



Hydrochemical budgeting of a tropical estuary Vis-à-Vis tidal dynamics: Ecosystem trophic status assessment

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ABSTRACT

The present study estimates the hydrochemical budgets of salinity and nutrients in the river-sea continuum of the Mahanadi estuary and evaluates their potential impacts on the adjacent coastal ecosystem. The spatial variability of physico-chemical parameters was investigated over a complete tidal cycle of 15 days during winter (low-flow period). The hydrochemical budget was calculated using the Land-Ocean Interactions in the Coastal Zone (LOICZ) model, with spatial data from upper and lower estuaries and adjacent coastal waters, to understand the ecosystem's nutrient pathways and trophic status. The biogeochemical mass balance, a simple box model, and a single-layer model were used to estimate fluxes of water, salinity, and nutrients between the lower estuary, the upper estuary, and the adjacent coastal waters. The results revealed very low (<1 day) water-mass residence times at both the upper and lower estuaries. The residence time also varied with the tidal cycle, being higher during low tide and lower during high tide. The nutrient budget revealed the upper estuary as the major source of nutrients, mostly dissolved inorganic phosphate (DIP). The +ve Δ DIN (dissolved inorganic nitrogen) and Δ DIP represented the upper estuary as a source, whereas -ve Δ DIN and Δ DIP represented the lower estuary as a sink. The positive net ecosystem metabolism (NEM) at the lower estuary signified an autotrophic ecosystem, whereas the negative NEM at the upper estuary represented a heterotrophic ecosystem. The budgeting revealed nitrogen fixation prevailing over denitrification in the lower estuary, and vice versa in the upper estuary.

1. Introduction

Estuaries serve as critical transition zones between freshwater and marine environments, receiving substantial influxes of organic and inorganic materials through freshwater discharge and marine flux (Barletta and Dantas, 2016). The estuarine ecosystem fosters a rich biodiversity, accommodating species adapted to both freshwater and marine conditions. Due to this unique ecological positioning, estuaries hold significant economic and environmental importance, contributing to primary production, fisheries, natural filtration of anthropogenic pollutants, recreational activities, and cultural heritage preservation (Edgar et al., 2000). Functioning as dynamic interfaces, estuaries assimilate nutrients from both riverine and oceanic sources, thereby

enhancing primary productivity and acting as natural carbon sinks by absorbing CO₂. However, the respiration of organic matter by microbial and aquatic organisms simultaneously releases CO₂, transforming estuaries into both sinks and sources of carbon, depending on the prevailing biogeochemical processes (Gupta et al., 2006; Biswas et al., 2004; Borges et al., 2008).

As the estuaries are the source of materials to the coastal waters, the trophic behaviour (autotrophy/heterotrophy) of the estuary may also reflect in the coastal ecosystem. In the past few decades, anthropogenic inputs into estuaries have increased, enhancing organic matter and inorganic nutrient loadings. Therefore, it is pivotal to estimate the trophic state of the estuarine-coastal water continuum to support effective ecosystem monitoring and management (Eyre and McKee, 2002).

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In the aforementioned context, a nutrient budget serves as an effective tool for evaluating ecosystem functioning in response to the estuary's biogeochemical complexity. By quantifying nutrient inputs, flushing rates, and export dynamics to adjacent coastal systems, nutrient budgeting helps determine the estuary's potential for internal production or consumption of key elements such as carbon (C), nitrogen (N), and phosphorus (P). Additionally, it provides insights into estuarine metabolism and overall ecosystem health (Smith and Hollibaugh, 1997). In this regard, the Land-Ocean Interaction in the Coastal Zone (LOICZ) biogeochemical modelling framework offers a valuable approach to understanding nutrient dynamics. This method helps elucidate whether coastal zones act as sources or sinks for C, N, and P while also supporting broader environmental impact assessments. By integrating hydrological and biogeochemical analyses, LOICZ modelling enhances the understanding of nutrient fluxes, ecosystem metabolism, and the factors influencing estuarine-coastal interactions (Wepener, 2007; Gordon et al., 1996).

The Mahanadi River estuary, connected to the northwestern Bay of Bengal, plays a crucial role in regional biogeochemical cycles due to its substantial river discharge, frequent coastal algal blooms, anthropogenic material influx, and significance as a fishery hotspot (Baliarsingh et al., 2021). It serves as critical habitat for a diverse array of aquatic species, supporting both migratory and resident fauna, which are essential for biodiversity conservation. Furthermore, it plays a pivotal role in the sequestration and cycling of organic matter, influencing carbon dynamics and sustaining the productivity of adjacent marine ecosystems. Given these dynamic environmental factors and the research gap, it is essential to assess the trophic status and nutrient flux of this estuarine system, particularly in relation to the semi-diurnal tidal cycle, which influences its ecological processes (Das et al., 1997; Baliarsingh et al., 2021; Dey et al., 2013).

Against this backdrop, this study aims to investigate the influence of tidal dynamics and riverine discharge on the hydrochemical budget of the Mahanadi estuary, assess its trophic status, and evaluate potential impacts on the adjacent coastal ecosystem. To achieve this, a comprehensive survey covering a full tidal cycle was conducted, encompassing various water-quality parameters across the lower estuary, the upper estuary, and coastal waters. This approach enables a detailed examination of the role of semidiurnal tidal fluctuations in shaping the estuary's hydrochemical characteristics.

2. Materials and methods

2.1. Study area

The Mahanadi estuary is a coastal plain estuary, which is a highly dynamic and ecologically significant system located at the confluence of the Mahanadi River and the Bay of Bengal near Paradip on India's east coast. Spanning approximately 857 km in length with a vast catchment area of 141,600 km², the Mahanadi River ranks as the third-largest river in peninsular India. The estuary itself extends over a length of 30–40 km, with a breadth of 600–1200 m, depths of 6–14 m, and an area of about 9 km² (Rao et al., 2007). Its hydrodynamics are significantly influenced by seasonal variations, particularly during the southwest monsoon, which accounts for nearly 75% of the river's annual freshwater discharge (Das et al., 1997). This seasonal influx, combined with tidal interactions from the Bay of Bengal, contributes to a constantly shifting biogeochemical landscape. The estuary experiences semidiurnal tides, with tidal amplitudes ranging between 1.45 and 2.20 m, classifying it as a microtidal system (Dey et al., 2013; Naik et al., 2020).

The estuarine environment promotes a rich biodiversity, serving as an essential breeding and nursery habitat for various fish and crustacean species (Alfred, 1998). Beyond its ecological importance, the Mahanadi estuary plays a crucial role in the region's economy due to its proximity to Paradip, which houses a major all-weather port, a major fishing harbour, and several industries, including fertilizer plants, oil refineries,

etc. However, previous studies suggest that the estuary may be experiencing increasing anthropogenic pressures, as there are concerns that untreated municipal sewage from Paradip City, agricultural runoff, and industrial effluents could potentially contribute to water quality deterioration by introducing higher levels of organic and inorganic pollutants (Panda et al., 2006; Sundaray et al., 2006; Mohapatra et al., 2009; Acharyya et al., 2021).

The estuary exhibits pronounced seasonal variability in biogeochemical parameters, primarily driven by fluctuations in riverine discharge, tidal mixing, and anthropogenic inputs. The nutrient regime, controlled by both natural and anthropogenic sources, is characterized by the non-conservative behaviour of key macronutrients such as nitrite, nitrate, ammonium, phosphate, and silicate. Phytoplankton biomass peaks during the post-monsoon season. Nevertheless, the estuary is increasingly subject to heavy metal contamination, with elements such as cadmium, nickel, cobalt, and lead exhibiting high sediment lability, thereby posing potential ecological risks. The seasonality of these biogeochemical regimes, estuarine dynamics, and increasing anthropogenic impacts underscore the need for long-term, high-frequency monitoring and research to ensure the sustainability and health of this vital estuarine ecosystem (Acharyya et al., 2021).

2.2. Survey plan, sample collection, and analysis

A comprehensive field survey was conducted during the low-flow period of the winter season, in February 2021, across three strategically selected time-series stations representing different salinity gradients: the upper estuary (E1), the lower estuary (E2), and the adjacent coastal waters (C1). Sampling was conducted during the winter season, when river discharge was relatively low, and precipitation was negligible, so the observed hydrodynamics represent the dry-season regime of the estuary. Station C1 was positioned in the adjacent coastal waters to represent the receiving marine water mass that interacts with estuarine discharge from the Mahanadi mouth. Its placement was guided by the documented influence of the Mahanadi River plume off Paradip, where freshwater discharge produces pronounced salinity gradients and seasonal phytoplankton blooms in the near-shore Bay of Bengal (Mishra et al., 2009). The location accounts for the prevailing coastal circulation and plume transport that disperse estuarine-derived materials seaward, and C1 therefore provides an appropriate marine end-member for the LOICZ budget calculations by characterizing the coastal water composition exchanged with the lower estuary. The survey aimed to capture the full extent of tidal influences throughout the tidal cycle on estuarine biogeochemistry, making this the first of its kind in the estuarine-coastal water continuum of the Paradip region (Baliarsingh et al., 2021). Water sampling and onboard measurements were systematically performed at each station over a complete semidiurnal tidal cycle, spanning 15 days. Observations were taken every 6 h (4 times per day, encompassing 2 high tides and 2 low tides) to provide a detailed understanding of estuarine hydrography and chemical fluxes. Additionally, estuarine bathymetry was recorded during each sampling period using an echosounder mounted on the survey vessel to assess depth variations across different tidal conditions.

The key hydrographic parameters, including temperature and salinity, were measured in situ using a CTD profiler (SeaBird 19plus), with operational depths adjusted based on the bathymetric conditions at each station. The SBE 19plus CTD profiler resolves conductivity over 0 to 9 S m⁻¹ with an initial accuracy of 0.0005 S m⁻¹ and a resolution of 0.00005 S m⁻¹, temperature over -5 to 35 °C with an accuracy of 0.005 °C and a resolution of 0.0001 °C, and pressure with an accuracy of 0.1% and a resolution of 0.002% of the full-scale range, thereby providing salinity estimates of sufficient accuracy to characterize the estuarine salinity gradient. Surface water samples were collected using a Niskin water sampler (General Oceanics) to estimate nutrient concentrations. The samples were collected and stored in pre-cleaned high-density polyethylene (HDPE) bottles and processed immediately to

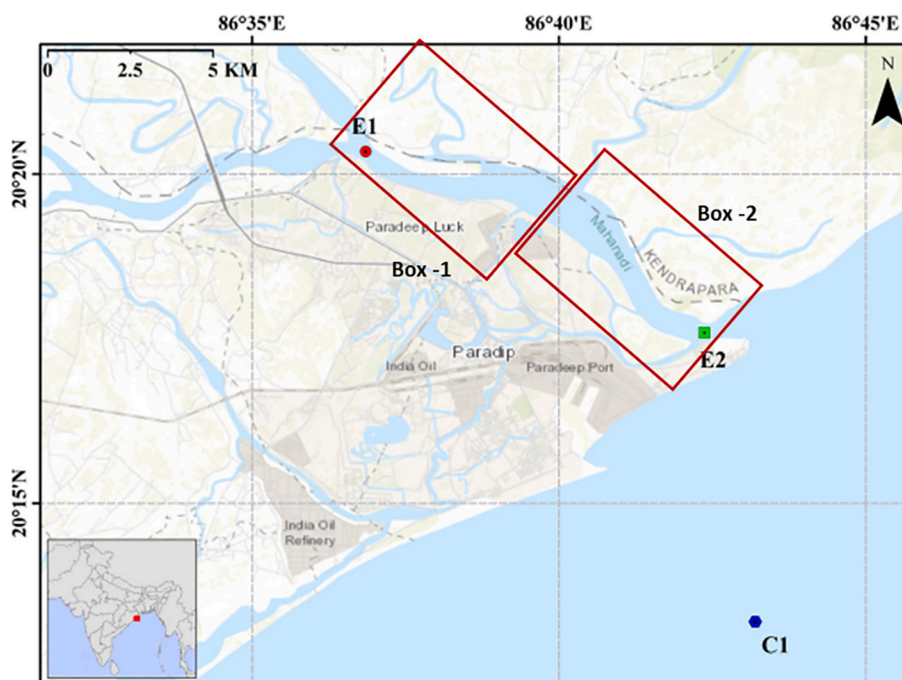


Fig. 1. Map of the study area representing the sampling locations in the upper estuary (E1: 20.33904444°N, 86.61419167°E), lower estuary (E2: 20.29318611°N, 86.70615556°E), and near coastal waters (C1: 20.22°N, 86.72°E) in the continuum of the Mahanadi estuary and coastal waters of Paradip.

minimize contamination. The collected water was filtered using a 47 μm membrane filter paper with a pore size of 0.45 μm under vacuum filtration. The filtered samples were subsequently analyzed for essential nutrients, including nitrate, nitrite, ammonium, phosphate, and silicate, using a Continuous Flow Nutrient Analyzer (Skalar San ++), adhering to the standardized analytical protocols outlined by Grasshoff et al. (1999). The SAN++ system has been used extensively for the determination of dissolved nutrients and provides highly reproducible, low-level colourimetric measurements, with detection limits in the sub-micromolar range for the analyzed nutrients under standard configuration. All nutrient determinations followed calibrated, quality-controlled procedures, with reagent blanks and certified standards run within each analytical batch to minimize analytical uncertainty.

2.3. Hydrochemical budget

In this study, the LOICZ hydrochemical budgeting model was used to analyze both conservative components, such as water and salt, and non-conservative elements, including key nutrients. Rooted in the principles of mass balance, the LOICZ model has been widely applied to over 200 estuarine systems worldwide, providing insights into their dynamics and trophic status (Swaney et al., 2011). The methodological framework follows the standardized protocols outlined in the LOICZ biogeochemical modelling guidelines (Gordon et al., 1996). To ensure accurate budget estimations, essential auxiliary parameters, including river discharge, surface water area, precipitation, meteorological data, and evaporation rates, were systematically collected or derived.

2.3.1. River discharge

The river discharge data for the survey period were obtained from the Central Water Commission (CWC) of the Government of India. Discharge measurements, recorded in cubic meters per second (m^3/s), were taken at Tikarpada, an upstream location approximately 230 km from the Mahanadi estuary at Paradip. Beyond Tikarpada, the Mahanadi River diverges into three branches, with only one contributing directly to the estuary's flow. To accurately estimate the discharge reaching the

Mahanadi estuary, satellite-based analysis was performed using Google Earth Engine and QGIS. High-resolution Sentinel-2 A/2B Level-2 imagery with 10-m spatial resolution served as the primary dataset for assessing water distribution and surface area coverage across the Mahanadi basin. The Normalized Difference Water Index (NDWI) was applied to a median composite image to delineate water bodies (McFeeters, 1996). From the designated water gauge station, distributaries and tributaries were identified, assigned unique identifiers, and their respective surface areas were computed. The proportional contribution of each branch to the total water area was then determined. The analysis produced exported raster outputs from Google Earth Engine, along with water body polygons in QGIS, enabling the calculation of the share of water flow attributed to each distributary of the Mahanadi River.

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)}$$

2.3.2. Estuarine area

Determining the estuarine area (km^2) is a crucial step in developing a biogeochemical budget, as it provides the spatial framework required for accurate calculations. In this study, the sampling strategy was designed based on the river's influence, particularly the salinity gradient, to ensure comprehensive coverage of estuarine dynamics. For budgeting purposes, the estuary was divided into two distinct zones: Box 1, representing the freshwater-dominated region, and Box 2, characterized by estuarine conditions (Fig. 1). The spatial extent of these zones was measured using the polygon tool in Google Earth Pro, allowing precise delineation of the estuarine area to aid the hydrochemical budgeting.

2.3.3. Precipitation

The daily precipitation data (mm) for the study period were collected from the World Weather Online portal (www.worldweatheronline.com) for Paradip, Odisha. No precipitation was recorded during the sampling period (Feb 7th-21st, 2021) in Paradip, and therefore precipitation was not accounted as a source to the estuary in budget estimation.

2.3.4. Meteorological parameters

The daily air temperature (°C), relative humidity (%), and wind speed (km/h) data were collected from the World Weather Online portal (www.worldweatheronline.com) for the sampling period. The units of the parameters were adjusted to meet budgeting requirements.

2.3.5. Evaporation

Various methods have been developed to estimate surface water evaporation (Jakimavičius et al., 2013), with the choice of method largely determined by the availability of necessary meteorological data for empirical calculations. In this study, evaporation (mm/day) in the Mahanadi estuary was calculated using equations based on the mass-transfer approach proposed by Vikulina (1979). The estimation process incorporated key meteorological parameters, including air temperature, surface water temperature, wind speed, relative humidity, and the surface area of designated estuarine zones (Fig. 1).

$$E = 0.14 \times (1 + 0.74 \times u) \times d$$

where “E” is the evaporation (mm day⁻¹), “u” is the wind speed (m s⁻¹), and “d” is the vapour pressure deficit (hPa). “d” was estimated following Teten's formula.

$$d = e_s - e_a$$

where,

e_s = Saturation vapour pressure at the water surface temperature and estimated using;

$$e_s = 0.61078 \times \exp\left(\frac{17.27 \times \text{water surface temperature}}{\text{water surface temperature} + 237.3}\right) \text{ kPa}$$

e_a = Actual vapour pressure of the air and estimated as;

$$e_a = e_{s,air} \times \frac{\text{Relative Humidity}}{100} \text{ kPa}$$

where, $e_{s,air}$ is the saturation vapour pressure at the air temperature and estimated as;

$$e_s = 0.61078 \times \exp\left(\frac{17.27 \times \text{air temperature}}{\text{air temperature} + 237.3}\right) \text{ kPa}$$

2.3.6. Hydrochemical budgeting

For the application of the LOICZ procedure, the Mahanadi estuary was categorized into two compartments (boxes) and one layer (surface) based on the spatial freshwater flow differences (observed through the salinity differences between the compartments), which was expected to influence the hydrochemical budget significantly. The LOICZ budgeting provides the water, salt, and nutrient (Dissolved Inorganic Nitrogen: DIN; Dissolved Inorganic Phosphate: DIP) budgets.

The water budget was calculated from the mass balance equation for water,

$$\frac{dV_1}{dt} = V_Q + V_P + V_G + V_O + V_{in} - V_E - V_{out}$$

where,

V represents the water mass, V_Q for river runoff, V_P for precipitation, V_G for groundwater, V_O for other inflows, V_E for evaporation, V_{in} is hydrographically driven advective water inflow, and V_{out} is advective water outflow from the system. dV_1/dt is the water changes in the system with time, which is generally considered as zero, as water is believed to be conservative in nature. V_{in} and V_{out} are the terminologies used in the equation and not measured. After rearranging the equation,

$$\frac{dV_1}{dt} = V_{in} - V_{out} = -V_Q - V_P - V_G - V_O + V_E$$

The difference between V_{in} and V_{out} is defined as the residual flow

$$(V_R)$$

$$V_R = -V_Q - V_P - V_G - V_O + V_E$$

In this study, input from groundwater (V_G) and other inflows (V_O) were negligible for the system, so they were not used in the budget estimation.

The salt budget was estimated using the mass balance equation of

$$\frac{dV_1S_1}{dt} = V_QS_Q + V_PS_P + V_GS_G + V_OS_O + V_RS_R + V_XS_2 - V_XS_1$$

where,

S is the salinity of the respective source and sink to the estuary, which are zero/negligible except for S_1 and S_2 . S_1 is the salinity of the system, and S_2 is the salinity of the adjacent system. This equation is necessary for estimating exchange flow (V_X). As salt is considered a conservative material, to maintain the salt balance, the salt leaving the system in the residual flow (V_R) must be balanced with the salt entering the system in the exchange flow (V_X). Therefore, by solving the above equation of salt balance,

$$V_X = \frac{V_QS_Q + V_PS_P + V_GS_G + V_OS_O + V_RS_R}{S_1 - S_2}$$

The exchange/residence time (τ) is the time for which the nutrient or water remained in the system before the eventual exchange with the adjacent system. It is calculated by dividing the volume of the system with the addition of absolute values of exchange and residual flow.

$$\tau = \frac{V}{|V_R| + |V_X|}$$

Nutrients are not only transported through the water in particulate or dissolved form but are also highly reactive in physical and biogeochemical processes. The nutrient budget includes net water movement, exchange, and uptake/release in the system. The budget for the non-conservative materials (DIP and DIN) was calculated from,

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

where,

Y is the DIN and DIP concentrations. Y_{in} is the nutrient concentrations of the sources to the system, and Y_{out} is the nutrient concentration going out of the system. ΔY denotes the net non-conservative flux of nutrients. Again, considering the system is at steady state,

$$\Delta Y = - \sum V_{in}Y_{in} + \sum V_{out}Y_{out}$$

The positive ΔY , when output exceeds the input, the system exports the nutrients and behaves as a source to the adjacent ecosystem. Alternatively, the negative ΔY represents the uptake of nutrients in the system by the process of primary production. Simplifying the above equation,

$$\Delta Y = -(V_P Y_P + V_Q Y_Q + V_G Y_G + V_O Y_O + V_R Y_R + V_X Y_2) + V_X Y_1$$

Here, Y_P , Y_Q , Y_G , Y_O , and Y_R are the nutrient concentrations of precipitation, river water, groundwater, other flows, and residual flow. Y_2 is the nutrient concentration of the adjacent system (source to the system), and Y_1 is the concentration of the system (source to the adjacent system from the system).

The stoichiometric ratio of the non-conservative materials, CNP (106:16:1), is also considered in the LOICZ for carbon and nitrogen budgets. For this, the DIP flux (Δ DIP) is the key input, as the phosphorus cycle involves the exchange of phosphorus between organic and inorganic forms, with no other forms. Whereas the carbon and nitrogen cycles involve various organic, inorganic and gaseous forms and are complex in nature. The Δ DIP, scaled with a C:P ratio, is used as the measure of net carbon flux, which can be termed net ecosystem metabolism (NEM).

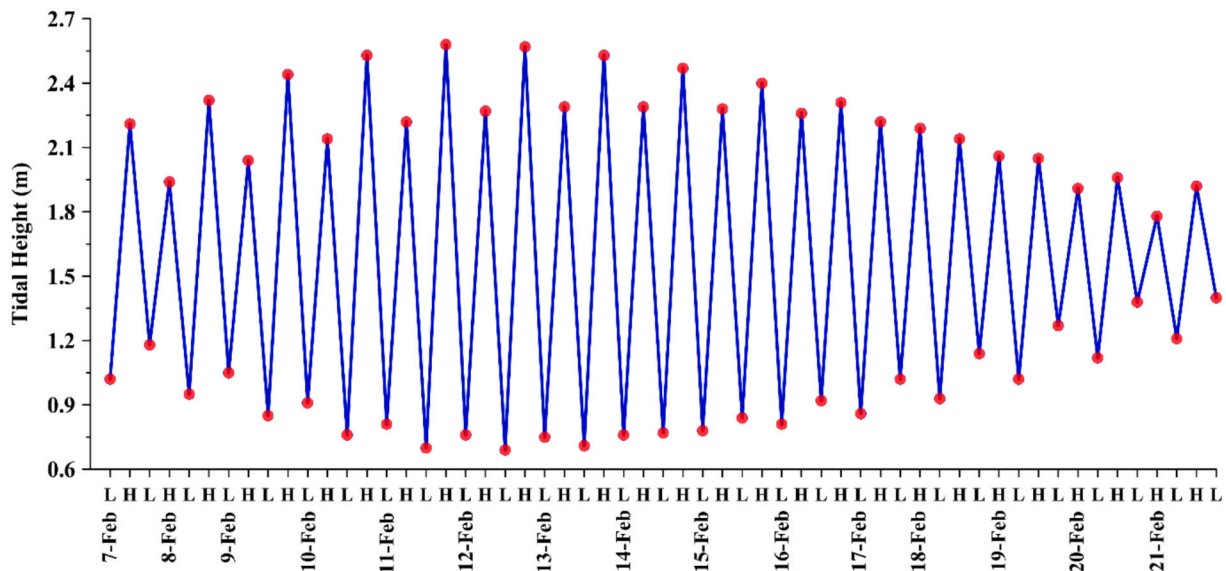


Fig. 2. Tidal amplitude at Mahanadi estuary during the study period.

$$NEM (\Delta DIC) = \Delta DIP \times (C : P)$$

Similarly, the net nitrogen flux (expected ΔDIN) estimated based on the N:P ratio is used to yield information on DIN flux associated with the production/uptake of dissolved nitrogen through the process of nitrification and denitrification in the system. The difference between the measured ΔDIN and expected ΔDIN (estimated from the $\Delta DIN < N:P$ ratio) is the estimate of the difference between nitrogen fixation and denitrification ($N_{\text{fixation-denitrification}}$).

$$\Delta DIN (\text{Expected}) = \Delta DIP \times (N : P)$$

$$N_{\text{fixation-denitrification}} = \Delta DIN - \Delta DIP \times (N : P)$$

2.4. Uncertainty, data quality, and budget reliability

LOICZ budgets are first-order, system-scale estimates and carry uncertainties that arise mainly from freshwater discharge estimation, salinity and nutrient measurements, end-member selection, and short-term temporal variability (Gordon et al., 1996; Smith et al., 2005; Swaney et al., 2011). In the present study, these uncertainties were constrained through standardized field protocols, calibrated instrumentation, and analytical quality control, while sampling at multiple stations across the salinity gradient over a complete tidal cycle characterized the estuarine compartments used in the budget. River discharge reaching the estuary was derived from gauged Central Water Commission data combined with satellite-based apportionment of distributary flow, and groundwater and atmospheric inputs were treated as negligible during the dry season, consistent with common practice in LOICZ applications.

A formal sensitivity analysis and error propagation were not undertaken, in keeping with the LOICZ framework's design as a tool for first-order, system-scale budgeting rather than exact flux determination, and with most published LOICZ applications (Gordon et al., 1996; Smith et al., 2005; Swaney et al., 2011). In a highly dynamic estuarine-to-coastal continuum, where hydrochemical parameters vary substantially in response to tidal forcing and mixing, the emphasis here is on resolving the direction and relative magnitude of water and nutrient fluxes. Uncertainty was accordingly minimised through quality-controlled observations and adherence to accepted LOICZ procedures, and the resulting budgets are interpreted as robust first-order indicators of estuarine metabolism and trophic status rather than precise flux values.

3. Results and discussion

The intricate interaction between riverine discharge and tidal dynamics plays a crucial role in shaping the biogeochemical properties of estuarine-coastal environments. This study employs the LOICZ model to conduct a detailed analysis of the hydrochemical characteristics of the Mahanadi River estuary, assessing its trophic status and nutrient fluxes. To present a clear understanding of the sequential processes involved, the outcomes of the hydrochemical budget and their interpretation are outlined in below sections, offering valuable insights into estuarine metabolism, carbon dynamics, and nutrient cycling, with a specific focus on the influence of semidiurnal tidal fluctuations.

3.1. Meteorological, tidal, and physico-chemical regimes

Meteorological factors such as rainfall and evaporation play a crucial role in shaping the hydrochemical balance of estuarine systems, influencing nutrient fluxes and salinity variations (Martínez-Alvarez et al., 2011). In the present study, rainfall and evaporation levels over the Mahanadi estuary during the study period were considered to assess their potential impact on nutrient dynamics. During the study period, the absence of precipitation in the Paradip region suggests that fluctuations in salinity, nutrient concentrations, and water temperature were predominantly governed by tidal exchanges and riverine input without the dilution effects typically induced by rainfall. Although the estimated evaporation rates over the estuary were minimal, they were still factored into the hydrochemical budget analysis to ensure comprehensive assessments of water balance and nutrient fluxes.

The Mahanadi estuary experiences a semi-diurnal tidal regime, characterized by two high tides and two low tides each day, playing a fundamental role in regulating the transport and exchange of nutrients between the estuary and adjacent coastal waters (Acharyya et al., 2021). During the 15-day observation period, the tidal height fluctuated between a minimum of 0.69 m and a maximum of 2.58 m, with distinct spring (highest high tide) and neap tide (lowest low tide) phases (Fig. 2). The highest high tide, recorded on February 11, 2021, and the lowest low tide, observed on February 12, 2021, had a significant influence on the residence time and transfer of materials from the upper estuary to the lower estuary and onward to coastal waters. These tidal fluctuations play a key role in estuarine circulation, affecting sediment resuspension, nutrient mixing, and organic matter retention within the system (Montani et al., 1998).

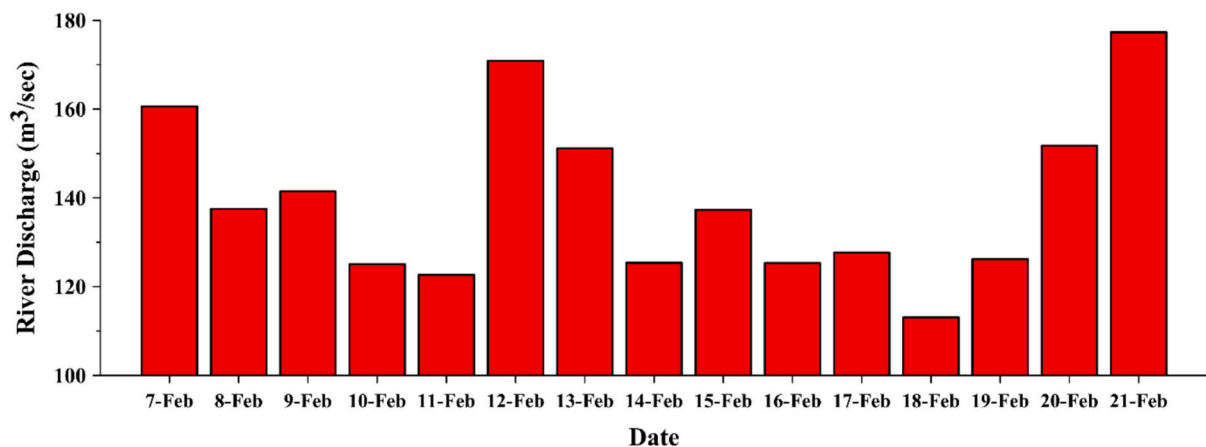


Fig. 3. Variability of freshwater influx through the Mahanadi River at the upper estuary over the study period.

The hydrodynamics of the Mahanadi estuary and adjacent coastal waters are primarily controlled by the complex interplay of riverine discharge and tidal forcing, which together control the physical and chemical properties of these ecosystems. River discharge during the study period ranged from 113.08 to 177.32 m³/s (Fig. 3), with peak discharge events occurring on February 7, 12, and 21, 2021, significantly contributing to estuarine hydrology and nutrient transport. In addition to river discharge, tidal amplitude played a key role in modulating salinity distribution, water temperature, and nutrient concentrations within the estuarine-coastal continuum (Jin et al., 2016; Chen et al., 2019). The salinity distribution pattern distinctly reflects the tidal influence, with strong semi-diurnal fluctuations observed in the lower estuary (5–28 psu), relatively stable high salinity in coastal waters (~25–30 psu), and low salinity (<10 psu) in the upper estuary, where freshwater input is dominant (Fig. 4). The strongest salinity fluctuations were recorded in the lower estuary due to the opposing influences of freshwater influx during low tide and saline water intrusion during high tide. In contrast, the upper estuary remained relatively unaffected by tidal variations, as its salinity was primarily regulated by river discharge, while coastal waters exhibited minimal salinity changes due to the buffering effect of the open ocean (Baliarsingh et al., 2021).

Water temperature within the Mahanadi estuary and coastal waters of the Bay of Bengal ranged from 21.7 to 27.07 °C (Fig. 4), predominantly influenced by the local diurnal heating and cooling cycle rather than tidal variations. Temperature patterns in the upper and lower estuaries closely mirrored each other, whereas coastal waters exhibited slightly lower temperatures, likely due to oceanic mixing.

DIP concentrations exhibited noticeable spatial and temporal variability, ranging from 0.31 to 6.14 μM. The highest variability was observed in the upper estuary (0.75–6.14 μM), while lower fluctuations were recorded in the lower estuary (0.31–1.44 μM) (Fig. 4). Peaks in DIP concentrations in the upper estuary coincided with certain tidal phases, potentially influenced by industrial effluents discharged in the vicinity of the Mahanadi estuary (Nayak et al., 2001). In contrast, DIP levels remained relatively stable in the lower estuary and coastal waters.

DIN concentrations also varied across the estuarine-coastal gradient, with the highest values recorded in the upper estuary (1.33–11.16 μM) and coastal waters (2.32–10.80 μM), whereas lower estuary concentrations ranged from 1.81 to 9.97 μM (Fig. 4). Although no distinct tidal pattern was observed for DIN fluctuations across the estuary and coastal waters, the lower estuary exhibited a notable shift in its variability. During the first seven days of the tidal cycle, the lower estuary followed the tidal variability pattern of coastal waters, coinciding with an increase in tidal amplitude. However, in the latter phase of the tidal cycle, as tidal amplitude decreased, the lower estuary's DIN fluctuations aligned more closely with those observed in the upper estuary. These findings indicate that the nutrient dynamics of the Mahanadi estuary are

influenced by a combination of riverine input, tidal flushing, and localized anthropogenic activities, highlighting the complexity of biogeochemical processes governing estuarine-coastal interactions (Sundaray et al., 2005).

3.2. Water budget and flux dynamics

The water budget analysis provides critical insights into the movement of water masses through two key flux components: the residual flux (the net export of water from the estuarine system) and the exchange flux (bidirectional water exchange between estuarine compartments and coastal waters). These fluxes regulate the hydrodynamic balance and material transport between the upper and lower estuary, as well as between the lower estuary and the adjacent coastal waters of the Bay of Bengal.

Since the residual flux is primarily controlled by freshwater inputs and losses from the estuary, the observed trends in both the upper and lower estuary exhibit a strong dependency on river discharge. In this study, riverine input served as the sole source of freshwater for both regions, leading to a broadly similar tidal variability trend in their residual fluxes (Fig. 5). However, the upper estuary exhibited a slightly higher residual flux, ranging between 0.405 and 0.637 × 10⁶ m³h⁻¹, compared to the lower estuary, where it varied between 0.402 and 0.636 × 10⁶ m³h⁻¹. This marginal difference can be attributed to the cumulative effect of continuous river discharge, which sustains a steady downstream flow with minimal variability in the residual flux.

In contrast, exchange flux showed significantly larger variability, particularly in the lower estuary, where it ranged between 0.421 and 22.507 × 10⁶ m³h⁻¹, compared to the upper estuary's lower range of 0.239–0.694 × 10⁶ m³h⁻¹ (Fig. 5). The pronounced variability in the lower estuary can be attributed to the dominant influence of tidal oscillations, which enhance bidirectional water exchange, facilitating the ingress of saline water from the coastal ocean and the export of freshwater from the estuary (O'Callaghan et al., 2007). Although both estuarine segments exhibited synchronous variability patterns related to the semi-diurnal tidal cycle, exchange flux showed prominent peaks during high tides, suggesting significant tidal influence reaching the upper estuary (Fig. 7). This reflects the tidal forcing's role in modulating the hydrodynamic regime, particularly through periodic saltwater intrusions that influence estuarine mixing processes (Allen et al., 1980).

The lower degree of variability observed in residual flux highlights the consistent seaward flow predominantly driven by river discharge, whereas the greater fluctuation in exchange flux, especially in the lower estuary, underscores the dominant role of tidal forces near the estuarine mouth. In contrast, the upper estuary exhibited smaller exchange flux relative to residual flux, reinforcing the dominance of river discharge over tidal intrusions in this region. This indicates that while the lower

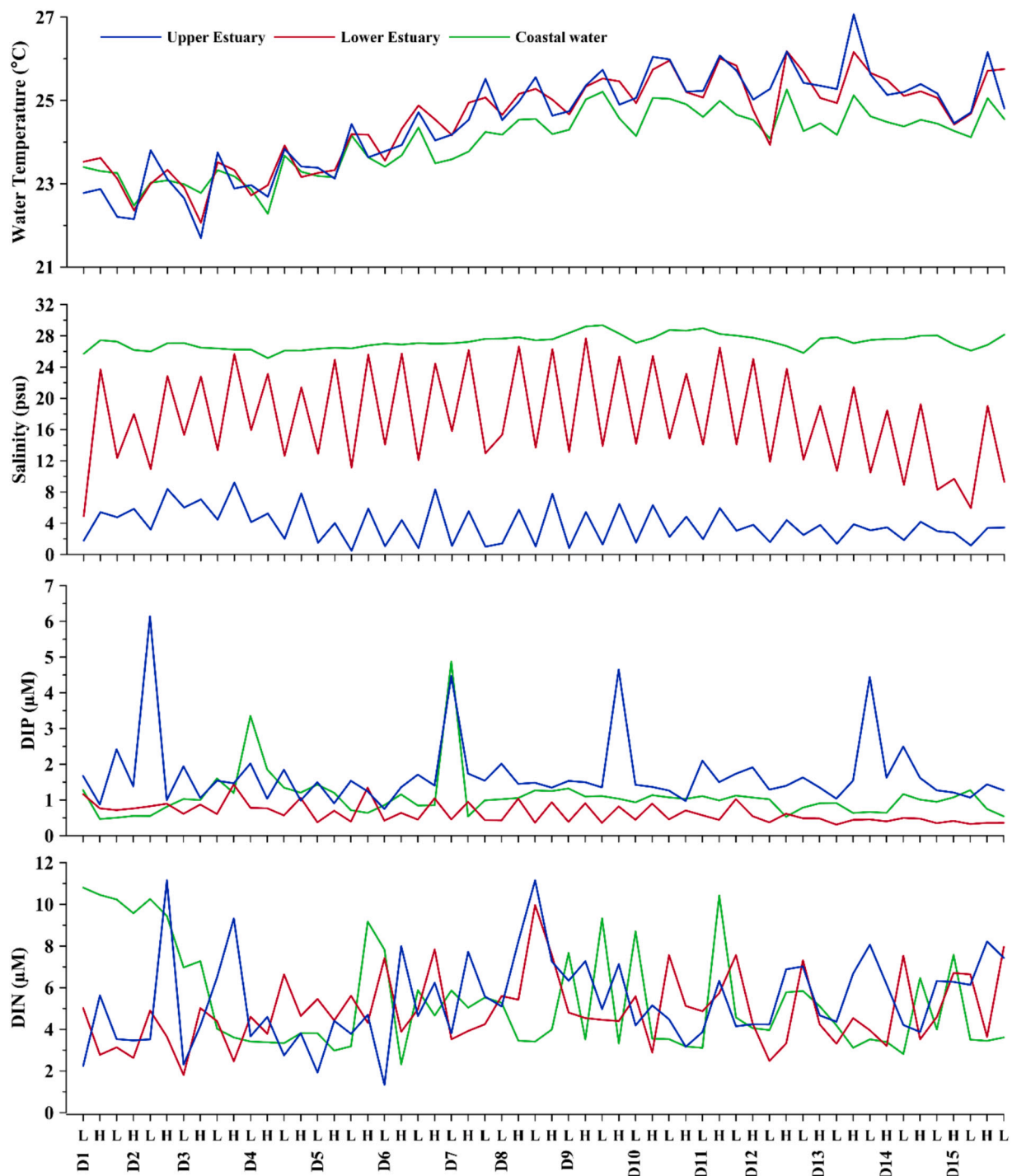


Fig. 4. Variability of physico-chemical parameters over the studied tidal cycle: upper to lower panel sequentially, Water Temperature, Salinity, DIP (Dissolved Inorganic Phosphate), and DIN (Dissolved Inorganic Nitrogen).

estuary functions as a dynamic mixing zone influenced by both riverine and tidal processes, the upper estuary remains largely controlled by freshwater inflows with relatively limited tidal intrusion (Wolanski and Elliott, 2015). The water budget outcomes signified the differential roles of river discharge and tidal forcing in controlling water transport processes along the estuarine continuum.

3.3. Salt budget and flux dynamics

The salinity budget provides essential insights into the transport and mixing of saline and freshwater masses within estuarine environments,

governed by the interplay between residual flux (net salinity export) and exchange flux (bidirectional salinity exchange). These fluxes are pivotal in determining the estuarine mixing regime, stratification, and overall hydrodynamic balance (Souza et al., 2003). In this study, both the upper and lower estuary exhibited nearly similar magnitudes of residual and exchange salinity fluxes (Fig. 5). However, the absolute values of both flux components were lower in the upper estuary than in the lower estuary, reflecting the predominant influence of freshwater discharge upstream. Specifically, salinity flux in the upper estuary fluctuated between 1.92 and 10.05×10^6 $\text{psu m}^3\text{h}^{-1}$, whereas in the lower estuary, it ranged higher, fluctuating between 7.66 and 16.11×10^6 $\text{psu m}^3\text{h}^{-1}$.

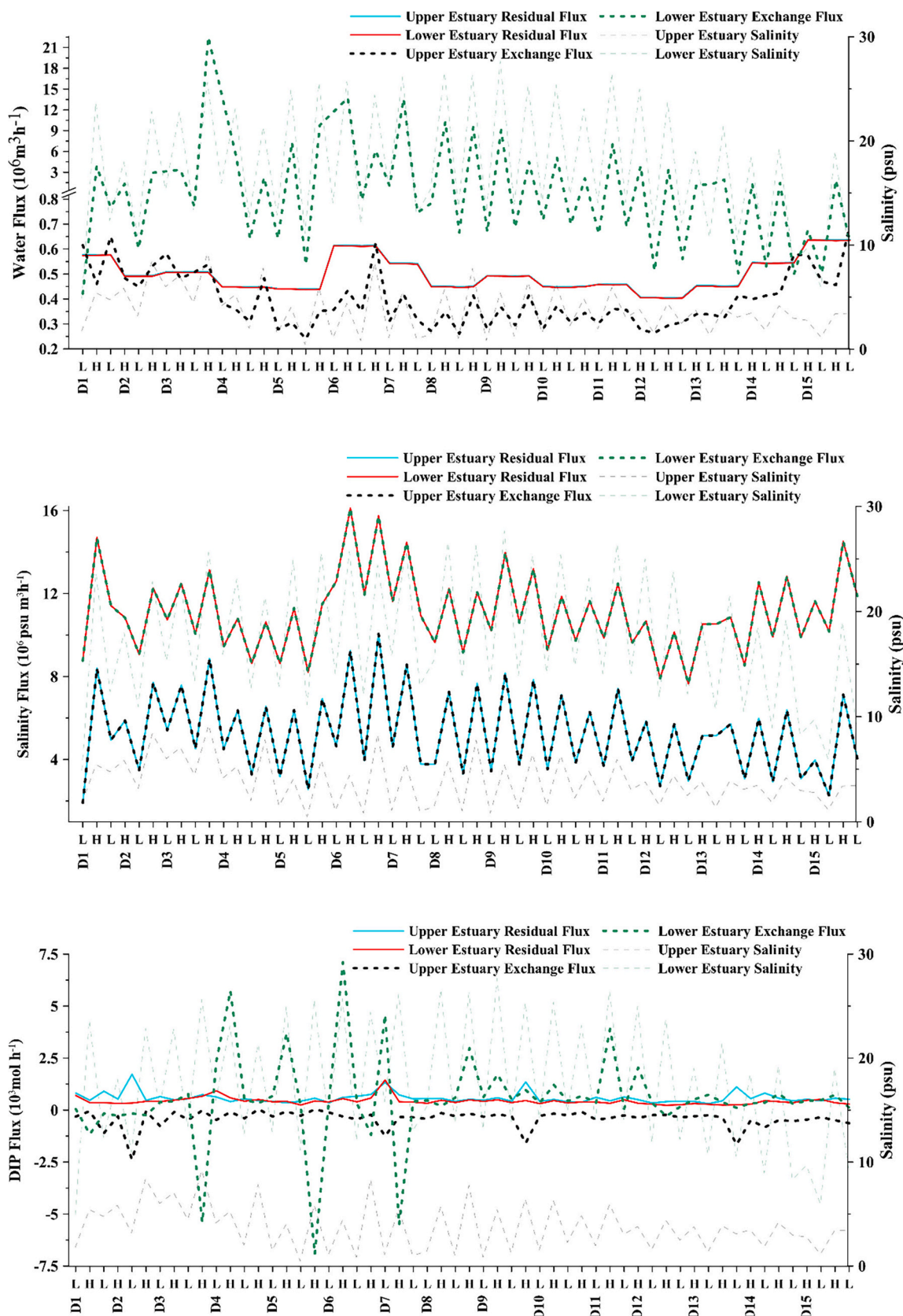


Fig. 5. Figure (upper to lower panels, sequentially) representing tidal variability of residual flux and exchange flux in the upper and lower estuary for Water flux, Salinity flux, Dissolved Inorganic Phosphate (DIP) flux, Dissolved Inorganic Nitrogen (DIN) flux, and for Exchange time. Note: The residual flux is always represented with a negative sign as it is flushing out of the system, but for the graphical representation of the comparison between residual and exchange flux, the residual flux is represented with a positive sign.

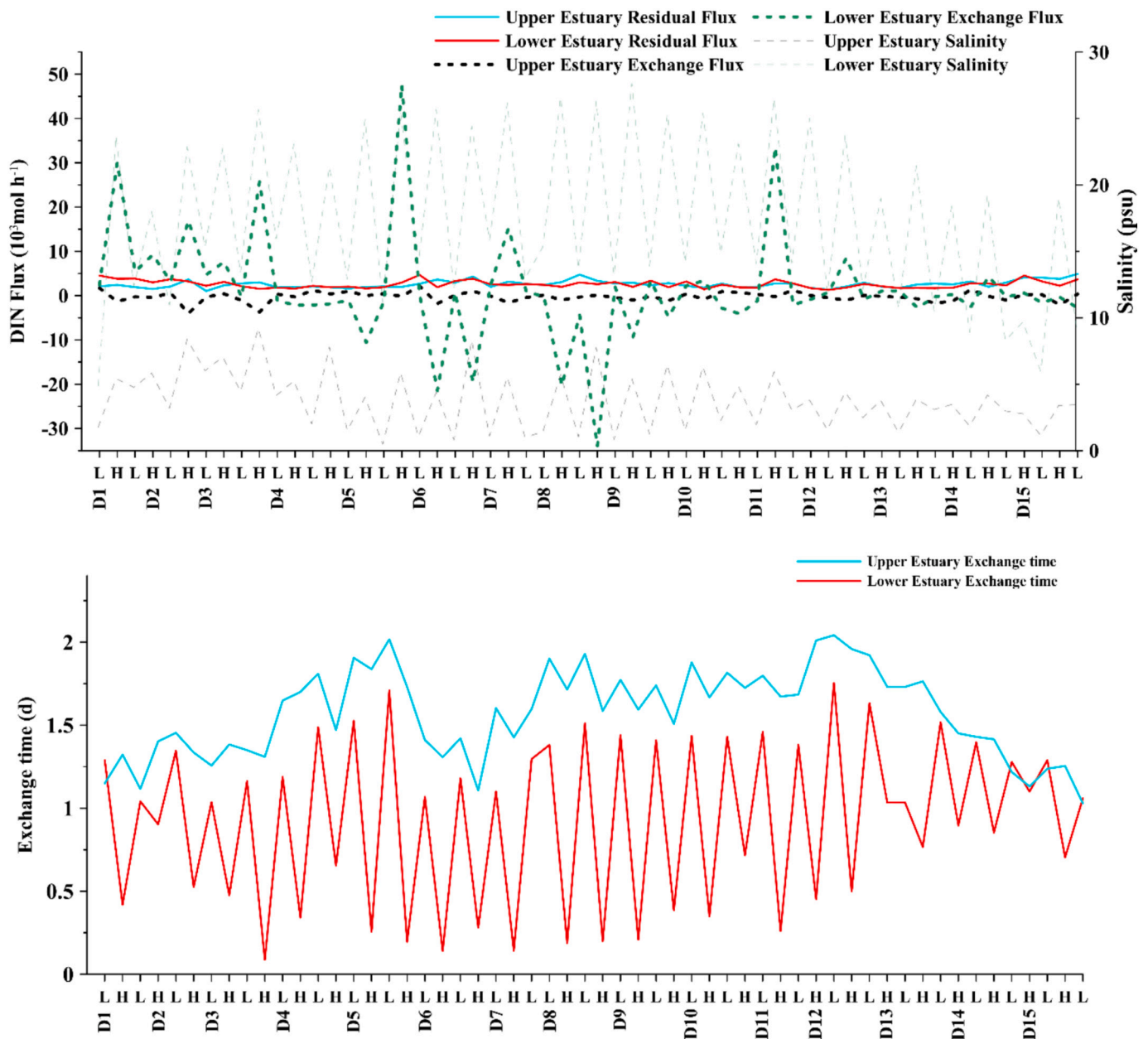


Fig. 5. (continued).

This distinction can be attributed to the stronger tidal influence in the lower estuary, which enhances saline water intrusion and intensifies exchange processes.

Throughout the semi-diurnal tidal cycle, both residual and exchange salinity fluxes demonstrated periodic variations, characterized by peaks during high tides and troughs during low tides (Figs. 5 and 7). This cyclical pattern highlights the dominance of riverine discharge during low tide, which drives seaward freshwater transport, and the opposing influence of tidal influx during high tide, which facilitates saltwater intrusion (Yu et al., 2020). The comparable magnitudes of residual and exchange salinity fluxes in both estuarine zones further indicate that the estuary exhibits a well-mixed characteristic during winter (low-flow) conditions, with substantial saline-freshwater interaction occurring across the tidal cycle (Gordon et al., 1996).

Despite this overall mixing trend, the lower salinity flux observed in the upper estuary suggests a restricted tidal influence, due to the

dominance of river discharge, which acts as a persistent freshwater source, limiting saltwater penetration. In contrast, the lower estuary exhibits a dynamic equilibrium influenced by both tidal forcing and riverine discharge, resulting in significant salinity flux variability that aligns with tidal oscillations (Bolla Pittaluga et al., 2015). This highlights the transition from a river-dominated upper estuary to a more tide-modulated lower estuary, where the balance between freshwater outflow and saline intrusion shifts dynamically with tidal amplitude and hydrological conditions (Bolla Pittaluga et al., 2015).

Understanding these salinity flux dynamics is crucial for assessing estuarine mixing processes, stratification patterns, and ecosystem responses to anthropogenic modifications, such as altered river discharge and coastal development (Gordon et al., 1996). By elucidating spatio-temporal variations in salinity transport, this study contributes to a broader understanding of estuarine biogeochemical functioning and hydrodynamic resilience under changing environmental conditions.

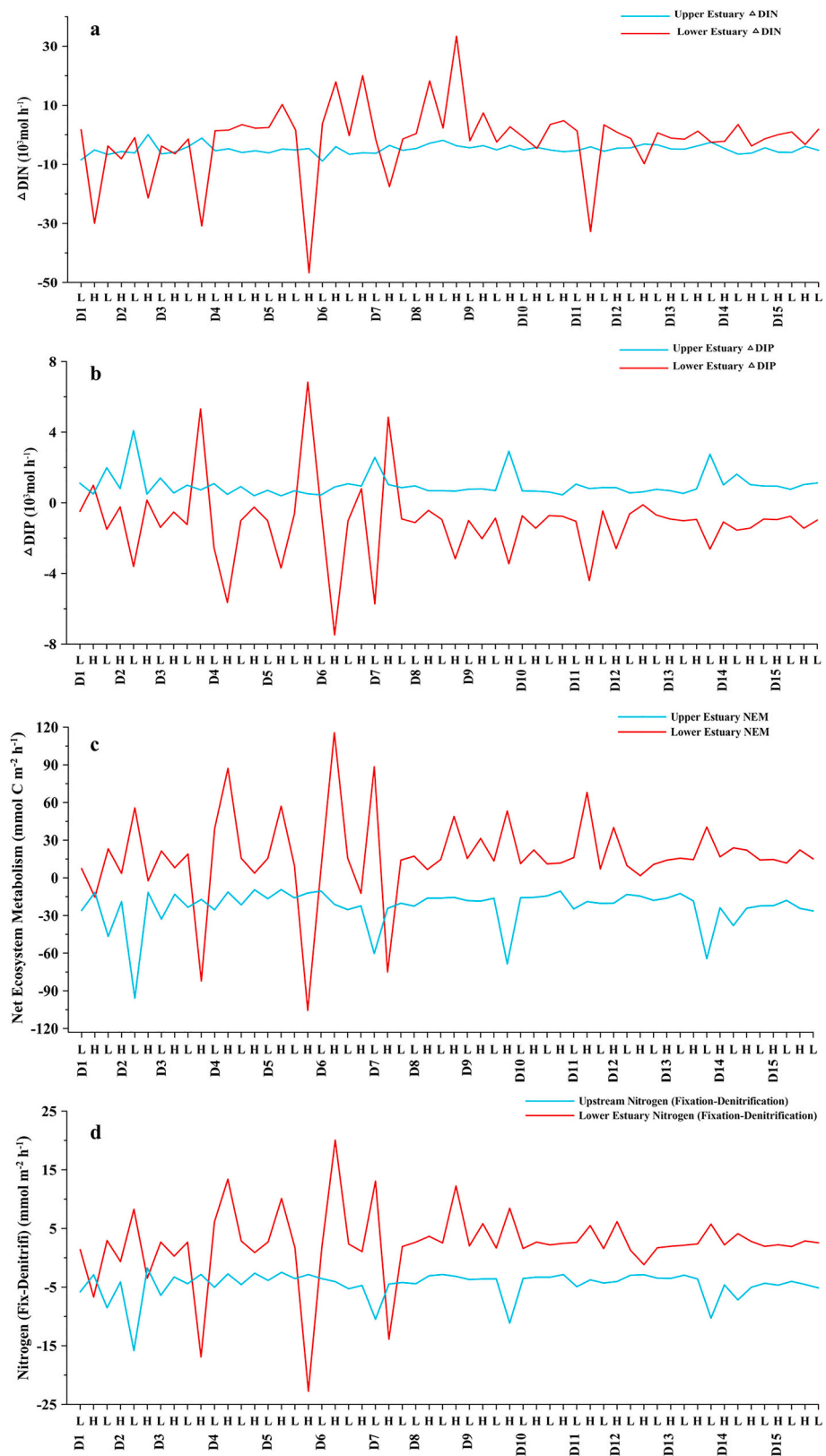


Fig. 6. Tidal variability of the processes explaining the net nutrient concentrations in the upper and lower estuary. a. ΔDIN (Dissolved Inorganic Nitrogen), b. ΔDIP (Dissolved Inorganic Phosphate), c. Net Ecosystem Metabolism (NEM), and d. nitrogen (Fixation-Denitrification).

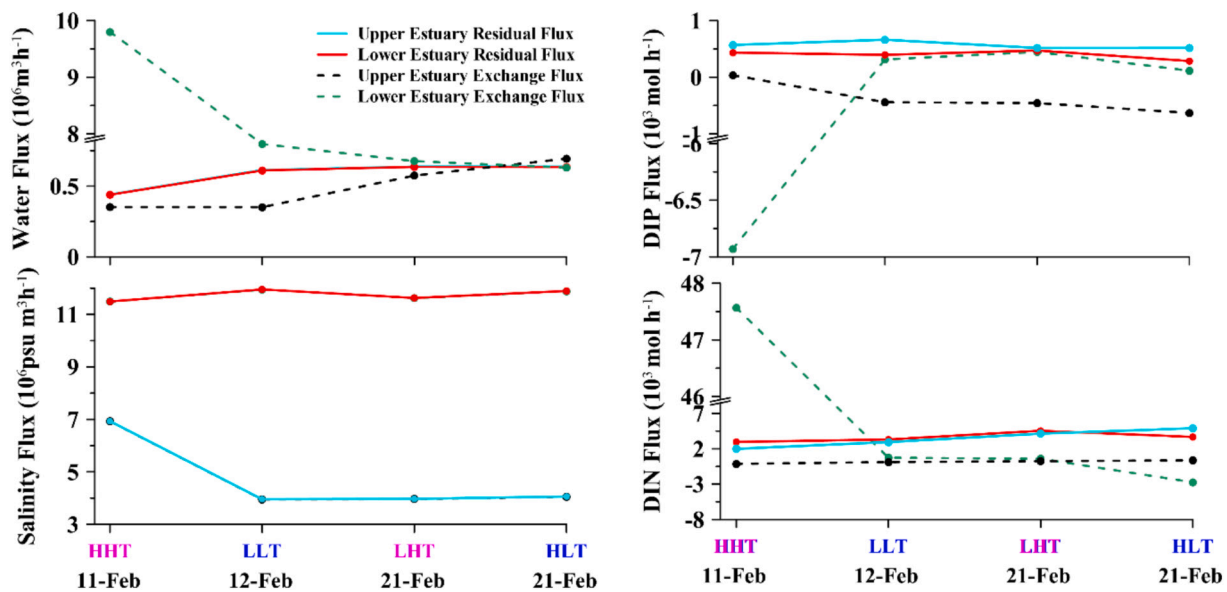


Fig. 7. Variability of residual flux and exchange flux in the upper and lower estuary during the HHT (Highest High Tide), LHT (Lowest High Tide), HLT (Highest Low Tide), and LLT (Lowest Low Tide) of Water flux, Salinity flux, DIP flux, and DIN flux.

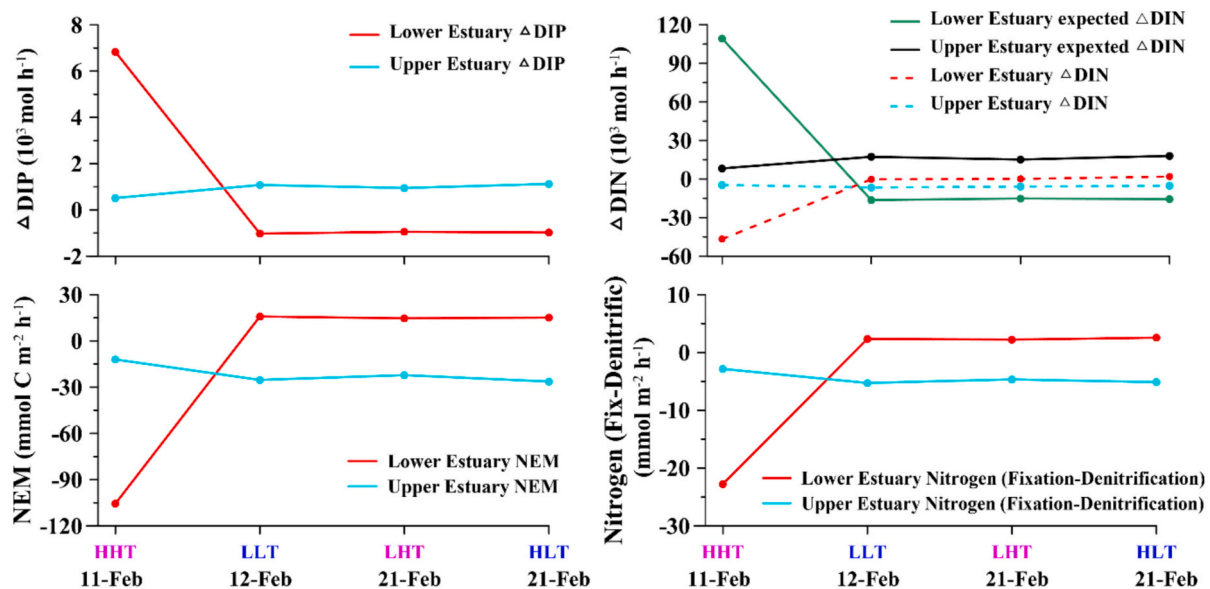


Fig. 8. Variability of processes explaining the net nutrient concentrations in the upper and lower estuary during the HHT (Highest High Tide), LHT (Lowest High Tide), HLT (Highest Low Tide), and LLT (Lowest Low Tide) of Δ DIN (Dissolved Inorganic Nitrogen), Δ DIP (Dissolved Inorganic Phosphate), Net Ecosystem Metabolism (NEM), and Nitrogen (Fixation-Denitrification).

The salinity budget reflects the salinity flux of residual and exchange flux across the tidal cycle in the upper and lower estuary. Both upper and lower estuaries exhibit almost identical magnitudes of their respective residual and exchange salinity fluxes. However, both the residual and exchange salinity flux are found to be lower in the upper estuary than in the lower estuary (Fig. 5). In the upper estuary, both the salinity flux fluctuates between 1.92 and 10.05 $10^6 \text{ psu m}^3 \text{ h}^{-1}$, and the lower estuary has a higher flux, fluctuating between 7.66 and 16.11 $10^6 \text{ psu m}^3 \text{ h}^{-1}$.

3.4. Exchange/Residence time

Exchange and residence times are critical parameters for understanding the hydrodynamic behaviour of estuaries, as they define the rate at which water and dissolved constituents, such as salinity and nutrients, are exchanged and retained within the system. These

parameters, derived from the LOICZ model, provide insight into water renewal efficiency, estuarine flushing capacity, and the degree of tidal influence across different estuarine zones (Xu et al., 2013).

In the upper estuary, the exchange time exhibits pronounced variability, fluctuating sharply between 1.03 and 2.04 days, whereas in the lower estuary, the variability is comparatively lower, ranging between 0.09 and 1.75 days (Fig. 5). This distinction highlights the fundamental differences in tidal responsiveness and water renewal rates between the two estuarine regions. The lower estuary demonstrates a more dynamic response to tidal variability, with significantly reduced exchange times during high tides, indicating rapid turnover and enhanced flushing capacity. This can be attributed to the strong bidirectional exchange between the lower estuary and adjacent coastal waters, facilitated by semi-diurnal tidal forcing (Liu et al., 2021).

Conversely, the upper estuary experiences longer exchange times,

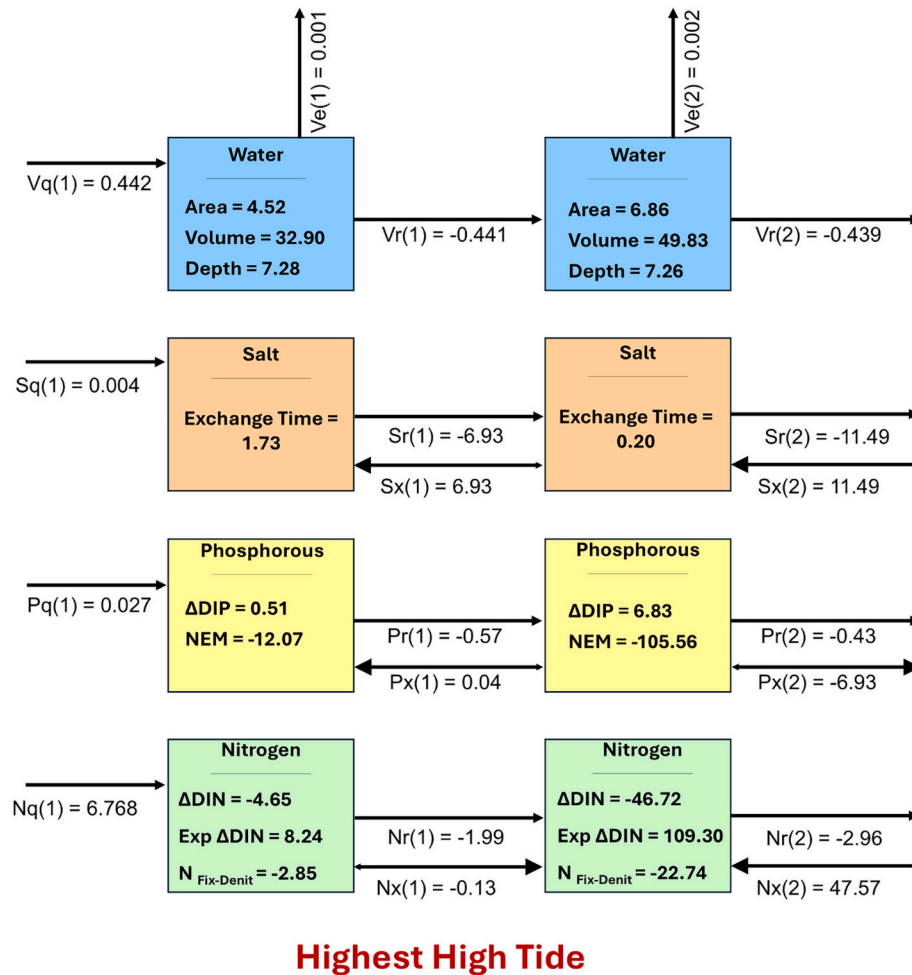


Fig. 9. Water, Salt, Dissolved Inorganic Phosphate (Phosphorous), Dissolved Inorganic Nitrogen (Nitrogen) budget of the Mahanadi estuary during the Highest High Tide, Highest Low Tide, Lowest High Tide, Lowest Low Tide (from upper to lower panels, respectively), and for cumulative 15 days. Water fluxes in $10^6 \text{ m}^3 \text{ h}^{-1}$, Salt fluxes in $10^6 \text{ psu m}^3 \text{ h}^{-1}$, nutrient fluxes in 10^3 mol h^{-1} , exchange time in a day, NEM (Net ecosystem metabolism) in $\text{mmol C m}^{-2} \text{ h}^{-1}$, and $N_{\text{Fix-Denit}}$ (Estimated N fixation – Denitrification) in $\text{mmol m}^{-2} \text{ h}^{-1}$.

signifying slower renewal rates and prolonged retention of water mass, nutrients, and other dissolved substances. The reduced tidal influence in this region results in more stable hydrodynamic conditions, where water movement is primarily governed by riverine discharge rather than tidal advection (Stark et al., 2017). Consequently, the upper estuary functions as a more enclosed system with slower salinity mixing and nutrient dispersion, which can enhance biogeochemical processing and organic matter transformation before the water mass reaches the lower estuary and coastal waters.

The contrasting exchange times observed between the upper and lower estuary underscore the interplay between tidal forcing and riverine discharge in shaping estuarine hydrochemical processes. While the lower estuary is heavily influenced by tidal dynamics, promoting rapid exchange and increased connectivity with the coastal environment, the upper estuary remains largely dictated by freshwater inflow, limiting tidal penetration and prolonging residence time (Khojasteh et al., 2021).

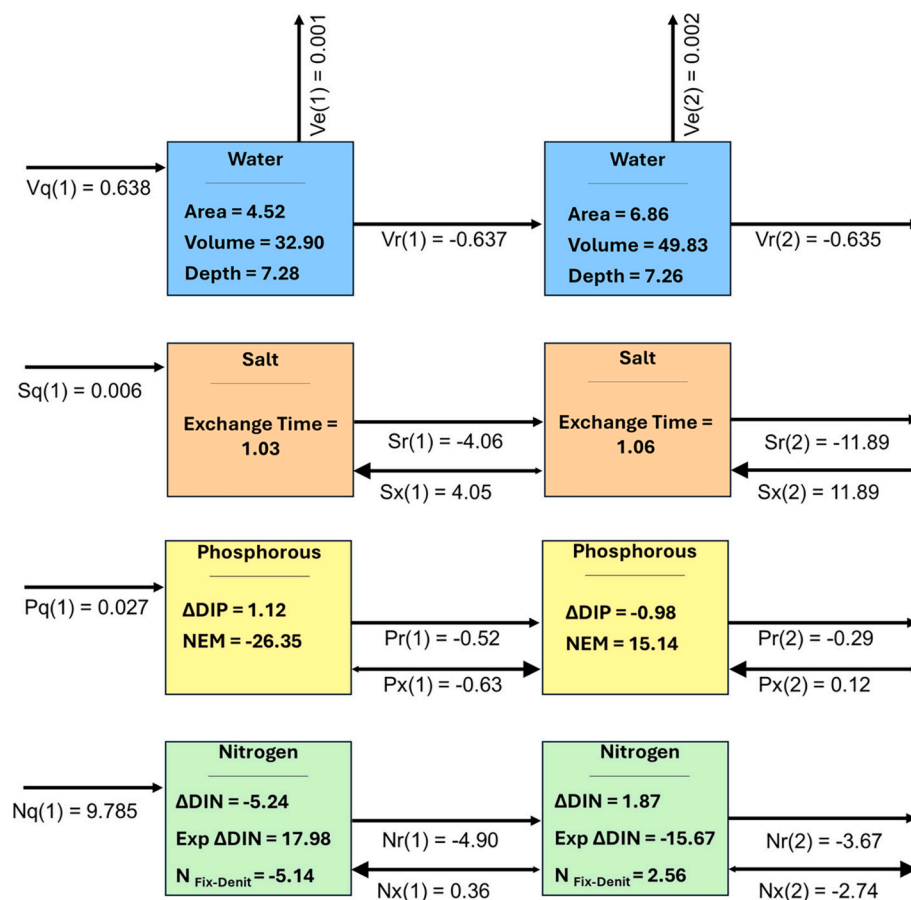
3.5. Nutrient budget

The spatio-temporal distribution and movement of dissolved inorganic nutrients (DIP and DIN) within estuarine-coastal systems are governed by a complex interplay of freshwater discharge, residual circulation, and tidal forcing. These hydrodynamic processes dictate

nutrient fluxes between the estuary and the adjacent coastal waters, influencing the biogeochemical cycling of essential elements (Kiwango et al., 2018). The LOICZ model-based nutrient budget analysis provides insights into the net transport, retention, and transformation of nutrients, emphasizing their role in modulating estuarine productivity and ecological function. The LOICZ nutrient budget was estimated as the difference between freshwater inflow into the estuary and outflow to the coastal waters, and between nutrient inflow from coastal waters into the estuary and subsequent outflow from the estuary to the coastal environment (Gordon et al., 1996). Additionally, the non-conservative nature of dissolved nutrients, attributed to biological uptake, remineralization, and sediment adsorption/desorption, further regulates nutrient flux dynamics (Gazeau et al., 2005). Since atmospheric deposition was found to be negligible, nutrient delivery via river inflow was the primary contributor to the nutrient budget calculations (Smith et al., 2005).

3.5.1. DIP flux dynamics

The residual DIP flux exhibited minimal tidal fluctuations, with higher flux from the upper estuary than the lower estuary, reflecting the dominant influence of riverine discharge in transporting DIP seaward (Fig. 5). In contrast, the exchange flux of DIP was driven by bidirectional tidal oscillations, with a negative exchange flux in the upper estuary, suggesting no significant tidal-driven DIP transport from the lower to the



Highest Low Tide

Fig. 9. (continued).

upper estuary. Conversely, in the lower estuary, DIP exchange fluxes varied significantly, with predominantly high, positive fluxes, indicating active DIP exchange between coastal waters and the lower estuary. This suggests that both riverine input and coastal waters serve as DIP sources to the lower estuary (Fig. 5).

3.5.2. DIN flux dynamics

The residual DIN flux analysis confirmed that the Mahanadi estuary acts as a net exporter of DIN, with continuous transport to the coastal waters primarily influenced by river discharge (Fig. 5). Compared to the residual flux, the exchange flux of DIN was significantly higher in the lower estuary than in the upper estuary. The exchange flux of DIN to the upper estuary remained negligible, suggesting that tidal mixing is not strong enough to drive nitrogen back into the upper estuary against the prevailing riverine outflow. However, the exchange flux in the lower estuary exhibited strong tidal modulation, reflecting the dynamic DIN transport between the coastal waters and the estuarine mouth. While no distinct tidal variability pattern was observed in the exchange flux, the dominance of negative exchange fluxes suggests that DIN transport is primarily directed seaward, with limited exchange from the coastal waters to the lower estuary (Gordon et al., 1996).

3.5.3. Tidal influence on nutrient flux variability

The variability in DIP and DIN fluxes was closely linked to tidal amplitude, reinforcing the role of tidal oscillations in regulating nutrient transport within estuarine zones (Potgieter, 2008). During the initial phase of the tidal cycle (lower tidal amplitudes), both DIP and DIN fluxes exhibited minimal variability. However, as the tidal amplitude

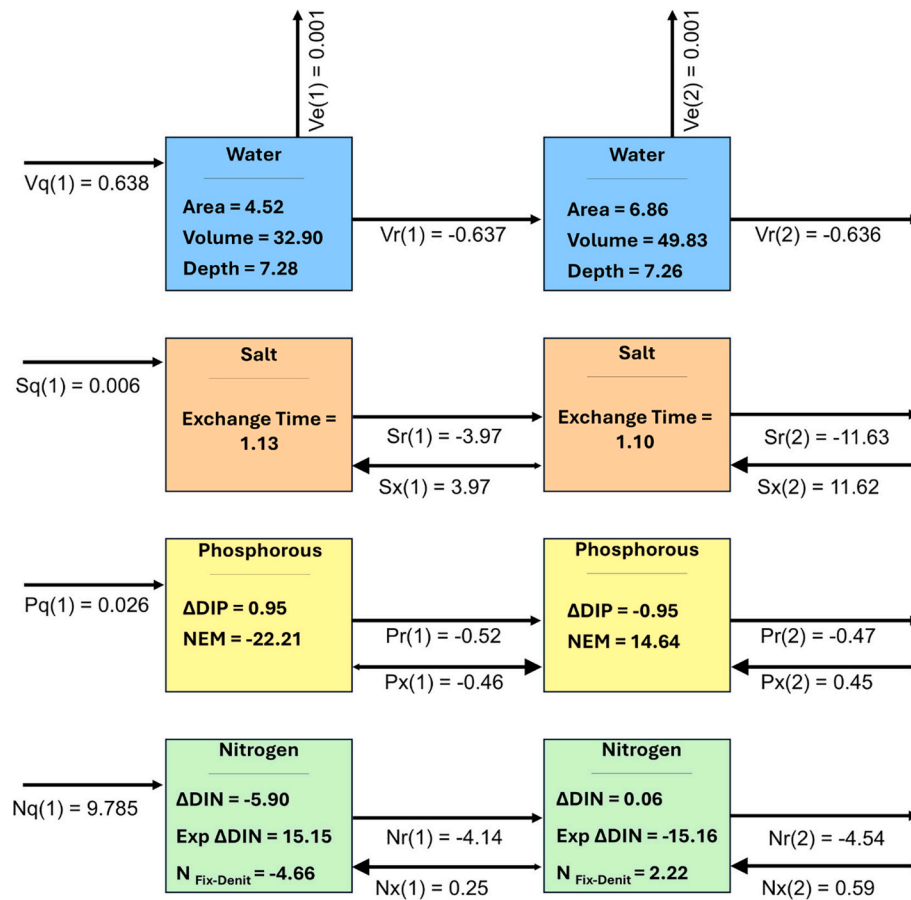
increased, significant fluctuations in nutrient fluxes were observed, followed by a stabilization period toward the end of the tidal cycle (Fig. 5). This pattern underscores the differential influence of riverine discharge and tidal mixing on nutrient fluxes across estuarine zones. The results suggest that (i) the upper estuary functions as a stable, river-dominated system, with nutrient fluxes primarily regulated by freshwater inflow and minimal tidal impact, and (ii) the lower estuary serves as a dynamic transition zone, with tidal oscillations exerting a significant influence on nutrient exchange processes (Fig. 7).

3.5.4. Estuarine trophic status: Net ecosystem metabolism (NEM) and nutrient balance

Beyond physical mixing processes, nutrient flux dynamics also determine the trophic status of estuarine systems, influencing their role as nutrient sources or sinks to adjacent coastal waters (Smith et al., 2005). In the LOICZ framework, Δ DIP approximates net nutrient uptake by primary producers or nutrient release via respiration.

3.5.5. DIP balance and carbon flux

In this study, a positive Δ DIP in the upper estuary throughout the study period suggested that this region functioned as a net source of DIP to the lower estuary. Conversely, the negative Δ DIP in the lower estuary indicated that this region acted as a DIP sink, where nutrient removal exceeded supply. The net DIP flux was further used to estimate carbon flux (Δ DIC) via the Redfield ratio (C:P = 106:1), an essential metric for evaluating organic carbon processing (Redfield, 1958). However, direct Δ DIC estimation is often complicated by atmospheric gas exchange, carbonate precipitation/dissolution, and sulphate reduction processes,



Lowest High Tide

Fig. 9. (continued).

making DIP-based approximations a valuable alternative for assessing organic carbon flux (Smith et al., 2005).

3.5.6. DIN balance and nitrogen processing

Unlike Δ DIP, Δ DIN represents the net DIN budget influenced by Net Ecosystem Metabolism (NEM), nitrogen fixation, and denitrification processes. These processes play a crucial role in shaping the estuarine nitrogen cycle, regulating ecosystem productivity, and maintaining nutrient balance (Gordon et al., 1996). During the study, NEM variability in the upper estuary remained lower than in the lower estuary, but both regions exhibited increasing variability with rising tidal amplitude and stabilization at lower tidal amplitudes (Fig. 6).

3.5.7. NEM and nitrogen fixation-denitrification

The NEM and nitrogen fixation-denitrification ($N_{\text{Fix-Denit}}$) trends followed similar patterns, reinforcing their complementary nature (Fig. 6 and 8). Higher metabolic activity was associated with greater nitrogen fixation, whereas reduced metabolism was associated with increased denitrification. The upper estuary exhibited consistently negative NEM and $N_{\text{Fix-Denit}}$ values throughout the tidal cycle, indicating a predominantly heterotrophic system (organic matter respiration > production). In contrast, the lower estuary displayed positive NEM and $N_{\text{Fix-Denit}}$ values, characterizing it as an autotrophic system where primary production exceeded respiration.

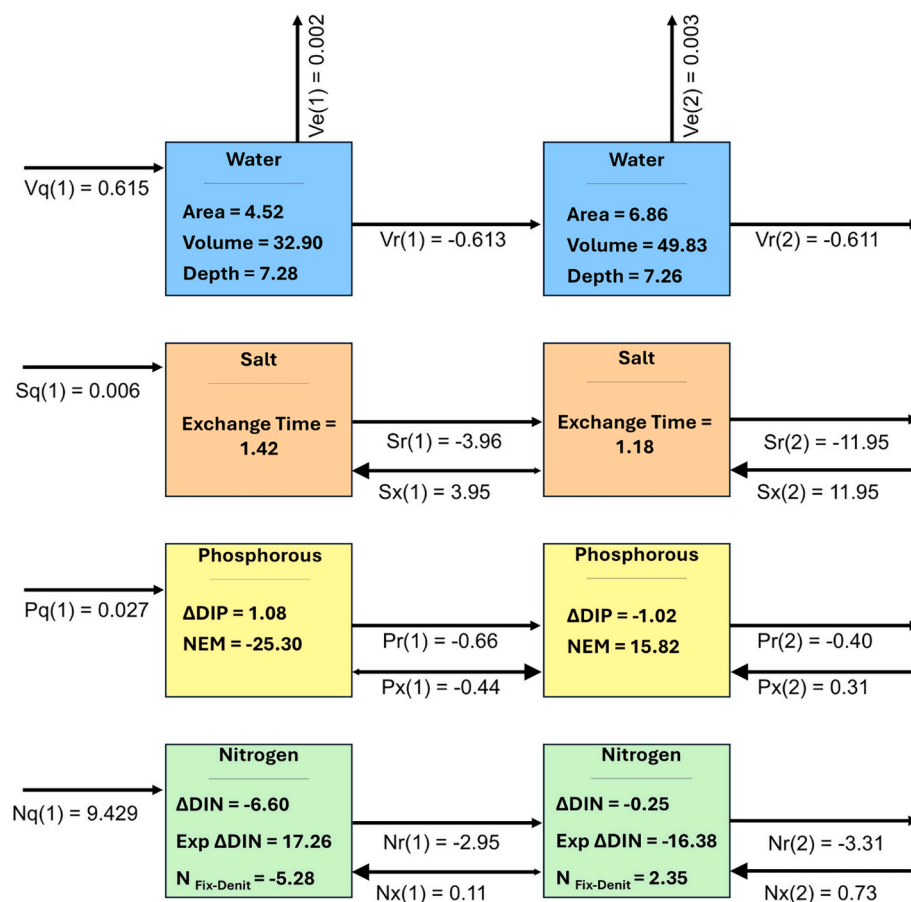
The findings emphasize that estuarine ecosystems exhibit distinct spatial and temporal variability in nutrient fluxes, dictated by hydrodynamic processes and biogeochemical transformations. The upper estuary, governed by riverine discharge, functions as a nutrient exporter

with limited tidal influence, whereas the lower estuary serves as a dynamic interface where tidal mixing significantly alters nutrient transport patterns. These differences underscore the need for integrated estuarine-coastal management strategies to assess nutrient budgets, ecosystem metabolism, and their cascading impacts on coastal productivity and water quality (Portman et al., 2012).

3.6. Comparison with other LOICZ and tropical estuarine studies

The very short water residence times estimated here, generally less than one day and ranging from 0.09 to 2.04 days across the tidal cycle, are comparable to or shorter than those reported for other tropical and subtropical estuaries budgeted within the LOICZ and related frameworks. In the neighbouring monsoonal Godavari estuary on the Bay of Bengal, apparent water ages of about 3 to 5 days have been reported, decreasing to less than a day during peak discharge (Rengarajan and Sarma, 2015). Modelled residence times in the Pearl River estuary are approximately 6 days in the dry season and 3 days in the wet season (Sun et al., 2014), whereas the larger, more turbid Changjiang (Yangtze) estuary exhibits residence times of roughly 7 to 25 days (Xu et al., 2013), and the very large, plume-dominated Amazon system retains shelf waters for weeks (DeMaster and Pope, 1996). The comparatively rapid flushing of the Mahanadi estuary reflects its small estuarine volume and the strong, tidally driven exchange flux in the lower estuary, which together promote efficient water renewal even during the low-flow winter period.

The nutrient budgets and metabolic status of the Mahanadi estuary are likewise consistent with patterns observed elsewhere. As in the



Lowest Low Tide

Fig. 9. (continued).

Godavari and Pearl River systems, riverine input is the dominant nutrient source, and the upper, river-dominated reach exports nutrients seaward while the lower estuary functions as a more dynamic exchange zone (Sun et al., 2014; Rengarajan and Sarma, 2015). The coexistence of net heterotrophy in the upper estuary and net autotrophy in the lower estuary mirrors the spatial heterogeneity in net ecosystem metabolism documented for other tide- and discharge-influenced estuaries (Gazeau et al., 2005; Smith et al., 2005). Tidal forcing exerts a stronger control on residence time and nutrient transformation in the Mahanadi estuary than in larger, discharge-dominated systems such as the Yangtze and Amazon; the short, tidally modulated residence times limit in-situ nutrient processing in the lower estuary and favour rapid export to the adjacent coastal waters, whereas the longer retention in larger systems permits more extensive internal nutrient transformation (Xu et al., 2013).

3.7. Assumptions of the LOICZ framework

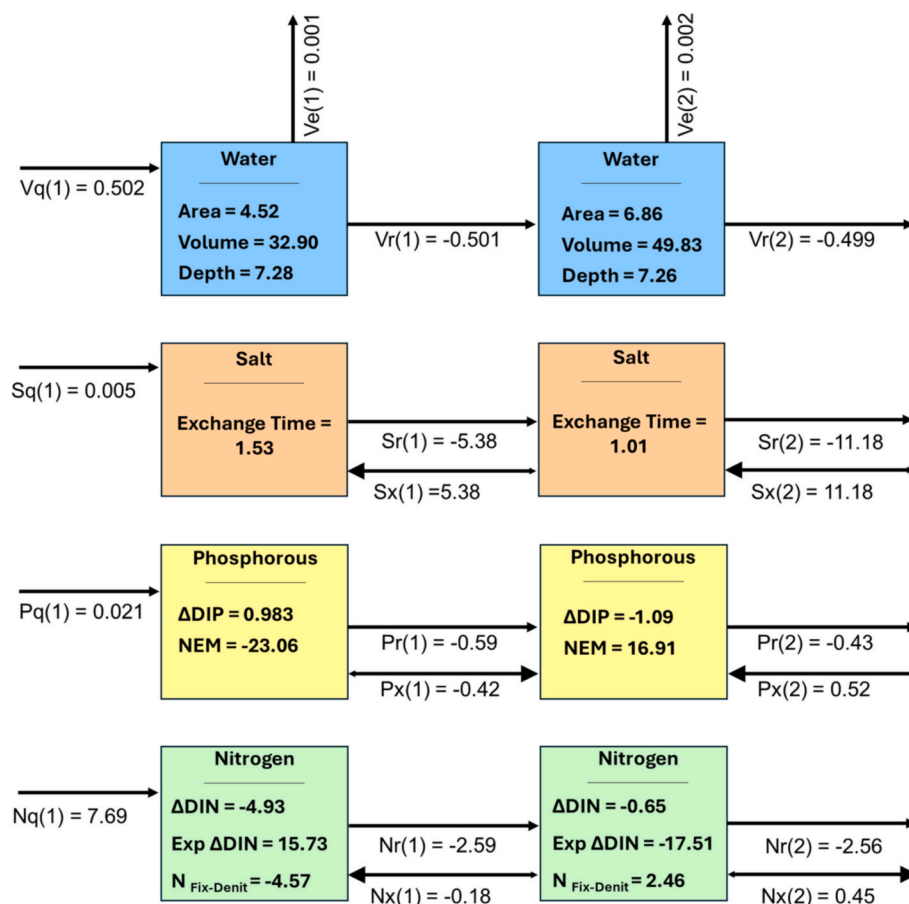
The budgets presented here rest on several standard LOICZ assumptions: that the system is at steady state over the survey period, that groundwater and atmospheric inputs are negligible, that salinity behaves conservatively, that each compartment is well mixed, and that the estuary can be represented as a simple box model (Gordon et al., 1996; Swaney et al., 2011). These assumptions are reasonable for the present winter survey, when river discharge was low and steady, precipitation was absent, and the salinity field was well-mixed within each compartment, conditions under which steady-state box budgeting is most defensible. The principal implication is that the budgets describe

the dry-season, low-flow state rather than the annual mean, and that neglected groundwater inputs, although likely minor in this setting, could introduce some underestimation of freshwater and nutrient loading, as quantified for the neighbouring Godavari system (Rengarajan and Sarma, 2015). Comparable assumptions have been adopted in the great majority of LOICZ applications worldwide (Smith et al., 2005; Swaney et al., 2011), supporting the comparability of the present results with those studies.

Because the present results characterize winter conditions, the monsoon season is expected to substantially modify the estuarine budget. High monsoonal discharge would sharpen the salinity gradient and displace it seaward, shorten residence times further, and increase the seaward transport of dissolved and particulate nutrients, as observed in the Godavari and other Indian monsoonal estuaries (Rengarajan and Sarma, 2015). Elevated turbidity and nutrient loading during high flow could shift the metabolic balance toward stronger net heterotrophy in the upper estuary while enhancing export-driven productivity in the receiving coastal waters, thereby altering the trophic status inferred here. These seasonal contrasts indicate that the winter budget represents one end of a broader hydrological spectrum, and that monsoon and post-monsoon observations are required to constrain the annual nutrient and metabolic balance of the system.

4. Conclusion

The intricate interactions between riverine discharge and tidal dynamics shape the biogeochemical properties of the Mahanadi River estuary. The outcomes from this study, employing the LOICZ model,



15 Days Budget

Fig. 9. (continued).

provide a detailed understanding of hydrochemical budgets, nutrient fluxes, and estuarine metabolism, with a specific focus on the influence of semidiurnal tidal fluctuations. The meteorological and physico-chemical parameters indicate that tidal exchanges and riverine input are the primary drivers of hydrochemical variability, particularly in the absence of significant precipitation. The semi-diurnal tidal cycle strongly modulates salinity distribution, water temperature, and nutrient concentrations, leading to distinct hydrochemical regimes across the estuarine gradient.

The analysis of the water budget and flux dynamics reveals that the residual flux is primarily governed by freshwater discharge, ensuring a consistent seaward flow, whereas the exchange flux exhibits pronounced variability due to tidal forcing. The lower estuary functions as a dynamic mixing zone, influenced by bidirectional tidal oscillations, whereas the upper estuary remains largely controlled by freshwater inflows, limiting tidal intrusion (Fig. 9). Similarly, the salt budget underscores the transition from a river-dominated upper estuary to a tidally modulated lower estuary, where salinity fluctuations align with tidal cycles, reinforcing the estuarine-coastal connectivity.

Nutrient flux dynamics further highlight the influence of tidal forcing and river discharge on estuarine trophic status. The upper estuary functions as a nutrient exporter, primarily regulated by riverine input, whereas the lower estuary exhibits significant tidal modulation of nutrient transport (Fig. 9). The observed variations in dissolved inorganic phosphorus (DIP) and dissolved inorganic nitrogen (DIN) fluxes underscore the combined effects of freshwater inflows, tidal mixing, and localized anthropogenic influences on estuarine nutrient cycling. The

trophic status assessment, based on net ecosystem metabolism (NEM), suggests that the upper estuary is predominantly heterotrophic, while the lower estuary exhibits autotrophic characteristics, with tidal mixing enhancing nutrient uptake and organic carbon processing.

The salient outcomes of this study are i) first hydrochemical survey over the full semidiurnal tidal period in Mahanadi Estuary, ii) first-of-its-kind comprehensive hydro-chemical budgeting of Mahanadi Estuary, iii) first use of GIS-based technique for Mahanadi River discharge estimation, iv) tidal forcing vs salinity revealed the estuary as a well-mixed system during winter conditions, v) significant tidal forcing on the lower estuary hydrodynamics, vi) upper estuary and coastal water as a nutrient source to the lower estuary, and vii) prevalence of autotrophy in lower and heterotrophy in the upper estuary. Overall, this study highlights the complex interplay of hydrodynamic and biogeochemical processes that govern estuarine-coastal interactions in the Mahanadi estuary. The findings underscore the necessity of integrated management approaches to assess nutrient budgets, ecosystem metabolism, and their cascading impacts on coastal productivity and water quality. Understanding these dynamic processes is critical for evaluating estuarine resilience and informing sustainable conservation strategies in the context of environmental changes.

Despite the novel insights this study provides, certain limitations should be acknowledged. The observations were confined to a single winter (low-flow) period, so the budgets characterize dry-season conditions and do not capture the pronounced seasonal variability driven by the southwest monsoon, which delivers most of the annual freshwater discharge. The LOICZ budgets are first-order estimates that rely on

steady-state and well-mixed assumptions, the conservative behaviour of salinity, and the exclusion of groundwater inputs, any of which may introduce uncertainty under non-winter conditions. Additional uncertainty arises from estimates of freshwater discharge reaching the estuary and analytical uncertainty in nutrient determination, while the absence of monsoon and post-monsoon validation limits extrapolation to the annual scale. Notwithstanding these constraints, the high-frequency sampling over a complete tidal cycle and the internally consistent budgeting provide a robust first characterization of the dry-season hydrochemical functioning and trophic status of the Mahanadi estuary, establishing a baseline against which seasonal and interannual changes can be assessed. Future work should extend the budgeting approach to the monsoon and post-monsoon seasons to capture the full range of discharge and tidal conditions, incorporate high-flow events and interannual variability, and quantify groundwater contributions, so that the seasonal and annual nutrient budgets, ecosystem metabolism, and trophic status of the Mahanadi estuarine-coastal continuum can be fully resolved.

CRedit authorship contribution statement

Susmita Raulo: Visualization, Software, Investigation, Formal analysis, Data curation, Conceptualization, Writing – original draft. **Sanjiba Kumar Baliarsingh:** Investigation, Formal analysis, Writing – original draft. **Alakes Samanta:** Investigation, Formal analysis, Writing – original draft. **Aneesh A. Lotliker:** Supervision, Resources, Investigation, Formal analysis, Writing – review & editing. **Sudheer Joseph:** Supervision, Resources, Writing – review & editing, Data curation. **Sambit Singh:** Investigation, Formal analysis, Writing – review & editing. **Tamoghna Acharyya:** Supervision, Resources, Funding acquisition, Data curation, Writing – review & editing. **Vikrant V. Patil:** Software, Data curation, Writing – review & editing. **T.M. Balakrishnan Nair:** Supervision, Resources, Writing – review & editing.

Consent for publication

Not applicable

Ethics approval and consent to participate

Not applicable

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Declaration of competing interest

The authors declare that they have no known competing financial or non-financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Copernicus programme of the European Space Agency (for providing the Sentinel data). This is INCOIS contribution no. 716.

Data availability

The datasets will be made available on reasonable request.

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