during the northeast and southwest monsoons. Typical salinity variations along the upstream and offshore stretch are shown in Fig. 2. The high variation in coastal water quality characteristics is largely due to meteorological influences. These natural influences, coupled with suspended solids from mining discharges and other pollutants, added stress to the Bay's ecosystem. Siripong, *et al.* (1981) used remote sensing (LANDSAT MSS data) to investigate the suspended sediment distribution in the inner Bay and the relationship between suspended solids and tidal currents at some outer Bay stations. These MSS data showed that the monsoons induced runoff and circulation in the Bay (Siripong, *et al.*, 1987).

The concentration of total suspended solids (TSS) was considered as one of the most significant influencing factors of the Bay. The Bay has a high content of TSS because of its capability of settling and resuspending in accordance with the tidal regimes. The TSS in the 3 areas of the Bay are summarized below.

Total suspended solid (TSS) concentrations were identical (12.8 ± 3.2 ppm) on both coasts while the inner Bay value was higher (18.1 ± 5.0 ppm). The pH values in the inner Bay water, affected by runoff, were lower ($\text{pH } 8.23 \pm 0.09$) compared to those ($\text{pH } 8.35 \pm 0.10$) on both coasts (Table 1).

The overall Bay-wide averages of salinity, temperature, dissolved oxygen (DO) and total alkalinity were 32.0 ± 0.8 ppt, $28.6 \pm 0.4^\circ \text{C}$, 6.5 ± 0.5 ppm and 134.0 ± 32.0 ppm CaCO_3 respectively. Occasionally, identical values of the same parameter were found in the three areas. However, the salinity in the inner Bay was generally lower.

Nearshore DO slightly exceeded that of the offshore water (6.3 ± 0.05 ppm), which may indicate a higher primary productivity. In general, the DO of the outer sites of both coasts was that typical of open sea water (Limpsaichol and Bussarawit, 1991).

Notably, the TSS patterns were closely related to water circulation in the Bay. During the northeast monsoon, the relatively high TSS (14.0 ± 2.0 ppm) of the inner Bay

water was probably attributed to being transported, partially settling off and being diluted along the counter-clockwise path to the west coast, while a relatively low TSS (10.1 ± 1.3 ppm) was observed along the east coast, where the partial mixing of runoff and seawater occurred.

Similar patterns of TSS were observed in the southwest monsoon. The magnitude was higher due to strong winds, a clockwise circulation and the strong flow of the subsurface water's counter flow. Thus, a very high value of TSS (96.8 ± 13.2 ppm) was recorded in the inner Bay with an intermediate value of **10.8 ± 2.0** . A comparatively low value (**20.8 ± 2.2** ppm) was observed in the west where the partial mixing occurred. The TSS in the inner Bay varied greatly from 615.0 ppm during the southwest monsoon to 41 ppm during the northeast monsoon (Table 1).

TSS in the inner Bay had a low organic content, inferring that the sediment consisted of loosely combined silt **and** clay, most likely derived from mine tailings. The subsurface TSS during ebb tides generally contained a lower organic load than the surface TSS, which indicated a strong re-suspension action.

During the northeast monsoon, the TSS content in the Bay was relatively uniform (14.0 ± 2.0 ppm) throughout ebb and flood tides. In contrast, the strong southwest monsoon's resuspending action occurred typically along a stretch about 1 km before and behind the coastline (Fig. 7). Thus, a very high TSS content was observed upstream during flood tides and vice versa during ebb tides. This showed that the majority of TSS in the Bay was derived mainly from the resuspension of deposited sediment along the shore.

Khokiattiwong, et al. (1991) found that the nearshore circulation was profoundly related to interaction between runoff and saline waters and was superimposed by the monsoonal current regime in the Bay. Significantly low organic fractions of TSS further implied that the depositable and resuspendable sediments consisted of loosely combined silt and clay. These were probably derived from previously discharged TSS from mines. The subsurface TSS during ebb tides generally contained a lower organic fraction than the surface values, which confirmed the above implication.

Similar salinity (31.93 ± 0.27 ppt) was recorded during the northeast monsoon at flood and ebb tides in the Bay, implying uniform circulation. The southwest monsoon subsurface inflow on the west coast resulted in a slightly higher salinity than on the east coast (32.28 ± 0.04 ppt) while relatively low salinity prevailed in the inner Bay water (31.06 ± 0.5 ppt). Quantitative assessment of diurnal salinity variation (4.3 ppt) was considerably higher than the value observed during the northeast monsoon (1.6 ppt). An upstream salinity variation of 11.9 ppt was observed (Table 2 and Fig. 7).

Table 1. Hydrological conditions Northeast monsoon (January-February 1988; from Limpasichol and Bussarawit, 1991).

Parameter	East coast	West coast	Inner bay	KK site	East coast	West coast	Inner bay	KK site
TSS, ppm	10.1±1.3	7±1.0	14.0±2.0	5.8-7.3	28.7±5.0	20.8±2.2	96.8±13.2	48.1±55.1
ΔTSS	18.1	18.1	41.0		115.3	48.6	615.0	48.1±55.1
OF(TSS)	LT 16.4±2.1	31.0±4.6	18.2±6.1	31.96-63.66	18.8±1.4	10.8±2.0	10.8±2.0	(75-106)
Salinity, ppt	31.93±0.27	31.39±0.27	31.93±0.27	27.84±30.8	32.28±0.04	32.41±0.02	31.06±0.5	26.9±28.4
Δ Salinity	1.20	1.57	1.56		1.0	1.0	4.3	(14.5156)
DO, ppm	6.84±0.34	6.26±0.31	6.26±0.31	3.80-4.45	Saturated	Saturated	Saturated	
ΔDO	2.05	1.82	2.41		-			
Alkalinity, ppm CaCO ₃	160.0±1.0	160.0±1.0	160.0±1.0	157-158	182±2.1	160.0±4.0	160.0±4.0	158.0-160.0
Δ Alkalinity	3.0	3.5	5.0		27.5	5.0	6.0	(59.0-64.0)
pH	8.27±0.02	0.12±0.04	8.12±0.04	7.53-7.78	8.08±0.03	8.18±0.01	7.97±0.04	7.49-7.72
Δ pH	0.08	0.16	0.36		0.57	0.09	0.62	(7.35-7.41)
Temperature, C	28.62±0.40	28.62±0.40	28.62±0.40	29.6-29.9	32.6±0.5	32.7±0.5	31.6±0.5	29.5-29.6
Δ Temperature	2	2	3		2	1.2	1.8	
Coliform bacteria								
MPN/100 ml	-	-	23-260	34-2,400	4-350	-	9-170	33-1,400

Notes : KK= Kokekrai cage mariculture; Δ Variation.
Data enclosed

Table 2. Upstream-offshore stretch salinity variation (from Limpasichol and Bussarawit, 1991).

Location		Northeast monsoon	Southwest monsoon	Potential variation
East coast	Salinity offshore	1.20 ppt 2 km	3.5 ppt 5 km	11.90 ppt 8 km
Inner bay	Salinity offshore	1 ppt 3km	2.5 ppt 6km	3.0 ppt 10km

During the northeast monsoon, the east coast's salinity varied by 1.20 ppt (Table 2). Salinity variation was highest in the nearshore area – within the first two km from shore. Beyond the first two km, the salinity remained uniform and relatively stable at (32.94 ± 0.27 ppt). During the southwest monsoon, salinity showed a higher variation. During the prolonged dry period of the southwest monsoon, a 3.5 ppt variation extended for 5 km offshore while an upstream variation of 12.0 ppt was enhanced during heavy rainfall periods.

The high salinity variations in the Bay had a negative effect on the development of mariculture, particularly for sessile organisms. Cockle (*Anadara* spp.) mortality was related to the abrupt drop in salinity due to intensive river runoff especially during the wet southwest monsoon (PPFO, 1987). This can be compared with occurrences in other areas of the world. Burrell (1977) reported that high mortalities in oysters and hard clams in the estuary of Santee River, South Carolina (USA), were caused by the drastic change in salinity from heavy runoff. The seaward migration of *Penaeid* spp. was also reported to be affected by nearshore low salinity stress in Brunei Darussalam Bay (Loo, et al., 1987). Environmental conditions of low total alkalinity favored rapid growth of coliform bacteria, making cultured fish highly vulnerable to disease infection (Dharnchalarnukij, et al., 1982).

The buffering property of the coastal Bay waters was relatively high, as indicated by the total alkalinity shown in Table 1.

The northeast monsoonal water temperature ($28.62 \pm 0.40^\circ$ C) in January was relatively lower than the southwest monsoonal value ($32.3 \pm 0.5^\circ$ C) in June. These values prevailed uniformly in the coastal waters where a 3° C diurnal variation was recorded, regardless of ebb or flood tides.

High nutrient contents (PO, and NO_x) were generated in the mangal upstream area during the northeast monsoon. Nutrients were diluted by the downstream water and moved into the Bay during ebb tide. The nutrient-rich stream water was then pushed backwards upstream during flood tide (Fig. 8). Thus, high nutrient contents were again recorded in the upstream water. Fluctuations in nutrient content from runoff of various sources occurred during the southwest monsoon. It was reported by Limpsaichol and Bussarawit (1989) that wasteload from aquaculture activities - mainly cage culture - occurred in Kokekrai (about 3 km upstream of Park Lao River) and affected the water quality in the area. This intensive cage culture site (400 cages) located near human settlements caused very turbid water (TSS 106 mg.l^{-1}) that exceeded the threshold value (NTAC, 1972) The TSS consisted of a high organic fraction (OF) of up to 63 ppm, and was mainly derived from the remainder of fishmeal.

The microbial decomposition caused very low DO levels (<3 ppm), which further decreased at night. Thukhvinars, et al. (1986) reported the DO content in estuarine waters

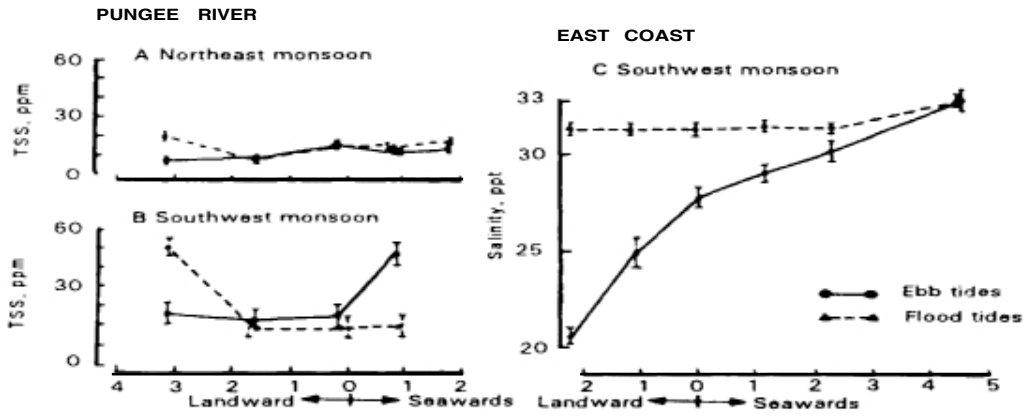


Fig. 7. Typical variation in TSS. Northeast monsoonal—uniform variation (A) Southwest monsoonal—high TSS (B) in upstream and offshore during flood and ebb tides, respectively. Typical salinity variation of 12 ppt (C) located upstream. It can be much larger under heavy rainfall (after Carr, et al, 1991).

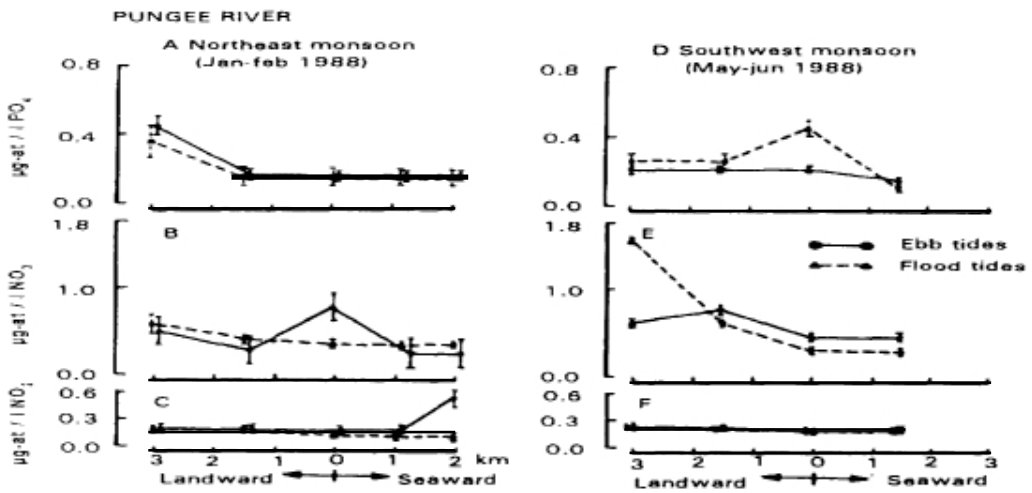


Fig. 8. Nutrients input (A, B, D, and E) during the northwest and southwest monsoons, seawards at ebb tides and seawater flushes upstream during flood tides. High nutrient was generated in the coastal waters (C), otherwise, it was uniform (C and F) (after Limpsachol and Bussarawit, 1991).

near aquaculture sites to be as low as 1.5 ppm at night, and caused high mortalities due to hypoxia.

High concentrations of cage culture in the Bay have restricted the natural hydrological processes that had previously kept pollutants well dispersed. This has led to a drastic drop in total alkalinity value (<60 ppm CaCO_3). Cultured fish become vulnerable to bacterial growths at such low levels of alkalinity (Dharmchalarnukij, *et al.*, 1982). A high coliform bacteria (1,700 MPN/100 ml) count, which exceeded the acceptable value of 1,000 MPN/100ml was recorded in the Bay by Unkulvasapaul and Simachaya (1986). High levels of coliform bacteria (1,400 MPN/ 100 ml) were also recorded at sewage discharge sites near the Kokekrai village.

Relatively high primary production was observed in the Bay. Sundstrom, *et al.* (1987) found an annual average production rate of about $384 \text{ gC m}^2\text{year}$. The high primary production of the area was related to the large area of mangrove swamps and their high productivity (Christensen, 1978). A high chlorophyll-*a* content was noted in coastal waters (1-5 m depth). However, relatively lower values of both parameters were observed in offshore waters. It was also noted that high densities of zooplankton were recorded during the northeast monsoon in the inner Bay (Boonruang, 1985). Abundance and distribution of zooplankton was affected by their feeding patterns and the hydrodynamic regimes of the Bay.

3.5 Land-Based Sources of Pollution

Land-based sources of pollution in Phang-nga Bay were studied by Kositratana and Kajornatiyudh (1991). The study revealed that pollution sources were scattered throughout the Bay. These included sources that entered into the riverine basins of the Bay as well as those entering directly into the Bay. Pollution sources originated from communities and industries (e.g., oil palm mills and rubber plants). However, the total generated load (TGL) and actual discharged load (ADL) of these sources were relatively small compared with mining activities. In the past, intensive mining activities operated by 14 mines showed a highly significant value of suspended solids at TGL of $280,000 \text{ kg day}^{-1}$ or approximately $50,400 \text{ tons year}^{-1}$. Daily rates averaged $70,000 \text{ m}^3 \text{ day}^{-1}$ of water supply and caused very turbid water ($4,000 \text{ ppm TSS}$). Subsequently, sedimentation increased and resulted in shallowness of rivers. The increased sedimentation also affected approximately 280 square km of inner Bay area including corals and mangroves.

Previous TGL of organic waste was calculated at $9,540 \text{ kg BOD day}^{-1}$ with a comparatively small ADL of $154 \text{ kg BOD day}^{-1}$ (approximately 1.6% of the total potential wasteload) (Kositratana and Kajornatiyudh, 1991). However, these values are presently elevated due to the large development of shrimp aquaculture farms in intertidal areas of the Bay. Water quality parameters of DO and BOD in upstream rivers of the Bay (Fig. 9),

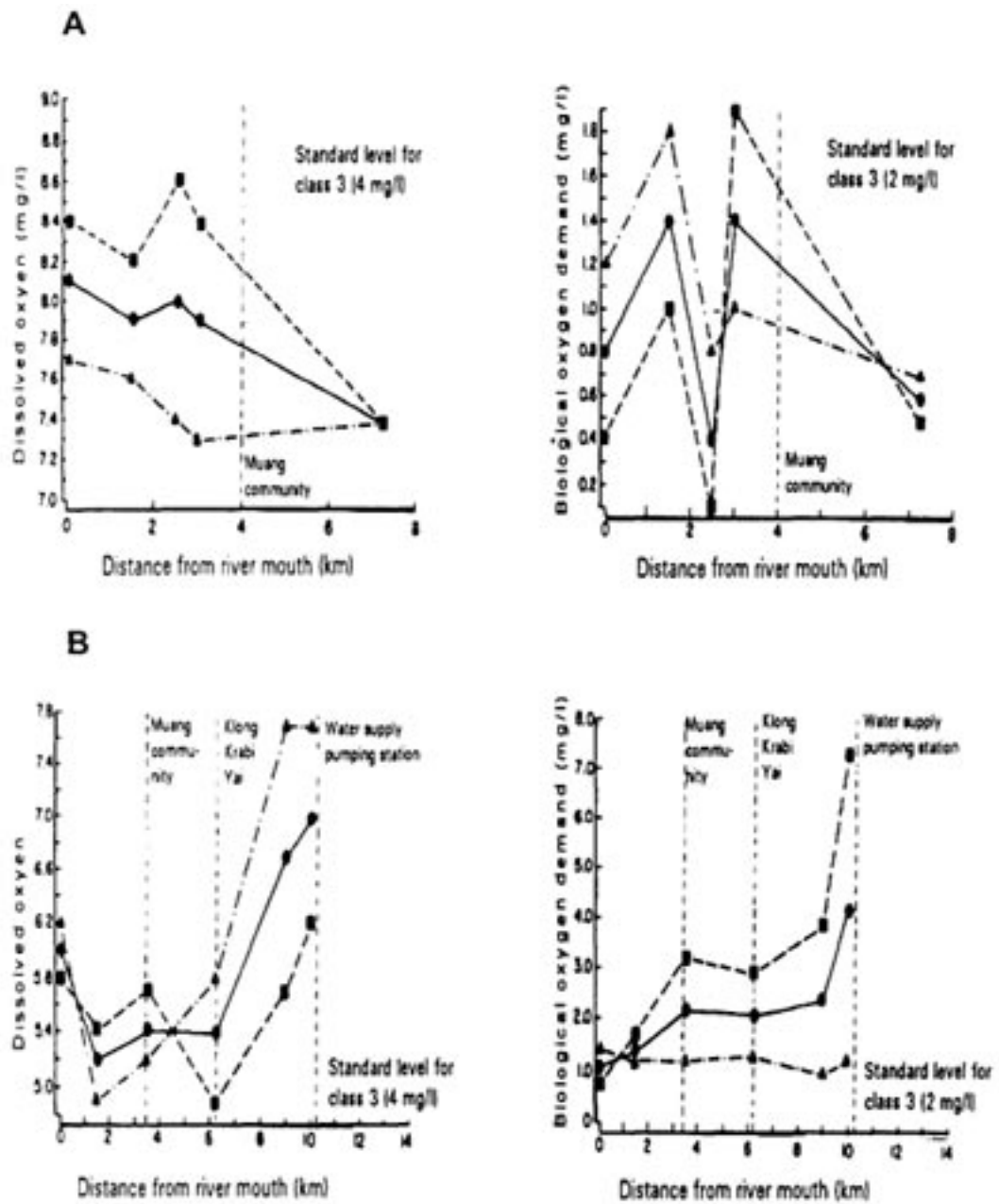


Fig.9. Changes of DO and BOD concentrations in: A) Phang-nga River; and B) Krabi River (after Kositrarana and Kajomatiyudh, 1991).

indicated that all values were within acceptable ranges of the National Surface Water Quality Standards. However, riverine contamination frequently occurred during times of sewage discharges, particularly along stretches of rivers located near city communities in Phuket, Phang-nga and Krabi Provinces. As a result, high concentrations of total coliform bacteria were reported especially during low tides and wet seasons. Such riverine contamination was comparable to that of bacterial contamination in coastal waters typically found near human settlements. Contamination was attributed to a great amount of extra wasteload **being** flushed out into receiving water during wet seasons.

3.6 Upstream NO₃ and PO₄ Distribution

Siripong, *et al.* (1987) studied the estuarine ecosystem of the Bay and concluded that high nutrient content distribution of NO₃ and PO₄ (4.333 μM NO₃-N and 0.326 μM PO₄-P) were located in the inner Bay waters. The nutrients largely originated in runoff waters. The data obtained in 1995 during monitoring studies (Khokiattiwong, *et al.* 1991) indicated that the concentrations of NO₃ and PO₄ were 2.454 ± 4.194 μM (NO₃-N) and 0.250 ± 0.134 μM (PO₄-P). The NO₃ level fluctuated. However, the average **content of** NO₃ tended to be generally elevated compared to the previous results 0.25-1.70 μM (NO₃-N) (Fig.8). The increment of NO₃ coincided with the high N-component of feeds given in aquaculture (fish, shrimp, etc.) activities. However the PO₄ levels showed no significant difference compared to previous data (0.20-0.40 μM (PO₄-P). Similarly, total coliform bacterial contamination in general did not show an additional load. Nevertheless, results indicated that the existence of fecal bacteria were generally around 20 ± 4 MPN/100 ml. Elevated values of bacteria were recorded in outflows of sewage waste near coastal communities.

3.7 Tidal Circulation Characteristics

Khokiattiwong, *et al.* (1991) investigated the monsoonal effects on circulation of the Bay, focusing on the cross-sectional residual flows of the inner Bay and along the east and west channels. The residual current structures showed that during the southwest monsoon, sea water entered the Bay as surface water through the west channel and Pak Pra Inlet and circulated through the inner Bay and out through the east channel into the Andaman Sea. As a result, relatively high salinity occurred in the northwest area in spite of high runoff and water mixing (Figs. 10 and 11).

However, although highly variated, the bottom residual flow brought sea water into the Bay through both channels (Figs. 15 and 16), then flowed northwards and out of the Bay as surface water (Fig. 14). This pattern would imply the existence of a weak gravitational circulation. The circulation structure during the northeast monsoon reflected the residual surface current outflow through the east and west channels with a relatively stronger current through the west channel and northwards (Figs. 17,18 and 19). This was

further associated with a weak northward inflow through the west channel and outflow through Pak Pra Inlet. The bottom inflow through both channels is in accordance with the surface flow. Surface residual currents were most variable during the northeast monsoon season. As a result, the salinity was generally low (31.5-32. ppt) during this season, with the lowest value in the northwest area of the Bay (Figs. 12 and 13).

During the pre-northeast monsoon season, the prevailing circulation and salinity characteristic was prolonged but tended to be highly variable. Similarly, the pre-southwest season showed trends of southwest monsoon characteristics. Similar trends occurred during the pre-northwest season.

3.9 Meteorological Characteristics

Meteorological data were taken at three locations around Phang-nga Bay including Phuket Town, Phuket Province, Takua-pa, Phang-nga Province and Lanta Island, Krabi Province (Khokiattiwong, et al, 1991). The time scale of calm periods was calculated from wind roses. It was found that winds were calm approximately 50% of the time, with the exception of the very outer Bay area (Lanta Island) where it was influenced by wind channel. The yearly average vector ranged 0.77-1.15 m s⁻¹ and varied seasonally. The outer Bay (Lanta) was dominated by low wind speed and 6.6% calm, in contrast with the inner Bay (Takua-pa) where winds were calm over 50% of the time. However, winds in Takua-pa could also be the strongest found in the Bay.

The wind regime during the transitional season of pre-southwest monsoons is dominated by weak northwesterly, westerly and southwesterly winds. However, easterly and northeasterly winds were also occasionally recorded. The pre-northeast monsoons are also governed by weak winds of easterly-northerly-northwesterly origin. Frequently, northerly and northeasterly winds were often observed in the far most outer Bay (Lanta Island).

During the northeast monsoon, the prevailing winds were from the northeast and east. However, in the inner Bay (Takua-pa), due to the influence of the landmass, winds frequently prevail from a westerly and northwesterly direction. During the southwest monsoon, the strong winds prevailing in the Bay come from the southwest, west and northwest. However the year-round prevailing winds are westerly.

3.10 Mean Air Temperature, Evaporation and Precipitation

Data accumulated over 35 years at Phuket town, and over five years at two additional locations in the Bay were calculated. It was reported that air temperature was relatively constant with a yearly average temperature of 27.8± 1.0° C over Phang-nga Bay. The average rainfall was highly seasonal. However, average monthly rainfall during the dry northeast monsoon was

below 100 mm, while the average monthly rainfall during the wet southwest monsoon was above 300 mm (Khokiartiwong, *et al.* 1991).

It was also reported by Khokiartiwong, *et al.* (1991) that average monthly precipitation of 178.6 ± 136.5 mm (rainfall) exceeded evaporation (by pan measurements) of 150.6 ± 23.3 mm. These findings implied that Phang-nga catchment was gaining a freshwater budget. The high freshwater runoff all year round caused seasonal salinity variations in the coastal areas. Lower salinity occurrence in the coastal areas, particularly during the wet season, significantly influenced circulation patterns within the estuarine ecosystem.

3.11 Numerical Model Application of Tidal Circulation in Phang-nga Bay

Sojisuorn, *et al.* (1994) developed a 2-dimensional, vertically averaged tidal circulation-dispersion model and applied it to Phang-nga Bay. The model used oceanographic data in relation to meteorological conditions. The model simulated tidal and wind-driven circulation and dispersions in the Bay. It then utilized two horizontal momentum balance equations and the continuity equation under the assumption of shallow water (Welander, 1957) and the notation of Blumberg (1977). The principle of depth-average momentum equations of the right-hand Cartesian coordinate system in x and y components are given below:

$$\begin{aligned} \frac{\partial uH}{\partial t} + \frac{\partial u^2 H}{\partial x} + \frac{\partial uvH}{\partial y} - fvH + gH \frac{\partial \eta}{\partial x} &= \tau_x^w - ku(u^2 + v^2)^{1/2} \\ \frac{\partial vH}{\partial t} + \frac{\partial uvH}{\partial x} + \frac{\partial v^2 H}{\partial y} + fuH + gH \frac{\partial \eta}{\partial y} &= \tau_y^w - kv(u^2 + v^2)^{1/2} \end{aligned}$$

As Phang-nga Bay is considered a shallow Bay where density is not significantly affected by pressure, a vertical average continuity equation can be applied:

$$\frac{\partial \eta}{\partial t} + \frac{\partial uH}{\partial x} + \frac{\partial vH}{\partial y} = 0$$

The momentum equations are nonsteady state, and include nonlinear inertia! terms, the Coriolis effect, pressure terms, surface wind stress and bottom friction (Kjerfve, *et al.*, 1990). The values of u and v are the depth-averaged velocities with respect to x and y coordinates. H is the instantaneous water depth given by $H=h+h$ where h = water depth at mean sea level and h is the surface elevation relative to mean sea level, f and g are the Coriolis and gravitational acceleration respectively, τ_x^w and τ_y^w are the x and y components of the 10 m wind stress and k is the non-dimensional bottom friction.