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Biogeochemical Variability of Vietnamese Coastal Waters Influenced by Natural and Anthropogenic Processes

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Abstract: The paper focuses on an analysis of the main characteristics of Vietnamese coastal zones and their biogeochemical cycles. Spatial and temporal variability in the distribution of chlorophyll, primary production, carbon, nitrogen and phosphorus are discussed. Biogeochemistry depends on hydrodynamics, especially on the upwelling from the seas, and on anthropogenic processes from the land.

Key words: Biogeochemical processes, coastal zone, Vietnam, chlorophyll, primary production, balance.

Introduction

More than 50% of a population of about 82 million live in Vietnam's coastal provinces that cover 41.30% of the country's total area (GDS, 2004). Their activities, especially those that are related to food production such as the development of aquaculture and fishing have brought enormous pressure on Vietnam's coastal environment. For example, the accumulation of waste from aquaculture has caused soil degradation, pollution and eutrophication in water bodies in general and, red tide blooms in coastal waters. Agricultural run-off and inputs of domestic and industrial waste have further contributed to changes in the distribution and behaviour of elements and cycling of carbon and other nutrient elements in coastal waters. Thus, not just the socio-economic but also the regulatory functions of the coastal waters are under threat. A better knowledge on the processes involved and their interactions with the overall structure and functioning of coastal ecosystems is a prerequisite for developing management measures towards the wise use and the protection of coastal marine resources. This paper gives a brief overview of the available information on the inputs from natural and land-based human activities to Vietnamese coastal waters and their influence on the biogeochemistry of coastal marine systems.

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The Main Characteristics of Vietnamese Coastal Zones

Vietnamese Coastal Zones

Vietnam has a coastline of a 3260 km in length that is very sinuous. As a result, many bays and lagoons have been formed along the coast. On an average, for every 20 km of coastline, an estuary or a bay is found. The landward boundary of Vietnam's coastal zones from coastal zone management programmes is set by the limit beyond which there is no influence of tidal or marine storms. The seaward boundary is set by the Exclusive Economic Zone (EEZ) which is up to 200 nautical miles from the coast. These boundaries vary from country to country and are dependent on the specific local conditions including geographical features and the legislative framework (Table 1).

Table 1: Examples of coastal area boundaries from coastal zone management programmes

Country or State	*Landward boundary*	*Seaward boundary*	*Comment*
New Jersey/USA	30 m-30 km	Tidal, bay and ocean state waters	State Coastal Programme
Rhode Island	200 feet from shoreward boundaries of coastal features + specified actions likely to damage coastal environments	Territorial sea (three miles) excluding fishery	State Coastal Programme
Hawaii	All land except state forest reserves	State waters	State Coastal Programme
Brunei	All land and water areas 1 km inland from MHWM and areas inundated by tides any time of the year	From MHWM to 200 m isobaths	ASEAN/US CRMP
Indonesia	Administrative and selected environmental units	60 m isobaths	ASEAN/US CRMP
Malaysia	District boundaries	Up to 20 km off shore to include islets off Mersing	ASEAN/US CRMP
The Philippines	Boundaries of coastal municipalities + inland municipalities with brackish-water aquaculture	100 fathom isobaths	ASEAN/US CRMP
The Philippines	Inner regions on marine dependant systems or 1 km whichever is the greatest	Outer reaches of fisheries resource systems which are associated with or influenced by the coast	ADB
Singapore	Entire island	Territorial waters and offshore islands	ASEAN/US CRMP
Thailand	District boundaries	Shallow continental shelf	ASEAN/US CRMP
Costa Rica	200 m from MHWM	n/a	National Coastal Programme Law of the Marine and Terrestrial Zone 6043
Sri Lanka	300 m from MHWM	2 km from MLWM	URI CRMP. Coast Conservation Act 1981
Ecuador	Variable line depending of issues in five special management areas.	n/a	URI CRMP
Vietnam	Limit which is not impacted by tidal or marine storms (about 100 km from coastline)	Up to 200 nautical miles, Economic Exclusive Zone	Institute of Oceanography, Vietnam

Source: modified from Lunkapis, 1998

Like many other coastal states, Vietnam's coastal zones are also characterized by the presence of ecosystems such as mangroves, coral reefs, sea grass meadows, which provide goods and services to coastal communities. They are also the preferred sites for urbanization. Coastal zones thus play a major role in the national economy. There is however enormous competition for land and sea resources and space by various stake holders that result in conflicts and the degradation of coastal ecosystems. Further challenges to the coasts come from: (1) erosion and siltation in coastal areas, (2) increasing population growth (growth rate of population in 2004 is 1.44%, that means population is 1.25 million people higher than in 2003) and (3) the dangers of natural hazards.

Meteorological and Hydrologic Settings

Vietnam is located in the Indo-Chinese Peninsula and covers tropical monsoon climatic zone. In the north, annual rainfall is approximately 2,000 mm while temperatures remain relatively constant—on average between 25-35°C. Most of the rainfall is between August and November. In the south, the annual rainfall is about 1560 mm with most occurring between May and November. The cities Ho Chi Minh in the south and Ha Noi in the north represent major economic centres within the coastal zone. Different from the north and the south, rainy season in central Vietnam is from August to January.

The water balance of Vietnam given in Table 2 shows that about 50% of the rainfall is removed as surface and

Table 2: The components of water balance in Vietnam

Components	*Volume (km^3)*
Rainfall water	640
Runoff water	313
Ground water	94
Surface water	219
Evaporation water	327

Source: CMESRC (2004)

groundwater runoff. There are about 2345 rivers—all longer than 10 km—discharging varying quantities of freshwater, sediments, nutrients and metals to the sea, account for a density of rivers of 0.6 km/km^2 (CMERSC, 2004, Table 3).

Because of the short distances between the sources of most of these rivers and their receiving marine waters, their impact on coastal seas is, in most cases, relatively fast and because of the intense human activities in their drainage basins, very severe. These important factors need to be considered in studying the ecology and biogeochemistry of the coastal zone.

Between July and November, Vietnam is hit by random, violent typhoons that develop off the coast in the East Sea. They typically hit the central and north coasts and have been increasing in frequency over the past few years. However, damage from them have fortunately remained less severe relative to other regions of SE Asia. But they do have an influence on marine dynamics.

Socioeconomic Setting

About 25.4% of the population of Vietnam is urban and the rest rural. Because of the rather slow rate of urbanization, the growth of urban population has not been significant (GDS, 2004). GDP (Gross Domestic Products) in 2003 was 7.24% higher than in 2002, in which the growth rate of agriculture forestry—aquaculture, industry and the services sector contributed, 3.2%, 10.34%, and 6.57% respectively (GDS, 2004).

Agriculture and aquaculture sectors remain however the major sectors affecting directly and indirectly the coastal waters (Minh, 2003). Between 2002 and 2003, there has been a slight reduction in the area where agriculture is practiced because of the conversion of non-productive agricultural land for aquaculture. Product-wise however, there has been an increase in both agriculture and aquaculture sectors.

The development of agriculture—aquaculture, consumer products industry as well as mining and maritime industry all have an effect on material runoff

Table 3: Annual discharge (tonnes $year^{-1}$) of some rivers in Vietnam

Factor	*Red river*	*Thai Binh river*	*Dinh river (Khanh Hoa province)*	*Cai River (Khanh Hoa province)*	*Han river (Da Nang City)*	*Thu Bon river (Quang Nam)*	*Dong Nai river*	*Mekong river*	*Vietnam*
Catchment area (km^2)	298050	28200				10590	47280	830780	
Runoff (km^3)	200.00	46.26	0.679	2.535	5.676	14.0	50.5	573.1	
TSS (10^6)	114		0.062	0.150	0.194			160	
COD	46400	45700			3236		99600	52000	
NO_3	24602	10466			2475	62	79570	27941	
NH_4	352								
TN			706	3776	6602	8613			
PO_4	14860	9888			36.3	16	10220	1470	
TP			58	108	62	265			
Fe			1029	2147	1782	2849			
Mn			79	160	126	192			
Zn	2015	3352	13	74	79		2921	12775	21739
Cu	2817	1100	6	22	37	62	500	1825	18084
Pb	730	154	0.4	3	16	16	102	190	2063
As	448	120			28			982	2407
Cd	118	164						128	1082
Co	254	20							503
Hg	11	16.5					25.6	<13	134

Source: National project KT03.07, 2001

from land to the coastal waters and affect the ecology and biogeochemistry of the coastal zones.

The Fluxes of Material Impact on Element Distribution in Coastal Waters

Enhanced nutrient inputs from intensive aquaculture to coastal waters have stimulated development of harmful algal blooms. Seven species of harmful algae were found in industrial shrimp farms in Do Son (Hai Phong) associated with such algal blooms. In many cases, environmental conditions in areas receiving discharge from intensive aquaculture reveal drastic deviation from allowed environmental standards in Vietnam. These have also led to formation of hypoxia; for example, H_2S content in Nghe An and Thanh Hoa was found to be 1.7 mg/L indicating an oxygen content of <2.0 mg/L.

Furthermore, human activities and development of industry also account for environmental pollution. The annual solid waste production of Vietnam is higher than 15 million tonnes, in which more than 80% is domestic wastes (MRNE, 2004, Table 4). Together with aquaculture, waste from shipping and navigation has increased the frequency of undesired impacts on coastal water environments and destroyed ecological balances in their ecosystems.

Oil pollution also appears to be a major problem in Vietnamese waters. According to CMESRC (2004), the average annual discharge of oil to the sea from Dong Nai river system is $2.7–3.3 \times 10^3$ tonnes, from Mekong river systems it is $27.5–55.0 \times 10^3$ tonnes, and from Red river system it is $7–8 \times 10^3$ tonnes. The total of oil discharged to the ocean was about 17.65×10^3 tonnes in 2000 (CMESC, 2004). In addition, the Vietnam coastal waters are touched by major Europe-Asia shipping routes and are affected by the heavy traffic.

In addition, construction of dams for hydroelectric power and irrigation purposes also have their impacts on coastal seas. On the one hand, retention of sediments in reservoir behind dams reduces the amount of sediments reaching coastal seas and thus affecting hydrodynamic systems and productivity in coastal waters (Milliman, 1997; Humborg et al., 1997; Ittekkot et al., 2000; Chen, 2000). Duc (2000) showed that building dams is an unsustainable way of development causing changes of ecosystem structures also within reservoirs behind dams mainly due to changing nutrient and sediment inputs. For example, with Hoa Binh reservoir near Hanoi, the constructed reservoir led to a reduction of forest coverage from 41% down to 17%; more than 167 million m^3 of sediment were trapped , which otherwise could have been discharged to lower catchments or to coastal waters.

Studies on the impact of changing river sediment inputs on coral reefs have been scarce. In one such study, An and Thu (2001) report that from November 29, 1998 to January 28, 1999, the coral reefs in southern part of Nha Trang Bay were covered by 0.52 g of sediment cm^{-2} with an estimated annual sedimentation rate of about 1.0–1.7 cm $year^{-1}$. This appeared to have led to the destruction of the reefs. Similar processes are probably occurring elsewhere along the coast.

Distribution of Elements and Biogeochemical Cycles in Vietnamese Coastal Waters

The Chlorophyll and Primary Production in the East Sea

There is strong spatial and temporal variability in the distribution of biogeochemical entities in Vietnamese coastal water. This related to the seasonality in material fluxes from land as well as in the prevailing

Table 4: Assessment of wastes discharged into marine environment of main areas

Area	*Kind of waste*	*Volume (m^3 day^{-1})*	*BOD (kg day^{-1})*	*COD (kg day^{-1})*	*TSS (kg day^{-1})*	*TN (kg day^{-1})*
Ha Long	Domestic	8500				
	Industry	59000	10158	16455	334585	22535
Ha Noi	Domestic	270000				
Da Nang	Domestic	44200	21879	38454	47515	
	Industry	9855	1350	3144	2188	
Dong Nai	Domestic	815205	107587	202773	87773	32832
catchments	Industry	153851	24880	39666	37030	8487
Mekong	Domestic	220312	109054	236835	236835	19828
	Industry	19216	2632	6131	4266	

Source: CMESRC (2004)

hydrodynamic conditions. This is best seen in the distribution of chlorophyll and primary productivity in the East Sea (Bien Dong) (Figures 1 and 2).

The chlorophyll content in the East Sea including upwelling regions ranges from 0.01 to 3.00 mg/m^3 while the primary production from 1 to 700 mgC/m^3/day. These values are higher than those available at the National Oceanographic Data Centre (NODC, 2002). Generally, chlorophyll-*a* content in coastal waters of the East Sea is higher than in offshore areas. Higher values along the coast are found in regions with large material fluxes from land such as off the mouths of the Red, Mekong and Dong Nai rivers and within some bays in central Vietnam (Figure 1). The places with high chlorophyll-*a* content are areas of high primary production (Figure 2). Especially high concentrations of chlorophyll and

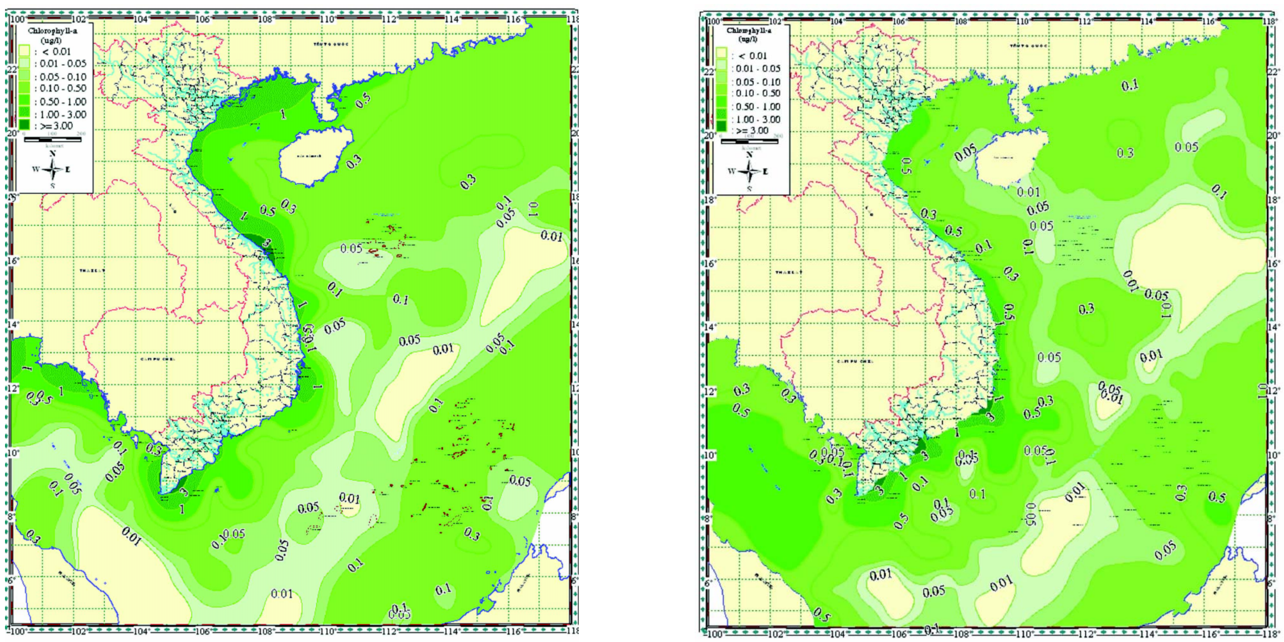

Figure 1: Distribution of Chlorophyll-*a* (mg/m^3) in the East Sea during the Northeastern (left) and Southwestern monsoon (right) seasons. (Source: National project: KC 09.02, 2004, unpublished).

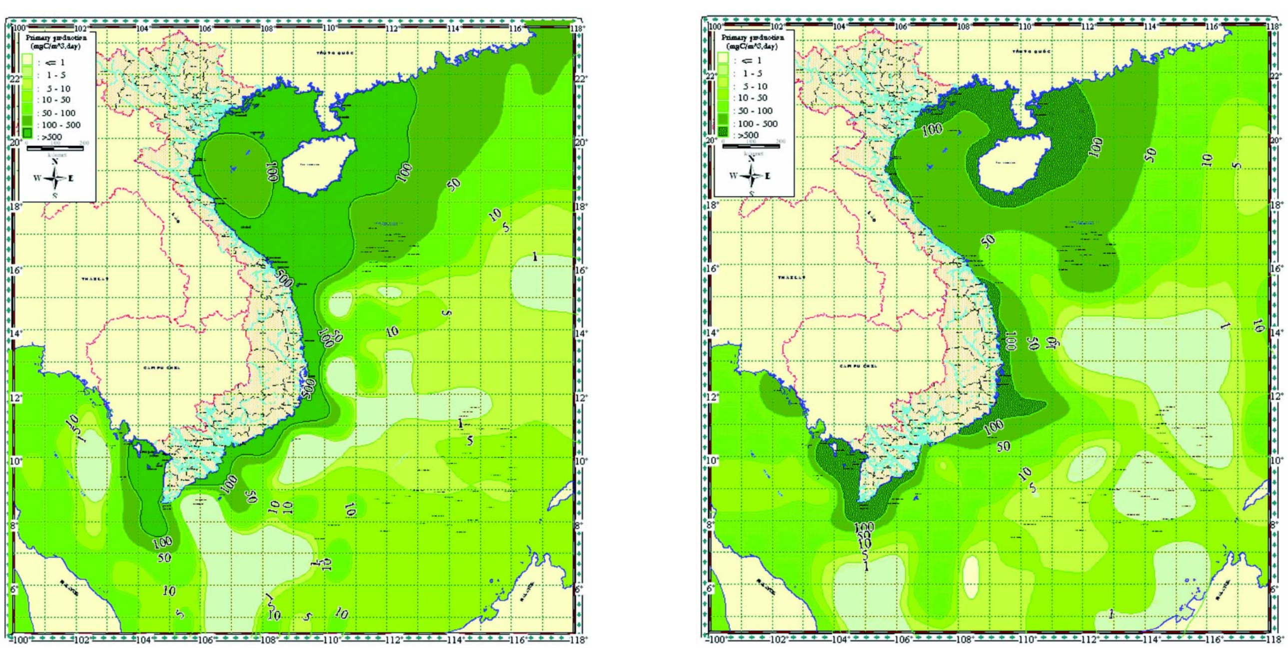

Figure 2: Distribution of primary production (mgC/m^3, day) in the East Sea during the Northeastern (left) and Southwestern monsoon (right) seasons. (Source: National project: KC 09.02, 2004, unpublished).

primary production are also found in upwelling areas in southwestern parts of the East Sea (An and Son, 2004; An et al., 2004). They exhibit average primary production of about 1980 mg C m^{-2} day^{-1} (An, 2003).

Material Cycles in Coastal Waters of Vietnam

Studies on the river systems of Vietnam based on the model in Box 1 (Gordon et al., 1996) show that the sources and sinks of C, N or P determine the biogeochemical cycling of elements in coastal waters. Furthermore, the current sources of elements from outside the ecosystem appear to balance biogeochemical budgets. Data presented in Table 5 show that estuarine systems are autotrophic ecosystems while bays or lagoons can be ranked from autotrophic to heterotrophic ecosystems. Cluster analysis shows however that only three rivers—Tien river (rainy season), Red river and Thu Bon river—are strictly autotrophic and exhibit the capacity to assimilate nitrogen ($P < 0.05$). In contrast, the other studied systems lack these characteristics (Box 2).

In a study of the Mekong River and the adjacent deltaic, estuarine, and coastal environment, An and Son (1998) could show differences in the elemental cycling between the river, front and plume, and shallow waters (Figure 3). They demonstrated that the estuarine systems in Vietnam are more eutrophic areas while the river and ocean can be ranked from eutrophic to oligotrophic. An and Son (1998) also could show that this model calculation was not influenced by sinks and sources of detritus from within the system. The model needs a standing production of 570 mgC/m^2/d for which a nutrient-consumption in the order of 118 mgN/m^2/day is required.

Box 1
Material balance within a system according to the model by Gordon et al. (1996)

For conservative material balance:

$$\frac{d(VS)}{dt} = \sum V_{in}S_{in} - \sum V_{out}S_{out}$$

Expanding this equation:

$$V\frac{dS}{dt} + S\frac{dV}{dt} = \sum V_{in}S_{in} - \sum V_{out}S_{out}$$

where ΣV_{in} and ΣV_{out} represent all of the hydrographic inputs and outputs and S_{in} and S_{out} are salinity of those water masses.

For non-conservative material balances:

$$V\frac{dY}{dt} + Y\frac{dV}{dt} = \sum V_{in}Y_{in} - \sum V_{out}Y_{out} + \Delta Y$$

where Y is material concentration in waters and ΔY = (Sources – Sink).

Table 5: Nonconservative fluxes and N-P biogeochemical cycles in Vietnamese coastal waters

Location	*Residence time (day)*	*ΔDIP mmol m^{-2} d^{-1}*	*ΔDIN mmol m^{-2} d^{-1}*	*p-r mmol m^{-2} d^{-1}*	*nfix-denit mmol m^{-2} d^{-1}*	*Reference*
Hau river	14*	+0.05	-0.02	-5	-0.8	Thu (2000)
Mekong river	4**	+0.40	+10.40	-42	+4.1	
Tien river	11*	+0.1	+1.2	-10	-0.5	Huan and Thu (2000)
Mekong river	1**	-2.2	+23.6	+233	+58.8	
Phan Thiet Bay	55*	+0.02	-0.3	-2	-0.7	Huan et al. (2000)
	6**	+0.22	-9.8	-23	-13.3	
Nha Trang Bay	67*	+0.05	-0.99	-6	-1.9	Huan (2000a)
	37**	+0.26	-0.35	-30	-5.0	
Van Phong Bay	61*	-0.0002	+3.2	+0.03	+3.2	Huan and An (2000)
	43**	+0.0002	+0.4	-0.03	+0.4	
Xuan Dai Bay	29*	-0.08	+0.009	+7.95	+1.21	Huan and Long (2004)
	5**	-0.14	+1.78	+15.41	+4.10	
Cu Mong Bay	71*	-0.004	-0.057	+0.37	-0.007	Huan and Long (2002)
	22**	+0.013	+7.658	-1.43	+7.45	
Thu Bon river	4	-25.58	-67.2	+271	+342	Huan (2000b)
Cau Hai lagoon	51*	-0.01	-0.39	+9.77	-0.21	Huong (2000)
	9**	-0.09	+0.56	+1.17	+0.65	
Red river	-	+0.96	+7.68	+288	+17.35	Wosten et al. (2003)

*: dry season, **: rainy season
p-r: Net ecosystem metabolism, nfix: nitrogen fixation and denit: denitrification

Box 2
Classification of N and P budgets in coastal waters in Vietnam

Hierarchical Cluster Analysis
Dendrogram using Average Linkage (Between Groups)
Rescaled Distance Cluster Combine

```
C A S E 0 5 10 15 20 25
Label Num +——+——+——+——+——+
VP R -+
CM D -¦
CH R -¦
PT D -¦
VP D -¦
Hau D -¦
NT D -¦
Tieu D -¦
CM R -¦
XD D -¦
CH D -¦
XD R -¦
PT R -+---------------------+
NT R -¦ +-------------------------+
Hau R -+ ¦ ¦
Tien R -----------------------+ ¦
Red -------+ ¦
ThuBon ----------------------------------------------+
```

VP: Van Phong Bay, CM: Cu Mong Bay, XD: Xuan Dai Bay, PT: Phan Thiet Bay, CH: Cau Hai lagoon, NT: Nha Trang Bay, D: Dry season, R: Rainy season

Factors Affecting the Biogeochemical Cycles of Ecosystems in Coastal Waters

It must be noted that the East Sea which receives most of the fluxes is a semi-enclosed marginal deep sea with its own seasonal dynamics, and this certainly has an impact on its biogeochemical processes. While being influenced by land-derived fluxes and near-coastal processes, biogeochemical processes driven by the internal East Sea dynamics in turn influence the former. This makes investigations of the processes difficult and there is a scarcity of information. In the following text we restrict ourselves to the three upwelling centres in the East Sea.

In the East Sea, the seasonally reversing monsoon system controls the surface circulation (Wyrtki, 1961). In summer, when the southwest monsoon prevails, winds blow primarily from south to north, and Indian Ocean surface water flows into the East Sea. In winter, these flow patterns are reversed by the northeast monsoon, and surface water enters the East Sea mostly from the western Pacific Ocean (Wyrtki, 1961). This brings with it a certain amount of nutrients which fuel primary production in the East Sea.

Total production in the northern East Sea has been determined to be ~38 mmol C m^{-2} d^{-1} (456 mg C m^{-2} d^{-1}) (Diego-McGlone et al., 1999) with particulate organic carbon export of about 2 mmol Cm^{-2} d^{-1} (12 mg C m^{-2} d^{-1}) (Michaels et al., 1994; Karl et al., 1996) and total export production about 5 mmol Cm^{-2} d^{-1} (60 mg C m^{-2} d^{-1}) (Emerson et al., 1997), while the primary production

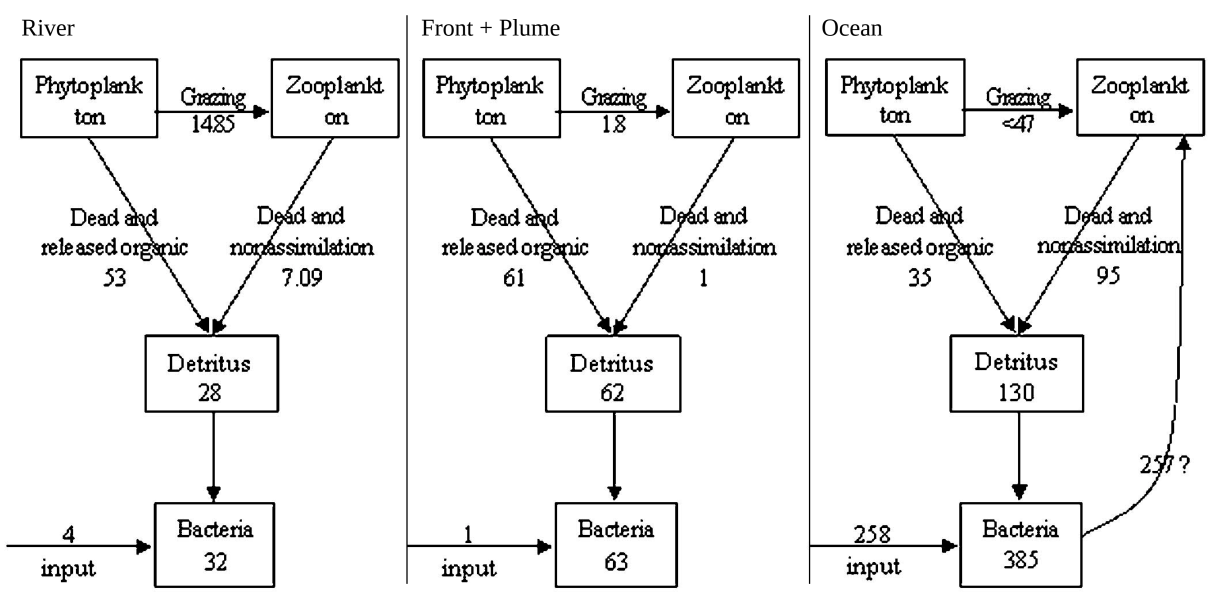

Figure 3: Carbon cycle for eutrophic zone of river, front + plume, ocean in Mekong Delta (unit: mg C/m²/day). (An and Son, 1998)

in waters off Vietnam was 569 mg C m^{-2} d^{-1} (An, 1995), in the continental shelf waters it was 776 mg C m^{-2} d^{-1}, and in the upwelling regions of southern central Vietnam it was 1980 ± 1969 mg C m^{-2} d^{-1} (An, 1997; An et al., 2004).

The East Sea is characterized by three upwelling areas: one between 16° and 19°N 100 km offshore the northwestern Philippines during winter (L area) (Chao et al., 1996; Shaw et al., 1996) and two centres located in the coastal areas of Vietnam during summer (Wiesner et al., 1996; Lanh, 1997) (V and S areas) (Figure 4).

Lanh (1997) found that maximum upwelling velocity in upwelling areas of coastal Vietnam is 13×10^{-4} cm s^{-1} at the 125 m water layer. The vertical upward fluxes in the East Sea play an important role in supporting the nutrient requirements in oligotrophic water bodies. In the coastal upwelling areas of Vietnam upwelling supplies about 0.05–0.10 mmol P m^{-2} d^{-1}; the upward phosphate flux in the Philippines upwelling area is 0.019 mmol P m^{-2} d^{-1}. However, the vertical fluxes of nitrate and phosphate to the euphotic zone contribute towards a molar N/P ratio significantly higher than the normal Redfield ratio of 16 throughout the region. It is 35 off the Philippines (Cai et al., 2002) and increases from 27 to 72 in the Vietnam upwelling regions. These values show that the upwelling does not play a role in relieving P limitation (Thom, 1997). Hence, it is implied that the East Sea is a P-limited system; that means the low productivity is due to the low vertical fluxes of phosphate (Cai et al., 2002).

Conclusions

The biogeochemical characteristics of Vietnamese coastal waters discerned from the distribution and behaviour of elements suggest that they are determined by human activities that control the material inputs from land as well by the prevailing hydrodynamics in coastal waters. Based on the observed biogeochemical characteristics,

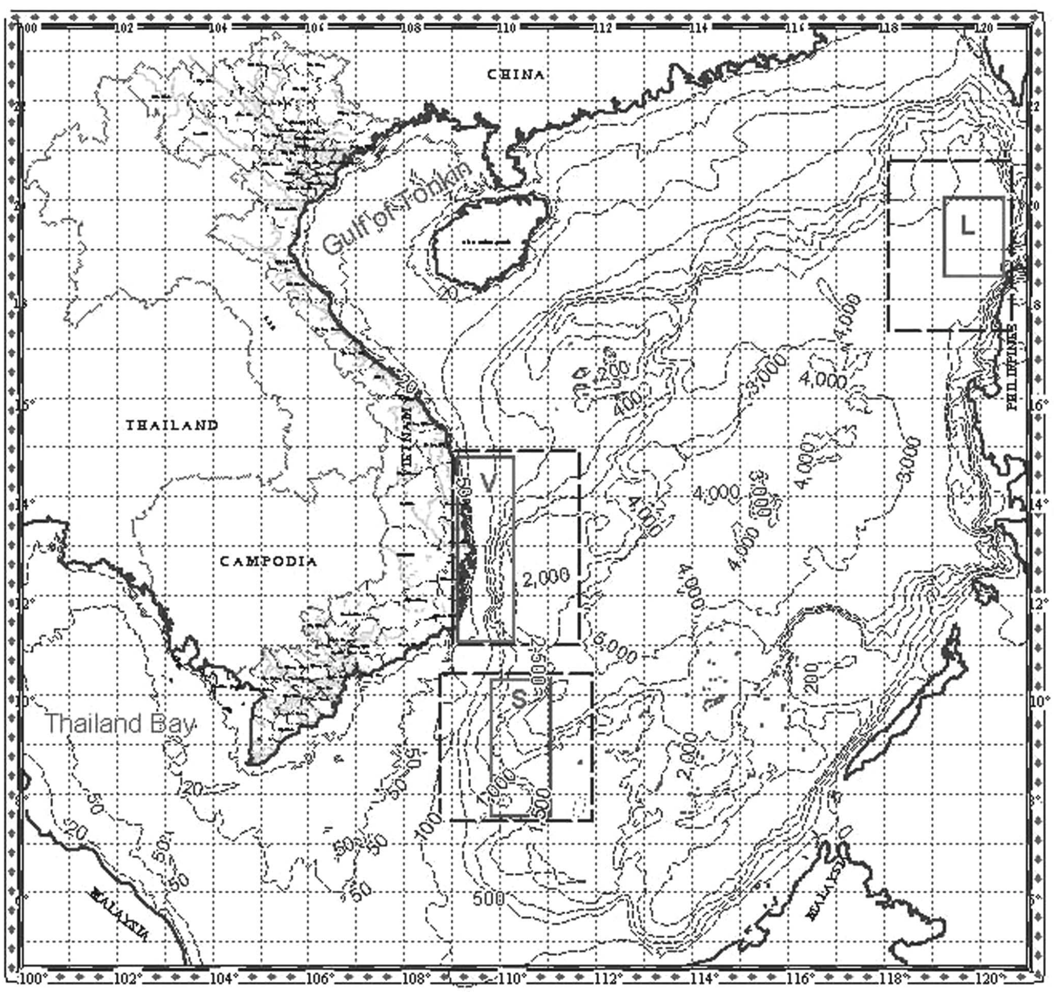

Figure 4: Three centres of upwelling in East Sea with high sea-surface chlorophyll concentrations. (modified from Lanh et al., 1997, Chao et al., 1996; Shaw et al., 1996)

the coastal waters can be classified into types: autotrophic and heterotrophic systems. Most of the larger estuaries are autotrophic systems whereas the others can change from autotrophic to heterotrophic systems or be heterotrophic systems. These findings have important implications in developing measures for the protection of environment and natural resources of coastal ecosystems of Vietnam.

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