



## Spatiotemporal mapping of chemical and physical fluxes at the river–ocean transition zone

Subburu Mahesh<sup>1\*</sup>; Dr. Balla Satyanarayana<sup>2</sup>; Shree Jayaram K<sup>3</sup>;  
Sreenivasa Reddy M<sup>4</sup>; Deepak Bhanot<sup>5</sup>; Shweta Ishwar Gadave<sup>6</sup>;  
Bhawna Kaushik<sup>7</sup>; Muninathan N<sup>8</sup>

Received: 31 December 2025; Revised: 15 January 2026; Accepted: 06 March 2026; Published: 20 April 2026

### Abstract

The proposed study characterizes the flow of chemical and physical fluxes on the river-ocean boundary, which is among the most significant ecological boundaries, as freshwater supplied by rivers and ocean water come together. These nutrient fluxes are crucial to the well-being of the ecosystem, the management of water quality, and curbing environmental degradation. This has significantly improved, but high-resolution data and the necessity of integrating real-time monitoring technologies to capture the variability of such fluxes is necessitated because of issues such as the river discharge, tidal cycles and human activities. The research utilized field sampling, in situ sensors, remote sensors and GIS to quantify the time and spatial distribution of the parameters such as salinity, nutrient levels, and dissolved oxygen. The results point out that there are significant differences in the fluxes among the sites with the river-mouth regions having higher nutrient and particulate fluxes compared to the nutrient-depleted coastal lands. As an example, River Mouth 1 had the maximum nitrate flux ( $6.2 \mu\text{mol}/\text{m}^2/\text{s}$ ) and Coastal Ocean 1 the lowest ( $1.8 \mu\text{mol}/\text{m}^2/\text{s}$ ). The optimal model performance was observed in River Mouth 1 (RMSE = 0.18,  $R^2 = 0.85$ ) and the poor performance in Coastal Ocean 1 (RMSE = 0.45,  $R^2 = 0.72$ ). The results establish the importance of understanding the forces in transitional

1\*- Assistant Professor, Department of Chemistry Vardhaman College of Engineering, Shamshabad, Hyderabad, India. Email: mahesh1589@vardhaman.org, ORCID: <https://orcid.org/0000-0002-5866-2088>

2- Associate Professor, Department of Civil Engineering, Pragati Engineering College, Kakinada District, Andhra Pradesh, India. Email: snballa1670@gmail.com, ORCID: <https://orcid.org/0009-0007-2072-0442>

3- Innovation & Incubation Centre, Meenakshi Academy of Higher Education and Research, Chennai, Tamil Nadu, India. Email: shreejayaram@maher.ac.in, ORCID: <https://orcid.org/0009-0002-2540-328X>

4- Professor, Department of Mechanical Engineering, Aditya University, Surampalem, Andhra Pradesh, India. Email: dypc@adityauniversity.in, ORCID: <https://orcid.org/0009-0008-0146-097X>

5- Centre of Research Impact and Outcome, Chitkara University, Rajpura, Punjab, India. Email: deepak.bhanot.orp@chitkara.edu.in, ORCID: <https://orcid.org/0009-0007-9870-0708>

6- Assistant Professor, Electronics & Telecommunication Engineering, Vishwakarma Institute of Technology, Pune, Maharashtra, India. Email: shweta.gadavel@vit.edu, ORCID: <https://orcid.org/0009-0003-3355-6582>

7- School of Sciences, Noida International University, Uttar Pradesh, India.

Email: bhawna.kaushik@niu.edu.in, ORCID: <https://orcid.org/0009-0001-9854-9207>

8- Scientist, Central Research Laboratory, Meenakshi Medical College Hospital & Research Institute, Meenakshi Academy of Higher Education and Research, Chennai, Tamil Nadu, India.

E-mail: muninathan@maher.ac.in, ORCID: <https://orcid.org/0009-0009-5747-3216>

\*Corresponding author

DOI: 10.70102/IJARES/V6I1/6-1-10

regions to improve coastal management, predict the environmental changes and shape sustainable policy. This paper recommends that there is a need to enhance real time data integration as well as the need to enhance predictive models so as to manage superior river-ocean systems and ecosystems.

**Keywords:** River-ocean transition zone, Spatiotemporal mapping, Chemical fluxes, Physical fluxes, Nutrient cycling, Coastal ecosystems, Environmental management

## Introduction

The river-ocean interface (also known as the estuarine/coastal interface) is a highly dynamic region in which river water flows into the ocean, blending with salty water. This is a central area in learning of biogeochemical cycles that regulate the flow and dislocation of chemical and physical fluxes in water bodies. These nutrient-rich, organic, and dissolved gaseous fluxes, as well as pollutant fluxes, play a crucial role in the processes of river and marine ecosystems. These fluxes are spatiotemporal and their mapping can give a clear picture of their time-space distribution, aid in identifying trends and help in identifying how human activities have modified them and how the environment is likely to evolve in future. River discharge, human intervention, and climatic changes are some of the factors that significantly affect the fluxes of water quality, nutrients, and pollutants in these transition zones. To illustrate, temporal-spatial dynamics of water quality indicate that river flow has a strong impact on parameters such as chlorophyll concentration and turbidity (Du *et al.*, 2017). The river flux and nutrient composition that influence the water quality of coastal waters in Hainan Island, China highlight the significance of nutrient discharge by rivers in the development of coastal ecosystems (Zhang *et al.*, 2020). The hypoxia in the

Pearl River Estuary formation highlights the importance of vortex dynamics and Biogeochemical processes in the coastal transition zones. Their research also emphasized the ability of river discharges to stimulate nutrient cycling, which leads to low oxygen levels, which are usually enhanced by human actions (Li *et al.*, 2020). To examine the phosphorus flux of a large river basin, which would inform about the effect of human-induced land use change on nutrient cycling and environmental health on spatial and temporal scales (Cui *et al.*, 2021). Besides cycling of nutrients, studies have been done in the Danube Delta regarding both lateral and atmospheric carbon fluxes. This examines the carbon cycling among the atmosphere, land and water, and shows there are important spatiotemporal changes in carbon fluxes in the area. This type of work is necessary to identify how the estuarine systems act as carbon sinks/sources, and significant consequences on global climate change studies (Maier and Wehrli, 2021). Besides, the effects of mid-oceanic ridge hydrothermal systems on oceanic chemical fluxes highlight the importance of these deep-sea processes in the evolution of the ocean chemical composition which, in its turn, may indirectly impact estuarine and coastal areas (Elderfield and Schultz, 1996). The choice of physical processes in improving nutrient transport and productivity in coastal transition zones is

essential in order to investigate the nature of biophysical dynamics in the areas (Olson, 2001). Additionally, biogeochemical linkages of land, ocean and atmosphere serve as a crucial lens to the riverine processes that bind these systems together and affect health at the coasts (Aufdenkampe *et al.*, 2011). To investigate how physical processes can increase nutrient transport and productivity in the subarctic NE Pacific, showing how analogous processes can contribute to the nutrient dynamics at river-ocean interfaces (Whitney, Crawford and Harrison, 2005). To examine the weathering mechanisms and chemical flows, illuminating the effects of the river on oceanic chemical composition and nutrient loads in the estuarine areas (Zhang *et al.*, 1995). All these findings affirm the importance of the understanding of the spatiotemporal variability of chemical and physical fluxes of the river-ocean transition zone. Such fluxes play a significant role in the management of water quality, the sustainability of the coastal ecosystems and also to mitigate the impacts of human activities on such fragile ecosystems. These fluxes are important to manage by mapping and modeling them.

### Key Contribution

- In the paper, the spatiotemporal mapping of chemical and physical fluxes at the river ocean transition zone, involving variation in such key parameters as salinity, nutrient concentrations, and dissolved oxygen are provided in detail.
- By integrating field measurements with remote sensing and GIS, the research offers a fine-scale

understanding of the seasonal and tidal cycle variations in fluxes, which may contribute to our ability to comprehend and predict water quality processes.

- The paper sheds light on the biogeochemical processes that occur at the river-ocean interface with the enriched areas by mixing, sediment interactions and the biological processes.
- The paper brings out the importance of hydrodynamic processes, including tidal movements and freshwater discharge, in determining the spatial distribution of chemical fluxes.

The different sections are preceded by this research. Section I presented the topic; Section II covered the literature review of other past papers and contained the research Gap. Section III described the conceptual framework of spatiotemporal mapping of chemical and physical fluxes of the river ocean transition zone. Section IV elaborated on the techniques and tools that were used in data collection, method of mapping, the software and the hardware configurations. Section V presented the results and analysis, including metric evaluation, model evaluation, and various analyses. The conclusion part was explained in section VI; it was predominantly devoted to the key findings of the research.

### Literature Review

It is a highly significant ecological boundary between the freshwater of rivers and the saltwater of oceans merging in a river-ocean transition zone to influence the river and ocean ecosystems. The spatial and temporal

mapping of the chemical and physical fluxes of these regions is essential in order to understand the nutrient cycling, transport of pollutants and the health of the aquatic ecosystems. Many researchers have studied the dynamics of these fluxes, and explained both natural and anthropogenic effects. In the study, to examined seasonal and annual nutrient and organic matter fluxes of large rivers to the Arctic Ocean, highlighting the importance of river systems in transporting organic carbon and nutrients to the coastal zones in influencing marine productivity and biogeochemical cycles of Arctic ecosystems (Holmes *et al.*, 2012). It's also provided useful information about the chemical composition of suspended sediments in world rivers, which represents a new database that can greatly improve our knowledge of how suspended particles in rivers impact nutrient cycling and water quality at the river-ocean interface (Viers, Dupré and Gaillardet, 2009). The chemical oxygen demand and nutrient fluxes in the coastal rivers, especially its impact on the water quality changes in the Bohai Sea. Their results showed that river discharge greatly contributes to the temporal and spatial changes in water quality, which affects nutrient levels and the general health of the ecosystem in the coastal regions (Li, Tian and Sheng, 2022).

The literature about carbon fluxes in coastal oceans, studying the processes of boundaries, which regulate carbon cycling in river-ocean systems. This paper has emphasized the significance of the study of such fluxes because are important in the coastal carbon budget and ocean carbon sequestration processes

(Dai *et al.*, 2022). To employed global modeling to assess the contribution of the pre-industrial rivers to the oceanic hotspots of biological production and CO<sub>2</sub> outgassing through the contribution of nutrients and carbon loads. Their results highlight the sustained role of riverine nutrient fluxes on ocean carbon processes, especially under the circumstances of historical human disturbance of river systems (Lacroix, Ilyina and Hartmann, 2020). In this evaluated the amount of organic carbon carried by rivers to oceans on terrestrial surfaces around the globe. The article highlights the significance of transport of riverine organic carbon in the global carbon cycle, which has a role in the dynamics of coastal and marine ecosystems (Chen *et al.*, 2025).

The attention to the contributions of coastal aquifers to ocean chemistry in terms of solute fluxes, which further illustrates the effect of the subsurface processes on coastal waters (Kiro, 2025). To investigated the interdependence of physical and biogeochemical processes in Arctic River plumes with the Mackenzie shelf as an example. Their labor provides valuable information in the interactions of nutrients and its impacts on coastal ecosystems particularly in the arctic region that are sensitive to climatic and environmental changes (Bertin *et al.*, 2025). The global view of river alkalinity and the impact it has on the coastal ocean carbonate chemistry. Their research underlines the significance of river alkalinity in buffering coastal waters and counterbalancing ocean acidification that is critical to the understanding of the overall impacts of river discharge on ocean chemistry (Da *et al.*, 2025). The

study of solid salt fluxes in molten aluminum provides a review of salt flux behavior, but not specifically in the context of river-ocean interactions, but suggesting the broader relevance of the study of material flux in industrial processes, which can be correlated to the study of environmental fluxes in other environments (Milani and Timelli, 2023). All of these studies emphasize the need to spatiotemporally map chemical and physical fluxes in the river-ocean transition zone. The combination of these fluxes allows researchers to have a more comprehensive understanding of how terrestrial, riverine and marine environments interact with each other, which can be useful in the management of ecosystems, conservation initiatives as well as in making predictions on changes in the environment in the future.

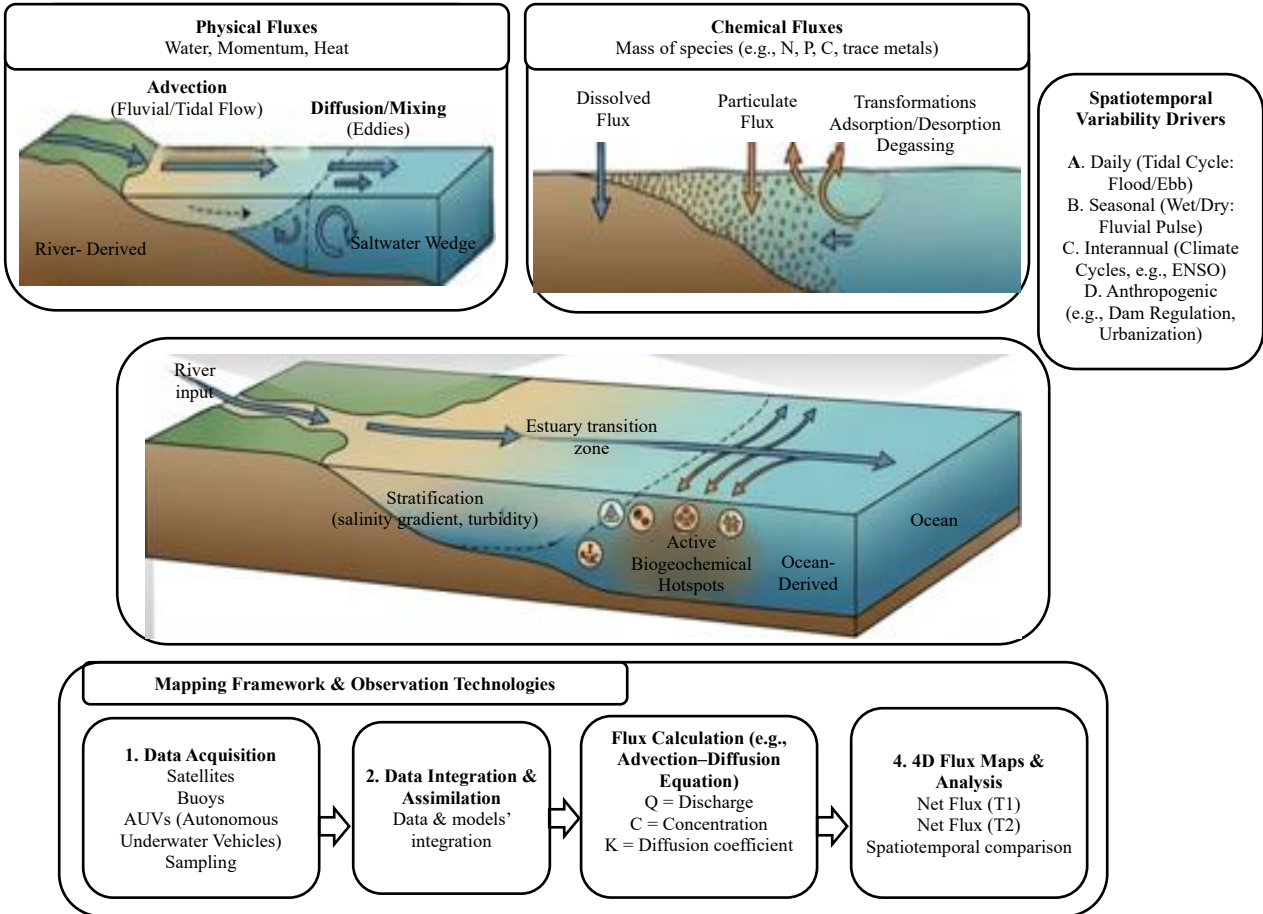
#### *Research Gap*

Although the studies of the chemical and physical fluxes in the river-ocean transition zone have made great strides, there are still a number of gaps in the research. Although nutrient and carbon fluxes have been the focus of much research, more detailed investigations into the relationships between several biogeochemical components, such as trace metals, organic pollutants and sediment dynamics, are required. Also, existing models do not have high-resolution time-space data, which restricts the capability to resolve short-term, episodic events that have a major impact on the river-ocean interface. The contribution of climate change, particularly to the change in discharge pattern of rivers and oceanic process is also under-researched, especially in the areas that are vulnerable to high levels of

anthropogenic strain. In addition, the consideration of subsurface fluxes and their effect on surface water chemistry needs additional research, as well as the integration of real-time sensors like remote sensing and autonomous platforms. By filling these gaps, this would offer a more comprehensive view of the river-ocean interface and enhance better management and conservation plans of the ecosystem.

Figure 1 depicts the conceptual framework of the complex dynamics of the chemical and physical fluxes at the river-ocean interface by the title "Spatiotemporal Mapping of Chemical and Physical Fluxes at the River-Ocean Transition Zone. It also emphasizes important physical fluxes (like water, momentum, heat) and processes (like advection (flow of fluids as a result of tidal and river discharge) and diffusion/mixing (as a result of eddies). These physical fluxes contribute to the process of delimiting freshwater to saltwater by creating a saltwater wedge which affects the biogeochemical dynamics of the estuarine zone. On the other hand, chemical fluxes include the transport of dissolved and particulate materials, such as nutrients, trace metals, and other species, as well as their transformations (adsorption, desorption, and degassing). Such fluxes play critical roles in the interpretation of the biogeochemical processes in river-ocean boundary.

### Conceptual Framework for Spatiotemporal Mapping of Chemical and Physical Fluxes at the River Ocean Transition Zone



**Figure 1: Conceptual framework for spatiotemporal mapping of chemical and physical fluxes at the river ocean transition zone.**

These fluxes vary spatially and temporally due to day to day (tidal) cycles, seasonal cycles (wet and dry seasons), interannual climate cycles such as El Niño-Southern Oscillation (ENSO), and manmade activities such as urbanization and dam regulation. These play a role in the temporal and spatial changes in water flow, chemical composition, and ecosystem wellness across the river-ocean boundary. The data acquisition and integration techniques are also described in the diagram to track these fluxes with the help of satellites, autonomous underwater vehicles (AUVs), buoys, and traditional sampling. The results of such methods are

combined with models to analyze the data more thoroughly, and an equation like the advection-diffusion equation (1) is calculated to determine the fluxes.

$$J = -DVC + vCJ = -DVC + vC \quad (1)$$

Where  $QC$  represents the quantity of chemical flux, and  $\frac{\partial C}{\partial x}$  is the concentration gradient across the spatial domain. This mathematical model can be used to measure the variation of the chemical and physical properties along time and space. The 4D flux maps and analysis component also captures the dynamic interactions in a spatiotemporal context, that is, how fluxes change with space and time. These estimations involve more

sophisticated equation, like heat and mass transfer equation (2).

$$\begin{aligned} \partial C \partial t &= \nabla \cdot (D \nabla C - vC) + S \partial t \partial C \\ &= \nabla \cdot (D \nabla C - vC) + S \end{aligned} \quad (2)$$

Where  $C$  is the concentration,  $D$  is the diffusion coefficient,  $S$  is the source term (such as river input or biological activity), and  $S \partial t \partial C$  captures the diffusion process. Finally, the objective of this framework is to enhance our knowledge of chemical and physical fluxes, especially their impact on the quality of water, carbon cycle and the health of the ecosystem. This information can subsequently be used to develop improved management practices of sustainable environmental management and policy planning.

#### *Flux Calculation Method*

Flux represents the movement of a substance (e.g., nitrate) across a given area over time. The flux can be calculated using a straightforward equation that involves concentration and discharge (or load). In aquatic or environmental systems, flux can be calculated using the following approach in equation (3).

$$\text{Flux} = \text{Concentration} \times \text{Discharge (or Flow)} \quad (3)$$

In equation (3) describes,

- **Flux (F)** is expressed in  $\mu\text{mol}/\text{m}^2/\text{s}$  (micromoles per square meter per second).
- **Concentration (C)** is the nitrate concentration in the medium (water or soil) and is typically expressed in  $\mu\text{mol}/\text{L}$  (micromoles per liter).
- **Discharge (Q)** is the volumetric flow rate (e.g., river discharge or groundwater flow) and is expressed in  $\text{L}/\text{s}$  (liters per second).

## **Methods and Materials**

### *Data Collection*

- *Chemical Fluxes*

Chemical fluxes are the movement and change of chemical elements such as nutrients, pollutants and trace elements through the river-ocean transition zone. Some of the elements found in these fluxes are nitrogen (N), phosphorus (P), trace metals and organic pollutants. Water sampling is done at different points at intervals in the river, estuary, and coastal waters to measure chemical fluxes. This can be analyzed in the laboratory with methods of colorimetry, atomic absorption spectroscopy (AAS), and inductively coupled plasma mass spectrometry (ICP-MS) of nutrients and heavy metals. In-situ sensors are also installed to measure parameters (e.g., dissolved oxygen (DO), pH, conductivity, and nutrient concentrations (e.g., nitrate, phosphate) continuously. These sensors are usually set at strategic locations along the river- ocean interface to help capture both the short-term variation and long-term trends. A monitoring of pollutants such as pesticides and pharmaceuticals, which are commonly found in low concentrations over time, can also be done using passive sampling devices, including DGT (Diffusive Gradients in Thin Films) and POCIS (Polar Organic Chemical Integrative Sampler).

- *Physical Fluxes*

Examples of physical fluxes in the river-ocean transition zone are water, sediment, heat and momentum transport and mixing. Important parameters are temperature, salinity and turbidity which

are important parameters in comprehending the dynamics of the saltwater wedge and the entire mixing processes at the river-ocean boundary. Conductivity-temperature-depth (CTD) sensors can measure temperature and salinity and are able to measure vertical profiles through various layers of the water column. Some nephelometers or turbidity sensors are used to measure turbidity, which is indicative of suspended particulate matter. Acoustic Doppler Velocity (ADV) meters, electromagnetic sensors or electro-optical sensors can be used to measure flow velocity and momentum fluxes, which are the rate of flow and motion of water masses. These parameters are crucial to comprehending the processes of transport, mixing, and sediment deposition in the transition zone.

- *Spatiotemporal Data*

Spatiotemporal data collection is the process of measuring both space (location) and time (temporal) to trace the variability of the chemical and physical fluxes between seasons, tides and years. Satellite images and drone surveys are remote sensing methods that provide extensive information about surface data such as temperature, chlorophylls, and turbidity. Some of the satellites such as Sentinel-1 and MODIS are global near real-time satellites that can be used to track spatial changes along the river-ocean interface. The buoy time-series data are a form of long-term (continuous) data of significant physical and chemical parameters (e.g., temperature, salinity, pH, dissolved oxygen) that help the researcher to observe daily and seasonal as well as

interannual variation. These buoys can be installed in areas that are sensitive such as in the mixing zone of the estuary or near the river mouth to measure the variation of time due to the tidal cycles or seasonal changes. Periodic field measurements of water, sediment and biological samples are also conducted in a regular manner so as to validate remote sensing measurements and provide on ground validation of measured flux.

### *Mapping Technique*

- *GIS and Remote Sensing*

The Geographic Information Systems (GIS) plays a crucial role in spatial and temporal analysis and visualization of data. GIS combines and overlaps information of different sources (satellites, sensors, field measurements) to produce detailed maps which illustrate the distribution and strength of chemical and physical fluxes in the river-ocean transition zone. Hotspots, change in fluxes, and future trends can be identified by using GIS tools, in different climatic or management conditions. Spatial data on the surface conditions of water bodies can be obtained using remote sensing technologies such as satellite imagery and drones, which offer high-resolution spatial data. Sentinel-2 satellites, as an example, can be used to take water turbidity, chlorophyll levels and other important environmental indicators. A smaller and more localized area can be surveyed with higher precision and resolution by drones, which have multispectral or hyperspectral cameras, providing detailed information about water quality, including the size or the saltwater wedge or the presence of pollutants.

- *Modeling Tools*

Numerical modeling is very important in modeling of the physical and chemical processes of the river-ocean interface. Simulation models such as MIKE 21, Delft3D, and SWAN are used to model water flow, the action of the tides, and sediment transport, which are used to predict how water masses will move and the development of the saltwater wedge. Biogeochemical models, including GEM and ERSEM, are concerned with how chemicals are transformed and cycled, including the uptake of nutrients and the removal of pollutants. Through the integration of these models, the interaction of physical and chemical processes in the river-ocean transition zone can be better understood leading to a better prediction of the changes that occur as a result of natural and human-induced processes.

- *Analysis Methods*

Spatiotemporal analysis of chemical and physical fluxes in the river-ocean interface is done using a range of statistical methods to learn about spatial, temporal and environmental relationships. Spatial interpolation schemes, such as Kriging and Inverse Distance Weighting (IDW) are used to predict values at unmeasured points, generating continuous maps of fluxes. The regression analysis measures the association between environmental parameters, linear and multiple regression measures simple and complicated associations respectively. Time-series analysis can monitor trends across time and detect patterns, such as seasonal decomposition and ARIMA models. Fourier transforms indicate cyclical variations whereas

cross-correlations indicate lagged relationships. Long term trend analysis, e.g. Mann-Kendall test, measures how flux changes with time. Spatiotemporal clustering determines regions which have similar patterns of flux and spatial autocorrelation statistics such as Moran I and Geary C display pattern of clustering or dispersion. Such statistical methods allow the researchers to know the variability in the fluxes that assist in managing the environment as well as predicting effects on the environment in the future.

*Software and Hardware Configuration*

Chemical and physical fluxes in the river-ocean transition zone are studied with the help of sophisticated hardware and software configurations. Satellites, such as Sentinel-1 and MODIS, and AUVs and buoys are used to continuously monitor parameters of water, including temperature, salinity, and dissolved oxygen. Passive samplers are able to track low-concentration pollutants, whereas data integration and simulation of hydrodynamic and biogeochemical processes are done with GIS tools and modeling software such as MIKE 21 and ERSEM. The important environmental factors are measured by such sensors as CTD, ADV, and turbidity sensors, and drones provide high-resolution data that can be localized. The technologies allow a complete insight into the flux dynamics and help to maintain sustainable management strategies.

**Results and Analysis***Metric Evaluation*

To facilitate the discussion of the spatiotemporal chemical and physical

fluxes in the river-ocean transition zone, various metrics and statistical evaluation tools can be employed to measure and confirm the fluxes, gauge the data accuracy, and give an idea of the variability and trends of fluxes across locations and seasons. The following are some of the key metric analyses that might be used,

#### Root Mean Squared Error (RMSE)

RMSE is often employed to estimate the quality of predicted values against the observed values. In the case of fluxes, it may be applied to compare the model outputs (e.g., in the case of nitrate flux, phosphate flux, suspended particulate flux) with real field measurements in equation (4).

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (4)$$

Where equation (4) describes  $y_i$  is the observed flux value,  $\hat{y}_i$  is the predicted flux value, and  $n$  is the number of observations.

#### Coefficient of Determination ( $R^2$ )

$R^2$  helps assess the proportion of variance in the dependent variable (e.g., nitrate flux) that is explained by the independent variables (temperature, salinity, flow velocity) in equation (5).

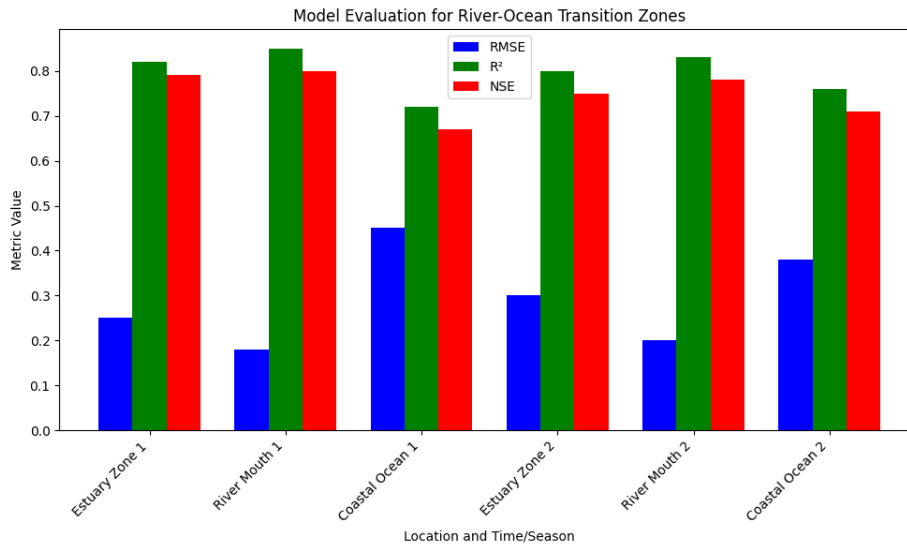
$$R^2 = 1 - \frac{\sum (y_i - \hat{y}_i)^2}{\sum (y_i - \bar{y})^2} \quad (5)$$

Where equation (5) describes  $y_i$  is the observed flux,  $\hat{y}_i$  is the predicted flux,  $\bar{y}$  is the mean observed value.

#### Model Evaluation for River Ocean Transition Zones

**Table 1: Model evaluation for river ocean transition zones.**

Location	Time/Season	RMSE	$R^2$	NSE
Estuary Zone 1	Spring (Day)	0.25	0.82	0.79
River Mouth 1	Summer (Day)	0.18	0.85	0.80
Coastal Ocean 1	Autumn (Day)	0.45	0.72	0.67
Estuary Zone 2	Winter (Day)	0.30	0.80	0.75
River Mouth 2	Monsoon (Day)	0.20	0.83	0.78
Coastal Ocean 2	Spring (Day)	0.38	0.76	0.71



**Figure 2: Model evaluation for river ocean transition zones.**

Table 1 and figure 2 indicate model evaluation of River-Ocean Transition Zones which depicts the model performance in space and time of the year in various locations. River Mouth 1, which is seen in summer (day) shows the most successful model performance with the lowest RMSE (0.18), highest R<sup>2</sup> (0.85) and highest NSE (0.80), with the model performing well in terms of accuracy and good representation of the observed and predicted values of the flux. Conversely, Coastal Ocean 1, which was observed during the autumn (day), exhibits the largest RMSE (0.45), smallest R<sup>2</sup> (0.72), and smallest NSE (0.67) indicating that the model does not work in nutrient-depleted oceanic conditions, where the fluxes tend to be smaller and less variable as well. The performance of the Estuary Zones is moderate with the values of RMSE, R<sup>2</sup> and NSE of Estuary Zone 1 = 0.25, 0.82 and 0.79 respectively and Estuary Zone 2 = 0.30, 0.80 and 0.75 respectively which indicates a reasonably good model

performance in transitional environments. River Mouth 2, which was observed during a monsoon (day), has RMSE of 0.20, R<sup>2</sup> of 0.83 and NSE of 0.78, which means that the model is highly effective and the predictions are accurate in high nutrient loading conditions because of high freshwater input. Lastly, Coastal Ocean 2, with spring (day) observations, has moderate values (RMSE = 0.38, R<sup>2</sup> = 0.76, NSE = 0.71), indicating that it makes stable, although less accurate predictions in nutrient-poor coastal settings. The model, in general, is most effective in river mouth areas, where fluxes are large and changeable, and least effective in coastal ocean areas, where fluxes are small and nutrient-depleted. This discussion, with the assistance of the graph, points out the difficulties in modeling the nutrient and sediment fluxes in various environmental areas; the model is more useful in predicting the fluxes in estuarine and riverine areas, than in the coastal areas.

*Analysis of Chemical and Physical Fluxes at the River Ocean Transition Zone*

**Table 2: Chemical and physical fluxes at the river ocean transition zone.**

Location	Temperature (°C)	Salinity (psu)	Dissolved Oxygen (mg/L)	Nitrate (µg/L)	Phosphate (µg/L)	Turbidity (NTU)	Flow Velocity (m/s)	Suspended Particulate Matter (mg/L)
Estuary Zone 1	24.5	18.3	6.5	45	5.2	3.2	0.75	12.3
River Mouth 1	22.3	14.7	5.8	60	4.8	2.1	1.00	14.5
Coastal Ocean 1	26.8	30.0	8.2	15	3.4	1.5	0.40	8.9
Estuary Zone 2	25.0	19.0	7.0	40	6.0	2.9	0.65	11.1
River Mouth 2	23.5	16.5	6.0	55	5.5	3.0	0.80	13.2
Coastal Ocean 2	27.1	31.2	8.5	10	3.0	1.3	0.45	9.3

Table 2 Shows data that has been obtained in different parts of the river-ocean transition zone indicates the variability of the environment in the different areas. Estuary Zone 1 is characterized by moderate temperatures (24.5 °C), salinity (18.3 psu), and oxygen dissolved (6.5 mg/L), moderate nutrient levels (45 mg/L nitrate and 5.2 mg/L phosphate). This means health yet nutritious environments. The temperature (22.3 °C) and salinity (14.7 psu) are slightly lower in River Mouth 1 (5.8 mg/L) as a result of the freshwater impact. An increase in nutrient concentrations (60 µg/L nitrate and 4.8 µg/L phosphate) indicates an increase in nutrient loading and turbidity (2.1 NTU) and flow velocity (1.00 m/s) indicate sediment transport. Coastal Ocean 1, having temperature of 26.8 °C and salinity of 30.0 psu represents the oceanic conditions, good levels of dissolved oxygen (8.2 mg/L) but low levels of nutrients (15 µg/L nitrate, 3.4 µg/L phosphate), and hence low nutrient availability. The turbidity (1.5 NTU) is less, the flow velocity is less (0.40 m/s). Estuary Zone 2 has

#### *Flux Distribution Analysis*

temperature of 25.0 °C, salinity of 19.0 psu and good oxygenation (7.0 mg/L) with moderate nutrient levels (40 µg/L nitrate and 6.0 µg/L phosphate) indicating balanced productivity. The temperature of River Mouth 2 is 23.5°C and the salinity is 16.5 psu with a dissolved oxygen reading of 6.0 mg/L and high nutrient levels (55 µg/L nitrate and 5.5 µg/L phosphate), like River Mouth 1. Turbidity (3.0 NTU) and flow velocity (0.80 m/s) indicate that there was active sediment movement. Coastal Ocean 2, which had the highest temperature (27.1 °C) and salinity (31.2 psu), has the highest dissolved oxygen (8.5 mg/L), however very low nutrients (10 µg/L nitrate and 3.0 µg/L phosphate), and the lowest turbidity (1.3 NTU), which represents clear, nutrient depleted waters common in Generally, the data indicates a shift towards nutrient-deficient, clearer waters at the coast as compared to the nutrient-rich in the estuaries and mouth of rivers, and physical conditions such as turbidity and flow velocity differ among the various regions.

**Table 3: Flux distribution analysis.**

Location	Time/Season	Nitrate Flux	Phosphate Flux	Temperature	Salinity	Dissolved Oxygen	Suspended Particulate	Flow Velocity	Turbidity
Estuary Zone 1	Spring (Day)	4.5	0.45	0.75	0.18	0.12	1.23	0.75	3.10
River Mouth 1	Summer (Day)	6.2	0.60	1.00	0.25	0.20	1.45	1.00	3.50
Coastal Ocean 1	Autumn (Day)	1.8	0.18	1.20	0.30	0.15	0.90	0.40	1.80
Estuary Zone 2	Winter (Day)	4.0	0.40	0.85	0.20	0.13	1.15	0.90	3.25
River Mouth 2	Monsoon (Day)	5.8	0.58	0.90	0.22	0.17	1.25	1.00	3.40
Coastal Ocean 2	Spring (Day)	2.0	0.20	1.25	0.35	0.18	1.00	0.60	1.90

The detailed analysis of the distribution of concentrations in various locations and

seasons in the river-ocean transition zone is provided in table 3. The data show that

there are high spatial and temporal differences in the concentrations of chemical and physical parameters. Estuary Zone 1, which is a spring (day) condition, has a moderate nutrient concentration, with 4.5  $\mu\text{g/L}\cdot\text{m}^2/\text{s}$  nitrate and 0.45  $\mu\text{g/L}\cdot\text{m}^2/\text{s}$  phosphate and a temperature of 0.75°C/m<sup>2</sup>/s, indicating moderate environmental mixing and nutrient availability. The summer day (River Mouth 1) has an increased nutrient concentration with nitrate and phosphate at 6.2 and 0.60  $\mu\text{g/L}\cdot\text{m}^2/\text{s}$  respectively, indicating an increased nutrient loading due to freshwater inputs. The temperature rises to 1.00 -1°C, informing of the impact of seasonal temperature change. In Coastal Ocean 1, fall (day) the nutrients are less, with a nitrate of 1.8  $\mu\text{g/L}$  and phosphate of 0.18  $\mu\text{g/L}$ , which are typical of ocean waters, where nutrient concentrations are usually lower. The turbidity concentration is also smaller (1.80 NTU), which means clearer waters. During winter (day) in Estuary

Zone 2, both the nitrate and phosphate nutrient concentrations decline slightly to 4.0  $\mu\text{g/L}$  and 0.40  $\mu\text{g/L}$ , respectively, implying a lack of nutrients or a drop in productivity in winter compared to spring and summer. In the monsoon (day), River Mouth 2, 5.8  $\mu\text{g/L}$  of nitrate concentration, which indicates high levels of nutrients due to higher rainfall and runoff. The suspended particulate load at 1.25 mg/L is also an indication of increased sediment movement during this period. Lastly, Coastal Ocean 2 spring (day) has the lowest nutrient concentration (nitrate 2.0  $\mu\text{g/L}$ , phosphate 0.20  $\mu\text{g/L}$ ) and this is a typical nutrient-depleted marine water. In general, the figures show seasonal and spatial differences, with greater nutrient and particle concentrations in estuarine and river-mouths than in the coastal ocean, due to the effects of freshwater inputs, seasonal variations, and the shift in nutrient-rich riverine sources to nutrient-poor ocean sources.

#### *Comparison Table for Chemical Flux*

**Table 4: Comparison for chemical flux**

Location	Nitrate Flux ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	Phosphate Flux ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	Suspended Particulate Flux ( $\mu\text{mol}/\text{m}^2/\text{s}$ )	Turbidity Flux (NTU·m <sup>2</sup> /s)
Estuary Zone 1	4.5	0.45	1.23	3.10
River Mouth 1	6.2	0.60	1.45	3.50
Coastal Ocean 1	1.8	0.18	0.90	1.80
Estuary Zone 2	4.0	0.40	1.15	3.25
River Mouth 2	5.8	0.58	1.25	3.40
Coastal Ocean 2	2.0	0.20	1.00	1.90

Table 4 shows the distribution of major parameters (nitrate, phosphate, suspended particulate matter and turbidity) in various locations within the river-ocean transition zone. River Mouth 1 exhibits the greatest nutrient fluxes with nitrate (6.2  $\mu\text{g/L}$ ) and phosphate (0.60  $\mu\text{g/L}$ ) indicating large nutrient inputs due to freshwater flows. It is also

the most active in terms of sediment transport (high suspended particulate flux 1.45  $\mu\text{mol}/\text{m}^2/\text{s}$ ) and turbidity flux (3.50 NTU  $\mu\text{mol}/\text{m}^2/\text{s}$ ), which is characteristic of river mouths. Coastal Ocean 1, in contrast, shows significantly lower levels of nutrient flux, with nitrate of 1.8  $\mu\text{mol}/\text{m}^2/\text{s}$  and phosphate of 0.18  $\mu\text{mol}/\text{m}^2/\text{s}$ , indicating nutrient-

depleted oceans. The suspended particulate flux ( $0.90 \mu\text{mol}/\text{m}^2/\text{s}$ ) and turbidity flux ( $1.80 \text{ NTU m}^2/\text{s}$ ) are also small, indicating more stable oceanic waters. Both Estuary Zone 1 and Estuary Zone 2 have moderate nutrient fluxes, with  $4.5$  and  $4.0 \mu\text{g}/\text{L}^{-1}$ -s, respectively, and phosphate  $0.45$  and  $0.40 \mu\text{mol}/\text{m}^2/\text{s}$ , respectively. Higher turbidity, suspended particulate flux ( $1.23$  and  $1.15 \mu\text{mol}/\text{m}^2/\text{s}$ , respectively) is also observed in these zones, typical of river and ocean waters mixing. Compared to River Mouth 1 (nitrate:  $5.8 \mu\text{mol}/\text{m}^2/\text{s}$ , phosphate:  $0.58 \mu\text{mol}/\text{m}^2/\text{s}$ ), River Mouth 2 has slightly lower nutrient flux (nutrient fluxes are lower), yet the particulate flux of the river ( $1.25 \mu\text{mol}/\text{m}^2/\text{s}$ ) and turbidity flux ( $3.4$  Lastly, the nutrient fluxes (nitrate:  $2.0 \mu\text{mol}/\text{m}^2/\text{s}$ , phosphate:  $0.20 \mu\text{mol}/\text{m}^2/\text{s}$ ) and suspended particulate flux ( $1.00 \mu\text{mol}/\text{m}^2/\text{s}$ ) are lower in Coastal Ocean 2 indicating clearer, nutrient-depleted oceanic waters. Generally, the river mouth areas receive the greatest nutrient and sediment loads, the estuarine areas are intermediate with moderate loads, and the coastal ocean regions have low nutrient levels and turbidity, which means that there is a gradient of nutrient-rich to nutrient-poor environments.

### *Discussion*

The data described indicate the clear spatial and temporal differences in the chemical and physical fluxes in the river-ocean transition zone. The maximum flux of nutrients is observed in River Mouth 1 ( $6.2 \mu\text{g}/\text{L}^2/\text{s}$ ) and River Mouth 2 ( $0.58 \mu\text{mol}/\text{m}^2/\text{s}$ ) with the highest levels of nitrate and phosphate, respectively, which demonstrates substantial nutrient transportation by

freshwater inflows. The areas also have high suspended particulate fluxes ( $1.45 \mu\text{mol}/\text{m}^2/\text{s}$ ), turbidity fluxes ( $3.50 \text{ NTU m}^2/\text{s}$ ) and indicative of active sediment transport which are typical of river mouths. In contrast, the coastal ocean regions, Coastal Ocean 1 and Coastal Ocean 2 show much lower nitrate and phosphate concentrations,  $1.8$  and  $2.0 \mu\text{mol}/\text{m}^2/\text{s}$  of nitrate and  $0.18$  and  $0.20 \mu\text{mol}/\text{m}^2/\text{s}$  of phosphate respectively, which indicates nutrient-depleted conditions in the sea. There is also lower suspended particulate fluxes ( $0.90 \mu\text{mol}/\text{m}^2/\text{s}$ ) and turbidity fluxes ( $1.80 \text{ NTU-1-m}^2/\text{s}$ ) and the waters are clear as it is seen in coastal ocean waters. The nutrient fluxes of the estuaries which are measured by the flux of nitrate ( $4.5 \mu\text{mol}/\text{m}^2/\text{s}$  and  $4.0 \mu\text{mol}/\text{m}^2/\text{s}$ ), phosphate ( $0.45 \mu\text{mol}/\text{m}^2/\text{s}$ ) The fluxes of the estuaries in the winter period are slightly low than the spring in the Estuary Zone 1 showing that there is a variation in the nutrient availability and the Overall, the data show a strong gradient between nutrient-rich river mouths and estuaries and nutrient-poor coastal oceans with the river mouth areas being associated with high nutrient and sediment fluxes that decline with the coastal ocean areas. The trend suggests that seasonal changes, fresh water influx and human activities contribute towards the changes in nutrient and sediment processes in these vulnerable regions.

### *Limitations*

The findings of the study have a number of limitations which can undermine the accuracy and reliability of the findings. Data collection had sampling gaps (both spatial and temporal) that were limiting because it might not adequately represent

the variability of chemical and physical fluxes in the whole river-ocean transition zone. Long-term measurements also can be inaccurate due to sensor malfunctions, calibration errors, and drift. Also, data from remote sensing can be limited by cloud cover and resolution, which reduces measurement accuracy. Mapping accuracy is influenced by interpolation assumptions, especially in areas with sparse data, and by the models applied, which may be based on simplified assumptions that do not fully describe the complexities of sediment processes, nutrient cycles, or human activities. Lastly, time constraints, such as seasonal changes in sampling, are not necessarily long-term patterns, nor are the influence of extreme events, such as floods or droughts. These reasons indicate that more continuous, more detailed data collection and better modeling methods should be used to obtain more reliable, representative outcomes.

## Conclusion

This study of the spatiotemporal map of chemical and physical fluxes at the river-ocean transition zone has a major benefit for understanding and controlling coastal ecosystems. The combination of field observations, in-situ sensors, remote sensing, and GIS tools provides the study with high-resolution, real-time data on the most important parameters, namely salinity, nutrients, dissolved oxygen, and sediment fluxes. Materials such as advanced sensors (CTD, turbidity, ADV), satellite data, and passive sampling apparatuses enabled extensive data collection across several sites and seasons. The findings indicate clear differences in the fluxes with river mouth areas having greater nutrient and

sediment fluxes and coastal areas having nutrient-depleted conditions. To illustrate, River Mouth 1 recorded the highest nitrate flux of  $6.2 \mu\text{mol}/\text{m}^2/\text{s}$  and Coastal Ocean 1 recorded the lowest of  $1.8 \mu\text{mol}/\text{m}^2/\text{s}$ , which depicts the clear gradients between freshwater and marine environments. The model assessments also indicated that areas around river mouths performed well, with the least RMSE (0.18) and the highest R<sup>2</sup> (0.85). These findings underscore the importance of river discharge and seasonal variations in determining flux processes. Future suggestions include better incorporation of real-time data, improved predictive modeling strategies, and the expansion of autonomous platforms for real-time continuous monitoring. Furthermore, the influence of climate change on flux patterns needs to be considered in future studies and pollutants and trace metals need to be studied to gain a more in-depth insight into river-ocean interactions.

## *Ethical Considerations*

The research ethics aligned with the aims of minimizing environmental impact in data collection, ensuring measurement integrity and accuracy through well-calibrated, validated instruments, and maintaining data transparency. The real-time monitoring technologies were used responsibly to facilitate data collection while protecting privacy and security. The research also recognized the role of human activities in ecosystems and highlighted the need to enhance sustainable practices and responsible resource management, based on its results. Such ethical procedures make the research have a positive impact on

scientific knowledge as well as on protecting the environment.

## References

- Aufdenkampe, A.K., Mayorga, E., Raymond, P.A., Melack, J.M., Doney, S.C., Alin, S.R., Aalto, R.E. and Yoo, K., 2011.** Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, 9(1), pp.53-60. <https://doi.org/10.1890/100014>
- Bertin, C., Carroll, D., Menemenlis, D., Dutkiewicz, S., Zhang, H., Schwab, M., Savelli, R., Matsuoka, A., Manizza, M., Miller, C.E. and Bowring, S., 2025.** Paving the way for improved representation of coupled Physical and biogeochemical processes in Arctic River Plumes—A case study of the Mackenzie shelf. *Permafrost and Periglacial Processes*, 36(3), pp.363-377. <https://doi.org/10.1002/ppp.2271>
- Chen, F., Bai, X., Luo, G., Zhang, G., Ran, C. and Luo, X., 2025.** Assessing the global flux of organic carbon transported from terrestrial surfaces to oceans by rivers. *Carbon Balance and Management*, 20(1), p.29. <https://doi.org/10.1186/s13021-025-00318-z>
- Cui, M., Guo, Q., Wei, R. and Tian, L., 2021.** Human-driven spatiotemporal distribution of phosphorus flux in the environment of a mega river basin. *Science of The Total Environment*, 752, p.141781. <https://doi.org/10.1016/j.scitotenv.2020.141781>
- Da, F., Stock, C.A., Dunne, J.P., Liu, X., Luo, J.Y., Lee, M. and Shevliakova, E., 2025.** A global perspective on river alkalinity: Drivers and implications for coastal ocean carbonate chemistry. *Global Biogeochemical Cycles*, 39(11), p.e2025GB008528. <https://doi.org/10.1029/2025GB008528>
- Dai, M., Su, J., Zhao, Y., Hofmann, E.E., Cao, Z., Cai, W.J., Gan, J., Lacroix, F., Laruelle, G.G., Meng, F. and Müller, J.D., 2022.** Carbon fluxes in the coastal ocean: synthesis, boundary processes, and future trends. *Annual Review of Earth and Planetary Sciences*, 50(1), pp.593-626. <https://doi.org/10.1146/annurev-earth-032320-090746>
- Du, C., Li, Y., Wang, Q., Liu, G., Zheng, Z., Mu, M. and Li, Y., 2017.** Tempo-spatial dynamics of water quality and its response to river flow in estuary of Taihu Lake based on GOCI imagery. *Environmental Science and Pollution Research*, 24(36), pp.28079-28101. <https://doi.org/10.1007/s11356-017-0305-7>
- Elderfield, H. and Schultz, A., 1996.** Mid-ocean ridge hydrothermal fluxes and the chemical composition of the ocean. *Annual Review of Earth and Planetary Sciences*, 24(1), pp.191-224. <https://doi.org/10.1146/annurev.earth.24.1.191>
- Holmes, R.M., McClelland, J.W., Peterson, B.J., Tank, S.E., Bulygina, E., Eglinton, T.I., Gordeev, V.V., Gurtovaya, T.Y., Raymond, P.A., Repeta, D.J. and Staples, R., 2012.** Seasonal and annual fluxes of

- nutrients and organic matter from large rivers to the Arctic Ocean and surrounding seas. *Estuaries and coasts*, 35(2), pp.369-382. <https://doi.org/10.1007/s12237-011-9386-6>
- Kiro, Y., 2025.** Coastal aquifers key contributors to ocean chemistry through solute fluxes. *Nature Communications*, 16(1), p.7082. <https://doi.org/10.1038/s41467-025-62411-8>
- Lacroix, F., Ilyina, T. and Hartmann, J., 2020.** Oceanic CO<sub>2</sub> outgassing and biological production hotspots induced by pre-industrial river loads of nutrients and carbon in a global modeling approach. *Biogeosciences*, 17(1), pp.55-88. <https://doi.org/10.5194/bg-17-55-2020>
- Li, D., Gan, J., Hui, R., Liu, Z., Yu, L., Lu, Z. and Dai, M., 2020.** Vortex and biogeochemical dynamics for the hypoxia formation within the coastal transition zone off the Pearl River Estuary. *Journal of Geophysical Research: Oceans*, 125(8), p.e2020JC016178. <https://doi.org/10.1029/2020JC016178>
- Li, Z., Tian, C. and Sheng, Y., 2022.** Fluxes of chemical oxygen demand and nutrients in coastal rivers and their influence on water quality evolution in the Bohai Sea. *Regional Studies in Marine Science*, 52, p.102322. <https://doi.org/10.1016/j.rsma.2022.102322>
- Maier, M.S., Teodoru, C.R. and Wehrli, B., 2021.** Spatio-temporal variations in lateral and atmospheric carbon fluxes from the Danube Delta. *Biogeosciences*, 18(4), pp.1417-1437. <https://doi.org/10.5194/bg-18-1417-2021>
- Milani, V. and Timelli, G., 2023.** Solid salt fluxes for molten aluminum processing—a review. *Metals*, 13(5), p.832. <https://doi.org/10.3390/met13050832>
- Olson, D.B., 2001.** Biophysical dynamics of western transition zones: a preliminary synthesis. *Fisheries Oceanography*, 10(2), pp.133-150. <https://doi.org/10.1046/j.1365-2419.2001.00161.x>
- Viers, J., Dupré, B. and Gaillardet, J., 2009.** Chemical composition of suspended sediments in World Rivers: New insights from a new database. *Science of the total Environment*, 407(2), pp.853-868. <https://doi.org/10.1016/j.scitotenv.2008.09.053>
- Whitney, F.A., Crawford, W.R. and Harrison, P.J., 2005.** Physical processes that enhance nutrient transport and primary productivity in the coastal and open ocean of the subarctic NE Pacific. *Deep Sea Research Part II: Topical Studies in Oceanography*, 52(5-6), pp.681-706. <https://doi.org/10.1016/j.dsr2.2004.12.023>
- Zhang, J., Huang, W.W., Letolle, R. and Jusserand, C., 1995.** Major element chemistry of the Huanghe (Yellow River), China-weathering processes and chemical fluxes. *Journal of Hydrology*, 168(1-4), pp.173-203. [https://doi.org/10.1016/0022-1694\(94\)02635-0](https://doi.org/10.1016/0022-1694(94)02635-0)

**Zhang, P., Ruan, H., Dai, P., Zhao, L. and Zhang, J., 2020.** Spatiotemporal river flux and composition of nutrients affecting adjacent coastal water quality in Hainan Island, China. *Journal of Hydrology*, 591, p.125293. <https://doi.org/10.1016/j.jhydrol.2020.125293>