

**SOURCES OF DISSOLVED INORGANIC NUTRIENT FLUXES IN THE GAZI
BAY AND IMPLICATIONS FOR COASTAL ECOSYSTEMS**

By

MWASHOTE, B.M.

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DEDICATION

To my wife **Shainance**, daughter **Charity** and son **David**. I deeply appreciate your faith, endurance, encouragement and support throughout the entire duration of the study.

God bless you abundantly.

ABSTRACT

Nutrient fluxes of dissolved NH_4^+ , NO_2^- , NO_3^- , PO_4^{3-} and $\text{Si}(\text{OH})_4$ in the water column and nearshore sediments were measured *in situ* in the Mangrove, Seagrass and Coral reef biotopes of the Gazi Bay. The measurements were made using benthic flux bell-jar chambers each of cross-sectional area 0.066 m^2 and volume 0.0132 m^3 . The objectives were: (1) to determine the influence of benthic fluxes, external sources (fluvial discharge) and seasonal variations on the nutrient budget in the Bay waters; (2) to determine the effect of tidal and spatial variations on the nutrient loads in the water column and (3) to establish the relative importance of the nutrient sources with regard to total community production of the Bay.

Measured benthic flux rates varied between -270 and +148; -60 and +63; -79 and +41; -79 and +75; and +30 and +350 micromoles/ m^2/h for $\text{NH}_4^+\text{-N}$; $\text{NO}_2^-\text{-N}$; $\text{NO}_3^-\text{-N}$; $\text{PO}_4^{3-}\text{-P}$ and $\text{Si}(\text{OH})_4\text{-Si}$ respectively. Assessment of these values showed that they were comparable to those theoretically calculated from interstitial sediment-water nutrient concentrations. However, differences in flux direction (+ve or -ve) and magnitude were attributed to external sources as well as interactive effects of the three biotopes.

It was established that benthic fluxes are the major sources of dissolved NH_4^+ ; NO_2^- and Si(OH)_4 species, while fluvial sources are important for NO_3^- and PO_4^{3-} loading in the Gazi Bay. Seasonal variations had a profound influence on the benthic PO_4^{3-} fluxes, N:Si ratios, fluvial nutrient discharge, plankton productivity, as well as fluctuations in temperature and salinity of the nearshore areas. By contrast, tidal and spatial variations had no significant effect on nutrient concentrations and net fluxes within the water column. The results imply that benthic fluxes are largely responsible for the nutrient dynamics of the nearshore coastal ecosystems especially where direct terrestrial inputs do not contribute significantly to the nutrient budget.

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CHAPTER ONE

INTRODUCTION

Mangroves, seagrass meadows and coral reefs form a marine ecosystem characteristic of the Eastern-Africa and other tropical coastlines. This ecosystem plays an important role in coastal stabilization processes and has a high economic value as it is a source of forestry and fishery products, coral blocks for building, and certain farming activities (Davis, 1940; Odum, 1969). In many areas however, these vulnerable ecosystems are today threatened by increasing resource consumption by the adjacent human populations.

Many interrelations which are considered as functional entities exist between mangroves and adjacent seagrass meadows (Lugo *et al.* 1976). The interrelations are both biotic and abiotic: Coral reefs are known for their diversity and abundance of their fish and invertebrate faunas; while mangroves and seagrass beds act as important nursery and feeding grounds for fishes and crustaceans (Weinstein and Heck, 1979, Pollard, 1984; Robertson and Duke 1987, 1990, Bell and Pollard, 1989; Flores-Verdugo *et al.* 1987). Evidence for the existence of biotic links between mangroves, seagrasses and coral reefs has been shown from studies on short term feeding migrations and life history of fish and invertebrate species between these systems (Ogden, 1976, 1980; Robblee and Zieman, 1984; Baelde, 1990).

There is also evidence that the mangroves are outwelling systems in terms of particulate organic matter. Boto and Bunt (1981), Flores-Verdugo *et al.* (1987), Robertson *et al.* (1988) and Alongi *et al.* (1989) have demonstrated mangrove carbon export using stable

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carbon isotope detection techniques in offshore suspended particulate matter and sediments. However, information available to date on dissolved nutrients indicates that the net transport may be negligible and nutrient import may even occur (Boto and Wellington, 1988). It has also been shown that a large proportion of the primary productivity of seagrass meadows may be exported to adjacent regions (Bach *et al.* 1986; Fry and Virmstein, 1988) resulting in nutrient losses in certain areas, and nutrient enrichment in others. The nutrient transfer is also aggravated by other processes such as nutrient diffusion from the sediment (Short, 1983) and exudation and leaching processes from living and dead plant material (Kirkman and Reid, 1979; Moriarty *et al.* 1986).

These losses are, however, counterbalanced by two important features of seagrasses: their capacity to capture nutrients from the water column and their effect on water flow velocities resulting in sedimentation and consequent nutrient input into the system (Hemminga *et al.* 1991). For this reason, seagrass vegetations may act as "purification filters" in the coastal zone (Short and Short, 1984).

Coral reefs on the other hand are known for their efficient recycling of nutrients, particularly in nutrient - deficient waters (Odum and Odum, 1955; Webb and Wiebe, 1975; Smith and Jokiel, 1975; Hatcher and Hatcher, 1981, Koop and Larkum, 1987, Johnstone *et al.* 1989). Particle binding characteristics of undisturbed mangroves and seagrasses are thought to contribute to the prevention of the smothering of the coral reefs by land derived sediments.

The Gazi Bay, which is comprised of vast areas of mangrove and seagrass vegetation, provides an interesting location for studies related to intersystem nutrient fluxes since all the three biotopes (mangrove, seagrass and coral reef) co-exist in the same Bay. However, those studies that have previously been carried out in the Gazi Bay are mainly of floristic and faunistic nature (Gallin *et al.* 1989) with majority of the results focusing on the former (Ruwa and Polk, 1986). Coppejans and Gallin (1989) working on the Kenya-Belgium project involving Marine Ecology and Management of the Coastal Zone, characterized the macroalgae associated with mangrove vegetation of Gazi Bay, while more recently Hemminga *et al.* (1994) described the carbon outwelling from a mangrove forest in the Bay. In view of the importance of information on interlinkages in the coastal ecosystems and the scarcity of the same in Gazi Bay (and the E. Africa coastal region as a whole), it was necessary to conduct the present study which was an attempt to elucidate the functional interdependence of these systems in terms of nutrient exchanges and fluxes. The project which is within the general objectives of STD-3, which are: strengthening of research capabilities in the Third World priority areas; strengthening and extension of scientific co-operation and progress on rational management of natural resources, is also in line with the central concerns of a similar global campaign of the Land Ocean Interactions in the Coastal Zone (LOICZ) project (Gordon *et al.* 1995). LOICZ which is a core project of the International Geosphere-Biosphere Program (IGBP), a study of the global change, established in 1993, is concerned with understanding the role of the coastal subsystem in the functioning of the total earth system, including the role of the coastal zone in the disturbed and undisturbed cycles of carbon, nitrogen and phosphorus.

1.1: Study objectives

The specific objectives of the work presented in this thesis were:

1. To determine dissolved inorganic nitrogen load (NH_4^+ , NO_2^- and NO_3^- fractions), phosphate (PO_4^{3-}) and reactive silicate (as $\text{Si}(\text{OH})_4$) in water-column, sediments and two rivers draining into the Gazi Bay in order to trace the sources of these nutrients into and within the Bay.
2. To study the rate of nutrient fluxes between the sediment and the water column in order to assess the contribution of sediments to the regeneration of nutrient loads in the mangrove-seagrass-coral reef systems and to the total gross ecosystem productivity *in situ*.
3. To assess the nutrient links between mangrove, seagrass and coral-reef ecosystems in the Gazi Bay as affected by tidal and spatial variations as well as seasonal changes.

CHAPTER TWO

LITERATURE REVIEW

2.1: Nutrient recycling in coastal ecosystems.

The distribution of dissolved inorganic nutrients in tropical coastal marine ecosystems (mangrove, seagrass beds and coral reef) can be influenced by a wide range of factors, including hydrodynamic processes (e.g. tidal effects) and river discharges (Bowman, 1977; Ho, 1977). The tidal water movement characterized by ebb and flood flows, has been known to serve as a vehicle for the fluxes of such nutrients between the different coastal ecosystems (Wolanski *et al.* 1980). The incoming flood tide is considered to be a source of dissolved nutrients to the mangroves, seagrass beds and the coral reef ecosystems; while the outgoing ebb tide water could leach nutrients from the mangrove swamp soils and act as a net exporter of dissolved nutrients from one locality to another in the adjacent ecosystems (Boto, 1982).

The productivity of phytoplankton and zooplankton in coastal waters is determined by the seasonal distribution and abundance of dissolved nutrients as well as hydrodynamic processes (Wheeler and Kichman, 1986). However, the patterns of variation and response of this productivity are not precisely known for the East African Coast (Kitheka *et al.* 1996). Where the inputs of freshwater from the rivers is seasonal, the plankton productivity shows highly seasonal signals which may be a reflection of the seasonally varying nutrient input. In regions where there is no direct surface freshwater supply, nutrients may be derived from the groundwater seepage and from the static sources such as the nitrogen - transformation process in sediments, as well as the dynamic tidal transport system (Boto, 1982).

Mangroves in general are known to have a very high primary productivity (Middelburg *et al.* 1996), which requires a high nutrient availability. This provision appears to be met by the highly efficient systems of nutrient trapping, uptake, recycling, and decay of organic detritus in sediment layers (Dye, 1983; Alongi 1989, 1994 a, b; Lugo and Snedaker, 1974; Boto and Wellington, 1984; Alongi *et al.* 1992; Hemminga *et al.* 1994). However, organic matter and nutrient cycles in mangroves are highly variable since they are regulated by a variety of factors including soil type and texture, tidal range and elevation, redox state, bioturbation intensity, forest type, temperature, rainfall and river transport of nutrients from upland sources (Lugo and Snedaker, 1974; Alongi *et al.* 1992). This is a typical scenario along the E. African Coast but little is known about the effect of these factors on nutrient distribution and primary productivity of the existing ecosystems.

2.2: Factors affecting dissolved nutrient dynamics in marine ecosystems.

The exchange of biogenic elements between bottom sediments and overlying water has long been recognized as one of the principal factors regulating chemical and biological cycles in lakes (Mortimer, 1942). However, it has only been in recent years that such exchanges have been found to be important in some coastal marine systems (Davies, 1975; Nixon *et al.* 1976; Hopkin and Wetzel, 1982; Rizzo, 1990). The constant reflux of solutes and particles between bottom sediments and their overlying waters is an important component of material cycles determining biological activity and chemical composition of aquatic environments. For instance, in nearshore regions, soluble nitrogen compounds released from the sea floor during

the decomposition of organic matter can account for 30 - 100% of the dissolved nitrogen taken up daily by phytoplankton in overlying waters (Davies, 1975; Rowe *et al.* 1975; Hartwig, 1976; Nixon *et al.* 1976; Billen, 1978).

Molecular diffusion within interstitial water is one of the fundamental factors contributing to the exchange of dissolved constituents across the sediment - water interface. However, mass balance calculations and *in situ* benthic flux studies done elsewhere have shown that other processes can enhance the diffusion flux rate (Calendar and Hammond, 1982). These processes include the physical stirring of sediments by currents (Hammond *et al.* 1977; Vandeborghet *et al.* 1977) as well as benthic invertebrates (Davis, 1974, Robbins *et al.* 1979), irrigation of sediments by macrobenthos (Goldhaber *et al.* 1977; Grundmanis and Murray, 1977, Aller and Yingst, 1978, Hammond and Fuller, 1979; McCaffrey *et al.* 1980), and transport through bubble tubes (Martens *et al.* 1980, Klump and Martens, 1981).

2.3: Nutrient profiles in marine ecosystems: some case studies.

Numerous studies have been reported on mangrove vegetation all over the world (Gallin *et al.* 1989). These studies are however short of exhaustive and conclusive information on two fronts: First, detailed chemical and biological links between mangroves and nearshore waters are either poorly correlated or not well understood (Boto and Wellington, 1988). Second, majority of these studies have been focused on temperate coastal climates (especially North America, Australia and S.E. Asia) but not the tropics.

Boynton *et al.* (1980) studied nutrient fluxes at Patuxent estuary, USA, and found that NH_4^+ -N and PO_4^{3-} -P were released to overlying water during summer but were directed into the sediments during winter when the water column concentrations were high. Net fluxes of NH_4^+ -N and dissolved inorganic phosphate ranged from -105 to 1584 $\mu\text{moles m}^{-2}\text{h}^{-1}$ of N and 1 to 295 $\mu\text{moles m}^{-2}\text{h}^{-1}$ of P, respectively. Hopkinson and Wetzel (1982) conducted a study in the nearshore zone of Georgia Bight, USA and reported similar observations. Callendar and Hammond (1982) determined the nutrient exchange across sediment-water interface in the Potomac river estuary, USA, and found comparatively low nutrient fluxes with typical values ranging from 1.0 to 21 $\text{mmoles m}^{-2}\text{d}^{-1}$ for NH_4^+ -N, 0.1 to 2.0 $\text{mmoles m}^{-2}\text{d}^{-1}$ for PO_4^{3-} -P, and 2.0 to 19 $\text{mmoles m}^{-2}\text{d}^{-1}$ for $\text{Si}(\text{OH})_4$ -Si. These variations were attributed to the processes occurring at the interface and within surface sediment at the study site. In another study, Harrison (1983) investigated the metabolism of inter-reef sediment communities and found that more carbon is used up by the sediment community than is produced and that both production and respiration processes are closely correlated with depth.

The dynamics of dissolved nutrient fluxes at the Bowling Green Bay, in Australia, was studied by Ullman and Sandstrom (1987) who reported fluxes ranging from -23 to +28; -154 to +890 and -990 to +1750 $\mu\text{moles m}^{-2}\text{d}^{-1}$ for dissolved inorganic P, total N(= NH_4^+ + NO_2^- + NO_3^-) and Si, respectively. These fluxes are significantly lower than those measured in sediments in most temperate regions. The low rates were attributed to the dilution of reactive marine detritus with unreactive marine or terrigenous debris. By contrast however, Johnstone *et al.* (1989) in another study observed strong concentration gradients with values as high as 50

$\mu\text{M NH}_4^+\text{-N}$ in One Tree Island, Australia, and attributed these to microbial processes such as nitrification, denitrification and ammonium utilization by *Psammodithic* algae in different horizons of the sediment.

Caffrey and Kemp (1992) described the variation of nitrogen cycling in estuarine sediment where *Potamogeton perfoliatus* was shown to exert a significant influence. The experiments demonstrated that *Potamogeton perfoliatus* can have a direct uptake of $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ of up to 25 % of the nitrogen removed from sediments. Rizzo (1990) working on the nutrient exchanges between the water column and subtidal benthic microalgal community at York River estuary in Virginia, USA, obtained results which suggested that shoal communities including mangroves may have as great an impact on the nutrient cycling and trophic dynamics as the autotrophic communities such as seagrass meadows. He estimated that shoal sediments released sufficient $\text{NH}_4^+\text{-N}$ and $\text{PO}_4^{3-}\text{-P}$ that contributed 36 % and 75 % of the phytoplankton nitrogen and phosphorus requirements respectively. However, although additional investigations involving other communities have been reported (e.g. Boynton and Kemp, 1985), there is little indication of the interdependence of mangroves, seagrass and coral reefs in terms of nutrient exchanges (Boto and Wellington, 1988; Alongi, 1990).

As a first major step in defining such interrelations, it is important to determine the rates and direction of material fluxes from these systems to adjacent coastal waters. Some of the studies on particulate and dissolved carbon/nutrient transport from salt marshes such as those by Settlemyer and Gardner, 1977; Valiela *et al.* 1978; Haines, 1979; Chrzanowski *et al.*

1988, Imberger *et al.* 1983 and Chalmers *et al.* 1985 have given equivocal and sometimes conflicting results (Boto and Wellington, 1988). It was therefore necessary to design experiments that would generate information to correct this scenario, hence the purpose of this project.

2.4: Description of the Gazi Bay

The Gazi (Maftaha) Bay is a shallow, tropical coastal water system with mean depth of less than 5.0 m. The Bay is situated in southern Kenya on longitude 39° 30"E and latitude 4° 22" S. It is approximately 50 km from Mombasa. The total area of the Bay excluding the area covered by the mangroves is 10.0 km². The mangrove forest covers an area of 5.0 km², and is dominated by the species: *Rhizophora mucronata*, *Sonneratia alba*, *Ceriops tagal*, *Bruguiera gymnorrhiza* and *Xylocarpus granatum* (Coppejans and Gallin, 1989; Gallin *et al.* 1989; Slim *et al.* 1993). The seagrass zone which is dominated by *Thalassia sp.* is found in the central region and covers an additional area of 7.0 km² which is approximately equivalent to 70 % of the total area of the Bay.

The Bay is open to the Indian Ocean through a relatively wide (3,500 m) entrance in the south (Fig. 3.1) This entrance is rather shallow with depths of about 3m in the east,

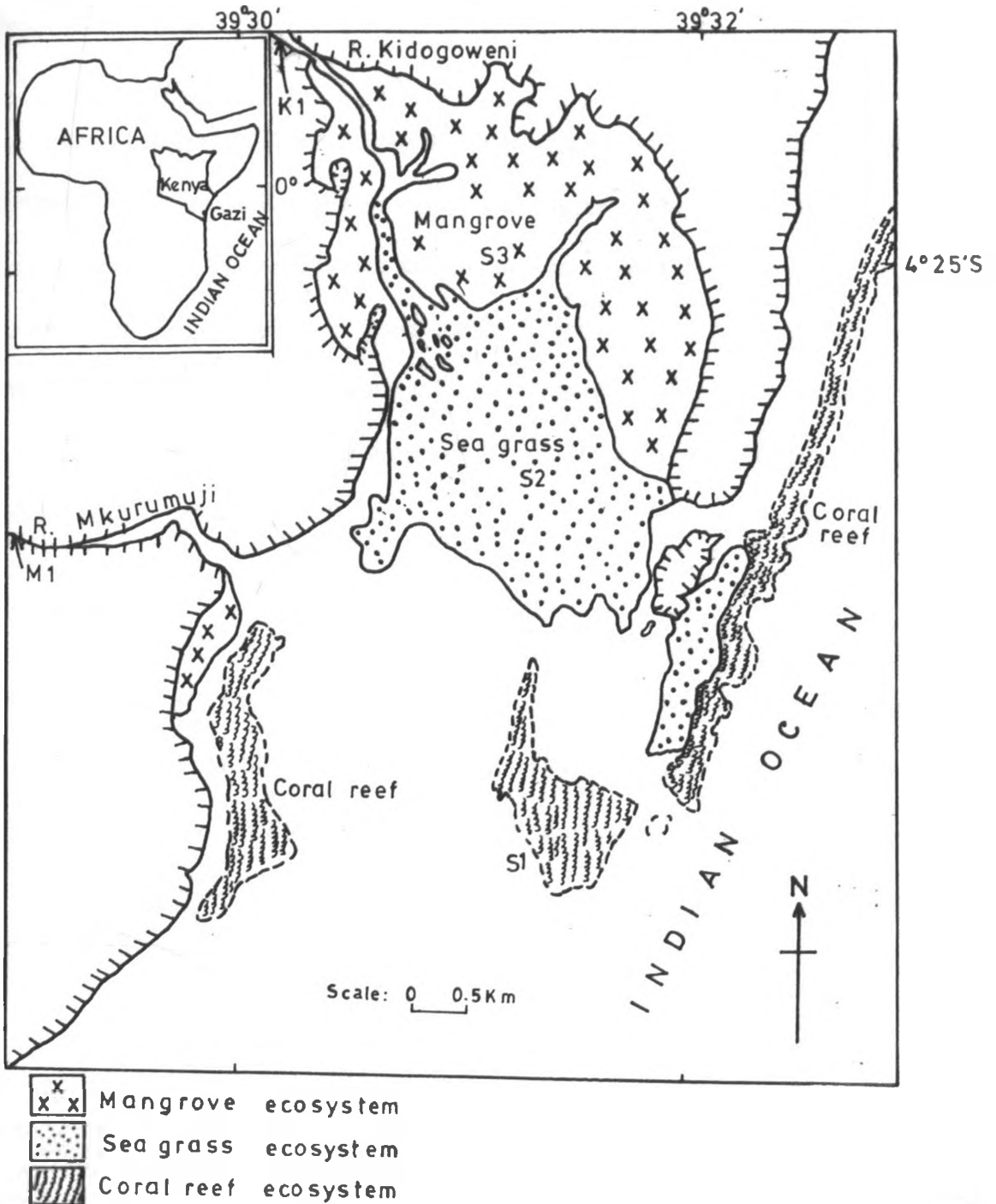


Fig.3.1: The location of Coastal and Marine ecosystems in the Gazi bay, Kenya.

increasing to 8m in the western region of the Bay. There are also a number of narrow and shallow cuts through the coral reef ecosystem, which is submerged most of the time but emerges at spring low tide.

There are two tidal creeks draining the upper region (which is dominated by mangrove vegetation). These are the Kidogoweni and Kinondo creeks and measure about 5 km and 2.5 km long respectively. The Kidogoweni creek receives fresh water from Kidogoweni river. By contrast, the Kinondo creek lacks direct surface freshwater input, although there may be groundwater influx as salinity of the water has been observed to fluctuate significantly during the wet season (Kitheka, 1996; Kitheka *et al.* 1996). Directly adjacent to the mangroves are the intertidal flats and shallow subtidal areas.

The Mkurumuji river with its higher flow rates, discharges into the south-western region of the Bay. The drainage basin of both Mkurumuji and Kidogoweni rivers extends into the coastal ranges of the Shimba Hills. The Mkurumuji river alone drains an area of 164 km², while the Kidogoweni river drains an area of 50 km² upcountry. River discharge fluxes during the wet seasons can reach up to 5.0 and 17.0 m³ sec⁻¹ for the Kidogoweni and Mkurumuji rivers, respectively.

The climatic seasons are attributed to the south-east monsoon which is responsible for the long-rains (April-June) and the north-east monsoon, which causes short-rains (November-December). The dry season is experienced in the months of August-October and January-March. Rainy seasons occur as a result of the location of the intertropical convergence zone

(ITCZ) which covers the East Africa region. Mean annual rainfall varies from 1000 to 1500 mm, while the rates of evaporation range from 1950 to 2200 mm per annum (Kitheka *et al.* 1996, Kazungu, 1996).

CHAPTER THREE

MATERIALS AND METHODS

3.1: Study sites

A total of five sampling sites were identified for the study. These were coded: S1, S2, S3, K1 and M1 (Fig. 3.1). Three of these sites (S1, S2 and S3) were within the Gazi Bay, while the other two were at specific points on rivers Kidogoweni (K1) and Mkurumuji (M1). Sites at the Gazi Bay were chosen such that they were located within the mangrove, seagrass and coral-reef ecosystems.

3.2: Sampling period

Flux measurements, water and sediment sample collection were done fortnightly at sites S1, S2 and S3, while only water samples were collected from the river sites (K1 and M1) at the same interval. The sampling was done between November, 1994 and July, 1995.

3.3: Chemicals and reagents

These were of analytical grade or better. They were obtained from the following international suppliers:

Aldrich Chemical Co. Ltd., Dorset, U.K:

Sodium fluorosilicate; Sodium bicarbonate; Sodium carbonate; Sodium chloride; Sodium hydroxide; Sodium hypochlorite (chlorox, 0.14% chlorine); Sodium iodide; Sodium nitrite; Sodium nitroprusside; Sodium sulfite; Sodium thiosulfate; Starch

indicator solution (1%); Sulfanilamide; Sulfuric acid; sodium citrate.

BDH Ltd., Poole, U.K:

Ascorbic acid; Cadmium filings; Carbon disulphide; Chloroform; Copper sulphate; Metol (p-methylaminophenol sulfate); N-(1-naphthyl)-ethylenediaminedihydrochloride; Oxalic acid; Trione (dichloroisocyanuric acid).

MERK Chemicals, Germany:

Ammonium chloride; Ammonium molybdate; Ammonium sulfate; Hydrochloric acid; Magnesium sulphate; Manganous chloride; Phenol; Potassium antimonyl-tartrate; Potassium dihydrogen phosphate; Potassium iodate; Potassium nitrate.

3.4: Glassware and plasticware

All apparatus and sample containers were soaked for 24 h in washing detergent and then for 24 h in 10% (v/v) hydrochloric acid. They were then thoroughly cleaned with tap water and finally rinsed with distilled de-ionized water before either drying in an oven at 80 °C or being allowed to drip dry in a dust-free environment.

3.5: Instruments and instrumental principles

3.5.1: Instruments

A SCHOTT pH-meter model CG840 (Germany) was used for all pH measurements while a SHIMADZU double beam spectrometer model UV-150-2 was used for all absorption

measurements.

3.5.2: Instrumental principles of absorption spectrophotometry

When an electromagnetic wave of a specific wavelength impinges upon an absorbing molecule, a fraction of the radiation is absorbed. This fraction is a function of the concentration of the substance in the solution and is also proportional to the path length of the transmitting medium (Willard *et al.* 1986). Radiant power is the quantity measured by detectors such as photocells and phototubes. The ratio of the radiant power transmitted by a sample to the radiant power incident on the sample is the transmittance, T . Transmittance is defined as the ratio of the intensity of unabsorbed radiation, I , to the intensity of the incident radiation, I_0 , as given in the equation (3.1):

$$T = I/I_0 \dots\dots\dots(3.1)$$

Absorbance, A , is defined as the logarithm (to the base 10) of the reciprocal of the transmittance:

$$A = \log I_0/I = -\log I/I_0 \dots\dots\dots(3.2)$$

Analytical applications of the absorptive behaviour of molecular species can be either qualitative or quantitative. The qualitative applications of absorption spectrophotometry depend on the fact that a given molecular species absorbs light only in specific regions of the spectrum, and to varying degrees characteristic of that particular species.

The absorptive characteristics of a given species obey two laws:

- (1) Lambert's Law which states that for a given concentration of the absorber, intensity of transmitted light decreases logarithmically as path length increases arithmetically,
- (2) Beer's Law which states that increasing the concentration of the absorber has the same effect as a proportional increase in radiation absorbing path length.

The quantitative aspect is based on the combined Beer and Lambert's law, expressed as:

$$\log I_0/I = Ebc \dots\dots\dots(3.3)$$

where,

E = molar extinction coefficient (molar absorptivity or molar absorbancy index)

b = thickness of absorbing medium traversed by radiation

c = molar concentration of the absorbing medium

I = intensity of unabsorbed radiation

I_0 = intensity of incident radiation

In developing a quantitative method for determining the concentration of a given species colorimetrically, the first step is to determine the absorption band (wavelength) at which absorbance measurements are to be made. This is the wavelength at which the absorbance of a given concentration of analyte is maximum (peak wavelength). Absorptivity at any given wavelength is constant and characteristic of the absorbing species.

The basic parts of a typical spectrometer are radiation source, the sample cell, the monochromator (wavelength selector), the detector (usually a photomultiplier) and the detector output electronics and recorder (Fig. 3.2). In UV/VIS spectrometers that allow molecular absorption measurements in the ultraviolet and visible regions of the electromagnetic spectrum, the sources are incandescent lamps (usually tungsten or deuterium discharge tubes). Prisms or dispersion grating are commonly used as monochromators. The photographic plate and photo-electric cells are commonly used as detectors.

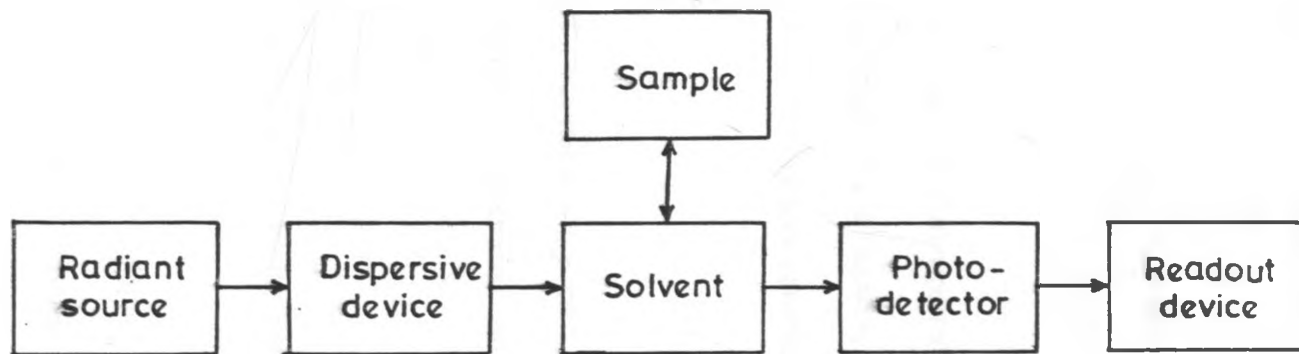


Fig.3.2: Instrument modules for measuring absorption of radiation.

3.6: Sample collection and storage

Sampling was started at high tide and continued until the entire tidal cycle was covered. Water samples in the Bay sites (S1, S2 and S3) were taken at mid-depth (approximately 1.5m) using a water sampler (Nansen bottle) at set time intervals. Water samples from the river sites (K1 and M1) were collected similarly at mid depth (approximately 0.5m for K1 and 0.8m for M1) in the middle of river channel. Replicate sediment cores of 5 cm in diameter were collected randomly at the three sampling sites within the Bay using a coring device.

Samples were soon after transported in a cooler box containing ice and processed in the laboratory immediately. Those requiring storage were kept in a deep freezer at $< -15\text{ }^{\circ}\text{C}$ prior to analysis but which were accomplished, utmost within three days of sampling.

3.7: Field measurements

Parameters measured *in situ* at each site included: temperature, salinity, pH, river flow rates and depth. The pH was determined using a digital pH meter. Salinity was determined by a portable refractometer.

3.8: Sediment - water column and community production measurements

3.8.1: Nutrient exchanges

The *in situ* sediment-water column nutrient exchange and total community production measurements were made using two transparent and two opaque plexiglass bell-jar chambers each covering 0.0660 m^2 of sediment and enclosing a total volume of 0.0132 m^3 . Figure 3.3

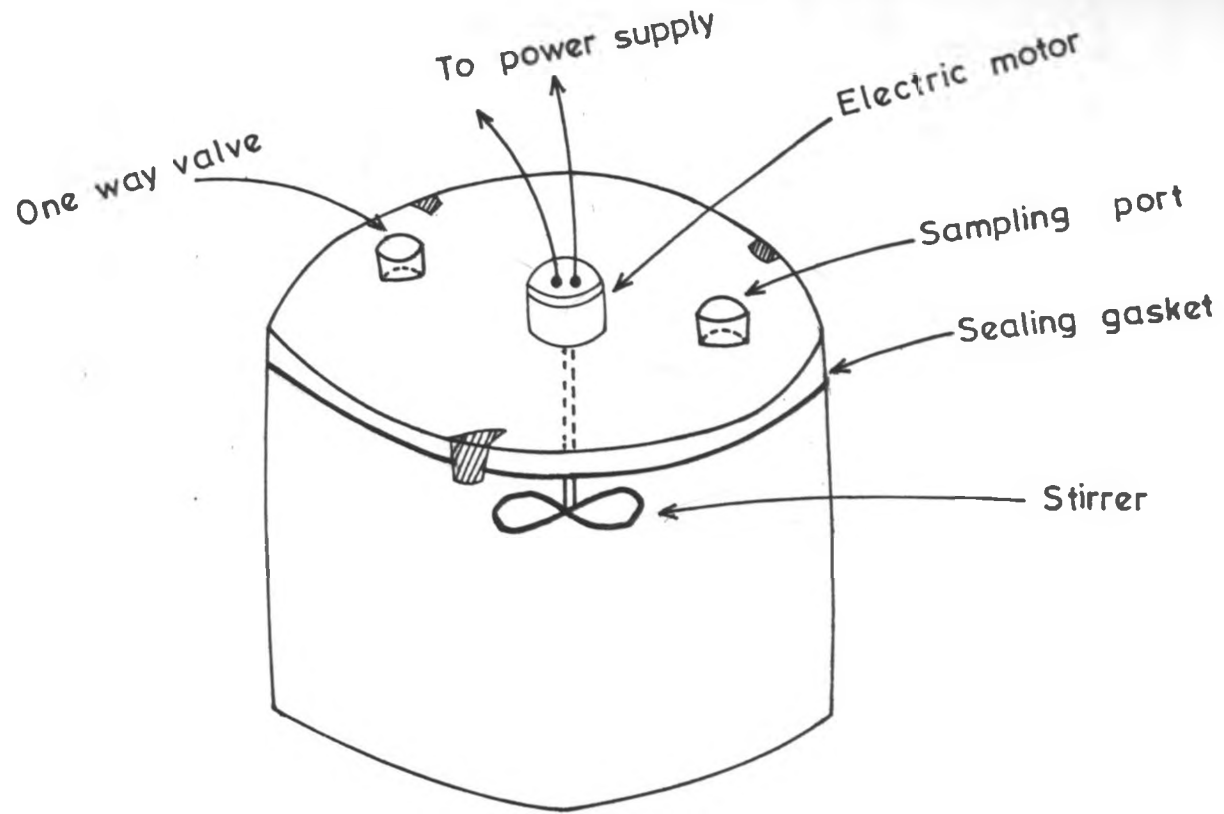


Fig. 3.3: A sketch diagram showing a typical benthic bell-jar chamber for flux measurements.

shows the typical design of a bell-jar chamber. Connected to this assembly is a stirrer for continuous mixing of the solution above the sediment. The chambers were placed randomly at the bottom of each sampling site in the Bay. Water in each chamber and in the immediate surrounding was sampled during a full tidal cycle.

Duplicate water samples (100ml) for analysis were withdrawn by a syringe at 3h intervals from each chamber. The volume of water during sampling was replenished with ambient seawater through one-way valves at the same periodic intervals. This was done to prevent any potential effects arising from oxygen supersaturation in the transparent (i.e. clear chamber which was not covered with black polythene material) chambers and oxygen depletion in the opaque (i.e. chamber which had been covered with black polythene material) chambers. Changes in dissolved nutrients and oxygen concentrations with time were used to calculate rates of sediment-water column exchanges and community productivity in the bell-jar chambers according to the method of Rizzo (1990).

For comparison with the *in situ* experimental measurements, theoretical calculations of the expected nutrient fluxes were made on the basis of the interstitial-water nutrient concentrations in sediment using the Rutgers van de Loeff (1984) relationship :

$$J = \dot{U} D_s \cdot dC/dx \dots\dots\dots(3.4)$$

where,

J = rate of flux

\dot{U} = sediment porosity

D_s = effective diffusion coefficient of nutrient

dC/dx = concentration gradient across the sediment/water interface.

3.8.2: Total community gross production

To assess the importance of sediment - water nutrient exchange for daily community production, the method of Rizzo (1990) was employed. The procedure takes into account two components: First is the daily net production, defined as the product of the mean hourly transparent chamber O_2 exchange and the photoperiod. Second, is the daily respiration, defined as the mean hourly O_2 change in the opaque chambers multiplied by 24. The daily gross production is then taken as the sum of the two components; daily production and daily respiration. Changes in O_2 concentrations were determined according to the procedure described in section 3.10.6.

3.9: Determination of porosity of sediments

Subsamples of 2 cm thickness were taken at different depths up to 12 cm. The pore-

water from each sub-sample was isolated by centrifugating at 3000 RPM (Johnstone *et al.* 1989), for 10 minutes. Samples were diluted 10-20 times or to any other appropriate dilution using artificial seawater immediately before analysis. This dilution was necessary because the nutrient concentrations found in interstitial-waters was relatively higher than the calibration range suitable for the water column nutrient levels. The sediment cores were assessed for porosity according to the procedure described by Rizzo (1990). The procedure involve measuring the weight loss occurring after drying a known volume of sediment to a constant weight at 105 °C.

3.10: Chemical analytical procedures

3.10.1: Determination of ammonium-nitrogen, NH_4^+ -N

NH_4^+ -N was determined according to the procedure of Parsons *et al.* (1984) with slight modifications given in procedure 4500-NH₃-F of APHA (1992). By this method, the ammonium ion in the seawater sample is buffered in alkaline citrate medium and then treated with sodium hypochlorite and phenol in the presence of sodium nitroprusside (which acts as a catalyst). The reaction in this mixture gives a complex, indophenol whose blue colour intensity is measured colorimetrically at 630 nm.

The phenol/sodium nitroprusside reagent was prepared by weighing exactly 38g phenol and 0.4g sodium nitroprusside and making up to 1000 ml in distilled de-ionised water. Similarly the trisodium citrate/sodium hydroxide/sodium hypochlorite reagent was made by weighing 240g trisodium citrate, 8 4g sodium hydroxide and 1g dichloroisocyanuric acid and made up to

500 ml in distilled de-ionised water.

Aliquots of the phenol/sodium nitroprusside reagent (1.5 ml) and the trisodium citrate/sodium hydroxide/sodium hypochlorite reagent (1.5 ml) were added to the sample (50 ml of sample) and the mixture stirred. The reaction was allowed to continue for at least 6 h at ambient temperature in the dark. Absorbance measurement was done at 630 nm against a reagent blank prepared similarly with distilled water replacing the sample.

Calibration standards in the concentration range 0 - 1.5 mg/l were made in filtered seawater which had been boiled to expel any ammonia present. The standards were prepared by serial dilution of a stock solution made from ammonium sulphate (5000 μM N) and preserved in chloroform. Sample concentrations were read directly from the calibration curve.

3.10.2: Determination of Nitrite-nitrogen, NO_2^- -N

NO_2^- -N was determined by diazotization according to procedure 4500- NO_2^- -B of APHA (1992). By this method, the nitrite in the sample is allowed to react with sulfanilamide in acid solution. The resulting diazo compound is complexed with N-(1-naphthyl)-ethylenediamine to form a highly coloured azo dye whose intensity is measured at 543 nm. This method offers two advantages: First, a reasonably wide linear working range (0 - 200 $\mu\text{g/l}$ of NO_2^- -N) and second, a high precision and sensitivity.

1.0 ml of aqueous sulfanilamide (1% w/v) solution was added to each 50 ml sample

aliquot, mixed vigorously and contents allowed to stand for 5 mins. 1.0 ml of aqueous naphthylethylenediamine reagent (0.1% w/v) was then added and the contents mixed immediately. The colour intensity of the solution was measured after 30 minutes against a reagent blank prepared similarly using distilled water.

Working standard solutions containing NO_2^- -N in the range 0 - 0.2 mg/l were made by serial dilution of an aqueous stock solution (1000 mg/l) made from anhydrous sodium nitrite in synthetic seawater (prepared by dissolving 31g NaCl, 10g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ and 0.05g $\text{NaHCO}_3 \cdot \text{H}_2\text{O}$ in 1l distilled de-ionised water).

3.10.3: Determination of Nitrate-nitrogen, NO_3^- -N

NO_3^- -N was determined according to the procedure of APHA (1992), method 4500- NO_3^- -E, in which NO_3^- is reduced to NO_2^- by passing through a reduction column packed with cadmium filings coated with copper (Fig. 3.4). The nitrite is then complexed as described in section 3.10.2 above.

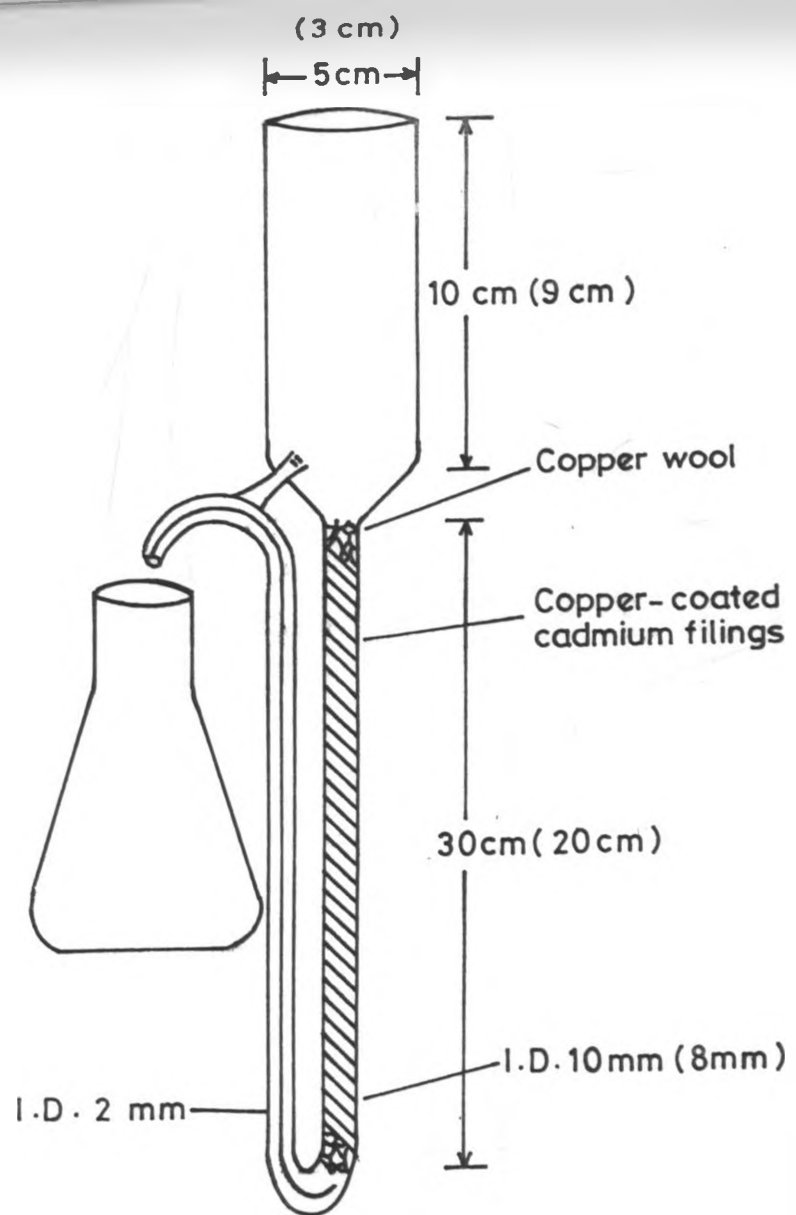


Fig.3.4: Dimensions of a nitrate reduction column. Numbers shown in brackets are for smaller columns which are especially useful for ammonia determination.

For the reduction, 10 ml of sample were eluted through the column at a constant flow rate of 10 ml/min, using 30 ml of NO_3^- free water. Quantitative reduction of the nitrite was checked and confirmed by running a series of potassium nitrate solutions of known concentration and determining the recovery of the NO_3^- -N initially added to the column. Mean recoveries of the order of 95% were obtained for test solutions of NO_3^- -N made at the 5.0 $\mu\text{g/l}$ level.

For calibration, working standard solutions containing NO_3^- -N in the range 0 - 1 mg/l were made by serial dilution (in synthetic seawater) of an aqueous stock solution (1000 mg/l) made from potassium nitrate. The concentration of NO_3^- -N ($C_{\text{NO}_3^-}$ -N) was then calculated according to:

$$C_{\text{NO}_3^-}\text{-N}(\mu\text{mol/l}) = (A_s - A_b)/b - C_{\text{NO}_2^-}\text{-N} \dots\dots\dots (3.5)$$

where A_s and A_b are the absorbances of the sample and of the blank sample respectively and $C_{\text{NO}_2^-}\text{-N}$ is the NO_2^- -N concentration (in $\mu\text{mol/l}$) observed in the same sample. b is the slope of the calibration curve.

3.10.4: Determination of Phosphorus (as phosphate, PO_4^{3-} -P)

The procedure followed was that reported by APHA (1992), method 4500-P-E (and also cited in Parsons *et al.* 1984) in which the seawater sample was mixed with phosphate reagent containing molybdic acid (20% v/v), ascorbic acid (20% v/v) and potassium antimony (III) tartrate (10% v/v). The resulting complex formed was reduced by ascorbic acid with trivalent antimony ions as catalyst to give a blue solution whose intensity was measured at 880

nm. The composition of the phosphate reagent or mixed reagent was obtained by mixing together 100 ml ammonium molybdate (3% w/v), 250 ml sulphuric acid (sp. gr. 1.82), 100 ml ascorbic acid (5.4% w/v) and 50 ml potassium antimonyl-tartrate (0.136% w/v) solutions.

To 100ml sample aliquot, 10ml of freshly made phosphate reagent were added and contents mixed thoroughly. After 30 minutes, the colour intensity was measured spectrophotometrically at 880nm against a reagent blank using 10 cm cells.

For calibration, working $\text{PO}_4^{3-}\text{-P}$ standards in the range 0 to 2 mg/l were made by serial dilution of a stock solution prepared from anhydrous potassium dihydrogen phosphate (by dissolving 439.3 mg anhydrous KH_2PO_4 in 1l) in synthetic sea water (prepared as in section 3.10.2). The colour of the solutions was developed in the same way as for the sample and absorbance measured. The sample concentrations were determined directly from the calibration curve.

3.10.5: Determination of Soluble Silicate, $\text{Si(OH)}_4\text{-Si}$

The method used here which is reported in APHA (1992) measures "reactive" silicate and does not indicate presence of polymerized silicate. The seawater is allowed to react with molybdate ions in solution. Presence of free silicate, phosphate or arsenate results in the formation of silicomolybdate, phosphomolybdate and arsenomolybdate complexes, respectively. When a solution containing metol and oxalic acid is added the silicomolybdate complex is selectively reduced to give a blue colour leaving phosphomolybdate and

arsenomolybdate intact. The resulting colour intensity is measured spectrophotometrically at 810 nm using 1 cm cells (APHA, 1992).

10ml of molybdate solution (0.8% w/v) were added to a 25ml of seawater sample and the mixture allowed to stand for 10 minutes. 15 ml of the reducing agent (made by mixing 100 ml of a solution containing 2% w/v metol and 1.2% w/v anhydrous sodium sulphite), 60 ml oxalic acid (10% w/v) and 60 ml H₂SO₄ (50% v/v) were then added rapidly, stirred and the mixture allowed to stand for 3h for complete reduction. The colour intensity of the solution was measured at 810 nm.

For calibration, a silicon stock solution was prepared by dissolving 1.3427g of sodium fluorosilicate in 1000 ml of distilled water to give a 200 mg Si/l solution. This solution was further diluted with synthetic seawater (prepared as in section 3.10.2) to give working standards in the concentration range 0 - 5 mg/l. The solutions were treated for colour development and the absorbance measured at 810 nm.

3.10.6: Determination of Dissolved Oxygen

The method described here is based on the classical Winkler procedure cited by Parsons *et al* (1984) and modified by APHA (1992). A solution containing Mn²⁺ ions and a strong alkali are sequentially added to the sample. Manganous hydroxide is precipitated but is immediately dispersed evenly throughout the seawater sample in the stoppered glass bottle. Any dissolved oxygen rapidly oxidizes an equivalent amount of divalent manganese ion to

higher oxidation states. When the solution is acidified in presence of iodide, the oxidized manganese is again reduced to the divalent state in a reaction which generates iodine by oxidation of iodide ions. The liberated iodine is titrated with standardized sodium thiosulfate solution and represents the amount of oxygen present in the original sample.

A sample aliquot (120 ml) was mixed with 0.96 ml of 60% (w/v) aqueous manganous chloride in a BOD (biological oxygen demand) bottle. The bottle was stoppered and its content mixed by inversion before adding a similar amount (0.96 ml) of alkaline iodide solution (an aqueous mixture of 32% (w/v) NaOH and 60% (w/v) NaI). 0.96 ml of 50% concentrated (sp. gr. 1.82) sulphuric acid was then added to dissolve the precipitate. One hour following acidification, 50ml portions of the treated samples were transferred to Erlenmeyer flasks and titrated immediately with 0.01M sodium thiosulphate solution under constant stirring conditions. When the solution had turned faintly yellow, 0.5 ml of starch solution was added and titration continued to the end point (until the blue color was discharged). A blank titration was carried out using oxygen-free seawater obtained by bubbling pure, "white spot" nitrogen through the solution for at least one hour. Subtract the blank to obtain the corrected titration volume, V in ml, and calculate the oxygen content in mg O₂/l as:

$$\text{mg O}_2/\text{l} = 0.1016 \times f \times V \times 16 \dots\dots\dots (3.6)$$

when a 50 ml aliquot is taken from a 120 ml BOD bottle and where f is determined as described below.

For calibration, a 120ml BOD bottle was filled with 118 ml distilled water and 0.96 ml of alkaline iodide solution. The contents were mixed thoroughly before adding 0.96ml of the

manganous chloride solution. A 50ml aliquot was withdrawn into a tainted titration flask and mixed with 5.0 ml of exactly 0.01M standard potassium iodate. The mixture was then titrated with the 0.01M thiosulphate solution. If V is the titration volume, then:

$$f = 5.00/V \dots\dots\dots (3.7)$$

where f should be the mean for at least 3 replicates.

3.11: Fluvial nutrient loads

Fluctuations in nutrient concentrations in the river water draining into the Gazi Bay were assessed from the chemical analysis data in relation to sampling season. Nutrient export (E) was then calculated from the equation (Linsley, 1988):

$$E \text{ (in } \mu\text{mol/s)} = Q_r \cdot C \dots\dots\dots (3.8)$$

where,

C is the mean nutrient concentration ($\mu\text{mol/m}^3$) and Q_r is the river discharge rate (m^3/s). The discharge rate was calculated using the relationship:

$$Q_r = \sum a_i \cdot V_i \cos(\Theta - \pi/180) \dots\dots\dots (3.9)$$

where,

a_i is the cross sectional area (m^2) of the flowing water mass, V_i is the cross component velocity (ms^{-1}) and Θ is the deviation of the current velocity in relation to the flow direction (Linsley, 1988).

3.12: Statistical analysis

Spatial and temporal variations in dissolved nutrients and flux measurements at

different sites as affected by seasonal changes were carried out using a combination of Analysis of Variance (one-way and two-way ANOVA) and Spearman's Rank Correlation Coefficient (SRCC). Various regressional relationships were also calculated using a Minitab statistical computer package (Minitab Release 6.1.1, Minitab Inc., 1987). All statistical analyses were based on the significance level at $p = 0.05$ and critical values of F at $\alpha = 0.05$ (Yule and Kendall, 1993).

CHAPTER FOUR

RESULTS

4.1: Environmental variables

4.1.1: Temperature

Variations in temperature within complete tidal cycles (Fig. 4.1) in the Bay ranged from 23.0 to 33 °C with a mean of 28.2 °C for wet season, and from 26.6 to 31.4°C (mean 28.6 °C) for dry season. Both the extreme temperatures were recorded at sampling site S3 (table 4.1). The two-way Analysis of variance (ANOVA) revealed significant differences in temperature between seasons ($p=0.01$), but there was no significant differences between site in temperatures ($p=0.270$).

Fig 4.1 (a): Dry season

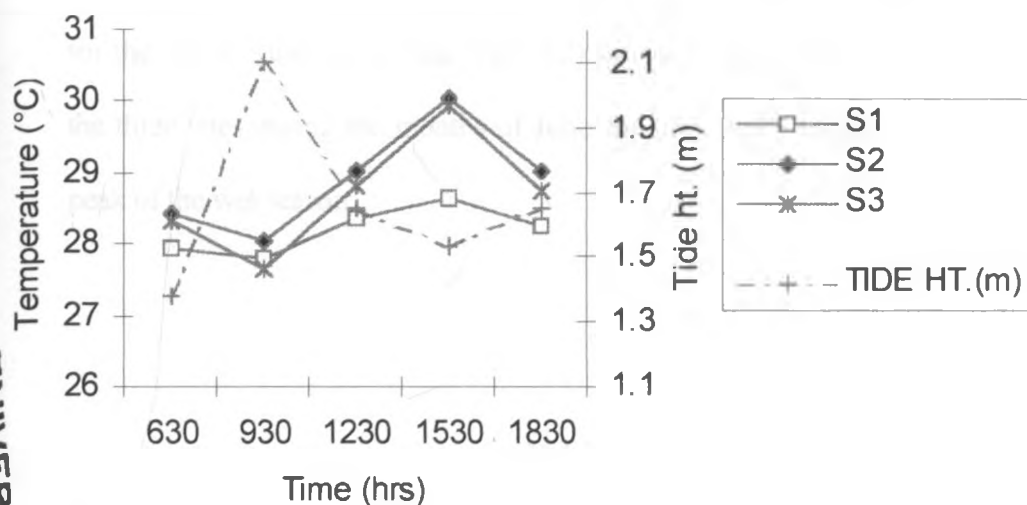


Fig 4.1 (b): Wet season

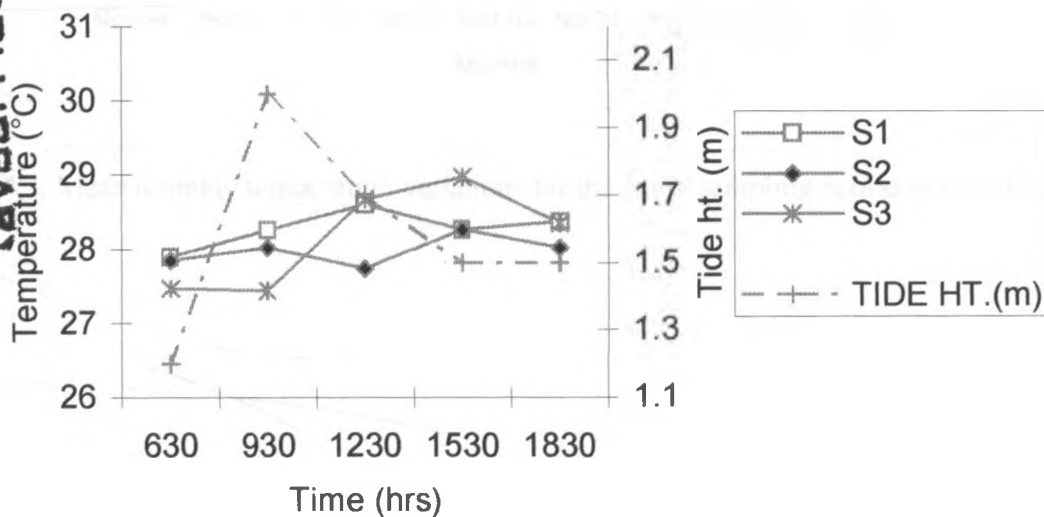


Fig. 4.1: Mean daily temperature variations with tidal cycle during dry and wet seasons in Gazi Bay.

*Note: For Figs. 4.1-4.25, (a) = dry season and (b) = wet season.

For the wet season there was no significant differences in temperature were observed within tidal cycle and also between sites. Monthly temperature variations for the whole sampling period (Fig. 4.2) show a general drop in temperature at all the three sites during the months of June and July 1995, which coincided with the peak of the wet season.

Fig 4.2

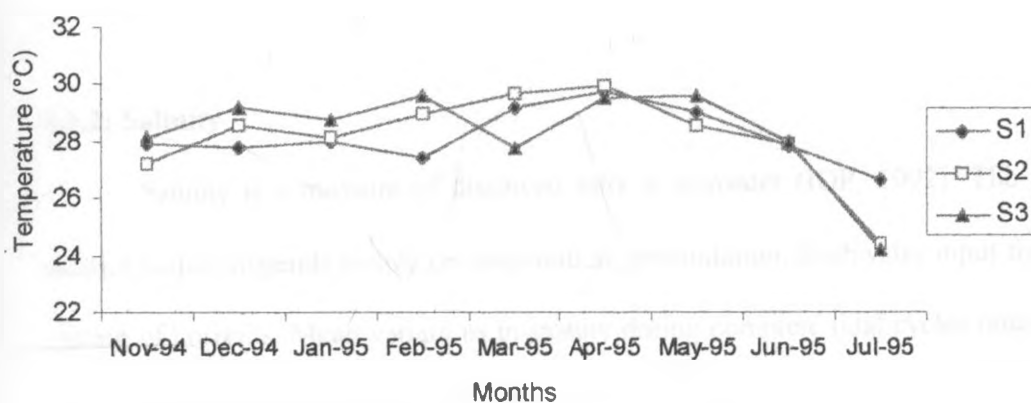


Fig. 4.2: Mean monthly temperature variations for the entire sampling period in Gazi Bay.

The variation in temperature of the ocean and coastal waters is one of the factors that control the distribution of marine organisms as well as the density of seawater. The high heat capacity of water makes the surface temperature of the sea vary far less than the land temperatures, thus providing a stable environment and coastal climate for marine life (IOP, 1992). The temperature variations of Gazi Bay throughout the sampling period were typical of a tropical coastal environment within the region (Johnstone and Mohammed, 1995 ; Kitheka *et al.* 1996).

4.1.2: Salinity

Salinity is a measure of dissolved salts in seawater (IOP, 1992). The salinity of the surface waters depends mainly on evaporation, precipitation, freshwater input from rivers, and mixing of currents. Mean variations in salinity during complete tidal cycles ranged from 26 to 37 PSU (Practical Salinity Units) within the three sampled sites in the Bay (Fig. 4 3). Wet season mean salinity was 34.1 (± 0.65) PSU and dry season mean salinity was 35.6 (± 0.51) PSU. Highest salinity levels were observed during the dry season with extreme values being recorded at sampling site S3 in the vicinity of the Kidogoweni river estuary. In general, the salinity values for the Gazi Bay during the entire sampling period were similar to the levels obtained before in the Bay by Osore, 1994 and Kitheka *et al.* (1996), who recorded values ranging from 25 to 35 PSU. Elsewhere within the region the levels were found to be in the range 26 to 38 PSU (Johnstone and Mohammed, 1995; Kazungu *et al.* 1989)

Fig 4.3 (a): Dry season

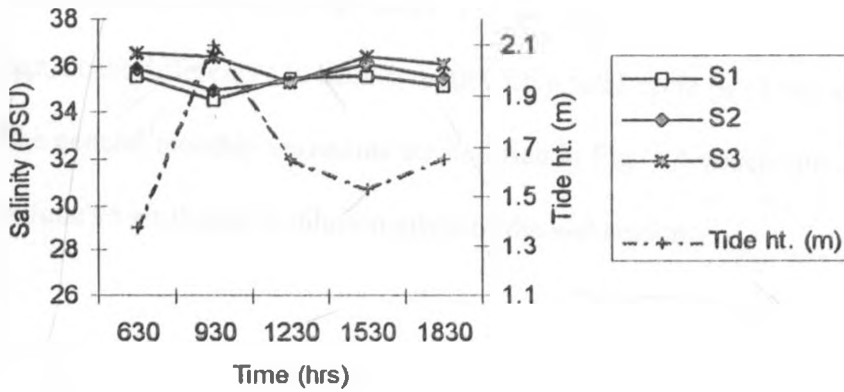


Fig 4.3 (b): Wet season

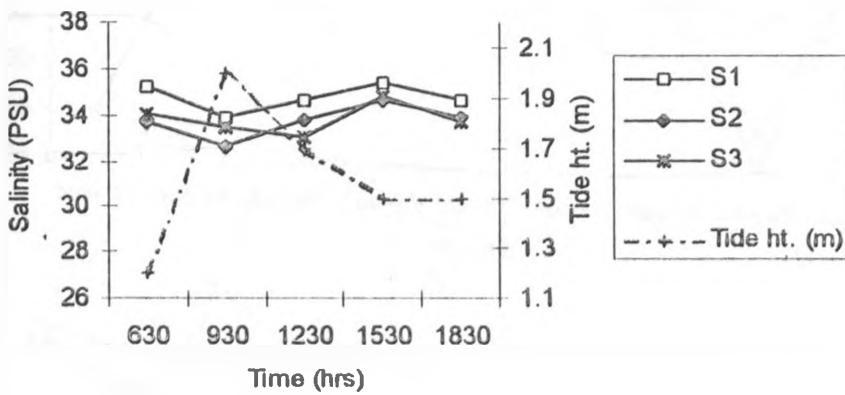


Fig. 4.3: Mean daily salinity variations with tidal cycle during dry and wet seasons in Gazi Bay.

For dry season salinity data, two-way ANOVA revealed no significant difference with respect to time of sampling but there were some differences in salinities between sites ($p=0.02$). For the wet season, data generally gave no significant differences in salinity both within tidal cycle ($p=0.10$) and sites ($p=0.06$). The general monthly variations are depicted in Fig. 4.4 which show lowest salinities in June'95 attributed to dilution effect of the wet season.

Fig 4.4

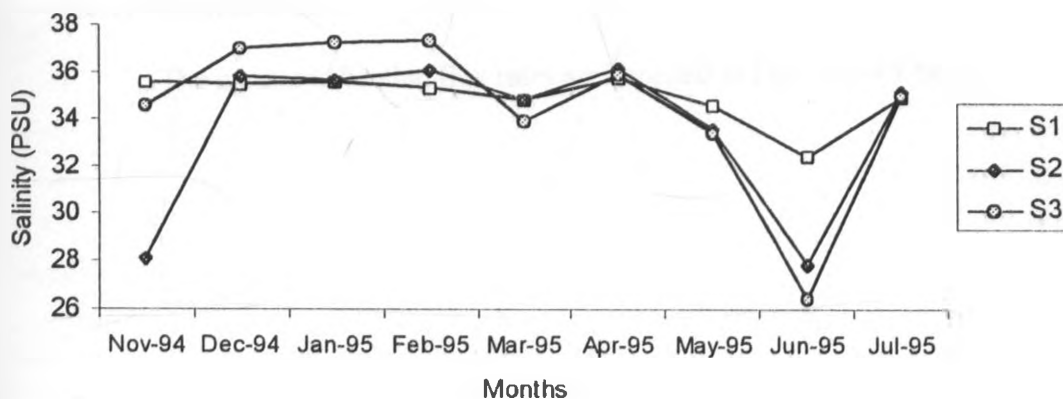


Fig. 4.4: Mean monthly salinity variations for the entire sampling period in Gazi Bay.

4.1.3: Dissolved Oxygen and pH

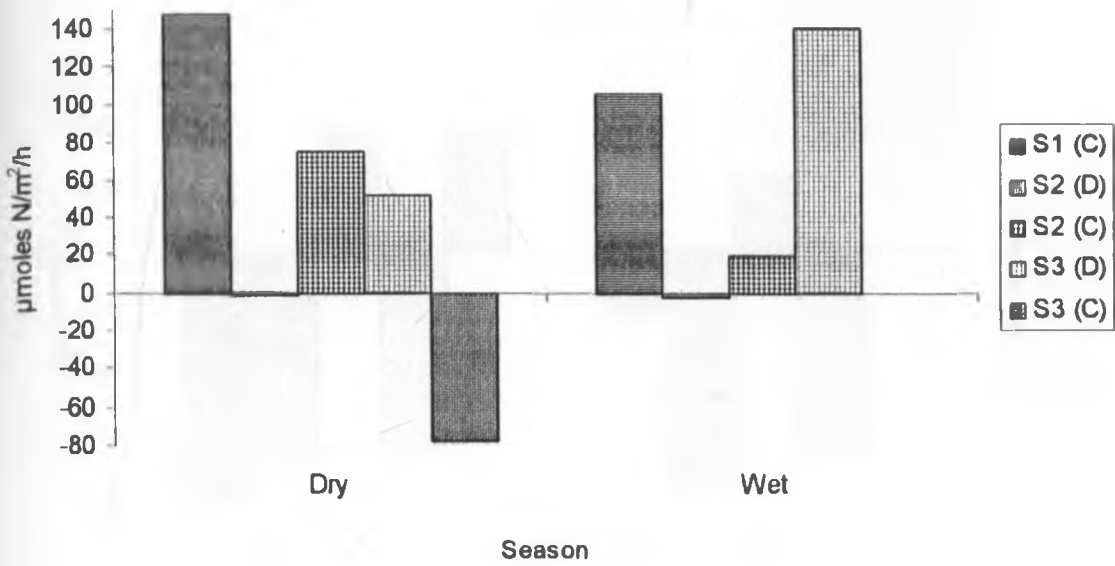
The average dissolved oxygen (DO) concentrations in the waters of Gazi Bay varied between 4.9 and 10.5 mg O₂/l with mean of 6.8 (±1.8) mg O₂/l. The pH of the Bay waters varied between 7.3 and 8.7 with mean 8.0 (±0.5). In general, the lowest values of both DO and pH were found in samples collected at site S3. These data are comparable to those found in similar environments such as the Hinchinbrook Channel in Australia (Alongi *et al.* 1989) where values were found to be in the range 6.6 to 8.0 mg O₂/l.

4.2: Sediment - water exchanges

4.2.1: Nutrient Flux

The measured benthic flux rates are depicted in Figs. 4.5-4.9 below.

Fig 4.5

Fig. 4.5: Mean hourly flux rates for $\text{NH}_4^+\text{-N}$ in the Gazi Bay during dry and wet seasons.

*Note: For Figs. 4.5-4.10, (C)=Clear chamber and (D)=darkened chamber.

Fig 4.6

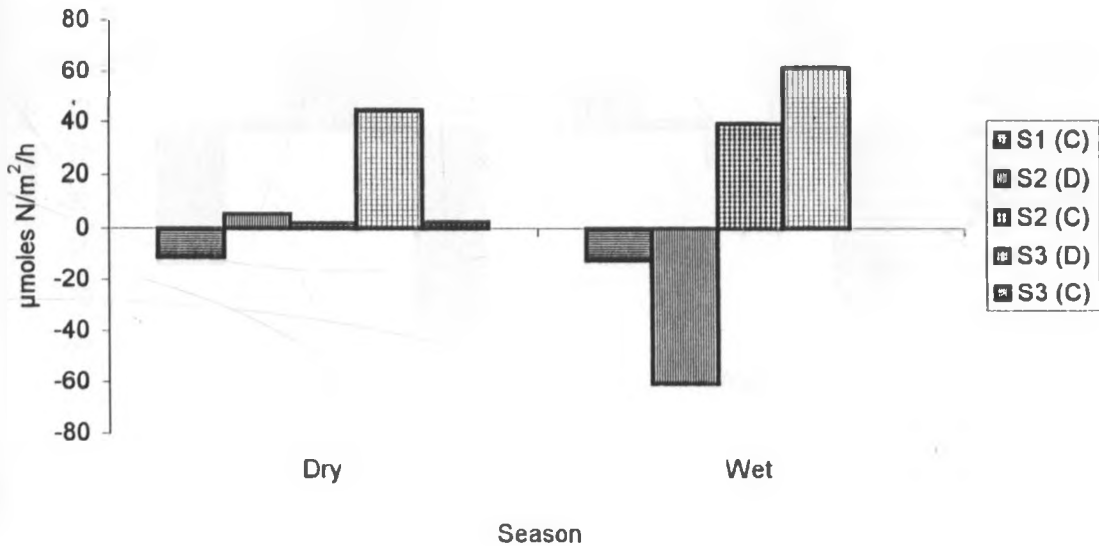
Fig. 4.6: Mean hourly flux rates for $\text{NO}_2^-\text{-N}$ in the Gazi Bay during dry and wet seasons.

Fig 4.7

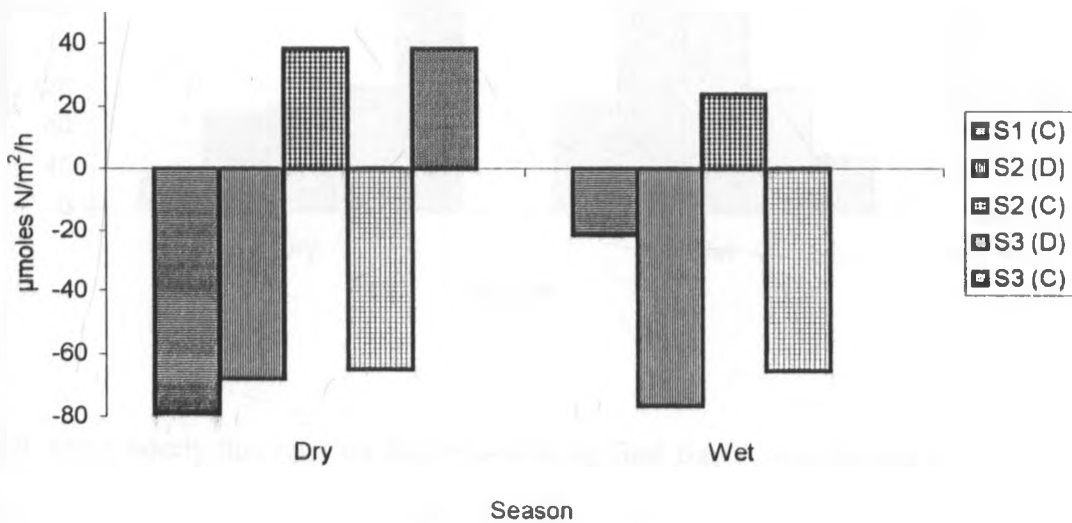
Fig. 4.7: Mean hourly flux rates for NO_3^- -N in the Gazi Bay during dry and wet seasons.

Fig 4.8

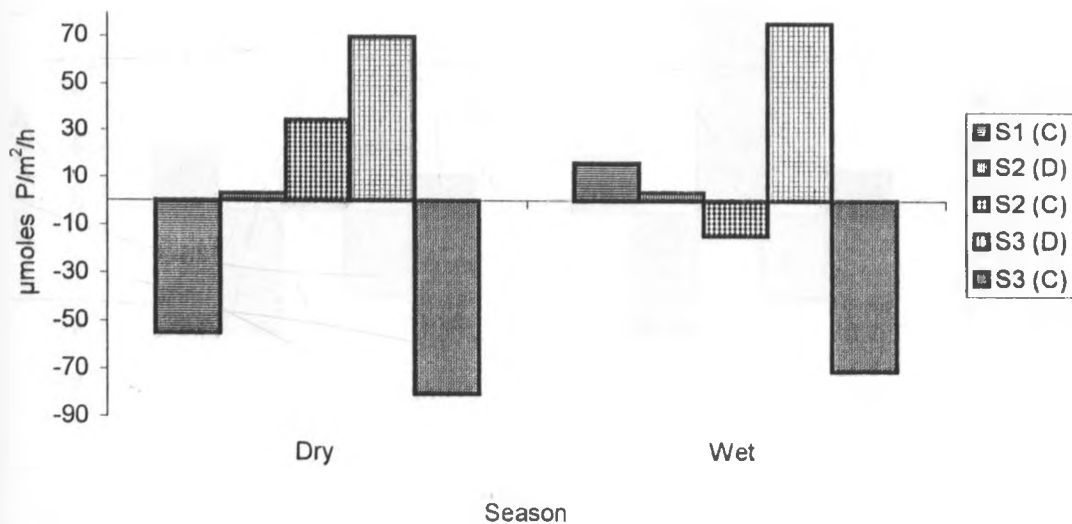
Fig. 4.8: Mean hourly flux rates for PO_4^{3-} -P in the Gazi Bay during dry and wet seasons.

Fig 4.9

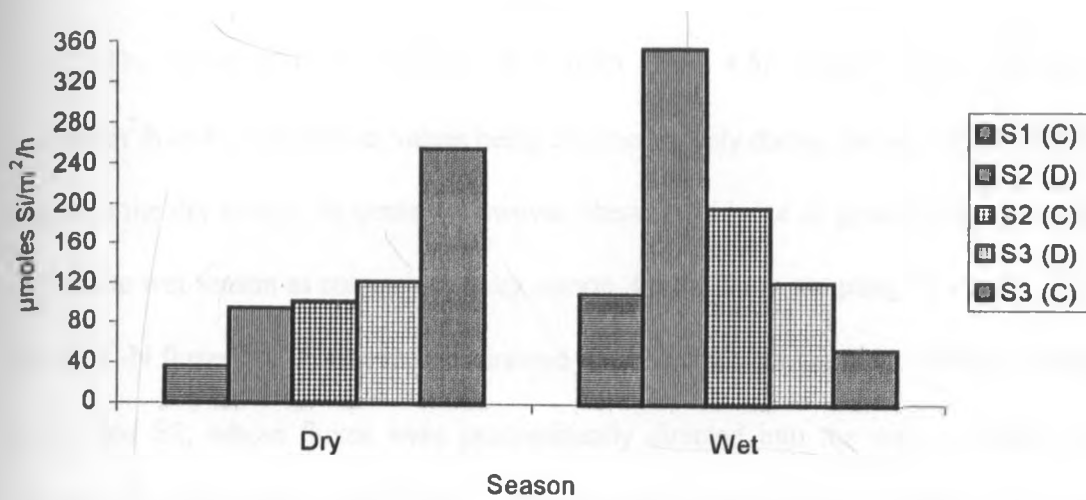
Fig. 4.9: Mean hourly flux rates for $\text{Si(OH)}_4\text{-Si}$ in the Gazi Bay during dry and wet seasons

Fig 4.10

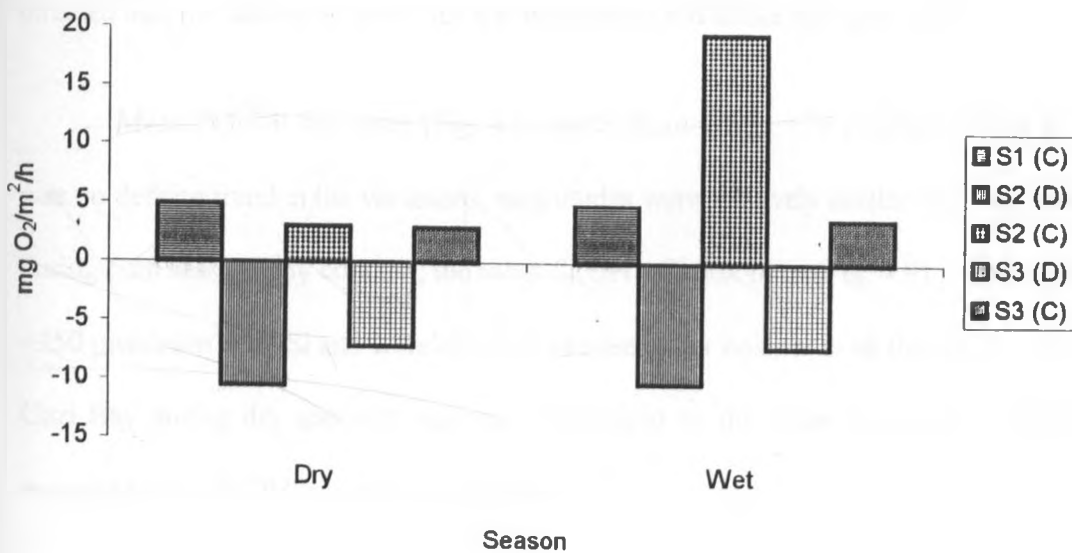


Fig. 4.10: Mean hourly benthic dissolved oxygen fluxes in the Gazi Bay during dry and wet seasons.

The mean NH_4^+ -N seasonal flux rates (Fig. 4.5) ranged from -270 to +148 $\mu\text{moles/m}^2/\text{h}$ of N, with lowest values being obtained mainly during the wet season and highest values in the dry season. In general, however, there is evidence of greater degree of variation during the wet season as compared to dry season. Of the three sampling sites in the Gazi bay, the NH_4^+ -N fluxes in S3 were mainly directed into the sediment (negative fluxes) as compared to S1 and S2, whose fluxes were predominantly directed into the water column (positive fluxes). The NO_2^- -N flux rates (Fig. 4.6) ranged from -60 to +63 $\mu\text{moles/m}^2/\text{h}$ of N with extreme values obtained during the wet season. The relative NO_2^- -N flux magnitudes are on average lower during the dry season as compared to the wet season, with biggest fluctuations at site S2. On the other hand, the NO_3^- -N mean flux rates (Fig. 4.7) were markedly variable during both dry and wet seasons in all the sampled sites in the Bay. The fluxes varied from -79 to +41 $\mu\text{moles/m}^2/\text{h}$ of N. In all the sites in the Gazi Bay, the fluxes were predominantly directed into the sediment, unlike for the ammonium and nitrite nitrogen species.

Mean PO_4^{3-} -P flux rates (Fig. 4.8) varied from -79 to +79 $\mu\text{moles/m}^2/\text{h}$ of P but there was no definite trend in the variations; magnitudes were relatively similar in all the sample sites during both seasons. By contrast, the mean Si(OH)_4 -Si flux rates (Fig. 4.9) ranged from +30 to +350 $\mu\text{moles/m}^2/\text{h}$ of Si and were directed into the water column in all the sampling sites in the Gazi Bay during dry and wet seasons. Compared to the other nutrients, the average flux magnitudes for Si(OH)_4 -Si were much higher.

The effect of environmental factors on the nutrient flux rates was examined by multiple linear regression where the nutrient flux data were treated as variable dependent on

temperature, initial water column nutrient concentration, respiration rate and gross production rate. These analyses showed existence of significant correlations between NO_2^- -N and initial concentration and Si(OH)_4 -Si and all the independent variables (Table 4.5) as evidenced by their correlation coefficients (r^2). It is most likely that the analytical problems in detecting small concentration changes during chamber deployments were the primary cause of the large variabilities observed in most nutrient flux results.

One way ANOVA of the flux rate data obtained for transparent or clear (C) and darkened (D) bell-jar chambers, as well as between nutrient concentration data for sampled waters from the different sites within Gazi Bay revealed no significant difference for all the nutrients considered ($p=0.42$) except for NH_4^+ -N concentrations whose variations were significant ($p=0.03$). However, variance analysis on all nutrient flux measurements revealed no significant differences between seasons ($p=0.66$).

Table 4.5: A summary of linear regression analyses relating temperature, benthic respiration, gross primary production, initial water-column nutrient concentration and benthic nutrient fluxes in Gazi Bay.

Inde. Variables	Regr. Parameters	Dependent Variables						
		Benthic Respir. $\text{gO}_2/\text{m}^2/\text{d}$	Gross Product. $\text{gO}_2/\text{m}^2/\text{d}$	Fluxes $\mu\text{moles}/\text{m}^2/\text{d}$				
				NH_4^+-N	NO_2^--N	NO_3^--N	$\text{PO}_4^{3-}-\text{P}$	$\text{Si}(\text{OH})_4-\text{Si}$
Temp ($^{\circ}\text{C}$)	b	34.1	33.9	10497	102	1012	-3611	-59130
	m	-0.0004	-0.0003	-330	-3.6	-78	121	2037
	r^2	0	0.13	0.25	0	0	0	0.63
	n	12	12	15	15	15	15	15
Benth Respir. $\text{gO}_2/\text{m}^2/\text{d}$	b	-	-1982	-950	190	4941	2215	14738
	m	-	1.47	0.169	-0.02	-0.93	-0.3	-1.39
	r^2	-	0.76	0	0.20	0	0.15	0.37
	n	-	12	12	12	12	12	12
Gross Product. $\text{gO}_2/\text{m}^2/\text{d}$	b	-	-	-812	138	-1768	542	13267
	m	-	-	0.125	-0.01	-0.1	-0.1	-0.99
	r^2	-	-	0	0.07	0	0	0.61
	n	-	-	12	12	12	12	12
Init. Nutr. Conc. (μM)	b	-	-	1504	-202	3304	-357	423
	m	-	-	-466	1716	-358	274	244
	r^2	-	-	0.35	0.92	0	0.10	0.36
	n	-	-	15	15	15	15	12

Note: b=y-intercept; m=slope; r^2 =coefficient of determination; n=sample size; Inde. = independent; Regr. = regression; Respir. = respiration; Product. = production; Temp. = temperature; Init. nutr. concn. = Initial nutrient concentration

The SRCC analysis for nutrient flux rates of all nutrients considered generally revealed independence between the three sites (see Table 5.1). Some comparison between calculated and measured mean fluxes for NH_4^+-N and NO_3^--N in samples from site S3 are shown in Table 5.4. The nutrient values obtained in this work agree with those obtained in a previous study in the same Bay (Kazungu, unpublished data).

4.2.2: Benthic Production

Table 4.6 gives daily net production, daily respiration (R) and gross production (P) determined for sites S1, S2 and S3 during dry and wet seasons. The mean net production values ranged from 1.13 to 7.49 g O₂/m²/d while the mean daily respiration rates were higher: 5.44 to 8.06 g O₂/m²/d.

Table 4.6: Mean (\pm S.D.) daily net production, daily respiration, gross production (units are in μ moles O₂/m²/d) and P:R ratios in Gazi Bay.

Site	S1		S2		S3	
Season	Dry	Wet	Dry	Wet	Dry	Wet
Daily net product.	59 \pm 44	58 \pm 44	37 \pm 248	234 \pm 456	35 \pm 26	46 \pm 217
Daily respir (R)	-	-	252 \pm 72	245 \pm 64	170 \pm 130	171 \pm 129
Daily gross prod.(P)	-	-	289 \pm 320	486 \pm 520	206 \pm 156	217 \pm 151
R:P ratio	-	-	1:1.2	1:2	1:1.2	1:1.3

Note: Daily net product. = daily net production; Daily respir. = daily respiration (R); Daily gross prod. = daily gross production (P)

It is evident that there was considerable variability in the net production and respiration rates (Fig. 4.10) at all the sites sampled during both seasons but there was no definite trend in the data. However, the overall results for daily gross production and daily respiration suggest that there is generally an autotrophic condition in the Gazi Bay as the P:R ratios were always

greater than 1 (Table 4.6).

Two-way ANOVA on benthic gross production data revealed no significant differences between seasons irrespective of the sites ($p=0.64$) However, the overall results were much higher than those recorded for temperate regions, for instance, the range found in a turbid zone of a coastal plain estuary, USA, was $2.1-4.1 \text{ g O}_2 \text{ m}^{-2} \text{ d}^{-1}$ (Boynton *et al.* 1980).

4.3: Fluvial nutrient input

The mean nutrient concentration levels for Kidogoweni and Mkurumuji rivers which flow into Gazi Bay are given in Figs. 4.11-4.15, which shows net elevation (though not significant, $p > 0.1$) of all the nutrient concentrations in both rivers except for $\text{Si(OH)}_4\text{-Si}$, during the wet season as compared to dry season.

Fig 4.11

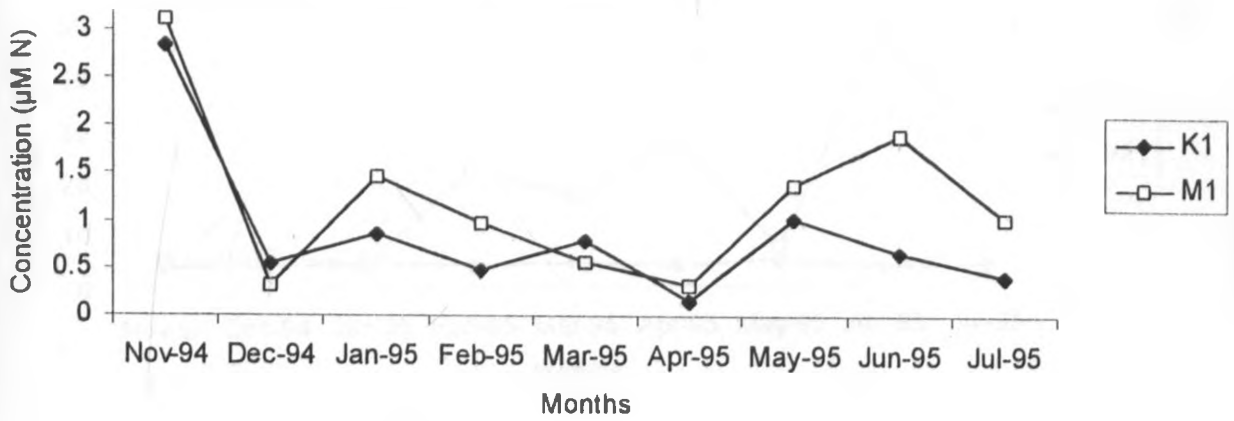


Fig. 4.11: Mean monthly river $\text{NH}_4^+\text{-N}$ variations for the entire sampling period in the Gazi Bay.

Fig 4.12

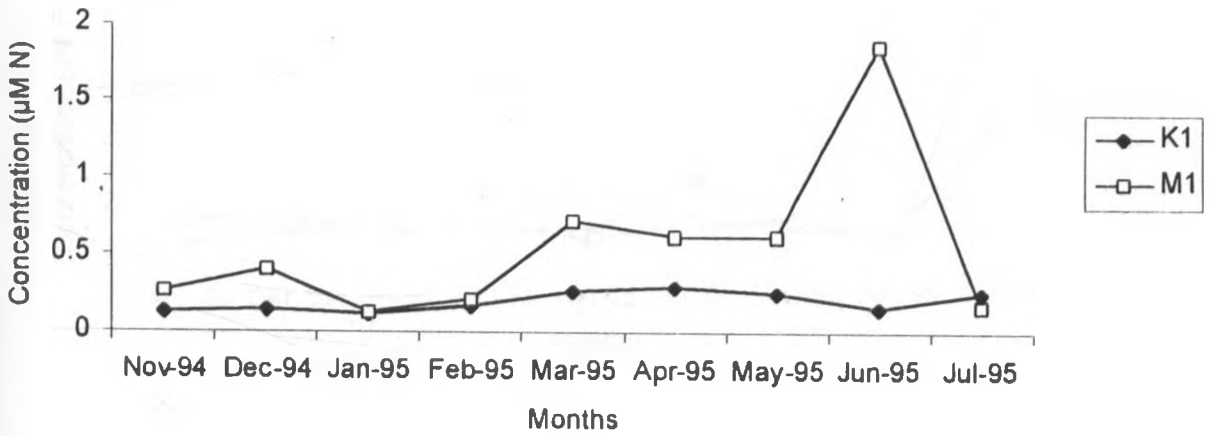


Fig. 4.12: Mean monthly river $\text{NO}_2\text{-N}$ variations for the entire sampling period in the Gazi Bay.

Fig 4.13

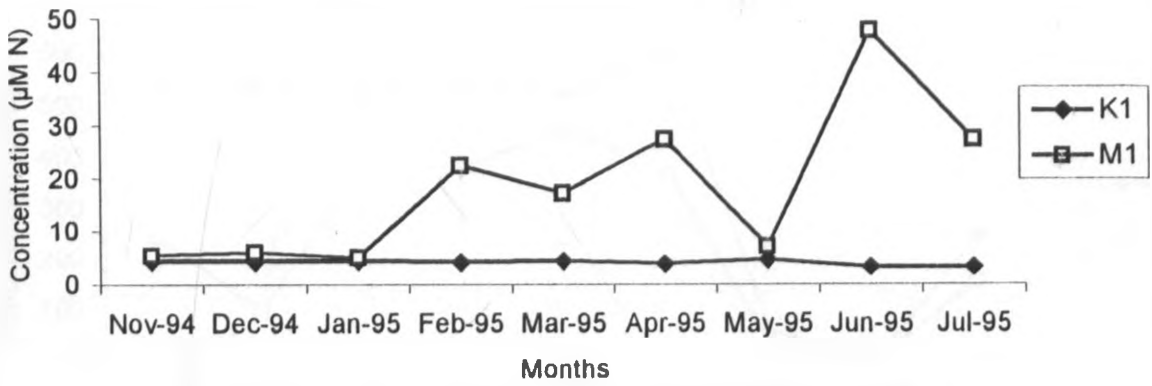
Fig. 4.13: Mean monthly river $\text{NO}_3\text{-N}$ variations during the study period in the Gazi Bay.

Fig 4.14

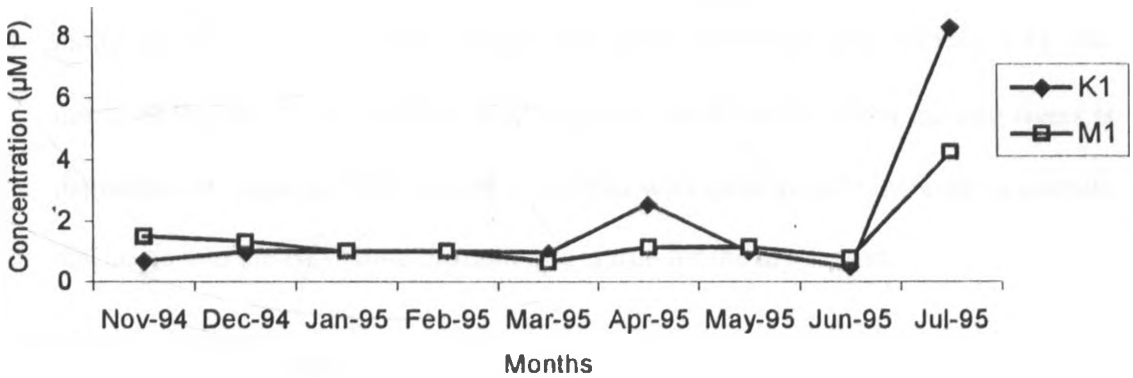
Fig. 4.14: Mean monthly river $\text{PO}_4^{3-}\text{-P}$ variations for the entire sampling period in the Gazi Bay.

Fig 4.15

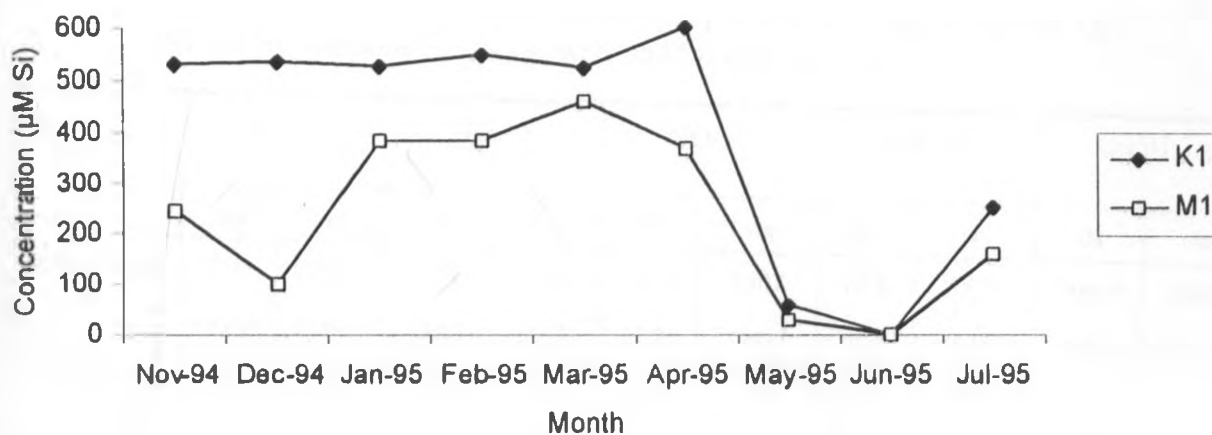


Fig. 4.15: Mean monthly river $\text{Si(OH)}_4\text{-Si}$ variations for the entire sampling period in the Gazi Bay.

The increased terrestrial run off during this period is thought to be the most likely cause of this observed effect. The river discharge data (Table 4.8) also indicates that the fluvial nutrient discharge into the Gazi Bay from the two rivers is dependent on seasons. Wet season is marked with considerable increase in nutrient discharge into the Bay while the converse is true for the dry season.

Table 4.8: Mean (\pm S.D) river nutrient discharges (g/day) during the dry (ds) and wet (ws) seasons for Kidogoweni and Mkurumuji rivers.

RIVER	NH ₄ ⁺ -N		NO ₂ ⁻ -N		NO ₃ ⁻ -N		PO ₄ ³⁻ -P		Si(OH) ₄ -Si	
	ds	ws	ds	ws	Ds	ws	ds	ws	ds	ws
Kidogoweni	7.06 (1.69)	1563 (1496)	1.79 (0.62)	336 (109)	41.7 (1.2)	6407 (941)	21.8 (0.4)	8578 (10150)	10643 (232)	1096030 (795420)
Mkurumuji	43.0 (15.9)	3015 (2172)	15.00 (0.01)	1474 (1271)	632 (312)	45169 (35000)	83.3 (15.8)	8436 (5775)	34864 (3029)	678500 (566570)
FLUVIAL NUTRIENT INPUT TOTALS	50.1	4578	16.8	1810	674	51570	105	17014	45507	1774530

It is also evident from Table 4.8 that the levels of NO₂⁻-N and NO₃⁻-N were found to be higher in the Mkurumuji river than Kidogoweni river, while the converse was true for Si(OH)₄-Si. The levels for NH₄⁺-N and PO₄³⁻-P are more or less similar in both rivers irrespective of the season. However, the monthly variation trend observed in all nutrients in both rivers is similar during the entire sampling period.

One-way variance analysis of the dry season mean data revealed no significant differences between nutrient levels in the two rivers ($p=0.33$) except for Si(OH)₄ whose concentrations varied significantly ($p=0.01$). Similarly, the wet season nutrient data revealed no significant variation differences ($p=0.36$) except for NO₃⁻-N whose concentration variations are

significant ($p=0.04$) This is in agreement with previous observations (Osore, 1994, Kitheka *et al.* 1996).

4.4: Water column nutrients

Mean variations in nutrient levels in the water column of Gazi Bay with tidal cycle and months are depicted in Figs. 4.16-4.25 for dry and wet seasons.

Monthly and seasonal trends in nutrient variations for NH_4^+ -N (Figs. 4.16-4.17), NO_3^- -N (Figs. 4.20-4.21) and Si(OH)_4 -Si (Figs. 4.24-4.25) were similar. Concentrations were highest during the wet season months. By contrast, NO_2^- -N and PO_4^{3-} -P levels were highest during the dry season months. Monthly trends for all the nutrients were similar for all the sampled sites: there was either a concomitant increase or decrease of the nutrients during the entire sampling period. The marked increase in NO_3^- -N concentrations in the river water during the wet season suggests a significant fluvial contribution of this nutrient into the Bay waters. However, the relative decrease in PO_4^{3-} -P during the wet season implies an insignificant fluvial contribution into the Bay. Kazungu *et al.* 1989; Johnstone and Mohammed, 1995 and Kitheka *et al.* 1996 who worked within the region also made similar observations.

Fig 4.16(a)

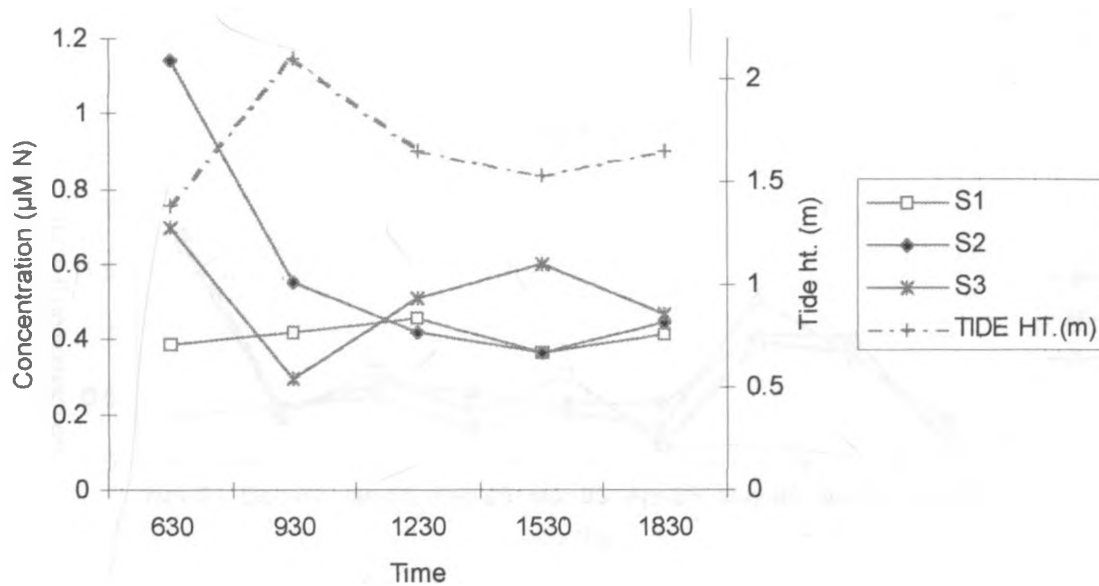


Fig 4.16 (b)

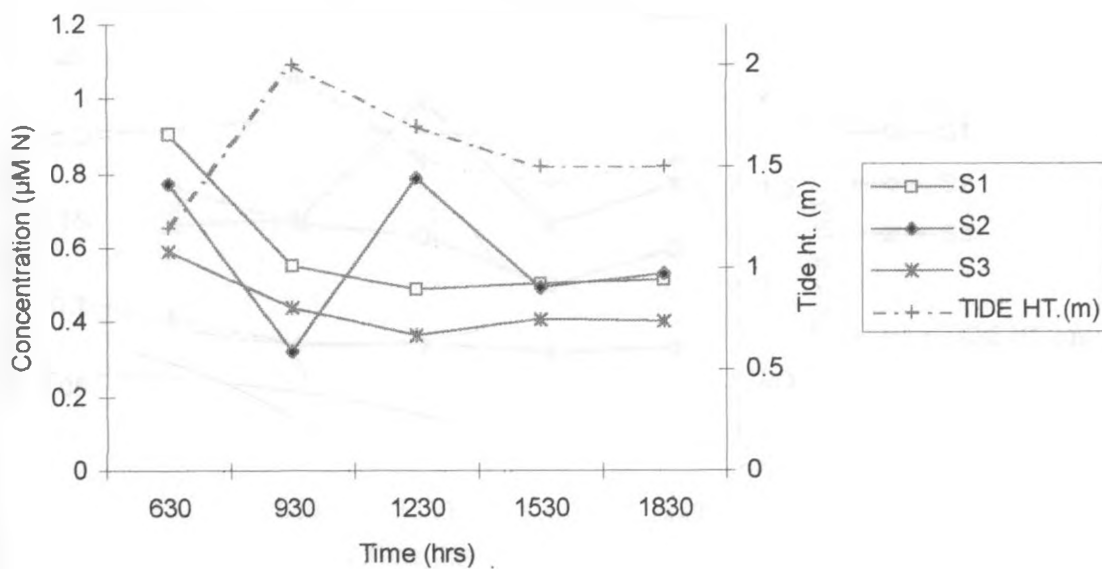
Fig. 4.16: Mean $\text{NH}_4^+\text{-N}$ variations with tidal cycle during dry and wet seasons in Gazi Bay.

Fig 4.17

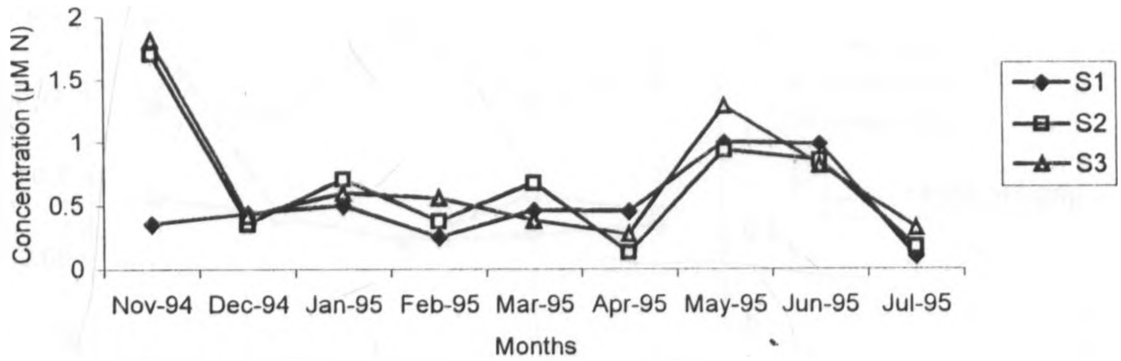


Fig. 4.17: Mean monthly variations for $\text{NH}_4^+\text{-N}$ in the Gazi Bay during the entire sampling period.

Fig 4.18 (a)

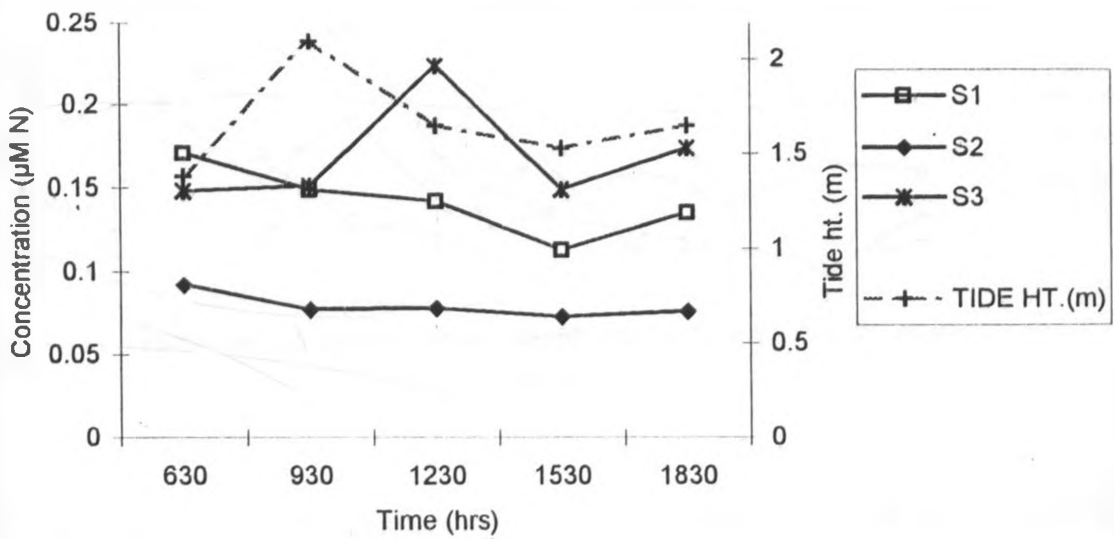


Fig 4.18(b)

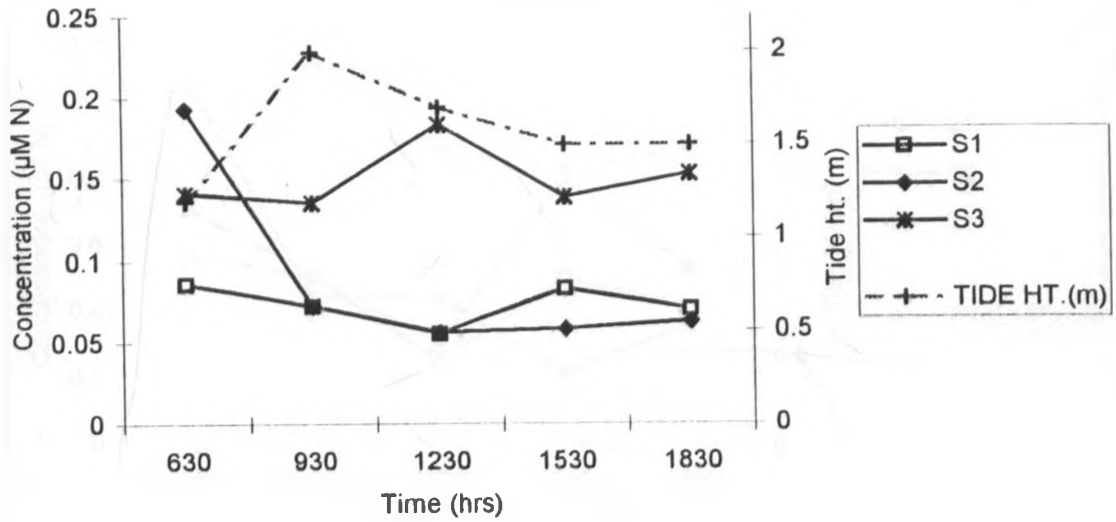
Fig. 4.18: Mean NO_2^- -N variations with tidal cycle during dry and seasons in Gazi Bay.

Fig 4.19

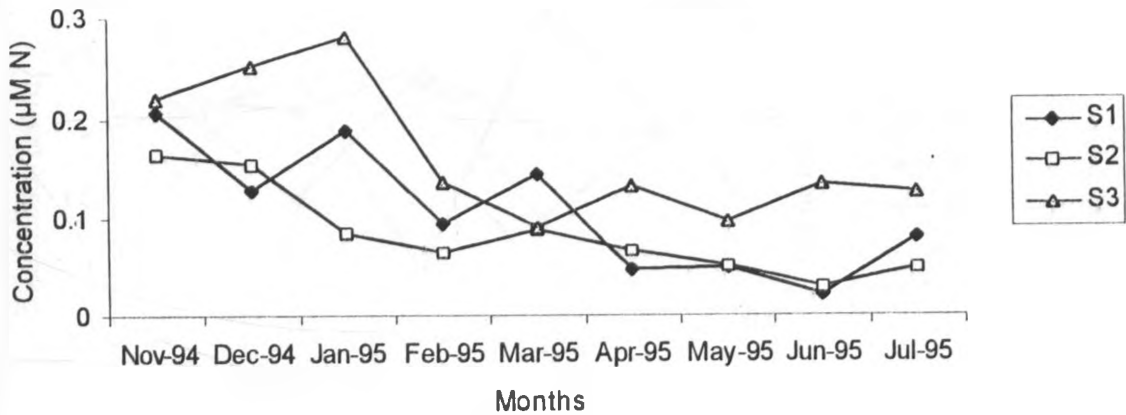
Fig. 4.19: Mean monthly variations for NO_2^- -N during the entire sampling period in Gazi Bay.

Fig 4.20(a)

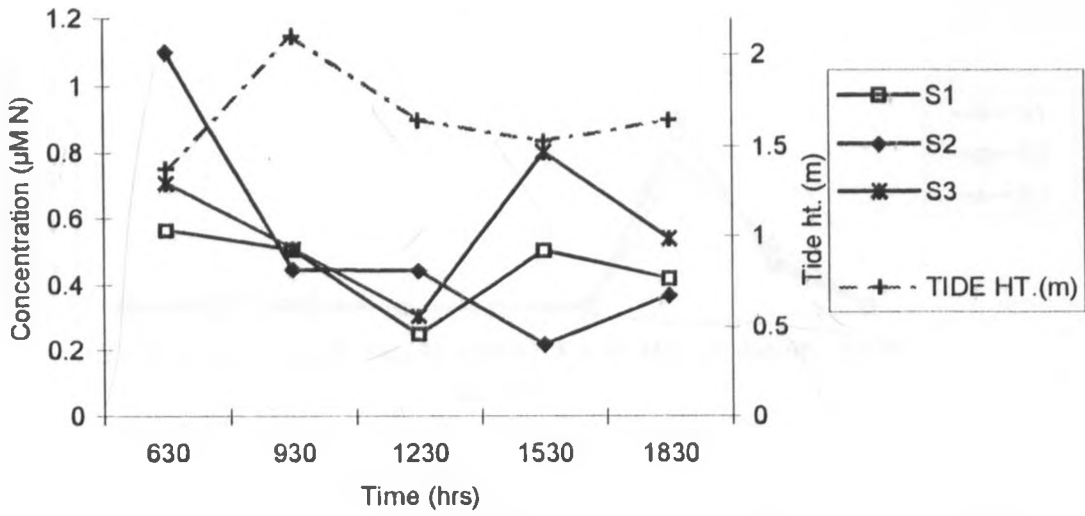


Fig 4.20(b)

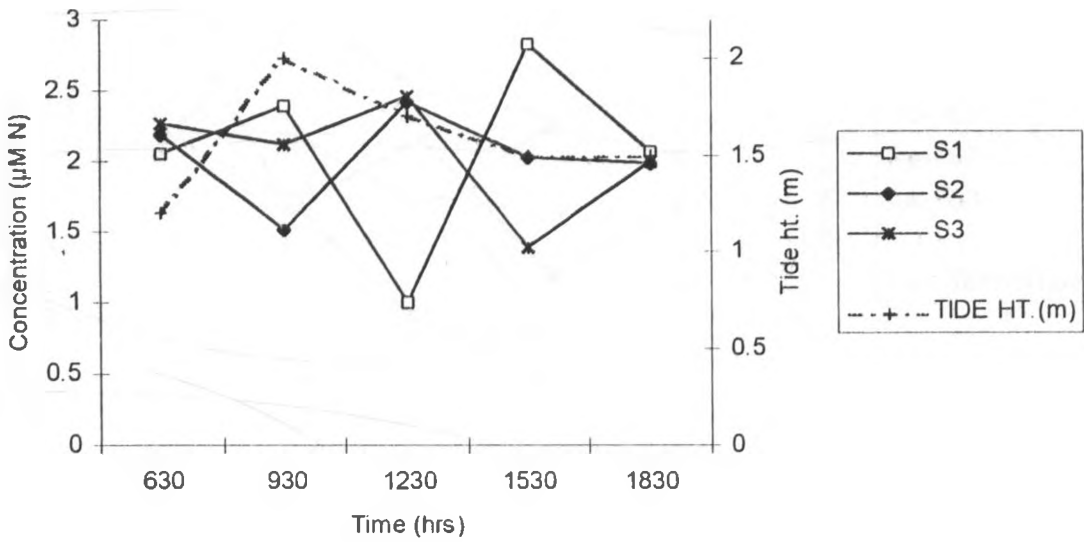
Fig. 4.20: Mean NO_3^- -N variations with tidal cycle during dry and wet seasons in Gazi Bay.

Fig 4.21

Fig. 4.21: Mean monthly variations for $\text{NO}_3\text{-N}$ during the entire sampling period in Gazi Bay.

Fig 4.22(a)

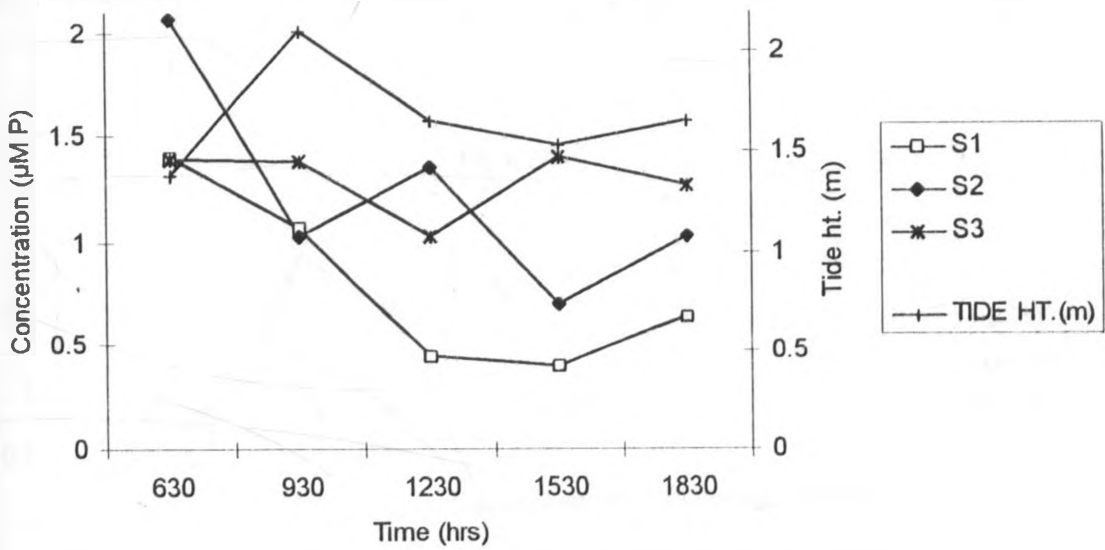


Fig 4.22(b)

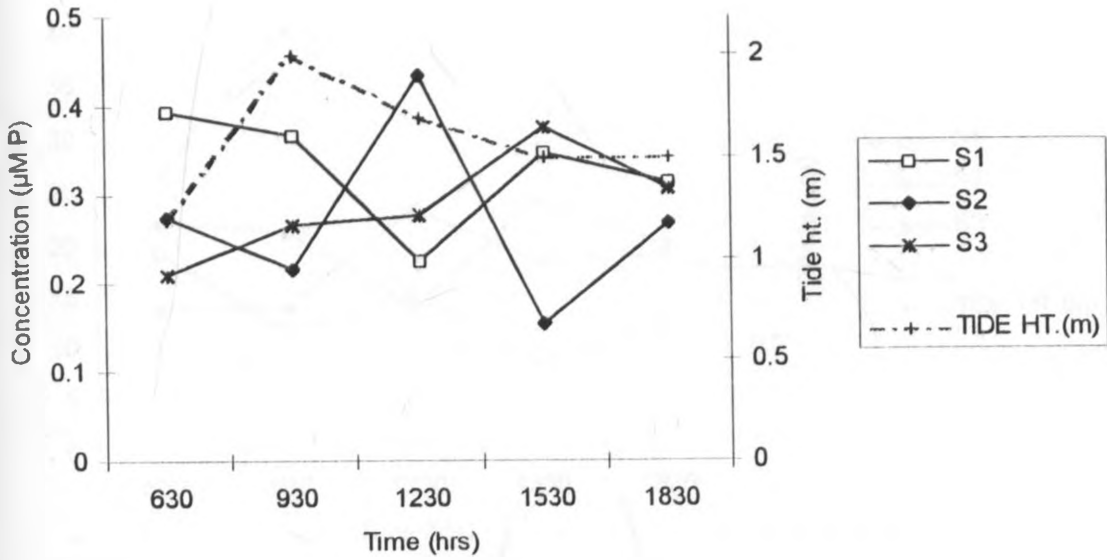


Fig. 4.22: Mean PO_4^{3-} -P variations with tidal cycle during dry and wet seasons in the Gazi Bay.

Fig 4.23

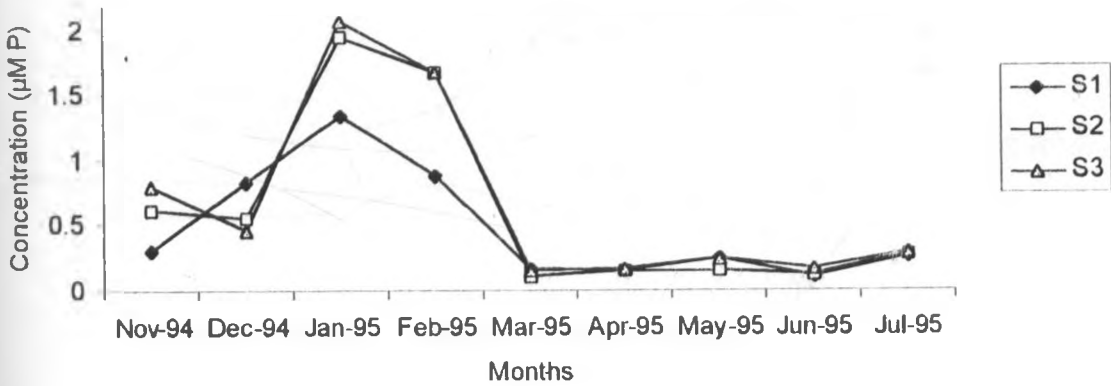


Fig. 4.23: Mean monthly variations for PO_4^{3-} -P during the entire sampling period in the Gazi Bay.

Fig 4.24(a)

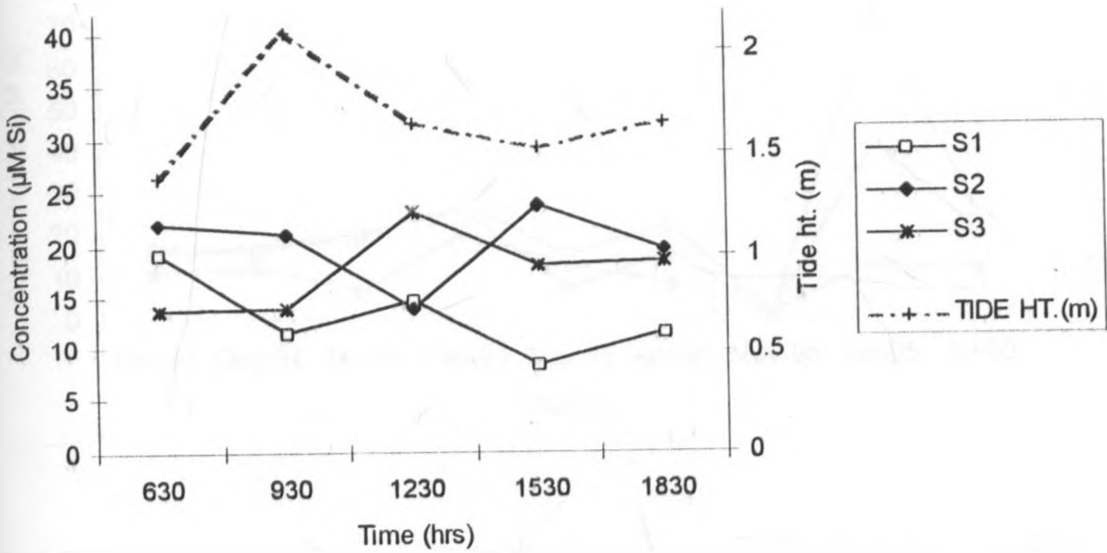


Fig 4.24(b)

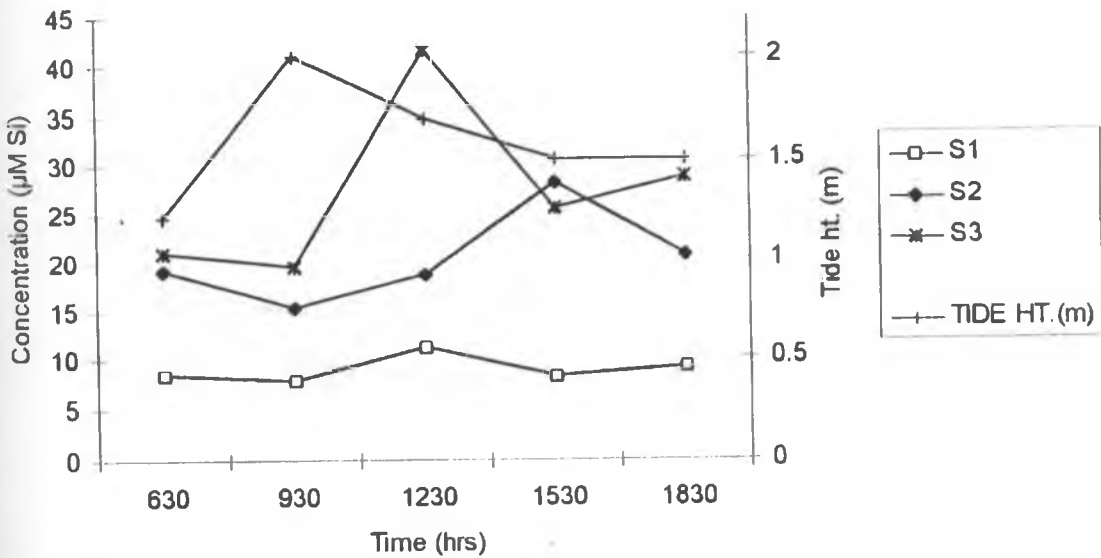


Fig. 4.24: Mean $\text{Si(OH)}_4\text{-Si}$ variations with tidal cycle during dry and wet seasons in Gazi Bay

Fig 4.25

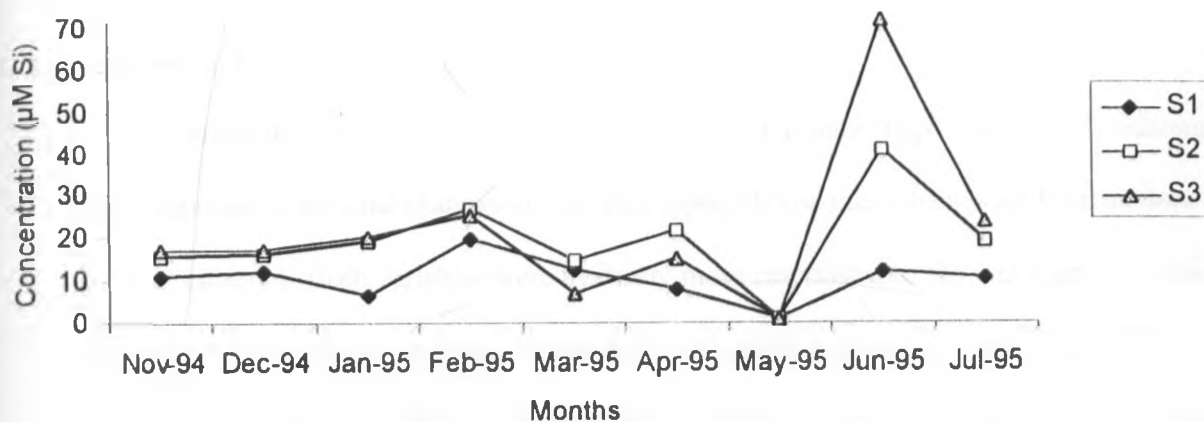


Fig 4.25: Mean monthly variations for $\text{Si(OH)}_4\text{-Si}$ in the Gazi Bay during the entire sampling period.

Variations in the water column nutrients with tidal cycle did not show striking differences for most of the nutrients in the Gazi Bay sites except for S3 where there was an apparent increase in $\text{NH}_4^+\text{-N}$ and $\text{NO}_3^-\text{-N}$ concentrations at low tides compared to the high tides. Two-way ANOVA revealed no significant differences between all nutrient concentrations with respect to sample sites and between tidal cycles except for Si(OH)_4 where differences were significant ($p=0.01$). One-way ANOVA of the nutrient data with respect to season, revealed that variations in nutrient concentrations with tidal cycles were significant for $\text{NO}_3^-\text{-N}$ ($p=0.00$) and $\text{PO}_4^{3-}\text{-P}$ ($p=0.01$) compared to the other measured nutrients.

CHAPTER FIVE

DISCUSSION

5.1: Environmental factors

Variations in temperature (Figs. 4.1 and 4.2) and salinity (Figs. 4.3 and 4.4) indicate a direct response to seasonal changes in Gazi Bay especially for sites which were located close to the river estuaries. Both variables were evidently more responsive to the wet season, a period when lowest values were recorded, especially at S3 which is closest to the Kidogoweni river estuary. The increased discharge of the river during the wet season is thought to be the main cause for the observed effect. On the other hand, the low pH and dissolved oxygen (DO) values observed at S3 were mainly related to the fact that this particular site is situated within a mangrove forest which is rich in litter and decomposing detritus material. Such conditions naturally impose a high oxygen demand to the system by creating a chemically reducing environment, leading to the observed trends in pH and DO. This phenomena has been pointed out previously in the region (Osore, 1994). The expected optimum DO content in seawater of salinity 34 PSU at 25°C and normal atmospheric pressure is 6.2 mg O₂/l (Parsons *et al.* 1984). The absence of any significant difference in temperature and salinity levels within the tidal cycle ($p = 0.14$) suggests that the general physical properties of the waters of Gazi Bay do not vary significantly within any given tidal cycle a situation also reflected in the nutrient compositions. The influence of river discharges which impose strong local influences around areas within the estuaries such as the Kidogoweni river also contributed to the observed differences in salinities which were however slightly significant ($p = 0.2$). Mkurumuji river would have been expected to provide a similar effect on S1 had this site been closer enough to the Mkurumuji estuary. In

addition, the prevailing dominant onshore wind generates a westward flowing current (Kitheka *et al.* 1996) which precludes the expected potential influence.

5.2: Benthic nutrient fluxes

5.2.1: NH_4^+ -N exchanges

Mean ammonium flux rates ($< 100 \mu\text{moles m}^{-2}\text{h}^{-1}$ of N) in Gazi Bay (Fig. 4.5) were lower compared to those reported in the temperate environments, such as the Patuxent River estuary in Chesapeake Bay, USA (Boynton *et al.* 1980) and Cap Blanc, Spanish Sahara (Rowe *et al.* 1975) where levels were 2 - 3 times higher. A number of factors may help explain the low NH_4^+ regeneration rates observed; among them the sediment organic matter composition of the near shore environments (T.M. Munyao personal communication). It is strongly believed that the relatively low NH_4^+ fluxes found in S3 were associated with the substantial dilution of the reactive planktonic organic matter by refractory terrigenous debris leading to a considerable reduction in sediment reactivity and nutrient remineralization rates. No significant differences were obtained between flux rates in clear and darkened bell-jar chambers, and this shows that the photosynthetic process had little or no direct influence on NH_4^+ exchange rates between sediment and the water-column. It is likely that the most important factors controlling NH_4^+ exchanges are the processes taking place at the benthic rather than the water column. Elsewhere, studies have shown that release of NH_4^+ -N is markedly reduced by sediments having a microautotrophic community. For example, Rizzo (1990) reported that majority of the variations in NH_4^+ -N release are attributed to respiration rate alone. This observation was to a great extent in agreement with results obtained in Gazi Bay where a notable correlation ($r^2=0.4$, $p=0.13$) between initial NH_4^+ -N concentration at the

water-sediment interface and the flux rate was observed (Table 4.5).

The highly variable negative NH_4^+ -N flux at S3 (Fig. 4.5) could largely be attributed to the predominant mangrove forest, *Rhizophora mucronata*, where the prevailing muddy and turbid conditions are inimical to primary productivity due to oxygen stress and reduced light penetrability into the sediment environment. However, Spearman's Rank Correlation Coefficient (SRCC) analyses between the different sites (Table 5.1) imply that factors controlling the rate of fluxes may not necessarily be the same between the different sampling sites as shown by the highly variable flux rates observed in these sites (Fig. 4.5).

Table 5.1: Spearman's Rank Correlation Coefficient (intersites) test on mean nutrient fluxes in Gazi Bay biotopes (sites S1, S2 and S3).

Note: Corr stat = correlation status; indep = independent;
 r_s = Spearman's Rank Correlation Coefficient; r_{crit} = critical value for the Spearman's Rank Correlation Coefficient

Nutrient	S1 vs S2			S1 vs S3			S2 vs S3		
	r_s	r_{crit}	Corr stat	r_s	r_{crit}	Corr stat	r_s	r_{crit}	Corr Stat
$\text{NH}_4^+ \text{-N}$	-0.4	1.0	indep	-0.8	1.0	indep	0.4	1.0	indep
$\text{NO}_2^- \text{-N}$	-0.6	1.0	indep	-0.2	1.0	indep	-0.2	1.0	indep
$\text{NO}_3^- \text{-N}$	-0.4	1.0	indep	0.2	1.0	indep	-0.8	1.0	indep
$\text{PO}_4^{3-} \text{-P}$	-0.4	1.0	indep	-0.4	1.0	indep	0.4	1.0	indep
$\text{Si(OH)}_4 \text{-Si}$	-0.4	1.0	indep	0.40	1.0	indep	0	1.0	indep

5.2.2: $\text{NO}_2^- \text{-N}$ and $\text{NO}_3^- \text{-N}$ exchanges

The variation in NO_2^- flux rates were lower than those of NO_3^- in Gazi Bay (Figs. 4.6 and 4.7). Lack of any significant difference between clear and darkened bell jar chambers for the two species strengthens the fact that there was less direct influence of photosynthetic activity on the flux rates of these nutrients in Gazi Bay. Furthermore, absence of spatial or temporal significant differences on flux rates for NO_2^- and NO_3^- is an indication that factors other than these are crucial in determining their flux rates in the Bay. Moreover, the overall flux direction for NO_2^- is towards the water column whereas for NO_3^- tends towards the

sediment layer (Fig. 4.6). This implies that the demand for these nutrients is quite different between the sediment and water column. The apparent existence of a strong correlation ($r^2=0.92$; $p=0.001$) between NO_2^- flux and the initial concentration of NO_2^- in the water column-sediment interface, could be attributed to the high demand for NO_2^- -N in the water column rather than in the sediment, whereas the converse is true of NO_3^- -N. This observation is further supported by the relatively low concentrations of NO_2^- -N in the water column compared to NO_3^- -N (Figs. 4.18-4.21). On the contrary however, Boynton and Kemp (1985) found that sediment NO_3^- -N uptake was proportional to water column NO_3^- -N concentration in the upper Chesapeake Bay, USA unlike in the present study where correlation was stronger for NO_2^- -N than NO_3^- -N. Boynton *et al.* (1980) suggested that the strong correlation between NO_3^- concentration in the water column and the negative NO_3^- flux implies a NO_3^- consumptive process in the sediment which for some unclear reasons may be limited by diffusion across the sediment-water interface. This process is apparently not closely linked to aerobic respiration. These relationships suggest that NO_3^- fluxes into the sediments represent the first stages of either denitrification ($\text{NO}_3^- \rightarrow \text{N}_2\text{O}$ and N_2) or nitrate respiration ($\text{NO}_3^- \rightarrow \text{NH}_4^+$). Denitrification rates have been shown to depend on NO_3^- concentration in the overlying water (Boynton *et al.* 1980). Since in general there was no commensurate amount of NH_4^+ -N flux out of sediments to suggest nitrate respiration (Fig. 4.5), it is strongly suggested that the NO_3^- uptake from water column to sediments was associated with denitrification. This has been shown to be the case for the Baltic-Kattegat system (Gordon *et al.* 1995) where model stoichiometric calculations have revealed that 70% of the nitrogen loss through denitrification occur in the sediments.

5.2.3: PO_4^{3-} -P exchanges

The range and mean of phosphate fluxes obtained in Gazi Bay (Fig.4.8) although relatively higher, were comparable to those found in studies elsewhere. For instance, the range for Gazi Bay (-79 to +75 $\mu\text{moles/m}^2/\text{h}$ of P) shows a higher variation than that of 23 to 60 $\mu\text{moles/m}^2/\text{h}$ of P observed in temperate coastal regions (Nixon *et al.* 1980., Klump and Martens 1981., Callendar and Hammond 1982). The existence of a difference which tended towards significant ($p < 0.04$) in phosphate exchange between flux chamber treatments suggests that photosynthetic process had a measurable influence on the fluxes. It has often been postulated that phosphate exchanges are largely controlled by the oxygen status of the sediment (Klump and Martens, 1981; Callendar and Hammond, 1982; Carlton and Wetzel, 1988). Under oxic (or adequate oxygenation) conditions, phosphate is bound to sediments as iron-manganese-phosphate complexes, which are rapidly desorbed under anoxic (or inadequate oxygenation) conditions. Results of the present study seem to agree with these observations especially for data obtained during the dry season at sites S1 and S3 (Fig.4.8). The significant albeit weak correlation between respiration rate and phosphate exchange (Table 4.5), may serve to support this observation. In addition, phosphate loss from water column could also result from direct uptake by micro-organisms (Fenchel and Blackburn, 1979) or as a result of transport into sediment by irrigating organisms. The lack of any significant difference in phosphate fluxes between the different sites ($p = 0.68$) and seasons ($p = 0.77$) suggests that the processes controlling the PO_4^{3-} fluxes could be similar in all areas of the Bay. Table 5.1 gives an indication that these processes appear to be operating independently of each other owing to the differences in existing biotopes in the Bay.

5.2.4: Si(OH)_4 -Si exchanges

In both dry and wet seasons, there was net silicate flux from the sediment to water column (Fig. 4.9). This signifies that silicate release from the sediment in Gazi Bay does not depend on seasonal changes. The lack of any significant differences between silicate flux rates during different seasons or different sites within Gazi Bay reflects the marked consistency in flux rate trends observed within the different biotopes in the Bay (Fig. 4.9). Although these flux rates are essentially independent of the biotope type (Table 5.1), the net fluxes into the water column at all the sampling sites are indicative of the fact that silicate fluxes in Gazi Bay are largely influenced by the abundance of this nutrient in the Bay as a whole and the processes taking place at the water - sediment interface irrespective of the biotope type.

It has been suggested that release of reactive silicates from sediments is due predominantly to the dissolution of opaline silica formed by diatoms (Schink *et al.* 1975). This study has obtained results which bear strong correlation (Table 4.5) between silicate flux rates and temperature ($r^2=0.63$; $p=0.01$) as well as gross primary production ($r^2=0.61$, $p=0.07$). Similar observations have been made in other studies carried out elsewhere (Kamatani and Riley, 1979; Wollast, 1974) which show dependence of initial dissolution rates of diatom frustules and freshly precipitated silica gel on temperature. The dissolution rates obey first order kinetics and are described by equation 5.1 below (Hurd, 1972, 1973, Wollast, 1974; Kamatani and Riley, 1979):

$$R = k(C_b - C) \dots \dots \dots (5.1)$$

where,

R = production rate of dissolved silica.

k = first order rate constant. This constant takes into consideration the effect of surface area.

C_b = asymptotic silica concentration or solubility

C = dissolved silica concentration.

One of the possible reactions taking place at the sediment - water interface resulting in the observed flux could be the nontronite breakdown to kaolinite, dissolved silica and other cations (M and M') in seawater or in solid phases (Lerman, 1978):



"nontronite"

"kaolinite"

In general the nutrient fluxes of the Gazi Bay are comparable to those measured in other regions (Table 5.2).

Table 5.2: Ranges of dissolved nutrient fluxes ($\mu\text{moles}/\text{m}^2/\text{d}$) for nearshore sediments from various studies.

LOCATION (Temperature, $^{\circ}\text{C}$) and reference)	$\text{PO}_4^{3-}\text{-P}$	$\text{Si}(\text{OH})_4\text{-Si}$	$\text{NH}_4^+\text{-N}$	$\text{NO}_2^-\text{-N}$	$\text{NO}_3^-\text{-N}$
Narragansett Bay (~ 20) ¹	160-7700	1800-17000	900-18000	-	-
Long Island Sound (22) ²	59-320	-	1300-4000	-	-
Long Island Sound (26.5 ± 1.5) ³	-	0-19800	-1000-8000	-	-
North Carolina (20 ± 5) ⁴	-48-1100	-	0-11000	0 - 164 ^a	
Potomac River (~ 20) ⁵	-600-4000	1000-25000	-3100-26000	-	-
Yangste River (13-25.8) ⁶	-	29-13200	-2600-11000	-1600 - 3200 ^a	
Bowling Green Bay (21.8) ⁷	-23.4-27.9	-990-1754	-159-759	-2.3-33.4	-6.2-149
Gazi Bay (28.4) ⁸	-1896-1800	720-8400	-6480-3552	-1440-1512	-1896-984

(Note: ^aReported as $\text{NO}_2^- + \text{NO}_3^-$ flux).

Sources: ¹Elderfield *et al.* (1981); ²Aller (1981); ³Aller and Bellinger (1981); ⁴Fisher *et al.* (1982); ⁵Callender and Hammond (1982); ⁶Aller *et al.* (1985); ⁷Ullman and Sandstrom (1987); ⁸Present study.

5.3: Benthic respiration and gross production

The benthic respiration rates obtained in Gazi Bay (Fig. 4.10) are relatively higher compared to those reported in other regions. For instance, mean values for the sites sampled in

Gazi Bay ($5.4 - 8.1 \text{ g O}_2/\text{m}^2/\text{d}$) are about twice ($2.1 - 4.1 \text{ g O}_2/\text{m}^2/\text{d}$) those obtained in summer in the Patuxent Estuary, Chesapeake Bay, USA (Boynton *et al.* 1980). The fact that no significant difference existed between seasons ($p=0.64$) and sites ($p=0.61$) indicate that benthic gross production rates in Gazi Bay are neither dependent on biotope type nor on the season of the year. The implication of this observation could be that the benthic processes responsible for gross production in the Gazi Bay are determined by other factors which are probably insensitive to either season or location within the Bay. Nonetheless, the strong correlation between benthic respiration and gross production (Table 4.6) is a confirmation of the fact that the magnitude of the process largely depends on the latter. With temperature however, whose changes are insignificant, these relationships are either weakly correlated or non-existent altogether (Table 4.5). This is contrary to the observations made in temperate regions where a strong relationship between temperature and production has been observed (Hargrave, 1969; Boynton *et al.* 1980) in many aquatic systems. Other studies have reported that the estimates of benthic respiration in various ecosystems could be related to an index of the amount of plankton production reaching the bottom, a conclusion which supports the observation of Hargrave (1973) and Nixon (1981) that organic matter supply, rather than temperature, regulates annual benthic respiration. However, individual effects of primary production, organic matter flux to the bottom, temperature and other factors in the Bay are confounded by the interactions with each other. Such interactions may be further explained by treating each variable using non-linear ecological simulation models.

5.4: Fluvial nutrient input

The contribution of Kidogoweni and Mkurumuji rivers, to the nutrient budget and distribution in the Gazi Bay is appreciable (Figs. 4.11-4.15) although there were no significant differences between seasonal concentrations of most nutrients. Differences in the total nutrient input could be attributed to the differences between average daily volumes discharged by the two rivers into Gazi Bay: Mkurumuji river discharges a higher volume than Kidogoweni river during both the dry (3050 m^3 vs 714 m^3) and wet ($1.61 \times 10^5 \text{ m}^3$ vs $1.19 \times 10^5 \text{ m}^3$) seasons, respectively. The freshwater influx is greatest during wet season when discharge results in considerable amounts of nutrients derived from terrestrial run off and drainage of rich agricultural areas where there is intensive fertilizer application. These observations concur with what has been reported in other regions. For instance, Wright (1989) observed that tropical which have rivers with large seasonal differences in discharge rates have higher output of chemical compounds during stormy situations. Gaudet (1976) on the other hand reported that runoff from agricultural areas, was high in nutrients and this varied considerably with rainfall intensity and local agricultural practices. However, when compared with concentrations of nutrients in other rivers, Kidogoweni and Mkurumuji rivers can be considered to be among least polluted rivers in the world (Table. 5.3).

Table 5.3: A comparison of mean nutrient concentrations in some unpolluted and polluted world rivers.

RIVER	NUTRIENT ($\mu\text{g/l}$)			
	$\text{PO}_4^{3-}\text{-P}$	$\text{NO}_2^-\text{-N}$	$\text{NH}_4^+\text{-N}$	$\text{NO}_3^-\text{-N}$
UNPOLLUTED				
Hubbard Brook (New Hampshire)	0.7	-	31	440
Niger	13	1.4	14	100
Zaire	24	3	7	90
Purari	1.5	-	40	40
Amazon	12	1	35	40
Lindaret (France)	4	1.5	19	190
Sungai Gombak (Malaysia)	19	3.3	60	150
Maroni (Guyane)	4.5	1.4	-	98
Sondu-Miriu (Kenya)	-	18	-	140
*Kidogoweni (Kenya)	51.5	2.7	11.6	5
*Mkurumuji (Kenya)	40	7	16.4	244
POLLUTED				
Rhine (Nederland)	217	-	1960	2450
Meuse (Belgium)	235	-	1820	3220
Thames (Great Britain)	2475	-	991	9300
Seine (France)	510	100	1700	3950
Trent (Great Britain)	1335	200	287	10100
Missouri (USA)	59	-	210	700

Sources: Meybeck (1982); Mwashote and Shimbira (1994); *Present study.

The drainage basin of these two rivers, which extends into the coastal ranges of the Shimba Hills, is less urbanized and with low human population pressure. Thus the most probable source of pollution could be the farming practices which are the dominant activities in the area.

5.5: Water column nutrient distribution

The observed results have revealed that there is little spatial and temporal variation in nutrient concentrations of the waters in Gazi Bay (Figs. 4.16-4.25) as shown by the variance analysis and SRCC results (Table 5.4). This was mainly

Table 5.4: Spearman's Rank Correlation Coefficient test on mean water column nutrient concentrations in Gazi Bay biotopes.

Nutrient	S1 vs S2			S1 vs S3			S2 vs S3		
	r_s	r_{crit}	Corr stat	r_s	r_{crit}	Corr stat	r_s	r_{crit}	Corr stat
NH_4^+ -N	0.01	0.56	inde	0.75	0.56	n.ind	0.07	0.56	inde
NO_2^- -N	0.77	0.56	n.ind	0.07	0.56	inde	-0.08	-0.56	inde
NO_3^- -N	0.75	0.56	n.ind	0.66	0.56	n.ind	0.87	0.56	n.ind
PO_4^{3-} -P	0.80	0.56	n.ind	0.72	0.56	n.ind	0.50	0.56	inde
$Si(OH)_4$ -Si	-0.10	-0.60	inde	0.31	-0.56	inde	-0.35	-0.56	inde

Note: Corr stat = correlation status; inde = independent; n. ind = not independent; r_s = Spearman's Rank Correlation Coefficient; r_{crit} = critical value for the Spearman's Rank Correlation Coefficient.

attributed to the short residence times of the oceanic waters (which varied between 3.1 to 3.6 hours). and the subsequent high water exchange rate (up to 90%) between Gazi Bay waters and the oceanic waters (Kitheka *et al.* 1996). This overwhelming influence on the Bay waters results in minimum spatial water column nutrient variations among the different biotopes found

in Gazi Bay. However, the significant difference observed between sites and seasons for the case of NO_3^- , PO_4^{3-} and Si(OH)_4 , can be associated with the influence created by the local influx of river nutrients, a phenomenon which is more noticeable during the wet season (when river water is relatively more laden with these nutrients). Similar observations have been recorded in neighbouring regions including the Mapopwe Creek in Zanzibar (Johnstone and Mohammed, 1995) where seasonal differences in nutrient levels observed have been attributed to changes in localized input of nutrients from forest runoff. However, compared to the Mapopwe Creek, the concentration of some nutrients such as NH_4^+ , NO_3^- , and PO_4^{3-} were generally higher in Gazi Bay owing to the fluvial contribution from the Mkurumuji and Kidogoweni rivers.

On the contrary however, the Gazi Bay mean nutrient levels have been found to be lower than those reported in the neighbouring Tudor Creek (Kazungu *et al.* 1989). This disparity could be associated with the fact that Tudor Creek is found within an urbanized locality (Mombasa town), and thus receives substantial amounts of pollutants through urban discharge of domestic and industrial effluent (especially through untreated sewage). Furthermore, the waters of this particular creek have a relatively lower rate of exchange with the oceanic waters (Kitheka *et al.* 1996) On the global scale, Gazi Bay nutrient concentration levels are comparable with those found elsewhere, such as the Long Island Sound (Bowman, 1977; Aller and Benninger, 1981).

5.6 Coupling nutrient fluxes and plankton

On the basis of the results given in Table 4.3 and considering each biotope in the Gazi Bay on individual basis, it would appear that most of the three biotopes (mangrove, seagrass and coral reef) found in the Bay act mainly as sources of most nutrients except for NO_3^- for which they all behave as sinks. A summary of the nutrient source/sink function for Gazi Bay biotopes during dry and wet seasons is given in Table 5.5. Table 4.3 shows that the flux of NH_4^+ from the sediments accounted for essentially all dissolved N transfer from the sediment to the water column since virtually all NO_3^- flux was directed into the sediments.

Table 5.5: Summary on nutrient source/sink functioning for the different biotopes in Gazi Bay.

BIOTOPE	NH ₄ ⁺ -N		NO ₂ ⁻ -N		NO ₃ ⁻ -N		PO ₄ ³⁻ -P		Si(OH) ₄ -Si	
	ds	ws	ds	ws	ds	ws	ds	ws	ds	ws
Coral reef (S1)	source	source	sink	sink	sink	sink	sink	source	source	source
Seagrass (S2)	source	source	source	sink	sink	sink	source	sink	source	source
Mangrove (S3)	sink	source	source	source	sink	sink	sink	source	source	source
NET FUNCTION FOR GAZI BAY	source	source	source	source	sink	sink	sink	source	source	source

Note: ds = dry season, ws = wet season.

Contribution of NO₂⁻ concentrations was relatively insignificant. On the other hand, the flux direction for PO₄³⁻ was largely variable within the different biotopes. This variability seemed to be different from one biotope to the other and essentially depended on the season. For instance, the fluxes for PO₄³⁻ were basically directed into the sediments during the dry season but leached out of the sediments during wet season. The NH₄⁺ and Si(OH)₄ fluxes in all the Gazi Bay biotopes were entirely directed from sediment into the water column during both seasons.

The stoichiometry of nutrient regeneration from Gazi Bay sediments can be assessed by comparing daily flux ratios of Si(OH)_4 : NH_4^+ : PO_4^{3-} (represented as Si:N:P ratio) in the measured benthic fluxes (Table 5.6). Although the *in situ* benthic Si:N:P flux ratios appear less variable for nearshore (e.g. S3) than for inner (e.g. S1) sites, the individual Si:N, N:P and Si:P ratios are evidently different. These observations may be attributed to the types of geochemical processes controlling the benthic flux of these nutrients within the various biotopes of Gazi Bay. Data in Table 5.6 also show that the N:Si ratio within these biotopes is influenced considerably by seasonal change. N:Si ratio for S1 was 49 during dry season but dropped to 12 during wet season.

Table 5.6: Stoichiometric ratios of Si(OH)_4 -Si: NH_4^+ -N: PO_4^{3-} -P for *in situ* benthic fluxes from near shore sediments of Gazi Bay biotopes.

BIOTOPE	DRY SEASON				WET SEASON			
	Si:N:P	Si:N	Si:P	N:P	Si:N:P	Si:N	Si:P	N:P
Coral reef (S1)	-	1:49	-	-	1:12:4	1:12	1:4	3:1
Seagrass (S2)	1:4:5	1:4	1:5	4:5	-	4:1	-	-
Mangrove (S3)	-	-	-	-	2:14:1	1:10	1:2	14:1
OVERALL FOR GAZI BAY	-	4:1	-	-	3:14:1	1:5	3:1	14:1

Since the organic matter entering the sediment surface is nitrogen rich, some other processes must have been operative in producing the generally low ratios observed (Table 5.6). Although

Nixon *et al.* (1976) reported similar results in Narragansett Bay, USA, the data indicated that nitrogen flux from sediments to water was a mixture of both NH_4^+ and dissolved organic nitrogen (DON). It was suggested that partitioning of the flux into inorganic and organic fractions (as is the case with Gazi Bay) may have been responsible for the low N:P benthic ratios and, to a lesser extent, the low N:P ratios observed in the water column. In the present study DON was assumed to be negligible, since a number of studies elsewhere have found this to be so (Boynton *et al.* 1980; Hartwig, 1976 and Gordon *et al.* 1995).

Interstitial phosphate may be controlled by both inorganic and organic processes but the Si(OH)_4 and NH_4^+ fluxes are enhanced by macrofaunal irrigation (Callendar and Hammond, 1982). Moreover, relatively large phosphorus fluxes may represent anoxic degradation of phosphorus containing iron oxyhydroxides (Krom and Berner, 1980). The values for N:P ratios found in Gazi Bay, though seemingly low, are quite comparable to those reported elsewhere (Nixon, 1981; Klump and Martens, 1981; Nixon *et al.* 1980).

The results of this study have indicated that benthic input supplies a major fraction of the nutrients which are utilized in the water column. There are several ways in which to place the importance of benthic fluxes into perspective. Based on the assessment procedure of Aller and Benninger (1981), the average water column nutrients in the sampled area through fluvial sources can be compared with those supplied by flux from the bottom sediment by simply considering data provided in Tables 3 and 8, in which the coverage area of the sampled sites of Gazi Bay have also been taken into account. From these tables, it is evident that with the

exception of NO_3^- and PO_4^{3-} for which fluvial contribution is far more important to Gazi Bay, the benthic nutrient fluxes are of significantly greater importance to the Bay during both dry and wet seasons. In addition, if we assume that atmospheric inorganic nutrient inputs into Gazi Bay are relatively insignificant in comparison to fluvial and benthic flux sources, and considering that there is no evidence of groundwater contribution to the Bay (Kitheka *et al.* 1996), it is clear that direct terrestrial inputs of the dissolved inorganic nutrients are minor compared with the overall contribution arising from benthic flux processes within the Bay.

In view of the small total area of Gazi Bay which is approximately 15 km^2 (mangrove = 5 km^2 , seagrass = 7 km^2 and coral reef = 3 km^2) and its moderate mean annual rainfall which varies from 1000 to 1500 mm (Kitheka *et al.* 1996; Kazungu, 1996), this striking observation is quite in conformity with results of studies done in other regions. For instance, a review by Meybeck (1982) found that in 22 unpolluted sites around the world, dissolved inorganic nitrogen (DIN) fall-out was between 300 and $600 \text{ kg km}^{-2}\text{yr}^{-1}$, the median being $450 \text{ kg km}^{-2}\text{yr}^{-1}$, while the corresponding atmospheric input of P was $5 \text{ kg km}^{-2}\text{yr}^{-1}$.

When the Gazi Bay is considered in terms of its constituent biotopes, some degree of variation in their net nutrient benthic flux directions is observed between the biotopes (Table 5.5). While the overall picture portrayed by the benthic fluxes of the Bay is that of behaving as a source for NH_4^+ , NO_2^- and Si(OH)_4 , and a sink for NO_3^- and PO_4^{3-} , the scenario is not necessarily the same when each particular biotope is considered individually. For instance, during the dry season, the coral reef and seagrass biotopes act as sources for NH_4^+ while the

mangrove biotope behaves as a sink for the same nutrient. On the contrary, during the same season, for the case of NO_2^- , the former two biotopes behave as sinks while the latter biotope acts as a source making the results to be in close agreement with similar studies conducted recently in Malaysia (Gordon *et al.* 1995). These observations appear to suggest some kind of mutual concomitant antagonistic processes which take place in terms of source/sink function between some of the biotopes in Gazi Bay, for particular nutrients. However, since many other processes such as denitrification and nitrification (Rivera - Monroy *et al.* 1995a) are involved in determining the net flux observed in any nearshore coastal system such as Gazi Bay, further work is needed in this area to provide a better understanding of the observed effect.

Considering the fact that since the Bay has an overwhelmingly high rate of exchange between its waters and oceanic waters, accompanied by a relatively short residence time (Kitheka *et al.* 1996), the foregoing data suggests that the Bay is a net exporter of inorganic NH_4^+ , NO_2^- and Si(OH)_4 and a net importer of NO_3^- and PO_4^{3-} . Similar observations have also been qualitatively made in the same Bay previously (Middelburg *et al.* 1996) and in other environment elsewhere (Rivera - Monroy *et al.* 1995 a,b).

Both phytoplankton and zooplankton distribution in Gazi Bay have been found to be strongly influenced by seasonal changes (Kitheka *et al.* 1996). The increased river discharges which occur during rainy season have been found to have noticeable but different effects on the abundance of planktons. For example, at the mangrove site, which has greater riverine influence from Kidogoweni river, has been found to record a low zooplankton count (as low as

2 individuals per m^3) apparently due to the resulting low salinities (Mwaluma *et al.* 1993). Conversely, the same riverine influence favors phytoplankton production (up to $1110\text{mg}/m^3/\text{day}$ of C) because of the overriding effect of increased nutrients resulting from higher river discharge. On an overall basis however the plankton production in the Bay has been found to be lower compared to similar environments within the region. For instance, gross phytoplankton production in the neighboring Tudor Creek was estimated to be $350\text{mg C}/m^2/\text{h}$ (Okemwa, 1989). These observations are again mainly attributed to the high exchange rate between offshore and inshore waters and the short residence time found in the waters of Gazi Bay. The same factors are also thought to be responsible for the lack of any observable eutrophic conditions which would have otherwise arisen due to the nutrient enrichment from river discharges. In this respect, the Gazi Bay can be listed among the unpolluted environments of the world (Meybeck, 1982).

Incidentally, during the dry season, it has been found (Kitheka *et al.* 1996) that the density distribution of planktons becomes more even among all the different biotopes in the Bay because the river discharges are reduced considerably, leading to less variable salinities (mean approximately 35 PSU) except for areas which are just within the very vicinity of the river mouths. Unlike similar environments elsewhere (Ullman and Sandstrom, 1987), the lack of any significant difference in nutrient flux rates between the different biotopes ($p = 0.55$) and seasons ($p = 0.66$) in Gazi Bay gives the impression that there is little effect of dilution by refractory terrigenous debris and turbidity associated with major runoff events during wet seasons. Such factors have often been found to lead to reduction in sediment reactivity and

nutrient remineralization rates in such environments. Such phenomena have been found to be a common occurrence in a number of other related environments (Aller *et al.* 1985; Shokes, 1976; Berner, 1978; Torgersten and Chivas, 1985).

Our nutrient flux study results have unequivocally demonstrated that all biotopes in Gazi Bay, in some way import NO_3^- following the apparent deficit created by the directional NO_3^- flux into the sediments. Although the mean theoretical calculations showed reversed fluxes for this nutrient (Table 5.7), this disparity is simply attributed to the effect of microbial processes prevalent at the sediment - water column interface.

Table 5.7: Comparison between some calculated and experimental mean nutrient flux rates in the Gazi Bay.

Constitution	Present study			Previous study	
	<i>In situ</i> flux	Calc. Flux	No. of samples (n)	Experimental flux	No. of samples (n)
NH ₄ ⁺ -N	-9±27	0.4±0.3	20	15±61	84
NO ₃ ⁻ -N	-68±249	0.05±0.02	20	3.3±17.6	87

Note: Calc. = calculated

It is however suggested that direct estimates of coupled nitrification - denitrification processes within the Gazi Bay biotopes are needed to evaluate the alternative source of N to the NO₃⁻ loss in the system. Moreover, studies of other similar systems in different geomorphological and hydrological environments are required for a better understanding and elucidation of the function of mangrove, seagrass and coral reef biotopes such as those found in Gazi Bay, in the overall nutrient dynamics of the coastal zone.

CONCLUSION

Seasonal variations were found to have a profound influence on the physical and chemical properties of the Gazi Bay environment especially to the areas which are within the vicinity of the river mouths. This effect was also strongly reflected in the plankton distribution of the Bay. While precipitation plays a significant role in this aspect mainly due to the increased river discharge and surface runoff into the Bay, tidal and spatial variations have little or no effect on both physical properties and water column nutrient concentrations of the Gazi Bay.

The nutrient concentration levels in both river and Bay waters are comparable to those found in unpolluted environments therefore suggesting that the Gazi Bay is largely a pristine environment. The short residence time and the relatively high rate of water exchange between the Bay and the oceanic waters is unfavorable to the development of any eutrophic conditions which would have otherwise arisen due to continued fluvial nutrient input into the Bay.

Within experimental uncertainty, the different treatments of benthic chambers had no effect on the resultant nutrient fluxes obtained in the Gazi Bay and theoretically calculated fluxes were in agreement with the *in situ* measurements. There is however, considerable seasonal influence on PO_4^{3-} nutrient fluxes and N:Si ratio in the Bay. The lack of any significant spatial or temporal variation in the benthic respiration and gross production in Gazi Bay strongly suggests that the benthic microbial process taking place in all the biotopes of Gazi Bay may be similar.

In an overall basis, benthic nutrient fluxes in Gazi Bay are a major supply for NH_4^+ , NO_2^- and Si(OH)_4 compared to inputs from fluvial sources, which are relatively more important in the supply of NO_3^- and PO_4^{3-} into the Bay. Sediments therefore appear to be quite efficient at recycling organic matter received from the water column. In this respect, the Gazi Bay as a whole acts as net sink for PO_4^{3-} and NO_3^- and a net source of NH_4^+ , NO_2^- and Si(OH)_4 . It is likely that the different biotopes in Gazi Bay act concomitantly in mutual antagonistic sense with respect to source/sink function for some nutrients. However, for this phenomena to become clearer, further quantitative work is suggested especially in relation to the different processes taking place at the sediment-water column interface within the different biotopes.

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APPENDIX

Table 4.1: Temperature (°C) and salinity (PSU) variations with tidal cycle during dry and wet seasons in the Gazi Bay.

	SITE	S1		S2		S3	
	TIME	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
T E M P E R A T U R E	0630	26.6-29.5	25.6-31.0	27.7-29.2	24.8-30.3	27.4-29.1	24.0-29.4
	0930	27.3-28.5	27.3-29.0	27.8-28.2	27.5-30.9	26.6-28.7	24.5-29.7
	1230	27.4-29.4	27.2-30.0	28.2-29.8	23.0-29.7	27.5-29.7	23.1-33.0
	1530	27.4-29.4	26.3-29.7	28.6-31.4	25.0-29.4	28.8-30.7	25.1-30.5
	1830	27.4-29.1	26.9-29.5	28.2-29.8	24.3-29.9	27.4-29.7	24.2-30.0
S A L I N I T Y	0630	35.3-35.5	34.0-36.0	35.4-36.4	25.1-36.1	35.0-37.5	28.0-37.3
	0930	33.0-35.4	32.0-35.5	33.2-35.9	26.0-35.8	34.8-37.5	24.0-37.5
	1230	35.1-35.7	30.0-36.5	35.0-35.6	26.0-36.2	32.5-36.8	25.0-36.8
	1530	35.2-36.1	34.0-37.4	35.8-36.4	30.0-36.1	33.5-38.2	29.0-36.9
	1830	34.6-35.7	32.0-36.0	34.7-36.0	27.0-37.7	33.6-37.3	26.0-37.0

Table 4.2: Monthly temperature (°C) and salinity (PSU) variations in the Gazi Bay.

SITE	S1		S2		S3	
MONTH	TEMPERATURE	SALINITY	TEMPERATURE	SALINITY	TEMPERATURE	SALINITY
NOV'94	27.4-28.8	35.2-35.8	26.1-28.3	23.5-31.8	27.7-29.4	33.3-35.8
DEC'94	27.2-28.3	35.3-35.7	28.0-29.4	35.5-36.1	28.2-30.5	36.8-37.3
JAN'95	26.6-29.1	35.3-36.1	27.7-28.6	35.4-35.8	27.4-30.3	36.8-38.2
FEB'95	27.3-27.7	35.1-35.8	28.1-30.1	35.6-36.4	28.7-30.7	36.7-37.6
MAR'95	28.5-29.5	33.0-35.7	28.2-31.4	33.2-36.0	26.6-28.8	32.5-35.0
APR'95	29.0-31.0	34.9-37.4	29.0-30.9	35.4-37.7	29.0-29.7	34.9-37.5
MAY'95	28.0-30.0	34.0-36.0	28.0-29.0	31.0-35.0	28.0-33.0	32.0-35.0
JUN'95	27.0-28.2	30.0-34.0	27.1-28.3	26.0-30.0	26.5-29.0	24.0-35.0
JUL'95	25.5-27.3	32.5-36.5	23.0-25.0	35.0-36.0	23.1-25.1	29.0-36.0

Table 4.3: Mean daily benthic nutrient fluxes (\pm S.D) in kg/day in the Gazi Bay sediments.

BIOTOPE	NH ₄ ⁺ -N		NO ₂ ⁻ -N		NO ₃ ⁻ -N		PO ₄ ³⁻ -P		Si(OH) ₄ -Si	
	ds	ws	ds	ws	ds	ws	ds	ws	ds	ws
Coral reef (S1)	148 (133)	106 (124)	-11.2 (12.2)	-12.3 (10.6)	-81.6 (66.7)	-21.5 (11.7)	-123 (100)	35.9 (63.8)	3.1 (0.5)	9.2 (5.7)
Seagrass (S2)	85 (306)	8 (76)	8.5 (15.3)	-25 (132)	-34.7 (16.4)	-62 (146)	99 (391)	-27 (156)	19.3 (88.3)	28.9 (85.5)
Mangrove (S3)	-24 (277)	118 (192)	39.4 (53.3)	54.3 (58.5)	-22.3 (8.8)	-19.2 (8.6)	-20 (247)	8 (248)	26.4 (53.5)	12.3 (46.9)
TOTAL BENTHIC FLUX IN GAZI BAY	209	232	36.7	17	-139	-103	-44	17	48.8	50.4

(Note: ds = dry season; ws = wet season; S.D = standard deviation)

Table 4.4: Comparison between some measured nutrient flux rates ($\mu\text{moles}/\text{m}^2/\text{h}$) and initial water-column nutrient concentrations (μM) at the water - sediment interface in Gazi Bay.

NH_4^+-N		NO_2^--N		NO_3^--N		$\text{PO}_4^{3-}-\text{P}$		$\text{Si}(\text{OH})_4-\text{Si}$	
Init. conc.	Flux rate	Init. conc.	Flux rate	Init. conc.	Flux rate	Init. conc.	Flux rate	Init. conc.	Flux rate
9.76	-194	0.14	3.1	14.7	-124	1.00	-50	7.52	-107
3.69	62.9	1.00	62.5	14.0	-130	1.39	37.9	41.8	443
5.21	64.5	0.05	-0.6	24.5	430	0.12	-3.8	6.61	332
1.53	20.0	0.11	6.8	3.50	86.7	0.05	2.10	16.5	156
0.78	18.9	0.07	-16	29.8	-789	4.28	34.4	14.0	196
0.38	-2.4	0.15	0.6	3.58	10.5	0.50	-26	3.53	-1.0

Note: Init. conc. = initial concentration

Table 4.7: Seasonal ($\pm\text{S.D.}$) mean nutrient concentration levels ($\mu\text{moles}/\text{l}$) for Kidogoweni (K1) and Mkurumuji (M1) rivers during dry and wet seasons.

Season	River	NH_4^+-N	NO_2^--N	NO_3^--N	$\text{PO}_4^{3-}-\text{P}$	$\text{Si}(\text{OH})_4-\text{Si}$
Dry	K1	0.71 ± 0.17	0.18 ± 0.06	4.17 ± 0.12	0.99 ± 0.02	531 ± 12
	M1	1.00 ± 0.37	0.35 ± 0.26	14.8 ± 7.3	0.88 ± 0.17	407 ± 35
Wet	K1	0.94 ± 0.90	0.20 ± 0.06	3.83 ± 0.56	2.32 ± 2.75	327 ± 237
	M1	1.34 ± 0.96	0.65 ± 0.56	20 ± 16	1.7 ± 1.2	150 ± 125

Table 4.9(a): Water-column $\text{NH}_4^+\text{-N}$ ($\mu\text{M N}$) variations with tidal cycle during dry and wet seasons in the Gazi Bay.

SITE	S1		S2		S3	
	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
0630	0.32-0.51	0.11-1.24	0.40-1.85	0.17-1.95	0.44-0.91	0.28-4.60
0930	0.41-0.43	0.04-1.87	0.34-0.68	0.06-1.68	0.07-0.55	0.17-1.36
1230	0.24-0.58	0.10-0.75	0.18-0.56	0.04-1.85	0.39-0.66	0.26-0.85
1530	0.06-0.54	0.07-1.58	0.27-0.44	0.19-2.40	0.48-0.66	0.09-1.30
1830	0.24-0.50	0.10-0.97	0.38-0.55	0.13-1.64	0.37-0.56	0.24-1.12

Table 4.9(b): Monthly variations in water-column $\text{NH}_4^+\text{-N}$ ($\mu\text{M N}$) in the Gazi Bay.

SITE	S1	S2	S3
NOV'94	0.11-0.56	0.85-2.40	0.70-4.60
DEC'94	0.30-0.75	0.04-1.21	0.17-0.84
JAN'95	0.41-0.55	0.34-1.85	0.48-0.74
FEB'95	0.06-0.43	0.18-0.68	0.27-0.92
MAR'95	0.32-0.38	0.44-1.18	0.07-0.66
APR'95	0.04-1.24	0.06-0.19	0.09-0.46
MAY'95	0.59-1.58	0.70-1.12	0.71-2.53
JUN'95	0.40-1.87	0.40-1.85	0.37-1.22
JUL'95	0.10-0.11	0.16-0.23	0.24-0.42

Table 4.10(a): Water-column NO_2^- -N ($\mu\text{M N}$) variations with tidal cycle during dry and wet seasons in the Gazi Bay.

SITE	S1		S2		S3	
	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
0630	0.05-0.29	0.03-0.62	0.03-0.11	0.03-0.43	0.05-0.33	0.06-0.21
0930	0.11-0.19	0.03-0.15	0.04-0.11	0.02-0.17	0.06-0.31	0.08-0.20
1230	0.08-0.19	0.02-0.13	0.07-0.08	0.04-0.11	0.11-0.39	0.12-0.40
1530	0.06-0.20	0.01-0.14	0.07-0.08	0.03-0.11	0.11-0.20	0.10-0.26
1830	0.11-0.16	0.08-0.12	0.07-0.08	0.03-0.13	0.10-0.27	0.11-0.26

Table 4.10(b): Monthly variations in water-column NO_2^- -N ($\mu\text{M N}$) in the Gazi Bay.

SITE	S1	S2	S3
NOV'94	0.05-0.62	0.04-0.43	0.12-0.40
DEC'94	0.07-0.17	0.11-0.26	0.13-0.40
JAN'95	0.11-0.29	0.08-0.11	0.11-0.39
FEB'95	0.05-0.16	0.04-0.08	0.07-0.20
MAR'95	0.06-0.19	0.07-0.11	0.05-0.14
APR'95	0.04-1.24	0.06-0.19	0.09-0.46
MAY'95	0.59-1.58	0.70-1.12	0.71-2.53
JUN'95	0.40-1.87	0.42-1.85	0.37-1.22
JUL'95	0.10-0.11	0.16-0.23	0.24-0.42

Table 4.11(a): Water-column NO_3^- -N ($\mu\text{M N}$) variations with tidal cycle during dry and wet seasons in the Gazi Bay.

SITE	S1		S2		S3	
	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
0630	0.50-0.63	0.40-6.33	0.70-1.50	0.30-9.44	0.30-1.05	0.18-7.31
0930	0.43-0.64	0.36-10.90	0.29-0.70	0.23-6.01	0.28-0.90	0.20-7.76
1230	0.15-0.39	0.10-4.45	0.10-0.80	0.16-7.44	0.25-0.35	0.30-9.95
1530	0.30-0.64	0.41-11.50	0.15-0.30	0.16-8.33	0.10-1.65	0.44-4.41
1830	0.38-0.45	0.35-8.95	0.20-0.57	0.23-7.26	0.23-0.97	0.33-6.36

Table 4.11(b): Monthly variations in water-column NO_3^- -N ($\mu\text{M N}$) in the Gazi Bay.

SITE	S1	S2	S3
NOV'94	0.40-1.08	0.48-0.88	0.38-0.69
DEC'94	0.39-0.56	0.16-0.67	0.70-1.28
JAN'95	0.30-0.56	0.20-1.50	0.30-1.65
FEB'95	0.15-0.64	0.29-0.70	0.28-0.78
MAR'95	0.20-0.64	0.10-1.10	0.10-1.05
APR'95	0.10-0.85	0.30-0.75	0.20-0.50
MAY'95	4.45-11.50	6.01-9.44	1.37-9.95
JUN'95	0.28-3.86	1.38-3.86	2.21-4.41
JUL'95	0.30-0.57	0.26-0.34	0.18-0.43

Table 4.12(a): Water-column $\text{PO}_4^{3-}\text{-P}$ ($\mu\text{M P}$) variations with tidal cycle during dry and wet seasons in the Gazi Bay.

SITE	S1		S2		S3	
	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
0630	0.19-3.00	0.05-1.40	0.18-3.00	0.16-0.50	0.17-3.00	0.16-0.63
0930	0.20-2.00	0.05-1.07	0.10-2.00	0.09-0.75	0.15-3.00	0.12-0.75
1230	0-1.25	0.10-0.48	0.07-3.00	0.06-1.37	0.10-2.00	0.06-0.98
1530	0-1.0	0.10-0.86	0.12-1.00	0.06-0.70	0.19-3.00	0.17-1.15
01830	0.33-1.42	0.09-0.69	0.10-1.67	0.07-0.67	0.15-2.33	0.16-0.84

Table 4.12(b): Monthly variations in water-column $\text{PO}_4^{3-}\text{-P}$ ($\mu\text{M P}$) in the Gazi Bay.

SITE	S1	S2	S3
NOV'94	0.05-0.86	0.40-0.75	0.63-0.98
DEC'94	0.48-1.40	0.13-1.37	0.06-1.15
JAN'95	0.13-1.60	0.30-2.84	0.30-2.97
FEB'95	0-3.00	0.10-3.23	0.096-2.87
MAR'95	0.10-0.20	0.07-0.18	0.10-0.19
APR'95	0.12-0.18	0.08-0.37	0.13-0.19
MAY'95	0.19-0.28	0.14-0.17	0.21-0.30
JUN'95	0.06-0.18	0.06-0.32	0.12-0.18
JUL'95	0.24-0.27	0.16-0.38	0.16-0.59

Table 4.13(a): Water-column $\text{Si(OH)}_4\text{-Si}$ ($\mu\text{M Si}$) variations with tidal cycle during dry and wet seasons in Gazi Bay.

SITE	S1		S2		S3	
	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON	DRY SEASON	WET SEASON
0630	10.3-36.5	1.1-19.2	7.7-44.4	1.0-38.1	3.4-22.3	1.0-3.4
0930	4.5-15.3	1.1-15.5	10.0-40.5	1.0-33.9	2.9-20.6	1.4-46.4
1230	5.2-21.3	0.6-20.5	8.4-21.2	0.9-41.2	7.9-40.6	0.8-138
1530	6.3-11.0	1.0-13.3	14.0-29.9	0.9-58.8	13.3-23.5	1.0-52
1830	5.7-15.7	0.9-12.9	16.1-22.3	1.0-41.5	8.0-27.5	1.1-78.8

Table 4.13(b): Monthly variations in water-column $\text{Si(OH)}_4\text{-Si}$ ($\mu\text{M Si}$) in the Gazi Bay.

SITE	S1	S2	S3
NOV'94	8.0-14.7	5.9-20.7	7.1-22.5
DEC'94	9.3-19.2	12.5-21.7	11.4-20.7
JAN'95	4.5-10.9	12.8-27.2	17.7-22.3
FEB'95	11.0-36.5	12.3-44.4	15.8-40.6
MAR'95	6.3-17.6	7.7-29.9	2.9-13.3
APR'95	5.5-11.7	3.5-58.8	6.4-25.6
MAY'95	0.6-1.1	0.9-1.0	0.9-1.4
JUN'95	8.8-20.5	28.8-49.5	43.4-138
JUL'95	5.3-15.5	14.1-29.9	13.8-41.5