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Nutrient budgets for Muthupet lagoon, southeastern India

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Budgets of nitrogen and phosphorus from the semi-enclosed Muthupet lagoon were constructed through monsoon observations and modelling. The lagoon is a shallow water body and hence surface water samples associated with the lagoon were collected and measured for hydrochemical properties, inorganic and organic nutrients (dissolved inorganic nitrogen, dissolved organic nitrogen, dissolved inorganic phosphorus and dissolved organic phorphorus). The average inorganic N and P concentrations of the lagoon were almost equal to that of their river concentrations, while organic phosphorus was lower by 30% and organic nitrogen was higher by 26%. Terrestrial inputs through run-off, mixing and residual fluxes were dominant forcing mechanisms in maintaining lagoon nutrient concentrations. Water exchange time of the lagoon was estimated at 1.4 days. However, the nutrient, especially DIP, DIN and DON, exchange time was higher by approximately 50% of water exchange time, whereas the same for DOP was half that of water exchange time. The nonconservative fluxes ΔDIP, ΔDOP, ΔDIN and ΔDON from the lagoon were 0.03, –0.06, 0.92 and 5.28 mmol $m^{-2} d^{-1}$ respectively, inferring that DIP, DIN and DON were removed from the system when DOP was added to it.

Keywords: Exchange time, nutrient budgets, non-conservative fluxes.

ANTHROPOGENIC nutrient inputs, in recent decades, into coastal seas have generally increased steadily[1–3], a phenomenon that may enhance primary production and provide an additional sink for atmospheric carbon. Simultaneously, however, natural and human-derived organic matter discharged into coastal seas may be partially or totally respired, providing a source of carbon dioxide. Despite difficulty in obtaining carbon and nutrient budgets through direct observations and syntheses, biogeochemists have employed various models to simulate nutrient and carbon budgets in well-defined systems, applying simplified calculations to existing data[4–8]. Meanwhile, LOICZ (Land–Ocean Interactions in the Coastal Zone) has developed

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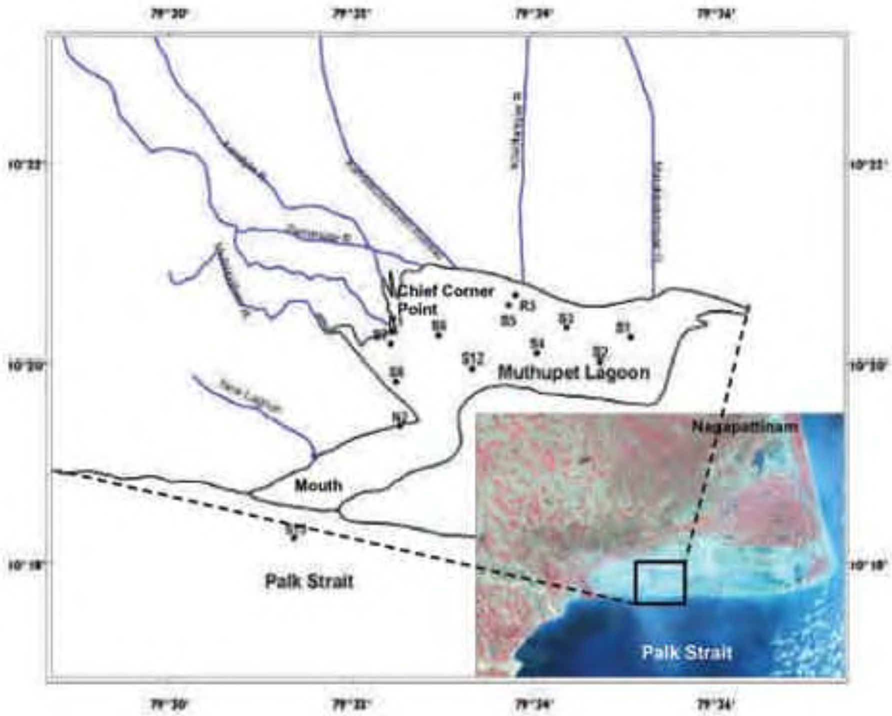

Figure 1. Location map of stations in Muthupet lagoon.

the biogeochemical modelling guidelines[9] to implement nutrient and carbon budgets during the early phase of programme implementation. This model has been widely tested and used for C–N–P budgets in estuarine and coastal systems[10–13]. Coastal typology may be applied for global synthesis in coastal carbon and nutrient budgets[14,15]. Nutrient metabolism in a shallow coastal body varies between temperate and tropical regions, primarily owing to rapid system response to change of external forcing[14]. This study aims to illustrate the nutrient budgets in the Muthupet lagoon, which may be associated with variations of external inputs and internal transformation.

The Muthupet lagoon is a semi-enclosed coastal lagoon located at the end of Cauvery delta in the southeast coast of India. The lagoon has a gentle slope towards Palk Strait of the Bay of Bengal (Figure 1). The lagoon is connected to the Palk Strait by a wide mouth located at the southern part of the mangroves. Twenty years ago, the mouth was about 2.5 km wide and 2–2.5 m deep, but today the mouth is just 1 km wide and not even 1 m deep due to silt deposition from the sea end[16]. Though the mouth is about 1 km wide, sea water enters the lagoon only through a narrow passage about 50–75 m wide. Also the mouth never closed completely, but considering the rate at which the width of the mouth is shrinking, there is fear that this may happen soon. It is found that no sand is deposited in the mouth region, it is only the fine silt brought from the sea that is being deposited[17].

According to 1996 remote sensing data, the wetland occupies an area of approximately 12000 ha, consists of 1855 ha healthy mangroves, 7178 ha degraded mangroves, 1700 ha water bodies, 375 ha other vegetation like *Prosopis*, 322 ha aquaculture and 910 ha saltpan[17]. Healthy mangroves occupy only 15% of the total area, whereas degraded mangroves constitute about 68%. Besides the lagoon, the wetland includes many tidal creeks, channels and small bays, bordered by thick mangroves and a number of man-made canals dug across the mangrove wetlands, particularly in their western part and fished intensively.

The distributaries of Cauvery, viz. Paminiyar, Korayar, Kandaparichanar, Kilathangiyar and Marakkakorayar empty their water into the wetlands and form a large lagoon before reaching the sea (Figure 1). The lagoon receives inflow of freshwater mainly during the northeast monsoon (October–December) through the above drainage arteries occupied by agricultural soils, mangrove swamps and aquaculture ponds. From February to September, freshwater discharge into the mangrove wetland is negligible. The soil in the forest is clayey silt and towards the landward side it is silty clay due to fresh silt deposits[17].

The total area of the lagoon as estimated from the satellite data IRS PAN image (using remote sensing software ERDAS), having a resolution of 5.6 m in space, for the period June 2003 is 13.32 km^2 and it has a volume of 9.6×10^6 m^3. However, the main body of the lagoon (between N2 and S1) accounts for >85% of the entire lagoon volume and the entrance channel, connecting the Palk Strait and the main lagoon (between S13 and N2), accounts for the rest of the volume.

Physico-chemical data from the lagoon were collected twice during September and December 2003, which represent SW and NE monsoon respectively. The characteristic of this region is that the SW monsoon remains dry and NE monsoon is highly active. The present calculations are based only on data collected during December 2003. There are in all 15 sampling locations in the lagoon apart from the river stations (Figure 1). A coastal station located at the mouth of the estuary defines properties of the coastal ocean water. Time-series surface-water samples were collected at two hourly interval between 8 AM and 4 PM at all river ends, sea end and at one station in the middle of the lagoon (S4). Random samplings were also made at all the 15 spatially distributed stations in the lagoon. Simultaneous flow measurements were also carried out at all the river ends as well as at the sea end using floats at 15 min interval for the same period. The cross-sectional area of all these points was measured and net discharge was estimated. The measured end-member salinity and nutrients were used to compute the respective time-series and net fluxes.

Tide and currents were recorded at 10 min intervals simultaneously at the mouth and Chief Corner Point by deploying self-recording tide gauges (Valeport, UK) and current meters (RCM 9, Aandera Instruments, Norway) for 20 days and analysed. The bathymetry of the lagoon was constructed using the depth soundings collected at about 400 points. The location of each point was recorded using Differential Global Position System and depth was recorded using lead weight. Data were corrected to tide with the measured water-level observations at the mouth and Chief Corner Point.

Niskin sampler was employed for surface-water sampling. Samples collected in polyethylene bottles were ice-preserved in the field and transported to the Chennai laboratory within 24 h for further analysis. Salinity was measured *in situ* using calibrated probe (WTW, Germany) with a reproducibility within 5%. *In situ* temperature was recorded using a thermometer. A part of each water sample was filtered through dried and pre-weighed 0.45 μm membrane filter and the filtrate was used to estimate dissolved nutrients following standard methods[18]. Suspended Particulate Matter (SPM) was calculated as difference between pre and post-weight of membrane filter. Chlorophyll was measured spectrophotometrically by extracting the pigments in 90% acetone[19]. Sediment organic carbon was estimated using CHN analyser. For computational purpose, data on salinity and nutrients within the lagoon were individually pooled and averaged.

The lagoon is shallow with a depth of 0.3–0.6 m during low tide and 0.9–1.2 m during high tide. However, the eastern portion of the lagoon beyond S2 is extremely shallow (<0.1 m). Sea water exchange is predominantly by tide, which is semi-diurnal in nature. The mean tidal range is about 0.3 m during spring and 0.15 m during neap at the mouth. The geometry of the lagoon influences the bathymetry of the lagoon. Tidal water from the mouth traverses a narrow channel for a distance of about 3.5 km before it suddenly opens into the wide lagoon, resulting in dropping of tidal height from 0.3 m at the mouth to about 0.1 m at Chief Corner Point, and thereby current intensity. Because of these weak currents, especially during the dry period, sufficient force does not exist to drive the suspended matter out of the lagoon. Hence, the lagoon remains highly turbid during dry periods (125–586 mg l^{-1}). During monsoon, though run-off-driven currents help in transporting significant suspended load to the Palk Strait, the lagoon still remains relatively highly turbid (89–380 mg l^{-1}). High turbidities throughout the year have a major role in controlling the biogeochemistry of the lagoon.

The biogeochemical fluxes of nutrients in the lagoon were estimated using the LOICZ biogeochemical budget model[9]. This biogeochemical budget is a steady-state box model from which nonconservative nutrient budgets can be constructed from nonconservative distributions of nutrients and water budgets, which in turn are constrained from the salt balance under a steady-state assumption. The nonconservative flux of a material is estimated from the flux deviation between inputs and outputs based on salt and water balances. Because of the distinct variability in freshwater and material inputs with time, water and nutrient budgets estimated from a box model for the lagoon are valid by assuming steady-state (the estuarine volume change with time is constant, $dV/dt = 0$) conditions during the observation period.

Using salt as a conservative tracer, water budget for the lagoon can be derived from the balance of salt transported through the lagoon. The conceptual model for transport of materials in the system is shown in Figure 2.

The process can be described as follows:

$$\frac{dM}{dt} = \sum \text{Inputs} - \sum \text{Outputs} + \sum \text{Sources–sinks},$$

where dM/dt is a change in mass of the material of interest. Assuming that the system is at steady state ($dM/dt = 0$), water and salt budgets for Muthupet lagoon are calculated and presented.

Water inflow includes run-off, direct precipitation, groundwater seepage, etc. and removal includes evaporation.

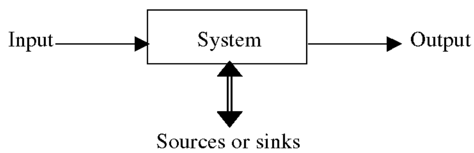

Figure 2. Conceptual model for transport of materials.

Table 1. Range and mean (parenthesis) concentrations of variables in the study area

Parameter	River	Lagoon	Ocean
Salinity (PSU)	0.64–2.23 (0.83)	0.61–4.33 (2.06)	6.83–20.22 (9.62)
SPM (mg l^{-1})	24–105 (51.8)	89–380 (136.0)	75–175 (93.0)
DIP (μM)	0.41–0.92 (0.73)	0.52–1.21 (0.74)	0.14–0.51 (0.33)
DOP (μM)	0.15–0.96 (0.37)	0.26–0.73 (0.48)	1.31–3.57 (1.67)
DIN (μM)	6.09–11.52 (9.04)	6.14–14.68 (9.81)	0.72–2.05 (1.00)
DON (μM)	37.8–51.8 (47.5)	32.9–77.8 (60.1)	22.2–51.5 (39.5)
Chlorophyll *a* (mg m^{-3})	0.003–0.005 (0.004)	0.001–0.005 (0.003)	0.004–0.014 (0.010)

DIP, Dissolved inorganic phosphorus; DOP, Dissolved organic phosphorus; DIN, Dissolved inorganic nitrogen; DON, Dissolved organic nitrogen.

Table 2. Nutrient fluxes in the Muthupet lagoon

Parameter	River flux (10^3 mol d^{-1})	Residual flux (10^3 mol d^{-1})	Mixing flux (10^3 mol d^{-1})	τ (days)
DIP	2.82	–2.07	–1.22	2.2
DOP	1.43	–4.15	3.55	0.6
DIN	34.93	–20.88	–26.29	2.0
DON	183.64	–192.45	–61.60	2.3

τ, Exchange time.

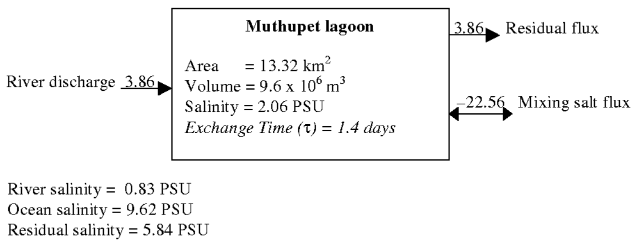

Figure 3. Water and salt budgets for the Muthupet lagoon. Water flux in 10^6 m^3 d^{-1} and salt flux in 10^6 PSU m^3 d^{-1}.

The total river discharge during the study was estimated at 3.86×10^6 m^3 d^{-1}. There was zero precipitation during the period of survey and groundwater seepage is assumed to be negligible as the soil is clay. Water loss due to evaporation is estimated using Meyer's formula and observed water temperature (27°C) and atmospheric temperature (28°C), wind speed (18 km h^{-1}) and relative humidity (63%) from nearest available data (collected at Chennai by ICMAM Project Directorate, Chennai for the same period). The estimated evaporative outflow (512 m^3 d^{-1}) accounts only to 1.3% of freshwater influx, which is highly insignificant and hence ignored[9].

Owing to the intense monsoon period, the temperature of the lagoon water was low and oscillated with atmospheric temperature. As the lagoon volume is less, its hydrological condition varied with time as a function of changes in freshwater input and tidal fluctuation. The lagoon witnessed large-scale changes during the NE monsoon. With the reversal of salinity due to monsoon discharge through the distributaries, the lagoon has become a mere freshwater body dominated by uni-directional flow towards the sea.

The salinity decreased from about 20 PSU at mouth to 6.18 PSU at N2 during highest high tide. But the rest of the body was dominated by mere freshwater with salinity between 0.6 and 2.0 PSU. The central portion of the lagoon (S4) exhibited marginal fluctuations in salinity (~10%) and nutrients (10–25%) over timescale. Further, spatial variations of salinity and nutrients within the lagoon are not significant, except that easternmost stations S1 and S2 recorded lowest salinity and highest nutrients (Table 1). Based on these observations, the entire lagoon is considered as a single box for the budget model. The uncertainties due to this approach may arise from the processes occurring in the small volume of the entrance channel. However, in view of high monsoonal flow and consequent flushing times, especially in the entrance channel, the single-box approach may lead to some minor variation in the magnitude of the computed budgets, but the conclusions of the model results will be unaffected.

Water budgets are critical in deriving nutrient budgets in the lagoon. A significant difference in salinity between the lagoon and oceanic system is required for the model to reliably determine the salt and water balances. Based on the salt balance in the box model, the freshwater inputs, residual and mixing flows were estimated. Figure 3 illustrates water budget for the lagoon. Since the evaporative outflow was insignificant, the river inflow was balanced by the residual outflow. The mixing flux was calculated as 2.98×10^6 m^3 d^{-1}, which is equivalent to 77% of the total freshwater inputs, apparently indicating that the lagoon is dominated by river influx and its characteristics. Both

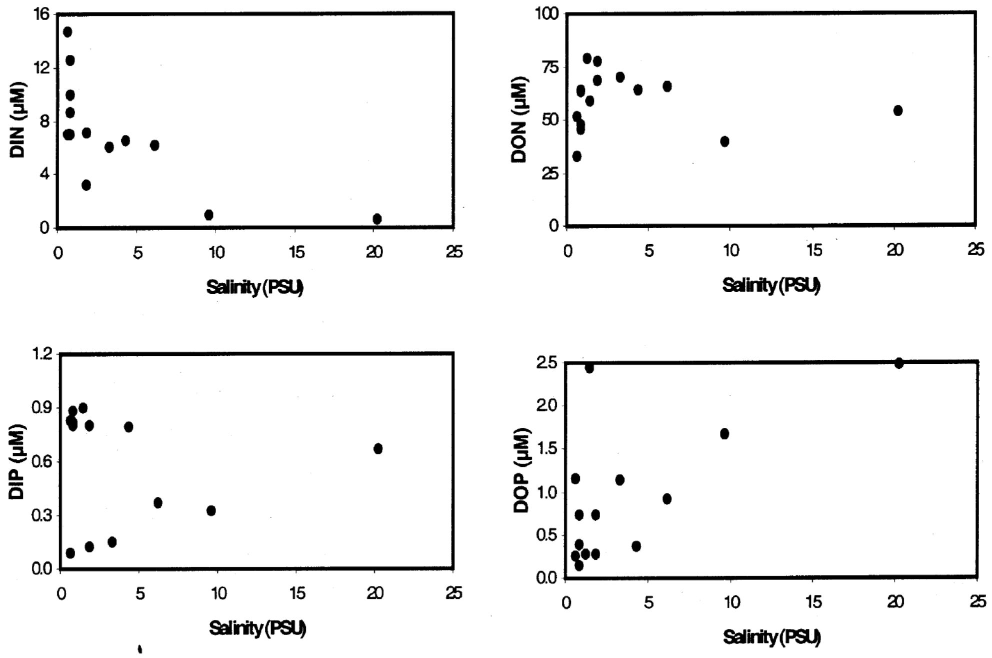

Figure 4. Nonconservative behaviour of nutrients in the lagoon.

Table 3. Nonconservative nutrient fluxes

Nutrient	Flux (10^3 mol d^{-1})	Flux (mmol m^{-2} d^{-1})
ΔDIP	0.46	0.03
ΔDOP	–0.83	–0.06
ΔDIN	12.23	0.92
ΔDON	70.40	5.28

residual and mixing fluxes were negative, indicating that their direction was towards the Palk Strait.

The water exchange time in the system (τ) was calculated as the total water volume of the system divided by the sum of the absolute value of residual flow and mixing volume. Accordingly, the water exchange time for Muthupet lagoon is estimated as 1.4 days. The water budget of the lagoon was apparently controlled by both freshwater inputs and exchange rates.

The monsoon discharge during this season carried the terrestrial and upstream nutrients into the lagoon, due to which the lagoon nutrients are several fold higher than during the dry season (average DIN: 2.34 μM; DIP: 0.35 μM). Distributions of dissolved phosphorus and nitrogen in the lagoon vary spatially. Dissolved inorganic phosphorus (DIP) dominated the distribution of total dissolved phosphorus (TDP), but dissolved organic nitrogen (DON) dominated over its inorganic fraction (Table 1). Among dissolved inorganic nitrogen (DIN) species, nitrate was the most predominant form. Concentrations of DIP and DIN were relatively high in the river inlets and low at the mouth.

System concentrations of nutrients were determined partly by mixing flux and internal transformation in the lagoon. Residence times of nutrients (DIP, DOP, DIN and DON), which are a function of their inventory and the residual and exchange fluxes in the lagoon (Table 2), were longer than those of the lagoon water. Even though the nutrient concentrations and their longer residence times in the lagoon are sufficient to trigger phytoplankton production, high levels of SPM (Table 1) inhibit the light availability for photosynthesis and in turn their growth.

The nonconservative behaviour of nutrients was evident from their nonlinear distributions against salinity (Figure 4). Physical and biogeochemical processes may be responsible for their nonconservative behaviour. The nonconservative flux of DIP (ΔDIP) is derived from the difference between total inputs and outputs (Table 3). Total inputs were fluxes from the river, and are denoted as positive values. Total outputs were summed from residual and mixing fluxes, which were negative because lagoon concentrations exceeded oceanic concentrations. Similar calculations were applied for ΔDIN and ΔDON using data from Table 1. However, the mixing flux of DOP is positive as oceanic concentrations are higher than lagoon concentrations, and hence considered as input. A positive nonconservative flux indicates that the lagoon is a source for the nutrient, while negative flux indicates the lagoon is acting as a sink.

The applied LOICZ model does not reveal the details concerning pathways for nutrient sources and sinks in the system. The very low primary production within the lagoon, as indicated by extremely low chlorophyll values (Table

1), apparently limited by light, does not appear to permit significant biological removal. Owing to high turbid cloud, the suspended particles are in continuous contact with solution, and sediment–water ion exchange is expected to be significant. And when the drainage basin is rich in humic substances, remineralization of sediment organic matter leads to release of nutrients to dissolved phase[20]. Even though there were no studies available on the humic content of Muthupet lagoon, studies on Mandovi–Zuari estuarine systems on the west coast of India[21] indicated that the systems influenced by run-off through mangroves will have high content of humic materials in dissolved, particulate and sedimentary fractions. Analysis of few sediment samples for organic carbon revealed that it is high in the lagoon (~2.5%) compared to the mouth (~1%). In view of high organic-rich suspended sediments, the lagoon is expected to be respiration-dominated and so nutrient production exceeds its consumption. Hence, the mineralization of sediment organic matter is expected to be the main source for nutrients. Although the lagoon is a source as well for DOP, it exhibits net sink as the oceanic inputs are in excess to those from the lagoon.

The study concludes that the Palk Strait has received nutrient fluxes from the Muthupet lagoon, but it is yet to be ascertained whether these fluxes are significant to the Palk Strait, owing to its vast area and volume.

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