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Open Sea Paralic Ecosystems South of Java Sea: Environmental Approach by Flow Cytometry

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ABSTRACT

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The organization and functioning of several sites of shrimp production along the northern Java and Sumatra coasts have been studied through the following parameters: usual hydrological parameters, total suspended matter, suspended organic matter, suspended mineral matter, planktonic chlorophyll *a* and phaeophytin contents. Additionally, the structure and composition of phytoplanctonic populations was analysed by flow cytometry.

From obtained data on the site of Jepara (which is representative of all sites south of Java Sea), it appears that all coastal environments including open marine environments undergo a high confinement level. This is depicted by the drastic simplification of the natural as well as aquacultural ecosystems; the natural benthic macrofauna is almost completely absent and the other organisms are only procaryotes which grow in such ecosystems at the continental edge of the paralic realm. Studied systems are rather stable through time and display gradients from offshore towards the most restricted parts of the aquacultural structures, *i.e.*, the semi-intensive and intensive ponds. These gradients move following the tidal cycles.

A studied site in Sumatra along the Malacca straits displays similar gradients but a lesser confinement which is indicated by the presence of more diversified phytoplanctonic populations. In all studied sites, the intensive aquacultural practices tend to increase the confinement level not only for the aquacultural installations themselves but also for the offshore environments.

ADDITIONAL INDEX WORDS: *Paralic, confinement, Java, phytoplankton, aquaculture.*

This contribution is a first step towards the knowledge of the organization and functioning of coastal environments south of the Java Sea. It summarizes the preliminary studies carried out as part of the ASEAN-CEE program which aims at establishing the ecosystemic place of aquaculture and its influence over the environments in South East Asia.

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GEOGRAPHICAL SITUATION

The Java Sea is bordered south and west by Java and Sumatra Islands (Figure 1). These are composed of a ridge of mountains flanked by coastal plains. On the Indian Ocean side, the coastal plains are very narrow. Furthermore, the continental shelf is little developped or absent and the depths reach rapidly several thousands meters. On the opposite side, *i.e.*, along the Java Sea, the coastal plains are much wider, up to 250 km in Sumatra. These plains are covered by a dense hydrographical network grossly perpendicular to the coastline.

The lower part of the coastal plains is made of the succession and juxtaposition of deltaic systems which are constantly prograding towards the open sea. The speeds of progradation widely vary from 12–30 m per year to more than 200 m per year at certain river mouths. The inner part of this region is generally occupied by rice fields which use the freshwater coming from the hydrographical basins. The outer coastal part is occupied by a multitude of basins (or tambaks) which are used for semi-intensive to intensive aquaculture, the production of which is nearly exclusively the prawn *Penaeus monodon*.

The Java Sea extends offshore and covers a wide submarine plateau (around 370,000 km^2). The Java Sea is remarkably shallow with a mean depth of 46 m. The deeper point is situated between Java and Kalimantan with less than 70 m. Thus the Java Sea is a very young one and the present bottom was totally emerged during the last glaciation (around 15,000 years BP), as well as the Gulf of Thailand (DICKERSON, 1941). The Holocene rise of sea level induced the transgression of restricted (paralic) environments on this plane area (GUELORGET and PERTHUISOT, 1983, 1992) with two large bays separated by a narrowing sill extending from Sumatra to Borneo. Even after the sill was swallowed, the active currents of the Java Sea tended to maintain this paralic bulk of water within the present limits of Java Sea. Thus, historically, the Java Sea has always been largely paralic from its origin.

The total volume of water of the Java Sea is quite small, around 2,000,000 km^3. The cumulated surface of hydrological basins (over Java, Sumatra and Borneo) which discharge into the Java Sea is of the same order of size as the sea itself. When considering the usual regional rainfall (which largely exceeds 1,000 mm/year), that means that the Java Sea is, and has always been, under a considerable continental influence which is underlined by salinities lower than in neighbouring oceans.

The climate is characterized by two alternating marked seasons. The dry season extends from April to October, the very rainy humid one from November to March. More or less depending upon the wind orientation, the general circulation of waters in the Java Sea is from west to east during the rainy season and the reverse direction during the dry season (WYRTKI, 1961). As a result, there is a swinging of the Java Sea water mass which is depicted by alternate invasions of salty water tongues at both tips of the sea. It is worth noticing that, southward and westward, the currents always flow toward the Indian Ocean through the straits that interrupt the Indonesian range.

In spite of the general movements of the Java Sea, the littoral drift along the northern coast of Sumatra and Java is always oriented eastwardly as depicted by the clockwise curve of the turbid plumes offshore the river's mouths. It is not possible to make allowances for the Coriolis force; it is very weak at such low latitudes, and would orientate the plumes to the other direction, at least in the southern half of Sumatra and in Java).

Finally the Java sea, as a whole, acts as a paralic system due to restricted exchanges with its oceanic environments and to the importance of continental inputs from surrounding lands and islands. This original situation is depicted by: the turbidity of coastal waters, the absence of coral reefs, and the mobility of coastlines under effect of deltaic progradation.

When considering this situation and before any detailed study, one may expect a high confinement (GUELORGET and PERTHUISOT, 1983, 1992) of coastal environments along the northern shores of Sumatra and Java Islands.

MATERIALS AND METHODS

The whole study took into account eight aquacultural sites from the extreme west of Sumatra to the extreme east of Java (Figure 1). Given the almost total absence of benthic macrofauna, this first scientific approach was concentrated on phytoplanktonic populations of littoral waters and of several rearing basins. These extend from extensive to semi-intensive then to intensive basins.

The usual hydrological parameters (pH, conductivity, dissolved oxygen content, temperature) were measured on the field using a multiparameter probe HORIBA. Water samples were collected for phytoplankton analyses and measures of the following parameters: total suspended matter (seston), suspended organic matter by fire loss at 450 °C, and suspended mineral matter.

The abundance of phytoplankton was evaluated by the chlorophyll *a* biomass and its degradation level by the percentage of phaeophytin. Both were measured by fluorimetry following the method described by NEVEUX (in AMINOT and CHAUSSEPIED, 1980). The structure of phytoplankic communities was analysed by flow cyto-

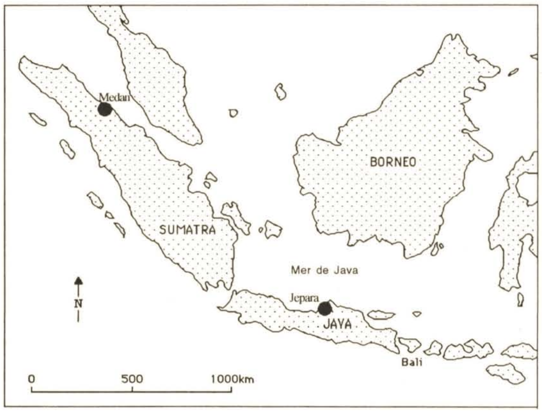


Figure 1. Sites of studies in Indonesia.

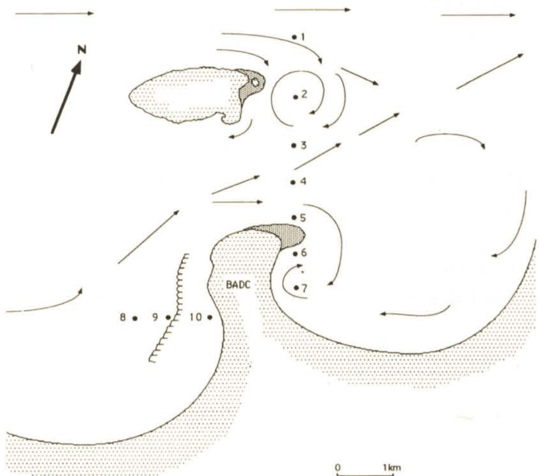


Figure 3. The offshore stations of studies and the littoral currents in the region of Jepara. □—Accumulation of sediment.

metry (Phinney and Cucci, 1989; Platt, 1989; Yentsch and Horan, 1989; Troussellier *et al.*, 1993). Fresh samples were fixed with paraformaldehyde (0.5% final concentration) and were kept in the dark at 0 °C (Vaulot *et al.*, 1989).

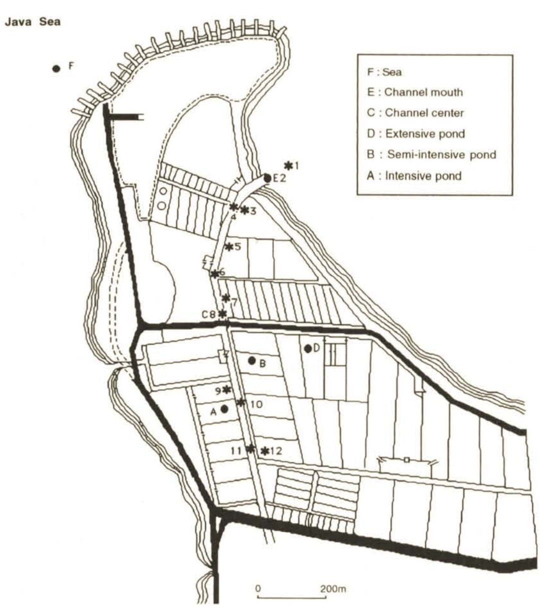


Figure 2. Situation of the stations of studies in the BADC Farm. *—mission 1990; ●—missions 1991–1992.

Flow Cytometry

Samples were analysed with a cell analyser equipped with a mercury lamp (ACR 1,400 SP, Bruker Spectrospin, Wissembourg-France). For phytoplankton, light excitation wavelength used was 470–490 nm, while green and red fluorescences were separated with a LP640 nm dichroic filter and selected using a BP580 ± 20 nm and a BP680 ± 20 nm filters. Duplicate sample volumes were measured for each station and the data stored in data mode and list mode. Four parameters per cell (forward and wide angle light scatters, green/yellow and red fluorescences) were recorded on a 3.3 decade logarithmic scale mapped onto 256 channels. Instrument calibration was achieved with 1 μm fluorescent beads (Polysciences, Warrington, PA, U.S.A.). Data collected on a HP-compatible computer were analysed with Flower software (Bruker-Spectrospin). Phytoplanktonic subpopulations of the samples were identified according to their light scatter (related to cell size) and their green/yellow and/or red fluorescence due to the presence of natural pigments (biliproteins, chlorophylls). The number of cells and the mean values of the cellular parameters for each subpopulation was computed after conversion of the logarithmic scales to linear ones. Used as an internal standard (because their light properties are stable), 1 μm fluorescent beads (Polysciences) normalized the mean subpopulation parameters

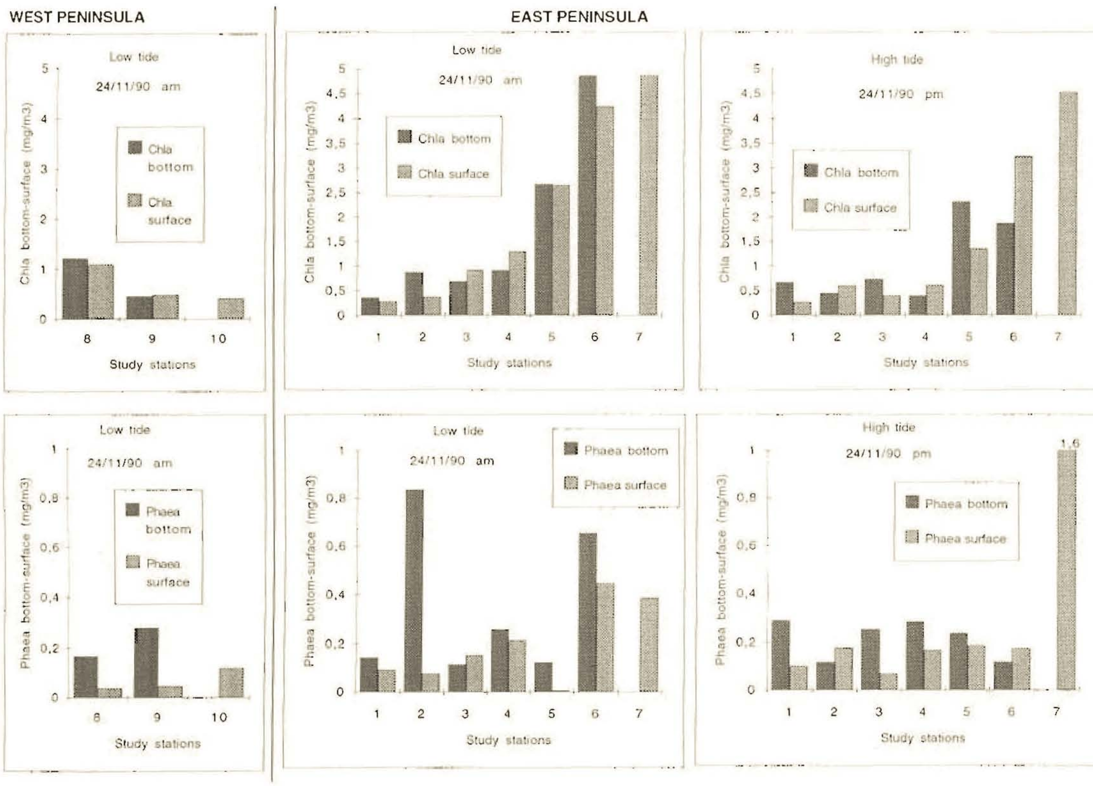


Figure 4. Variations of chlorophyll and phaeophytin biomass in the sea.

through division by the corresponding parameters measured on the beads. The study of phytoplanktonic populations, so characterized by their relative size and pigment contents, could be extended to large areas to evaluate their spatial and temporal evolutions.

Among the eight sites studied (Figure 1), seven are very similar, or identical for all measured parameters and phytoplanktonic communities structures. It was unnecessary in this paper to multiplicate examples; thus, only the Jepara site is presented here as representative of the whole South Java Sea coastal ecosystem. The eighth site, Medan, situated at the western end of Sumatra Island closer to the ocean, is rather different. It is also presented.

THE SITE OF JEPARA

The site of Jepara (Figure 1) is a wide bay cut by a peninsula which stretches towards an island a few kilometers offshore. This situation is very typical of the southern shore of the Java Sea, along which bays and peninsulas alternate more or less regularly. Islands often stand on the prolongation of peninsulas. An aquacultural farm (BADC) was set up on the Jepara peninsula for both experimentation and production of *Penaeus monodon* (Figure 2). Interestingly, this farm is composed of all types of rearing basins, from the traditional ones to the intensive ones. Given the surface occupied by aquaculture farms all along the coast, the channels and ponds have to be considered together with coastal open waters as functioning parts of a single ecosystem. This is the case for all the southern coast of the Java Sea.

Offshore

The studied parameters give indications on the system dynamics. The general direction of currents is parallel to the coast, eastward. This is depicted by sedimentary bars pointing eastward from the island and the peninsula (Figure 3). This

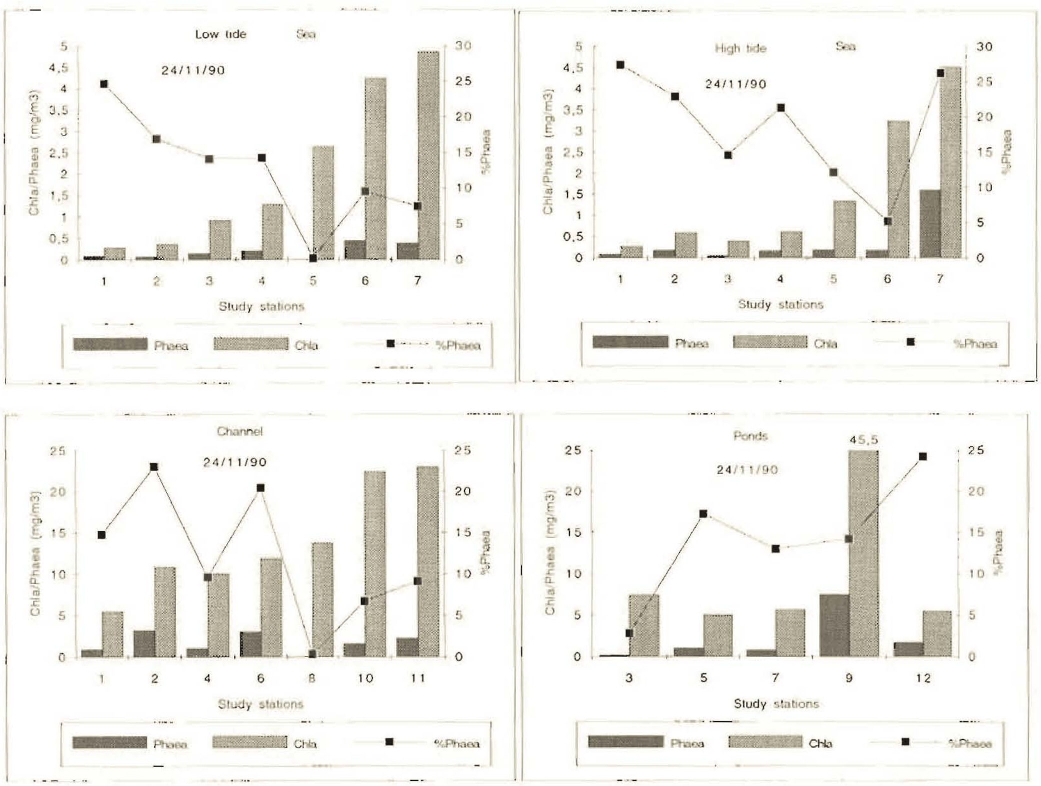


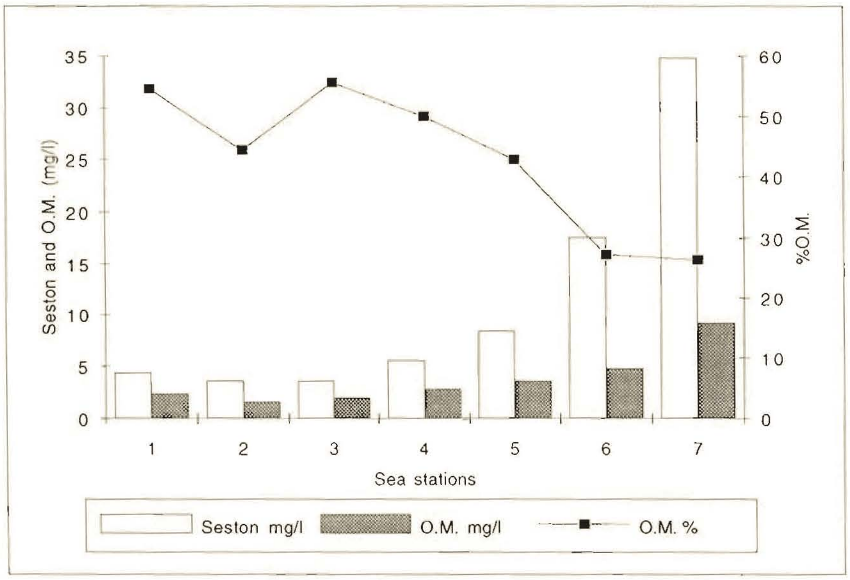
Figure 5. Variations of chlorophyll *a* and phaeophytin *a* biomasses.

situation has prevailed for a long time; it is also depicted by the presence of a fossil coral reef solely off the eastern coast of the peninsula. Several zones of current stagnation, also called hydraulic umbilicus (GUELORGET *et al.*, 1989; PERTHUISOT and GUELORGET, 1992) situated downstream from emerged obstacles (island, cape), are characterized by high chlorophyll biomass and high phaeophytin percentage on the bottom; this depicts the sedimentation of degenerating cells at the Stations 2 and 6 (Figure 4 and 5).

In the axis of the strait between the peninsula and the island, the currents accelerate which induces a decrease in the chlorophyll biomass and in the percentage of phaeophytin. Downstream from the strait, northeastward, the drift breaks into two branches. The southern one curls around the eastern bay towards the BADC peninsula; it tends to maintain the stagnation of waters in the shelter of the peninsula and is near the entrance to the farm. This entrance is thus situated in the most unfavourable location. As a matter of fact, these stagnant exhausted waters are of bad biological quality. Besides, as this zone receives the water out-put of the farm, the problem increases severely.

Globally, there is a permanent positive gradient of the phytoplanktonic biomass and of the percentage of phaeophytin from offshore stations towards the edge of the bays. Concurrently, there is an increase of total suspended matter even though the percentage of organic matter decreases (Figure 6). As there is neighbouring continental input to the system, this could only be explained by an increase of bacterial mineralisation, especially carbonate production (CASTANIER, 1987).

These gradients are not disturbed by the tidal cycles (the maximum tidal range is 1 m). They only shift following flood and ebb tides (Figures 2, 7 and 8).



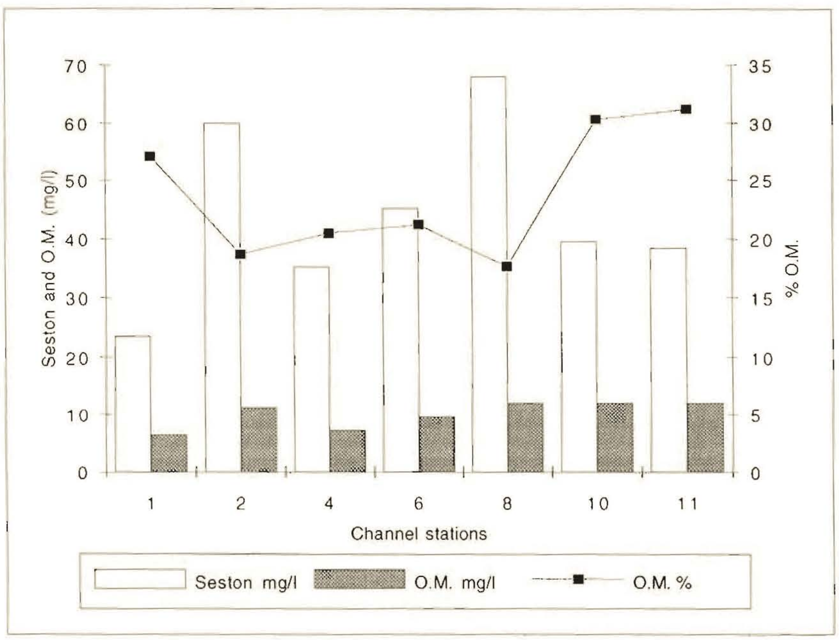


Figure 6. Variations of the seston and the organic matter (O.M.) from offshore to inshore in the sea (up) and in the channel of the farm (down), (24/11/1990).

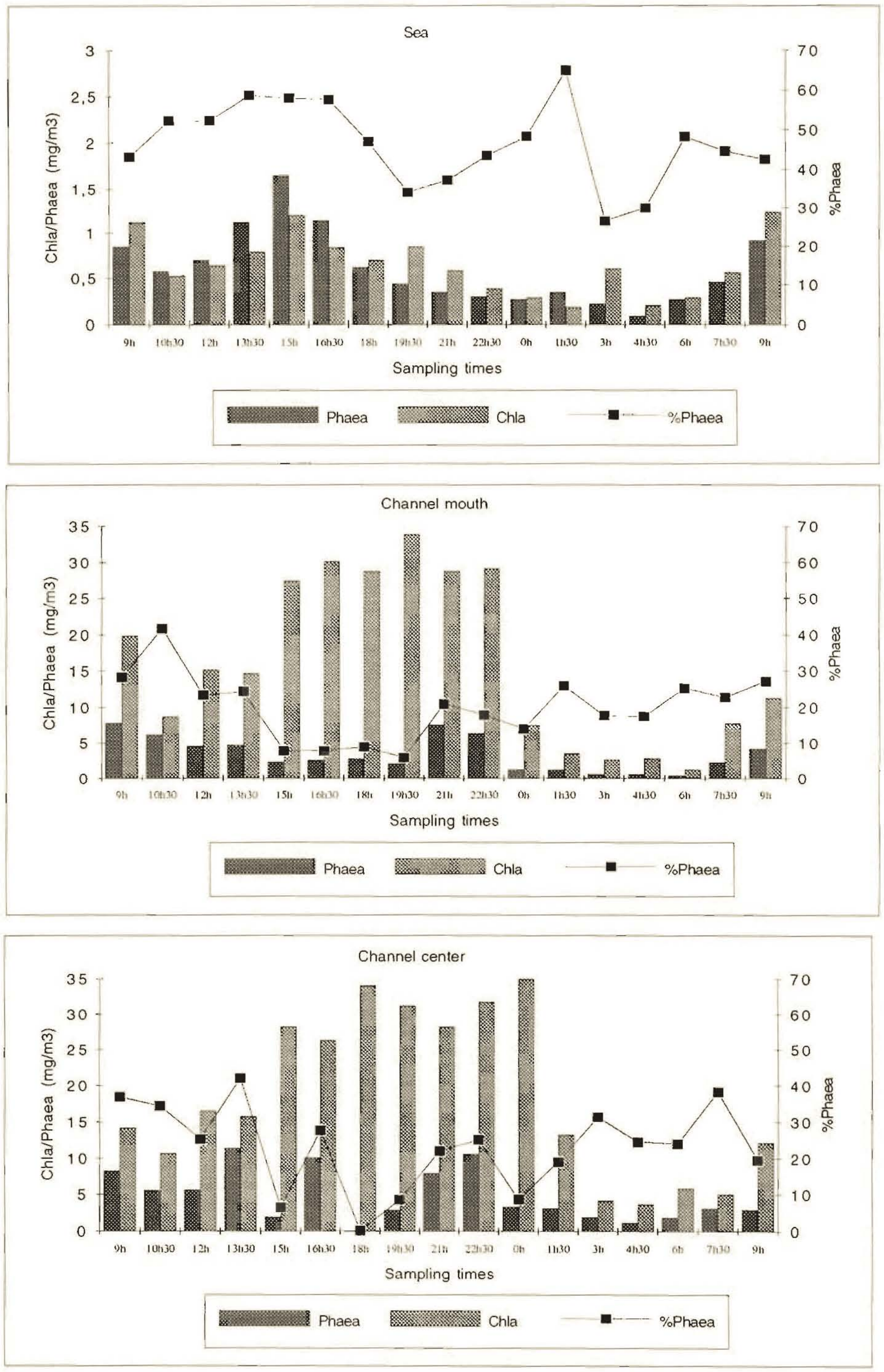


Figure 7. Diurnal variations of chlorophyll *a* and phaeophytin *a*.

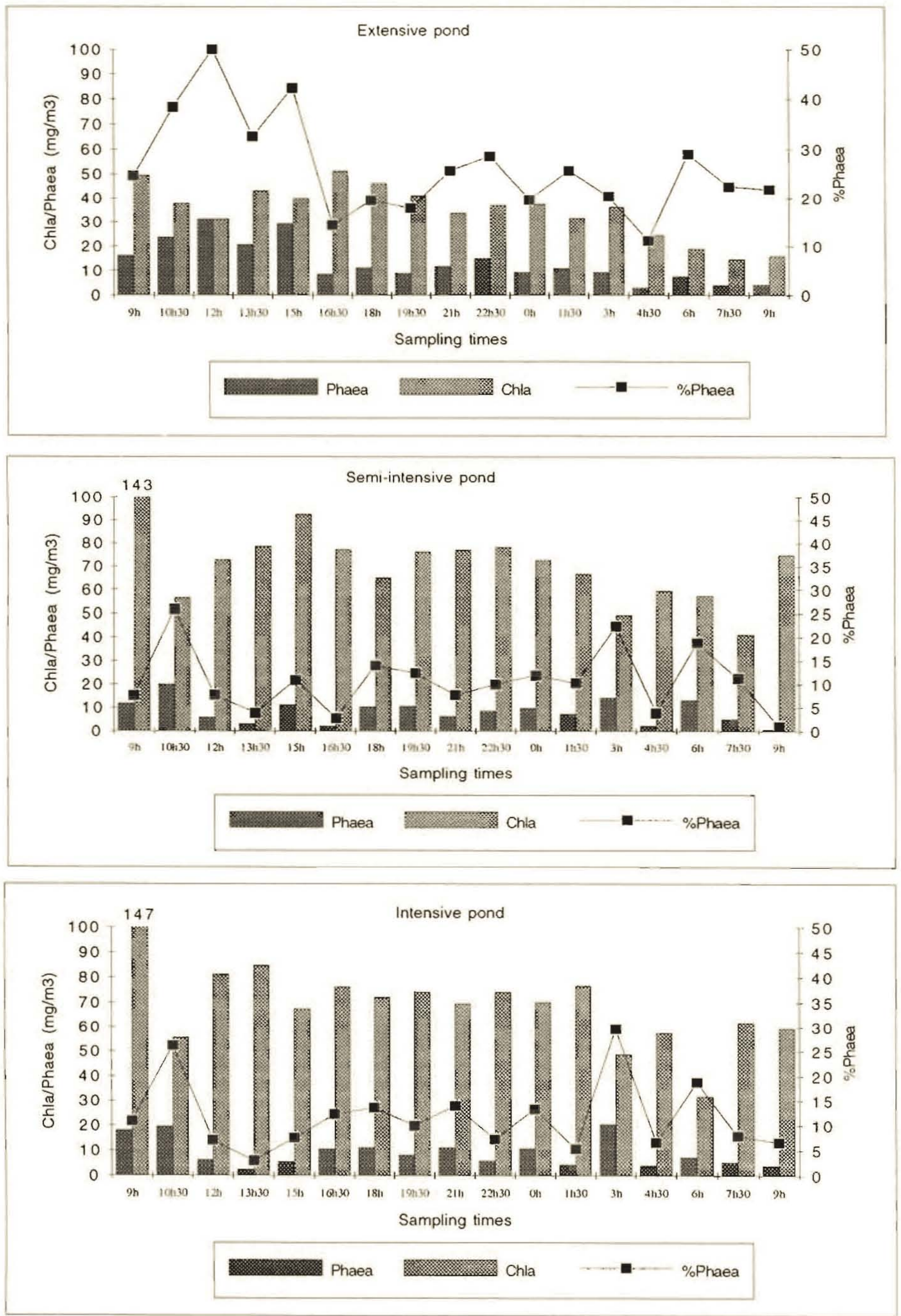


Figure 8. Diurnal variations of chlorophyll *a* and phaeophytin *a*.

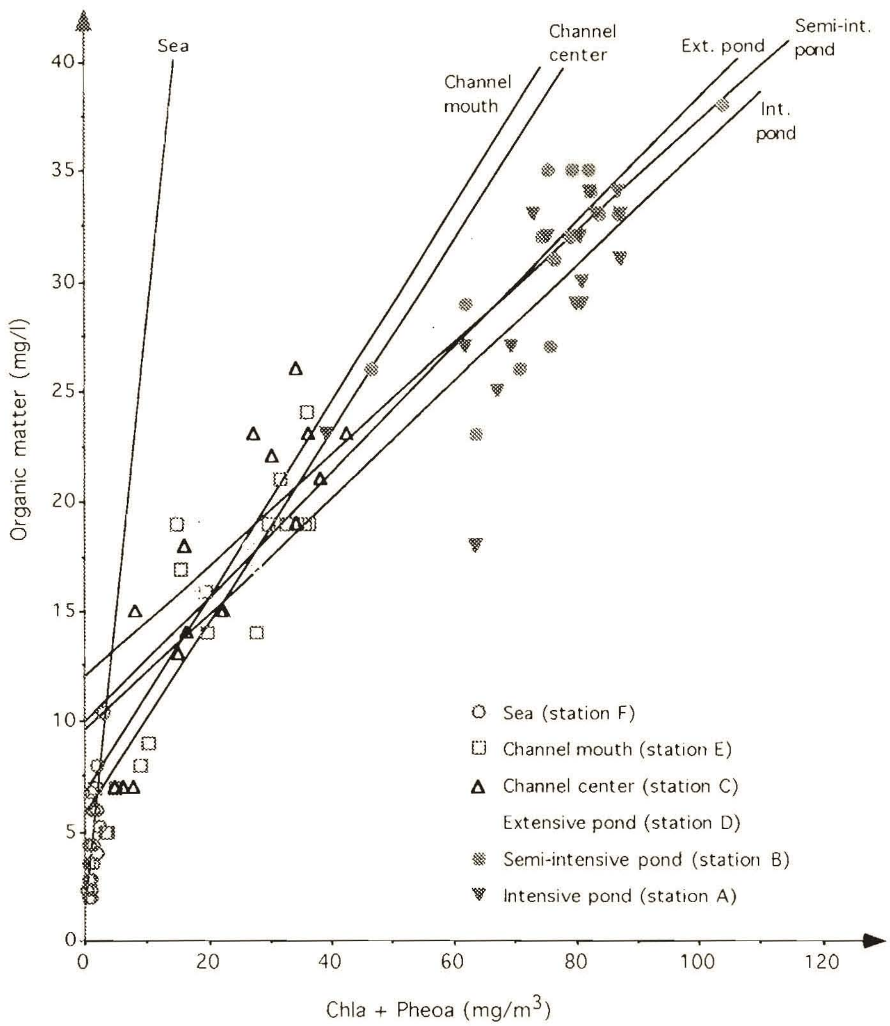


Figure 9. Relations between organic matter and chlorophyl *a* + phaeophytin *a* biomass.

Linear correlation informations

Stations	Frequency:	R:	R^2:	Adj. R^2:	Std. Error:
F	17	0.78	0.61	0.58	1.5
E	17	0.9	0.8	0.79	2.83
C	17	0.89	0.8	0.78	2.87
D	17	0.71	0.5	0.47	4.71
B	16	0.78	0.61	0.58	2.66
A	16	0.74	0.55	0.52	3.09

Finally, the coastal system is very stable and the quantitative variations of the phytoplanktonic, and more generally, the sestonic load remains moderate (Figure 9). Such an homogeneity is also found for hydrological parameters which depict very weak gradients and no stratification of waters. Meanwhile, the comparison between total suspended organic matter (TSOM) in suspended

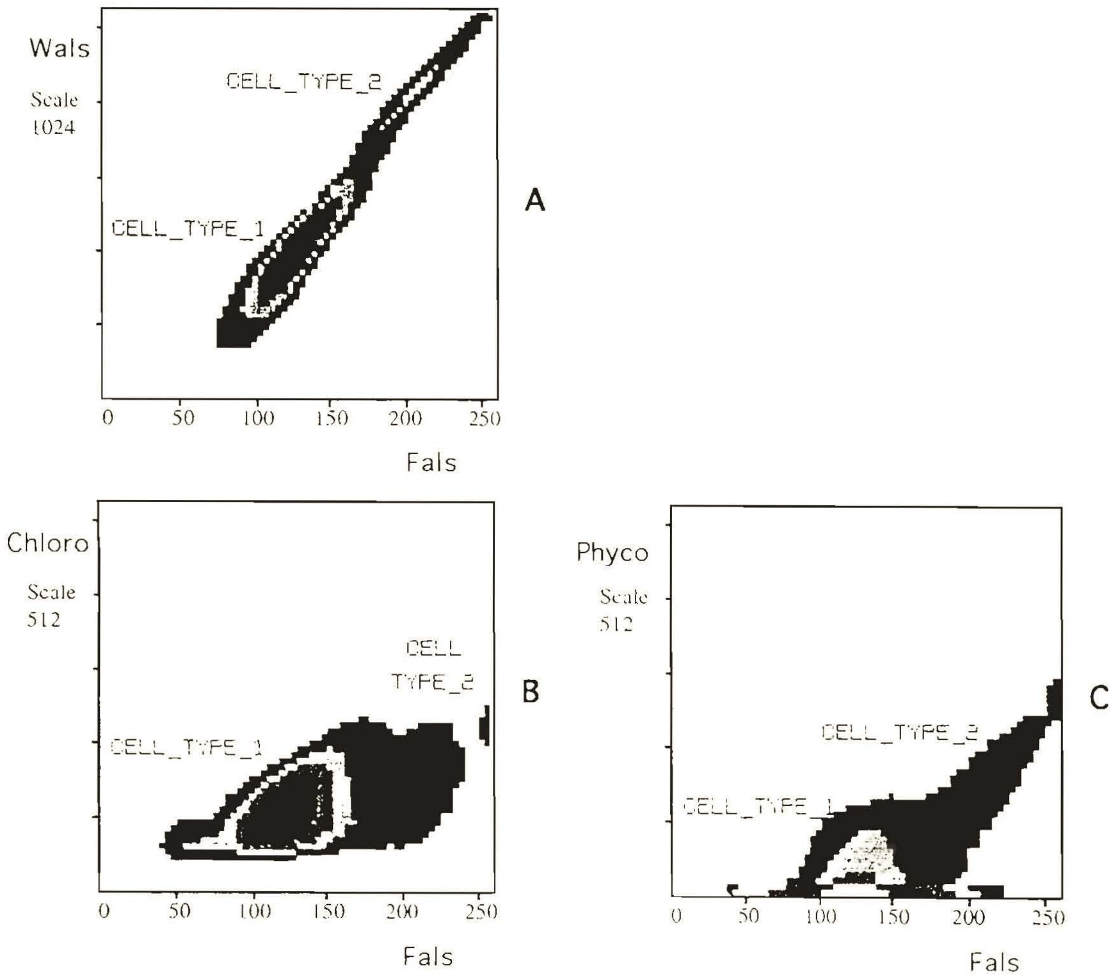


Figure 10. Flow cytometry analyses of the phytoplanctonic assemblage of Jepara. Datas from samples up to 0.5 ml are presented as two dimensional flow contour plots. Measurements were performed using a Bruker-Spectrospin 1,400 SP flow cytometer (TROUSSELLIER *et al.*, 1993). Left: A—Forward and wide angle light scatter cell properties related to cell size. B—Forward angle light scatter *versus* red fluorescence related to chlorophyll *a* content (660–700 nm). Right: C—Forward angle light scatter *versus* green fluorescence related to phycoerythrin content (540–630 nm).

matters and pigments (Chlorophyll *a* plus phaeophytin) biomass (PB) displays a clear lateral gradient from offshore towards intensive ponds (Figure 9). Besides, at each station there is a good linear correlation between TSOM and PB so that it is possible to write:

$$TSOM = a\ PB + b$$

a is the slope of the regression line, b is its intercept at the origin.

This means that at each station the variations of biomass are directly due to the variations of chlorophyllian metabolic activity, *a* decreases from station F to station A and B which indicates a decrease of the efficiency of planktonic photosynthesis from offshore towards the most confined environments in the farm and is probably a more or less gradual change in the physiology and/or composition of the chlorophyllian planktonic populations. b is nil at station F which indicate that offshore the whole suspended organic matter is of chlorophyllian origin. b increases to station

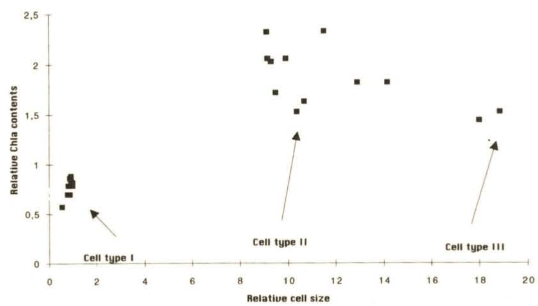


Figure 11. The different phytoplanctonic populations characterized by their light scatter and pigment properties normalized with 1 micrometer beads.

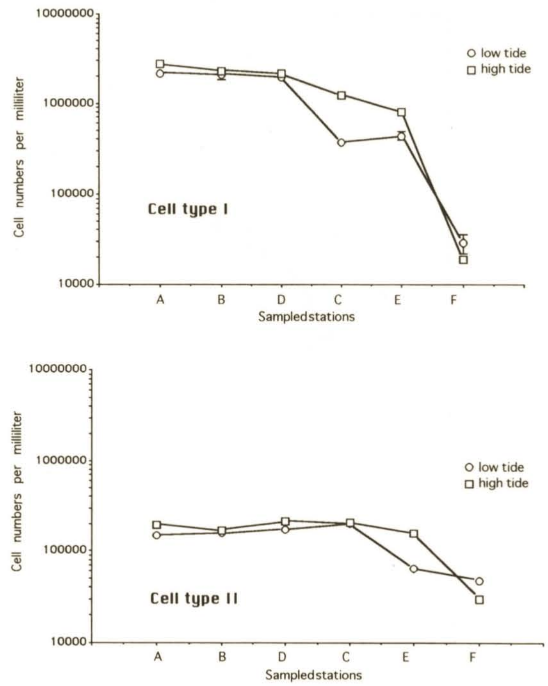


Figure 12. Cell numbers per milliliter in Jepara sampled stations (low tide and high tide).

E to stations A and B which means that part of the suspended organic matter is not of chlophyllian origin and that its proportion within suspended matter increases towards the most confined parts of the farm. The origin of this organic matter is still unknown but must come from the aquacultural activities, *i.e.*, bacteria and/or detritus from the grown prawns; no continental matter enters into the farming system. Obviously, the aquacultural activities are a major factor of confinement for the whole coastal system. The situation as outlined here occurs during the dry season. During the rainy season conditions should be slightly different because of freshwater inputs into the system.

The analysis of chlorophyllian plankton by flow cytometry depicts two main populations of cells (Figures 10 and 11). The first one (Cell Type I) is composed of small cells with a relative low content in chlorophyll. The second one (Cell Type II) is composed of larger cells with a higher relative chlorophyll content. Microscopic observations confirm the presence of small cells most probably belonging to the composite genus *Synechococcus* (Cell Type I) and of filamentous cyanobacteria (Cell Type II). Additionally there are some larger cells with a pigment content similar to Cell Type II. They could belong to a third cell type or to degenerating individuals of Cell Type II. An additional population (Cell Type III) may be evidenced when comparing the relative cell sizes and the relative chlorophyll contents of phytoplanktonic cells (Figure 11). It is far less important than the populations cells Type I and II. The filamentous cyanobacteria are possibly removed from the microbial mats with several genuses, among which is *Lyngbya* that covers all the intertidal substrates. The composition and structure of this chlorophyllian plankton remains stable through space, up to several kilometers offshore, and time, notably with tidal movements.

The Farm

The farm is composed of an axial channel in which the water comes and goes freely with tides. Several types of ponds are arranged on both sides of the channel. In the traditional extensive ones, the water renewal is submitted to the tidal oscillations. In the semi-intensive and intensive ponds, the water renewal is regulated by pumping from the channel at high tide and gravitarian outflowing in the same channel at low tide. Given the situation of the entrance of the channel at the bottom of the bay, near a hydraulic umbilicus, it is nearly the same bulk of water which is recycled into the aquacultural system at each tide. It is worth noting that nearly all aquacultural farms on the north coast of Java and Sumatra are organized in the same way, with a single axial chan-

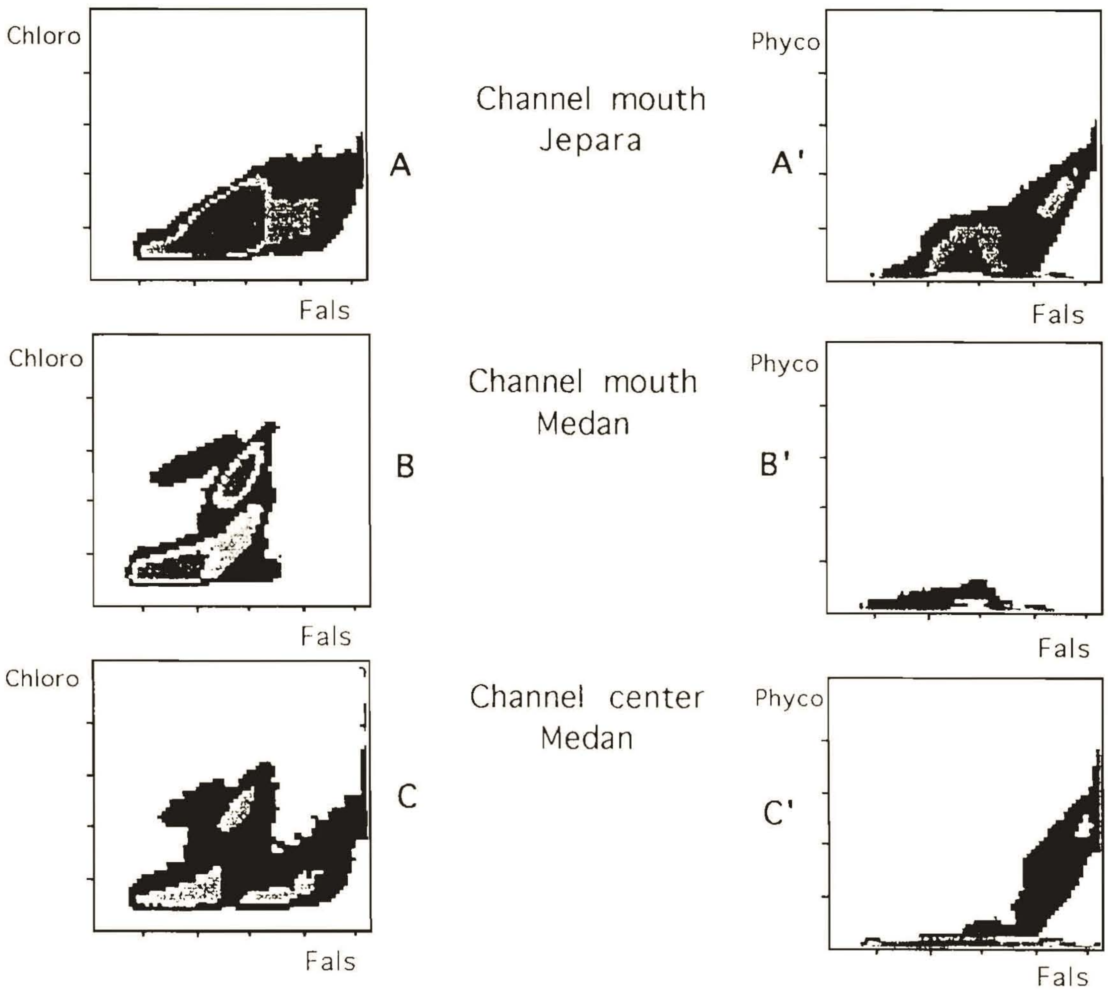


Figure 13. Flow cytometry analyses of the phytoplanctonic assemblage of Jepara and Medan. Datas from samples up to 0.5 ml are presented as two dimensional flow contour plots. Measurements were performed using a Bruker-Spectrospin 1,400 SP flow cytometer (TROUSSELLIER *et al.*, 1993). Left: Forward angle light scatter *versus* red fluorescence related to chlorophyll *a* content (660–700 nm). A: Jepara; B and C: Medan. Right: Forward angle light scatter *versus* green fluorescence related to phycoerythrin content (540–630 nm). A': Jepara; B' and C': Medan.

nel. Additionally, they are located in similar geomorphological situations, in bottoms of bays, at river mouths, or on their lateral levees.

The measurements carried out in this system show that the gradients described offshore continue inside the channel, at the end of which the chlorophyll biomass reaches nearly 25 μg/l. The maximum biomass is obtained in the intensive ponds with often high percentage of phaeophytin. Over a tidal cycle, the only variation is a general increase of chlorophyll biomass at high tide and a general decrease at low tide. This corresponds only to the tidal translation of the biomass gradient.

This is confirmed by the homogeneousness of the planktonic association which is only composed of Cell Type I and Cell Type II and by their gradients of abundance (Figure 12).

Finally, the whole coastal zone, offshore as well as in the aquacultural installations, is occupied

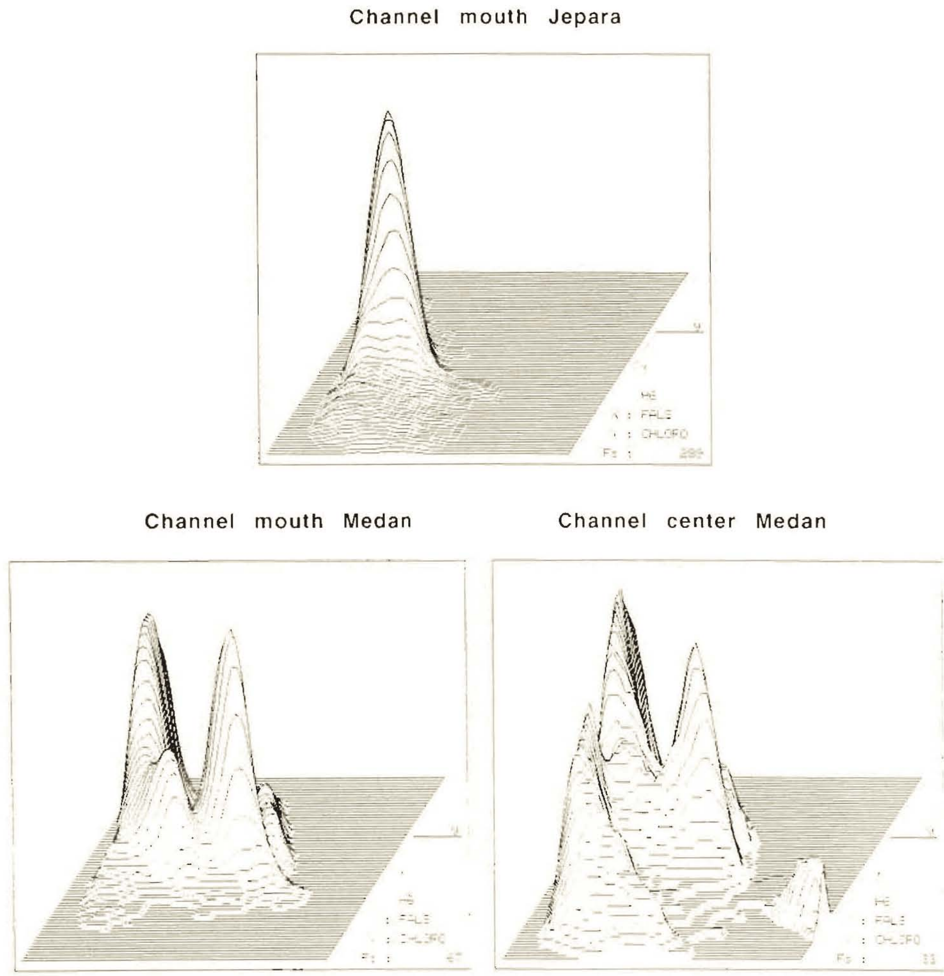


Figure 14. Tridimensional representation of phytoplanktonic assemblage of Jepara and Medan (Figure 16: A, B and C). x: Forward angle light scatter (Fals), y: Chlorophyll *a* content, z: Number of cells.

by a single chlorophyllian planktonic population. Furthermore, there is always a positive gradient of biomass (*i.e.*, of density of the population) from offshore towards the most restricted tips of aquacultural installations. The only variation is a horizontal shifting or translation of the whole system following the tidal movements. All data and observations, notably the total lack of benthic macrofauna, indicate that the whole littoral zone, several kilometers wide, is a highly confined (restricted) environment (Zone V and VI) following the classification proposed by GUELORGET and PERTHUISOT (1983, 1992). The biological populations are only composed of Prokaryotes (Cyanobacteria and bacteria).

Here, in apparently open marine conditions, stands the most confined zone of "Near Paralic" subdomain, as defined by GUELORGET and PERTHUISOT (1992), which usually occupies the most restricted continental parts of lagoonal systems. Thus, at least a large part of the Java Sea must be considered as "lagoonal" and belongs to the paralic domain (GUELORGET and PERTHUISOT, 1992). The drastic simplification of this ecosystem shows the exhaustion of the medium and its incapacity for classical farms of aquaculture. The site of Jepara is representative of the whole ecosystem that follows the whole southern coast of the Java Sea all along Java and Sumatra Islands.

THE SITE OF MEDAN

The main difference between Medan and Jepara is the location of the farms situated on the coast of Malacca Strait, *i.e.*, in the vicinity of Indian Ocean waters. Meanwhile, the geomorphologic environment and aquacultural setting are similar. Offshore data are lacking but the flow cytometry analyses of samples collected in the axial channel of a shrimp farm show that the chlorophyllian planktonic population is rather different from that of Jepara (Figures 13 and 14). At the entrance of the channel (channel mouth), the population is diversified with at least 6 or 7 cell types. The Cell Type I is present again and very abundant. The other cell types seem to belong to chlorophycean groups. Further inland (channel center), the population is similar but a large number of filamentous cyanobacteria (Cell Type II) appears.

The interpretation of such results is difficult. The abundance of Chlorophyceae might indicate a lesser global confinement than at Jepara under the vivifying influence of Indian Ocean waters. The filamentous cyanobacteria must be considered as autochthonous, *i.e.*, related to the farm itself, especially to its most restricted parts. The coccoid cyanobacteria could then be considered as a contamination of this region by the planktonic populations carried through the Malacca Strait from the southern coast of Java Sea. This hypothesis should be tested at intermediate stations along the Malacca Strait.

Anyhow, the site of Medan seems to be a better environmental condition for aquaculture when considering the diversity of phytoplankton as compared to that of Jepara. Meanwhile, the possibility of increased contamination in the ultra confined coastal system of the southern coast of Java is a real fear.

CONCLUSION

This first study shows the existence along the southern coast of the Java Sea, apparently in open marine conditions, of extremely confined environments. This exceptional situation is partly due to the configuration of the sea, to the hydrological system and probably also to the recent story of the sea. Obviously, the generalization of aquacultural practices along the Sumatra and Java coast are mainly responsible for the high rate of confinement of coastal waters. From this point of view, one may consider that the intensification of aquaculture is responsible for the falling of the whole southern coastal zone of the Java Sea into a cyanobacterial realm, stable over the long haul and unsuitable to support an economically profitable aquaculture.

The newly acquired knowledge of the organization and functioning of coastal and paralic systems, together with modern scientific technological investigation, allow a rapid evaluation of the potentialities of a given environment, the proper place for different species to be reared, the different types of aquaculture to be implemented, the maintenance of the productivity level and the impact of development. In order to be relevant, those studies must be carried out within the framework of the functional unit which contains the prospective site previous to any development.

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□ RESUME □

L'organisation et le fonctionnement de plusieurs sites de production de crevettes le long des côtes nord de Java et Sumatra ont été étudiés à partir des paramètres suivants : paramètres hydrologiques classiques, matières en suspension, biomasses pigmentaires du phytoplancton. En outre, la structure et la composition des populations phytoplanctoniques ont été analysées par cytométrie en flux.

Les résultats obtenus à Jepara (site représentatif de l'ensemble de la côte sud de la Mer de Java) montrent que l'ensemble des environnements côtiers, y compris ceux du milieu marin apparamment ouvert, est soumis à un confinement élevé. Celui-ci se traduit par une simplification extrême des écosystèmes réduits pour l'essentiel aux procaryotes. Les sytèmes étudiés sont assez stables et les gradients des différents paramètres qui s'étendent de la mer ouverte vers les bassins les plus confinés des établissements aquacoles subissent de simples translations en fonction des mouvements de la marée.

Le site étudié sur la rive sud du détroit de Malacca montre des gradients semblables mais un confinement moins élevé se traduisant par une diversité spécifique plus grande des populations phytoplanctoniques. Dans tous les cas les pratiques d'aquaculture intensive apparaissent comme un facteur important du confinement non seulement pour les installations aquacoles elles mêmes mais aussi pour l'ensemble des environnements de la frange côtière.