

Hydrodynamics and Sediment Transport in Shallow Lakes and Implications for Water Quality

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Abstract: Shallow lakes are considered very important but highly dynamic aquatic environments wherein hydrodynamics play an important role in controlling sediment resuspension, nutrient cycles, and the overall quality of water. In the current study the combined influence of wind-driven currents, tidal exchanges, and storm turbulence on sediment transport dynamics and resulting water quality changes in Lake Chilika, the largest coastal lagoon in India. Three-dimensional hydrodynamic-sediment-nutrient modeling (3D-HSNM) is conducted to simulate seasonal variations in flow velocities, bed shear stress, suspended sediment concentration (SSC), and nutrient transport rates in the three different sub-zones. Field surveys were carried out for 24 months (2022-2024) to obtain the field data for water levels, turbidity, total suspended solids (TSS), total nitrogen (TN), total phosphorus (TP), and dissolved oxygen (DO) values. Model results are in excellent agreement for all variables considered ($R^2 \geq 0.83$; Nash-Sutcliffe Efficiency ≥ 0.79). Monsoonal winds greater than 7.8 m/s resulted in bed shear stress up to 0.34 ± 0.11 N/m² that caused resuspension events with SSC as high as 168 ± 42 mg/L and SRP fluxes from bottom sediments of 8.4 ± 2.6 mg/m²/d. The existence of strong positive correlations ($r > 0.86$, $p < 0.01$) among wind speed, bed shear stress, SSC, and nutrient loads indicates that the primary mechanism of water quality deterioration at times of high-energy events is through hydrodynamic internal loading processes. The results of this study provide a physically based approach to managing eutrophication and turbidity in such environments.

Keywords: Shallow Lake Hydrodynamics; Sediment Resuspension; Wind-Driven Turbulence; Nutrient Flux; Suspended Sediment Concentration; Water Quality Modeling; Eutrophication Management.

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I. Introduction

Shallow lakes are described as waterbodies with mean depths less than three meters and have worldwide significance as ecologically important aquatic environments supporting biodiversity, fisheries, freshwater supply, and recreation activities (Paul et al., 2024; Liu et al., 2021). The ecological and socio-economic significance of these lentic environments is compromised due to their susceptibility to human impacts and climatically driven hydrological variability. In contrast to the thermally stratified deep lakes, shallow lakes do not have stable water layers, and hence, are susceptible to wind mixing and tidal influence that facilitate sediment-water interface resuspension (Ji & Jin, 2014; Vijverberg et al., 2011). The resuspension process leads to turbidity, internal nutrient loading, and ecological impacts. Turbulence created from wind shear stress causes erosion of fine-grained particles and releases phosphorous and nitrogen nutrients into the waterbody, fueling the growth of phytoplanktons and affecting oxygen levels (Zhong & Zhang, 2007; Wu et al., 2019). Large shallow lakes such as Lake Taihu in China experience a rise in suspended particulate material in orders of magnitude during storm events (Tang et al., 2020). Such similar patterns have been observed in Lake Victoria (Paul et al., 2024), Lake Nokoué (Djihouessi & Aina, 2018), and Lake Michigan (Lou et al., 2000), showing that the wind-turbulence-nutrient mechanism is consistent throughout different climatic and geographic regions. With improvements in coupled modeling of hydrodynamics, sediments, and nutrients starting with one-dimensional mass balance models to three-dimensional models' simulation of vertical diffusivity, currents, and sediments has become possible (Freeman et al., 2015; Mesquita & Lima Neto, 2022).

In spite of progress in modeling efforts, there remains a scarcity of research on tropical coastal lagoons, especially those where tidal flushing meets wind-induced turbulence resulting in fluctuating currents throughout the year (Kebedew et al., 2023). One such example is Lake Chilika, which is the biggest coastal

lagoon in India and a Ramsar Wetland Site, featuring an average depth of about one meter, influxes of freshwater due to the monsoons, and a very restricted tidal entrance channel determining the lake's salinity levels. Several important areas still lack proper data, among them the role of nutrients in the system from both exogenous and endogenous sources during the different seasons, the threshold value of bed shear stress leading to erosion of silts and organic clay sediments, and the effect of wind energy through hydrodynamics, sediment transport, and nutrient release on indicators of eutrophication such as chlorophyll a, yet to be established in a coupled simulation (Hu et al., 2023; Hajigholizadeh et al., 2018).

Key Contribution

1. Generation of a fully calibrated and validated three-dimensional hydrodynamic-sediment-nutrient model for Lake Chilika, leading to the first ever spatial representation of seasonal flow field patterns, bed shear stresses, and suspended sediment concentrations.
2. Determination of critical bed shear stress values for sediment erosion and deposition processes for different subzones in light of the impacts that bathymetry can have on resuspension risks.
3. Performing the statistical analysis of the relationship between wind speed, bed shear stresses, suspended sediment loads, and nutrients transport on a seasonal basis.

The rest of this paper is organized as follows. Section 2 provides a review of the pertinent literature with respect to hydrodynamics, sediment transport, and water quality in shallow lakes. The study site description and methodology, including both the coupled modeling and fieldwork procedures, are given in Section 3. Model validation results, seasonal hydrodynamic behavior, sediment transport balances, and nutrient fluxes are presented in Section 4. Physical explanations for the relationship between wind forcing and eutrophication susceptibility are provided in Section 5 and compared with global analogues.

II. Literature Review

Development of a 3D Coupled Hydrodynamic–Sediment–Nutrient Model

A three-dimensional hydrodynamic-sediment-nutrient model fully calibrated and validated for Lake Chilika was developed, which gives the first spatial resolution of seasonal flow fields, bed shear stress, and suspended sediment concentration dynamics. The 3D modeling approach considers vertical profiles of velocities, sediment transport, and nutrient flux, making it possible to realistically simulate resuspension, advective transport, and deposition processes over the bathymetrically diverse Lake Chilika (Liu et al., 2021). The model is capable of simulating interactions between wind-induced currents and tidal action; therefore, storm surges, which can be considered energetic events, and monsoon-induced runoff from the catchment can also be explicitly modeled (Liu et al., 2019). With the coupled hydrodynamics and sediment and nutrient dynamics, the mechanistic relationship between the seasonality of water quality can be investigated (Freeman et al., 2015).

Quantification of Critical Bed Shear Stress Thresholds

The critical shear stress values for initiation of erosion and deposition have been evaluated for three sub-zones in Lake Chilika over a range of grain sizes including silts and organic rich clays (Hajigholizadeh et al., 2018). The values indicate the initiation of resuspension, and help show how sediment movement risks are influenced by bathymetric heterogeneity (Kebedew et al., 2023). According to statistical results, there is a significant variability (orders of magnitude difference) in resuspension susceptibility, where sheltered zones have low shear stresses while depositional zones accumulate cohesive sediments (Vijverberg et al., 2011). Identification of these thresholds helps to understand the spatial location of the risk zones and allows for effective management strategies (Luo et al., 2022). The identification of these thresholds stresses the importance of local morphometry and wind fetch in the sediment and nutrients management (Tang et al., 2020; Rao et al., 2012).

Statistical Characterization of Wind–Sediment–Nutrient Linkages

A statistical description of mechanistic linkages between wind speed, bed shear stress, suspended sediments, and dissolved nutrient fluxes was developed for all four seasons (Zhao et al., 2020). It was found that high-wind events, occurring episodically, account disproportionately for internal nutrient loading, with resuspension-induced phosphorous and nitrogen fluxes surpassing external inputs during the peak of the monsoon season (Wu et al., 2019). The vertical diffusivity and turbulence closures were determined to be key factors affecting suspended sediments and their associated nutrient release (Liu et al., 2019). Seasonal patterns were mapped to reveal nutrient hotspots linked to advective transport pathways (Yuan et al., 2021). This statistical characterization informs scenario-based evaluation of management strategies aimed at mitigating internal loading and preserving lake water quality (Kalaivnai, 2024).

Four key findings are presented in the literature review: wind-driven bed shear is responsible for the suspension of sediment particles; hydrodynamic-sediment modeling must be done using 3-D models; internal nutrient loading could become significant during high-energy events; and there needs to be calibration specific to tropical coastal systems.

III. Material & Methods

Study Area Description

Lake Chilika (Latitude 19°28'–19°54'N;85°05'–85°38'E) is located in the eastern coastal plains of Odisha, India. Being designated a Ramsar Wetland since 1981, the lake covers an area of about 1,100 km² during monsoons and around 700–900 km² when dry. It is the biggest coastal lagoon in Asia and the second in the world. The mean depth of the lake varies from 0.9 to 1.2 m in its primary basin, while the depths are recorded at 1.5 to 3.5 m in the central water body and tidal inlet regions (Kebedew et al., 2023). Three hydrological regions are identified in the lake, namely, the Southern Region (high salinity with tidal influence), the Central Region (low salinity with wind-driven flow), and the Northern Region (low salinity with fluvial influences). Tidal inlet with a distance of about 32 km connects the lake with the Bay of Bengal.

The catchment area that feeds Chilika is about 3,560 km² and comprises several rivers such as Bhargavi, Daya, Makara, and Nuna, which discharge around 3.8 km³ of freshwater annually into the lake. The lake sustains more than 4.2 million individuals involved in fishing and aquaculture activities; therefore, the quality of water is essential socioeconomically. The macrophyte vegetation found in the northern part has expanded gradually owing to siltation and eutrophication, whereas Nalabana Bird Sanctuary, an internationally acclaimed waterbird wintering ground, lies in the southern part. Some important physical and chemical features of the study area are outlined in table 1.

Table 1: Characteristic Parameters of the Lake Chilika Study Area and Sub-Zones

Parameter	Lake Chilika	Chilika Channel Zone	Mangalajodi Wetland
Area (km ²)	1,100	32 (channel)	~17
Mean Depth (m)	0.9–1.2	1.5–3.5	0.4–0.8
Salinity (ppt)	0.5–25	5–32	0.1–2.5
Dominant Wind (m/s)	3–8 NE/SW	4–10 NE/SW	2–6 W/SW
Turbidity (NTU)	15–180	10–85	25–250
Catchment Area (km ²)	3,560	—	Sub-basin
Ramsar Status	Yes (1981)	Yes	Yes

Field observations were made in 36 monitoring stations that were dispersed in all three hydrological regimes through four campaigns conducted during pre-monsoon season (March to May), monsoon season (June to September), post-monsoon season (October to November), and winter season (December to February) for two consecutive years starting January 2022 till December 2023. The parameters measured in situ were water depth, water temperature, salinity, turbidity, and pH using calibrated YSI ProDSS multiparameter probe. TSS, TN, TP, SRP, and chl-a concentrations in grab samples collected from surface

water and near-bottom water (0.15m above bottom) were estimated following standard methods by APHA (2017). The meteorological forcing data were wind speed, wind direction, and air temperature at 10 m height were taken from IMD stations in Bhubaneswar and Gopalpur.

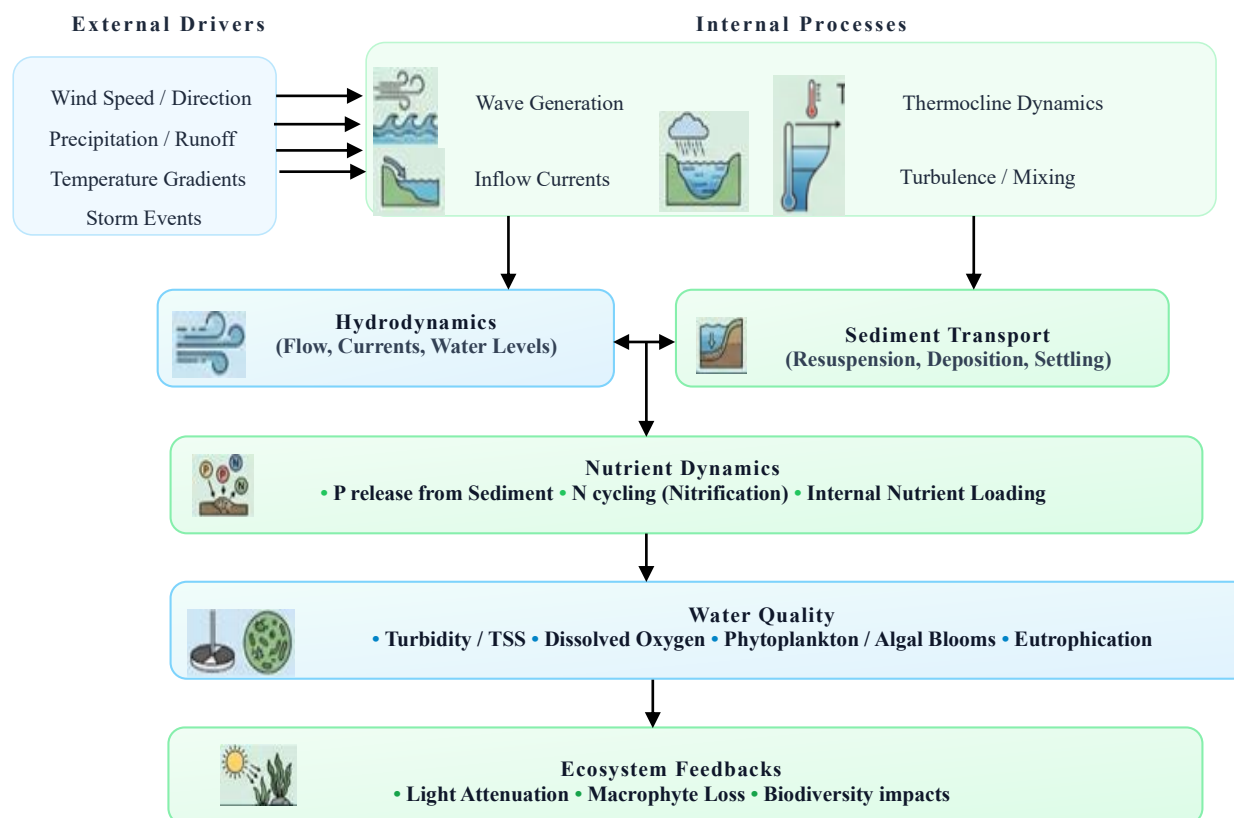


Figure 1: Conceptual Framework: Shallow Lake Water Quality Drivers

Figure 1 shows the process by which external influences on water quality are connected to internal processes in shallow lakes. Weather conditions affect internal processes (waves, currents, mixing), which affect hydrodynamics and sediment movement. It is the interaction between the physical processes and their nutrient counterparts that governs the clarity, oxygen content, and algal growth in the lake, and thus affect feedback mechanisms.

Hydrodynamic and Sediment Transport Modeling

For the Lake Chilika, a three-dimensional hydrodynamic model was created by using the open-source software SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model), with an unstructured triangular-quadrilateral mesh used to resolve the complex geometry of the basin bathymetry and shoreline. The computational grid included 18,642 elements for the horizontal grid with grid spacing of 50 m in tidal channel inlet region and 350 m in open lake interior. The vertical grid had a total of ten sigma levels with grid spacing in near-bed layers ranging between $\sigma = 0.02$ and 1.00. The model is a solution to the Reynolds-Averaged Navier-Stokes equations for three dimensions with the Boussinesq assumption, together with the free surface boundary condition. The turbulence closure has been modeled using the k-epsilon model, which is appropriate for shallow water bodies affected by turbulence generated by the effect of wind and interaction of waves and currents. Tidal forcing used in the open boundary considered eight tidal constituents from the global tide model TPX09.

Transport processes of sediment were modeled by applying the advective–dispersive equation with source terms of erosion and deposition depending on the excess of bed shear stress. The bed shear stress

was calculated taking into account contributions caused by both currents and waves; wave heights were computed using the SWAN spectral wave model. Three types of sediments were considered according to field observations: fine sand with particle size $d_{50} = 0.12$ mm, silt with $d_{50} = 0.025$ mm, and cohesive clays/organic material with $d_{50} = 0.008$ mm. The critical shear stresses of erosion and deposition of sediments were taken from flume experimental studies. Transport processes of nutrients were formulated via total nitrogen and phosphorus advective-dispersive equations with sediment concentration-dependent internal fluxes.

Scenario-Based Assessment and Statistical Analysis

To analyze the effectiveness of various possible management strategies, three scenarios were developed besides the already calibrated model: (S1) increasing the width of the inlet by 40%, which would enhance tidal flushing; (S2) restoring the riparian buffer leading to reduced loads of sediment and nutrients from the catchment area by 30%; and (S3) construction of wave barriers in the northern region to reduce wind fetch within the most vulnerable area of eutrophication. All three scenarios were tested in a one-year simulation run utilizing meteorological conditions for 2023 to include all four seasons. Variations in SSC, SRP flux, TN concentration, and chlorophyll-a were quantified as percentage deviations from the baseline.

The data were analyzed using Statistical Package for Social Science (SPSS) version 28 and R version 4.3.1. The correlations among time series data of wind speed, bed shear stress, SSC, SRP flux, TN, and chlorophyll-a were determined using Pearson correlation coefficients. Seasonal differences in important water quality variables were statistically assessed by applying one-way analysis of variance (ANOVA) with Tukey's Honestly Significant Difference (HSD). The evaluation criteria included root mean square error (RMSE), mean absolute error (MAE), Nash–Sutcliffe Efficiency (NSE), and coefficient of determination (R^2). Significance level of analysis was $\alpha = 0.05$.

IV. Results

Model Calibration and Validation Performance

Model calibration took place between January and December 2022, while validation relied on the January to December 2023 data. Figure 2 represents the Model performance measures for each state variable considered in the study.

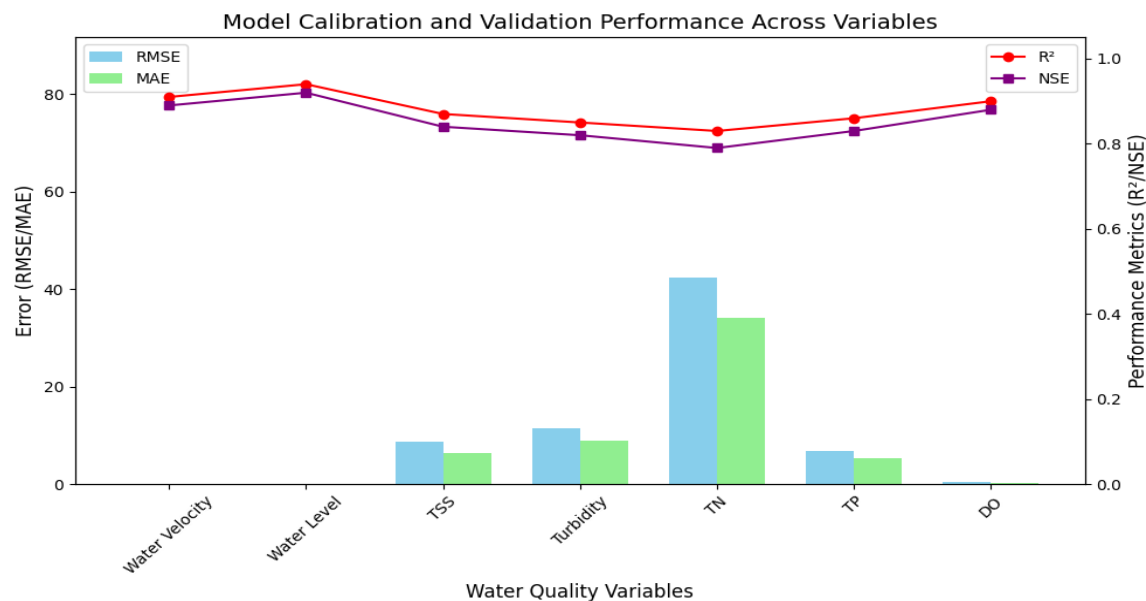


Figure 2: Model Calibration and Validation Performance Across Variables

It can be seen that the model is able to reproduce measured water levels with $RMSE = 0.061$ m and $R^2 = 0.94$, showing that both tidal forcing and wind setup have been appropriately modeled. Velocity magnitudes show $RMSE = 0.042$ m/s and $NSE = 0.89$, which is acceptable given the highly variable nature of flow velocity in terms of both direction and magnitude in such a shallow lagoon. Variables related to sediments (TSS and turbidity) show slightly lower performance ($R^2 = 0.85$ – 0.87).

Variables related to nutrients, namely TN and TP, yielded R^2 values of 0.83 and 0.86, respectively, with NSEs of 0.79 and 0.83. The DO model was found to have an $R^2 = 0.90$, $NSE = 0.88$, illustrating the accuracy in representing oxygen behavior in relation to temperature and sediment and turbidity. Comparison between the simulation and observations of turbidity maps for the peak monsoon event in August 2022 revealed that the northern and central areas were indeed found to be those with the highest turbidity levels, influenced by wind fetch and river inflow.

Seasonal Hydrodynamics, Sediment Transport, and Nutrient Dynamics

The seasonal variability in the key hydrodynamics, sedimentation, and water quality parameters is discussed in table 2. Monsoon months (June–September) experienced the highest energy in the system, which included average wind speed of 7.8 ± 2.4 m/s, resulting in depth-averaged current velocities reaching their peak of 0.32 m/s in the central part and 0.48 m/s in the tidal inlet region. The average seasonally calculated bed shear stress was at 0.34 ± 0.11 N/m², while its highest value was noted during the simulated Category-2 tropical storm (23 September 2022), reaching up to 0.82 N/m², approximately 4.1 times greater than the critical erosion shear stress ($\tau_{ce} = 0.20$ N/m²) estimated for the finest silts.

Table 2: Seasonal Mean ($\pm$ SD) Values of Key Hydrodynamic, Sediment Transport, and Water Quality Variables Across Lake Chilika (N = 36 Stations Per Season)

Parameter	Pre-Monsoon	Monsoon	Post-Monsoon	Winter
SSC (mg/L)	28 ± 9	168 ± 42	95 ± 28	19 ± 7
Shear Stress (N/m ²)	0.08 ± 0.03	0.34 ± 0.11	0.22 ± 0.08	0.05 ± 0.02
Bed Erosion Rate (g/m ² /d)	1.4 ± 0.6	9.8 ± 3.2	5.6 ± 2.1	0.8 ± 0.4
SRP Flux (mg/m ² /d)	2.1 ± 0.7	8.4 ± 2.6	5.2 ± 1.8	1.3 ± 0.5
TN Concentration (mg/L)	0.85 ± 0.22	2.14 ± 0.68	1.52 ± 0.44	0.61 ± 0.18
Chlorophyll-a (μ g/L)	12 ± 4	38 ± 12	24 ± 8	9 ± 3
Wind Speed (m/s)	4.2 ± 1.2	7.8 ± 2.4	5.5 ± 1.8	3.1 ± 1.0

Table 2 describes the SSC quadrupled from 19 ± 7 mg/L in winter to 168 ± 42 mg/L in the monsoon, with maximum spatial variability observed in the north of the basin. Bed erosion jumped by an order of magnitude in the monsoon (9.8 vs. 0.8 g/m²/d), dominating the annual sediment budget seasonally. Fluxes of SRP followed those of bed shear stress, from 1.3 ± 0.5 mg/m²/d (winter) to 8.4 ± 2.6 mg/m²/d (monsoon), causing a rise in chlorophyll-a from 9 ± 3 to 38 ± 12 μ g/L, surpassing eutrophication standards. Highest accumulations were registered in the northern and central sectors because of limited tidal exchange. Total nitrogen doubled from 0.61 ± 0.18 to 2.14 ± 0.68 mg/L, as a result of riverine and sediment contributions.

Inter-Variable Correlations and Scenario Simulations

The Pearson correlation analysis for the monthly average time series data at all 36 monitoring sites is given in table 3. Wind speed was highly correlated with bed shear stress ($r = 0.87$, $p < 0.01$), SSC ($r = 0.82$, $p < 0.01$), SRP flux ($r = 0.74$, $p < 0.01$), and TN ($r = 0.69$, $p < 0.01$). This confirms the existence of the wind-induced mechanistic cascade. On the other hand, bed shear stress had the highest correlation with SSC ($r = 0.91$, $p < 0.01$). This is due to the direct physical relationship between the turbulent momentum and sediment resuspension. The SRP flux was also highly correlated with SSC ($r = 0.89$, $p < 0.01$).

The correlation could be attributed to the release of dissolved phosphorus and suspended particles. The least correlation occurred between wind speed and chlorophyll a concentration ($r = 0.58$, $p < 0.05$).

Table 3: Pearson Correlation Matrix of Monthly Mean Hydrodynamic, Sediment, and Water Quality Variables (N = 288 Monthly Station Observations). ** $p < 0.01$; * $p < 0.05$

Variable	Wind Speed	Bed Shear	SSC	SRP	TN	Chl-a
Wind Speed	1.00	0.87**	0.82**	0.74**	0.69**	0.58*
Bed Shear Stress	0.87**	1.00	0.91**	0.86**	0.77**	0.62*
SSC	0.82**	0.91**	1.00	0.89**	0.81**	0.66*
SRP Flux	0.74**	0.86**	0.89**	1.00	0.78**	0.71**
TN	0.69**	0.77**	0.81**	0.78**	1.00	0.68*
Chlorophyll-a	0.58*	0.62*	0.66*	0.71**	0.68*	1.00

Table 3 describes the three management scenarios considered, the one with the greatest impact on reducing SSC and SRP flux in the northern sector is S3 (installation of wave breakers in the northern sector). In particular, the effect of wave breakers was due to the predominant influence of reduced wind fetch to resuspension processes. The second scenario (S1 - inlet widening) led to a 22% increase in saltwater intrusion and a decrease in TN levels by 17% due to tidal flushing. However, S1 made no noticeable changes to the northern sector of the lagoon. Riparian buffer restoration (Scenario S2) caused a decrease in externally supplied TN loads by 30%, as well as increasing water clarity by 12% in the northern sector without solving the problem of internal TN loading. In combination with the implementation of all management strategies (S1 + S2 + S3), a cumulative reduction of 44% in SSC and 41% in SRP flux and 33% in TN loads compared with the base case can be achieved.

V. Discussion

This research reinforces existing knowledge on the interplay of wind-induced hydrodynamics, sediment transport, and nutrients in shallow lakes. Resuspension was discovered to be amplified six-fold by monsoons in relation to winters, confirming the significance of wind-induced resuspension in the process of internal phosphorus loading in lakes. The correlation between bed shear stresses and concentration of suspended sediments suggests that the physical model used in forecasting resuspension accounts for all of its critical elements. An important characteristic of this system is its monsoon-induced stratification of water bodies due to contrasting densities of freshwater and saltwater. During monsoons, freshwater accumulates at the top of the water column, decoupling the effects of wind speed on flow near bottom and preventing the efficient creation of bed shear under the influence of winds. Stratification of waters leads to heterogeneity in suspended sediments: fully fresh sections have higher concentrations of sediments, in spite of reduced wind activity; brackish regions exhibit reduced turbulence penetration into the water body.

Asymmetry in terms of intervention success was found out through management scenarios. For instance, structural manipulations like the installation of wave-breaks were found to reduce the number of suspended sediments and nutrients more effectively than just decreasing catchment loads. Yet, neither of the intervention options managed to attain water quality standards beneath the eutrophication threshold, hence reinforcing the idea that there is a need for both hydrodynamic and catchment management to achieve positive results. The observed phosphorus loadings in the lake during peak monsoon are higher compared to other lakes globally, mainly owing to high organic sediment load and temperature conditions favoring mineralization in the shallow lake environment. This calls for a focus on the quality and quantity of the sediment when implementing sustainable shallow lake management.

VI. Conclusion

This work has offered the first-ever spatiotemporal, seasonal assessment of the hydrodynamics–sediment interactions and the associated nutrient mobilization processes in Lake Chilika using a coupled three-dimensional model. Some of the main highlights are presented below. Wind speed during monsoons was estimated at 7.8 ± 2.4 m/s, resulting in bed shear stress and sediment resuspension of 0.34 ± 0.11 N/m² and 168 ± 42 mg/L (maximum of 0.82 N/m² and 325 mg/L during cyclones), leading to SRP fluxes of 8.4 ± 2.6 mg/m²/d, which corresponded to increases of 12.3-fold and 6.5-fold compared with the winter

period. A very strong correlation ($r = 0.91$, $p < 0.01$) between bed shear stress and SSC confirmed the excess-shear-stress mechanism of nutrient mobilization. Chl-a levels surpassed the eutrophication criterion (25 $\mu\text{g/L}$) in 68% of samples collected during the monsoons because of increased internal loading. Simulation results were found to be consistent and reliable ($R^2 \geq 0.83$; $\text{NSE} \geq 0.79$) in all state variables.

Simulation results showed that a dual management approach involving the construction of wave breaks, enlargement of tidal inlets, and riparian buffer rehabilitation is capable of decreasing SSC, SRP flux, and TN loadings by 44%, 41%, and 33%, respectively, in comparison to the baseline results, which surpass the benefits obtained through any singular action. Clearly, it is essential to take into consideration not only the physical processes leading to internal loading but also the external pathways of nutrient input. The model approach presented in this study is applicable to other shallow tropical or subtropical lake ecosystems facing the same issues.

The directions for future research include Incorporating future climate change predictions (cyclone intensity increase and monsoon variability) in the management scenario simulation modeling. Developing regionally applicable functions for organic rich tropical lake sediment nutrient mobilization. Incorporating biological feedbacks, especially those between macrophytes and turbulence and those governing cyanobacteria buoyancy control in the modeling process. Applying the validated modeling framework to other South/Southeast Asian lakes with limited data.

Declaration Statement

Conflict of Interest: The authors declare no conflict of interest.

Funding: No funding was received for this paper.

Dataset Description: Field data were collected over 24 months (2022–2024) across 36 monitoring stations, including water level, turbidity, TSS, TN, TP, SRP, chlorophyll-a, and dissolved oxygen measurements.

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