Wetland hydrodynamics and their typhoon efforts at biodiversity conservation and sediment movement

Dr. Abhijeet Madhukar Haval[1]; Md Afzal[2]; Dr. Komal Khatter[3]

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Abstract

Intertidal Wetlands (IW) are generally seen as susceptible to storm effects. Although considerable focus has been directed towards the impact of hurricane or typhoon landfall on regional deposition and soil erosion in tidal wetland areas there is limited understanding regarding the influence of distant storms or typhoons on these ecosystems, as well as the overall effects of such storms on hydrodynamics, transport of sediments, and seabed security. This study examines the potential impact of thirteen typhoons that struck the western part of the Pacific in the summer-autumn of 2018 on an IW in the River. The research observed the effect of eight hurricanes for half of their lifespan when they were between 460 and 2500 km distant, the closest distance recorded for each typhoon relative to the valley. These distant typhoons resulted in 2-6 5-fold maximum rises in fluid dynamics and suspended debris concentration. Significant net erosion of mudflats and deposition of marshes were recorded. The research ascertained that hurricanes can significantly impact intertidal marshes, even those occurring hundreds of kilometers distant. These results enhance comprehension of the extent to which storms and typhoons impact intertidal ecosystems and augment the understanding essential for managing the coast.

Keywords: Wetland, Hydrodynamics, Biodiversity, Sediment movement

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1- Assistant Professor, Department of CS & IT, Kalinga University, Raipur, India.
Email: ku.abhijeetmadhukarhaval@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0003-1776-4795
2- Research Scholar, Department of CS & IT, Kalinga University, Raipur, India.
Email: md.afzal@kalingauniversity.ac.in, ORCID: https://orcid.org/0009-0007-2214-2105
3- Associate Professor, New Delhi Institute of Management, New Delhi, India.
Email: komal.khatter@ndimdelhi.org, ORCID: https://orcid.org/0000-0001-6933-8745
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Introduction

Intertidal Wetlands (IW) (Pérez *et al.*, 2024) constitute some of the most important wetlands globally, delivering essential ecosystem activities and services. The ecological equilibrium of tidal wetlands is likely a crucial component for the health of this species. The enduring stability of IWs is affected by sediment availability and relative sea-level fluctuations (Etuk *et al.*, 2024; Sindhu, 2023). Their reactions to river sediment reduction, land subsidence, and global sea-level rise have been extensively examined. Storms significantly disrupt the short-term equilibrium of IWs. Tropical cyclones (hurricanes/typhoons) are severe storms that often affect the coastlines of the Pacific, Atlantic, and Indian Oceans (Sahu and Kumar, 2024). While significant ambiguity exists over the potential increase in the number of tropical cyclones, most studies indicate that the strength of tropical cyclones is expected to rise with climate warming. IWs are generally seen as susceptible to storm assault. Most prior research has concentrated on the significant accretion and erosion induced by storms and typhoons upon their landfall at IWs (Rogers *et al.*, 2023; Park *et al.*, 2015). There is limited understanding of the distant impact of storms and hurricanes and their general impact on hydrodynamics, transport of sediments, and erosion/accretion. It is imperative to enhance studies in these domains, as the impact zone of hurricanes and typhoons extends well beyond their landfall location, and the ramifications of storm effects encompass more than mere bed-level alterations (Kang, 2020; Iyengar and Bhattacharya, 2024).

The research addresses the aforementioned information gap by examining the Delta as a model structure, given its status as one of the largest deltas globally and the vulnerability of its IW regions to typhoons each summer (Priyalatha, 2024; Kadhim *et al.*, 2024). By integrating qualitative descriptions with quantitative analyses, the research aim to: (1) Categorize remote typhoons or their course into affecting and non-impacting segments; (2) Examine the numerical attributes of the impacting hurricanes; (3) Measure the scales of both average and maximum typhoon impacts; and (4) Formulate an impact factor to establish a quantitative connection between a distant typhoon and its effects (Yin *et al.*, 2021). This study is distinctive in its examination of the frequency of typhoons originating in the Pacific Seaboard, their length of influence on the wetlands of this delta, the statistical attributes of the influencing typhoons (such as their intensity and proximity to the delta), and the extensive consequences of these typhoons, encompassing hydrodynamic processes, conveyance of sediment, and alterations in bed levels and marshes, grounded in high temporal-resolution field observations (Sengupta and Deshmukh, 2024).

Materials and Methods

Data Extraction

Typhoon track information and highest wind speeds around the typhoon centers throughout the 2018 hurricane season were acquired from the National

Meteorological Administration. (Xie *et al.*, 2021) Data on wind speed recorded every three hours and wave height recorded every six hours at the near-shore stations in the river over the identical timeframe were sourced from the European Center for Medium-Range Weather Forecasting. The East Sea Division of the State Oceanic Administration supplied the lunar tide data.

Empirical Observations

Field studies were conducted using a tripod method at tidal wetlands on the riverfront. The breezes in the River are affected by rainfall and hurricanes, with a multi-year mean velocity of approximately 5 m/s (Vasquez and Mendoza, 2024). The waters in this region are classified as semi-diurnal, with a mean tidal variation of 3.4 meters at the study location. The intertidal zone measures roughly 950 meters wide, comprising a salt marsh (upper 160 meters) and a mudflat (lower 780 meters). The viewing location is below the Mean Sea Level (MSL) and 650 meters offshore from the barrier.

A 25-plus Seagauge Waves and Tide Recording (5 Hz) was affixed vertically to the bed top to quantify wave parameters and water depth at 15-minute intervals (the burst duration was 512 seconds, yielding 1024 observations) (Nauman *et al.*, 2023). An Aquadopp HR-Profiler (2 Hz) was positioned on a tripod, with its downward-facing probing situated 0.6 m above the bottom of the ocean to assess the water's current profiles. An Alec Present Meter (2 Hz) was affixed to the gimbal to gauge point winds at an altitude of 0.6 meters. The currents were recorded at five-minute intervals. An Argus Surface Meter (ASM) (6 Hz), equipped with sensors and a measurement profile of about 1 m, was installed to acquire the turbidity profiling at 2.0-minute intervals (Li *et al.*, 2023).

The heights of the cross-shore IW characteristic were scanned before and following typhoons, utilizing a high-resolution, high-accuracy, real-time kinematics global positioning device with a vertical and horizontal accuracy of ≤ 2 mm. Each investigation utilized a uniform reference embedded in a concrete barrier at the origin of the central cross-shore characteristics, with subsequent elevation surveys performed at designated wetland locations. To mitigate the impact of imprints on survey data, the researchers cautioned against disturbing the sandy ground at the survey locations (Becker *et al.*, 2024). During the elevation measurement, the research maintained a distance near the sediment surface, ensuring it did not penetrate the soil.

Water specimens were collected at the monitoring site to measure the Suspended Sediment Content (SSC). Surficial sediments from the bed were gathered daily during the ebb tide to assess water quantity and the size of grains (Naseer and Devi, 2019). The research employed a buried-plate technique to assess relative bed-level alterations between tidal periods. The buried plate location was 5 meters from the base on the longshore side to prevent tripod interference. The research inserted a square porcelain tile 0.4 m below the silt surface. The research leveled the sediment top to align with the adjacent regions (Malhotra and Iyer, 2024). The initial evaluation was conducted two tidal cycles following the burying of the tile, at the moment when the mudflat had returned to its pristine condition. The research quantified the distance from the top of the sediment to the plates by employing 16 slender sticks placed horizontally into the soil. To mitigate the effects of the ripples, the research placed eight poles on the peaks and an additional eight in the valleys. The difference between the two observations determined absolute bed-level alterations (Truchelut *et al.*, 2022).

Data Processing

In situ turbidity measurements acquired from the ASM were transformed into suspended matter concentration information by a calibration formula in the lab, utilizing water specimens acquired in situ. Grain shape studies of surficial soil were conducted in the research facility using a Laser Diffraction Particulate Size Tester, following the removal of organic materials to derive the particle size dispersion curves of the sediment. The average bed shear stress from coupled wave-current activity (Tew) over 10-minute intervals and the essential shear stress for bottom sediment eroding (Te) were calculated to analyze sediment transportation and bed level alterations. The primary methodology in this investigation is illustrated in Figure 1.

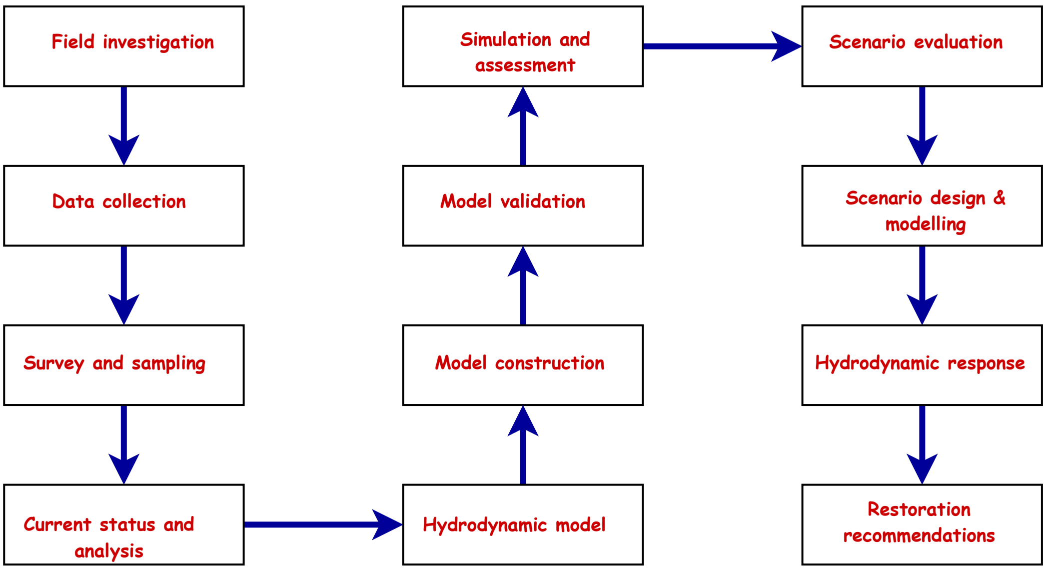

Figure 1: Workflow of the design.

Results

Present Condition of the Wetland Ecosystem

The field investigation indicates that Suaeda salsa is the predominant plant species in the estuary wetland of Liaodong Bay. Field findings suggest that community coverage spans from 25% to 100%, while plant height varies from 4.5 cm to 43.2 cm. Suaeda salsa is predominantly found in the upper beach region of the research area, with a dispersed distribution pattern. Moreover, the limited coverage and elevation are evident along the tidal streams of the marsh. Macroinvertebrate concentration approached 0 in the upper beach, whereas the maximum density can attain 3500/m² near the tidal creeks. The macroinvertebrate population in the northern region of the research area is significantly greater than that in the central and southern regions. The interplay of hydrology and topography is somewhat accountable for influencing geographic distribution and patterns over various historical periods.

A field investigation in the research region indicated that the average concentrations of total phosphorus, biologically accessible phosphorus, pH, total nitrogen material, and moisture material in the sediment were 0.07 ± 0.002%, 0.92 ± 0.3%, 17.1 ± 2.5 mg/kg, 9.4 ± 0.2, 0.09 ± 0.03%, and 45.1 ± 5%, respectively. Edaphic variables, including soil salinity, moisture, pH, and organic matter, significantly affect vegetation distribution in estuary wetlands. The alteration in the environment is the primary element influencing vegetation. For instance, low-density vegetation communities experienced adverse consequences from a variable high-salinity soil state, partially attributable to tidal influences. Compared to a prior study, the wetland's soil salinity, pH, water, and nutrients demonstrate markedly increasing patterns and deteriorating conditions, likely attributable to limited tidal inputs through the floodgates and corresponding weak hydrodynamic circumstances. It is determined that the existing macroinvertebrate varieties in the wetland have significantly diminished compared to the 28 species documented in 2008. These prior findings indicate that wetland ecology has undergone a degradation pattern. According to hydrodynamics, several scenarios were suggested to optimize the flow conditions and promote the ecological status of wetlands.

Hydrodynamic Conditions and Evaluation of Models

Despite the study region being a tidal-dominated wetland structure, the floodgate connecting the reservoir and the vast open sea remains closed throughout the simulation. The geographical water extents are anticipated to show slight variation across the four designated periods, owing to the minimal impact of vaporization and precipitation on wetland hydrodynamics. The extensive water bodies are primarily located in the tidal streams of the marsh, characterized by low-flow conditions. The water level of the wetland is approximately less than 3 m, with most wetland regions displaying an exposed condition. Due to stable and unstable hydrodynamic conditions, the research did not conduct field surveys to measure water levels and flow velocities. The wetland’s water, derived from the satellite imagery product and simulated findings, exhibited strong concordance throughout the study period, demonstrating a comprehensive ability to capture the hydrodynamic characteristics of the estuary wetland.

Impact of Varying Tidal Magnitudes on Hydrodynamics

Tides can be considered external inputs that possess sufficient energy to enhance the hydrodynamic conditions of a wetland. Throughout the majority of the year, the existing wetland exhibits a markedly low hydrodynamic circumstance, characterized by a water velocity approaching 0 m/s, attributable to the closure of floodgates and the silting of tidal creeks. As anticipated, the opening of all floodgates significantly influences wetland hydrodynamics due to heightened tidal magnitudes. The spatial reactions of the hydrodynamic forces are significantly constrained when tidal levels fall below about 1 meter. When maximal tidal amplitudes attain approximately 1.6-2 m, the hydrodynamic domains demonstrate notable alterations in water area and flow velocity. Significant reactions across the entire wetland are more probable when tidal magnitudes range from 2 to 2.9 m, owing to the combined influence of tidal supplies and floodgates on water level and flow speed. The variations in flow velocities within tidal creeks are anticipated to be significantly greater than those in other wetland regions, particularly at elevated tidal levels (e.g., >3 m), indicating a combined influence of wetland morphology and hydrological conditions.

Influence of Hydraulic Interconnectivity (Floodgate and Tidal Stream) on Hydrodynamics

The findings indicate that establishing additional floodgates significantly enhances hydraulic connection in the southern sections of the wetland. River flows in the wetland can be viewed through floodgates, exhibiting greater velocities in the tidal streams compared to the baseline state. The scenario MS appears to exert a minimal influence on hydrodynamics in the central region. On the other hand, scenario MS3 significantly influences the hydrodynamics of the central and northern areas due to the expanded width of Gates 6 and the corresponding tidal inputs. The findings indicate that floodgates are essential in regulating tidal and energy contributions from the Liaodong Sea. The findings suggest that floodgates engineered to introduce seawater into the wetlands to restore the ecosystem can effectively regulate varying water levels for restoration purposes.

The simulations indicate that the augmented depth (~0.6 m) of tidal streams generally improves the motion of tidal flows and transverse connectivity. However, it minimally impacts the hydrodynamics of the central region. The combined influence of creek depth (~0.6 m) and creek width (~20 m) significantly impacts wetland hydrodynamics, especially in the central and northern regions. The alteration of tidal creeks is more likely to improve longitudinal connection and lateral connectivity regarding the evident reaction of the entire wetland. Floodgates, both antiquated and contemporary, tidal creeks, and depths significantly influence the dynamics of the estuary wetlands. The tide in the streams traverses various wetland regions through existing and new barriers during rising and lowering phases. Prior studies further illustrate that engineering interventions concerning hydraulic connections might enhance wetlands' hydrodynamic conditions through the implementation of floodgates and modifications to the water level of tidal streams. The surface geography and floodgate rules are anticipated to directly affect the interconnectedness of the wetland system, potentially improving hydrodynamics.

Consequences and Prospective Investigations

The repair and sustainability of global estuarine wetlands are primarily jeopardized by elements of nature and human activities, such as water and sediment influx, rising sea levels, ongoing coastal erosion, and significant entry of seawater. In recent years, the estuary wetlands have encountered ecological issues, including wetland deterioration, coastline erosion, and environmental contamination from natural and anthropogenic influences. The findings of this study underscore the significance of hydrodynamics in enhancing neighboring wetlands within intricate estuarine ecosystems. While floodgates generally facilitate water drainage most of the time, opening them to introduce seawater into the examined wetland to restore ecosystems is not readily achievable. The operation of floodgates alone is inadequate for sustaining varying water depths for restoration objectives.

Prior estuarine evaluations have extensively investigated estuarine wetland ecosystems' hydrodynamic and biological reactions to sediment availability, sea level fluctuations, and tidal activities. Numerous pertinent studies indicate that topographic variation influences various facets of wetland environments, including organism dispersion and abiotic component trends. In conjunction with external factors, surface geography predominates in different regions of the wetland ecosystem and across various hydrological phases, potentially resulting in spatially diverse habitats within estuarine marshes. Wetland conditions are anticipated to be susceptible to alterations in diverse external settings, particularly concerning the microtopography in fluid wetland systems.

Tidal input and hydraulic connection in coastal wetland ecosystems can enhance inundation depths and flow speed. Tidal inflows often improve hydrodynamics in wetlands and influence sedimentary and soil characteristics. In addition to tidal effects, topography and hydraulic systems alterations significantly enhance tidal components' influence, especially during periods of diminished tidal magnitude. Ecosystem-based engineering methods are likely the most viable long-term strategies for restoring estuarine ecosystems and ensuring the continued existence of low wetlands. Integrating various techniques is regarded as an efficacious method in the design and execution of wetlands restoration initiatives. The present work is crucial in informing plans for Liaodong Gulf and other estuarine structures, advocating for landscape administration, connectivity organizing, and related hydrodynamic reactions.

Future field investigations must investigate the correlations among hydrological conditions and ecological markers. The impact of inundation depth on wetlands during various hydrological periods warrants increased investigation. Tidal variations and fluctuations influence the properties of marsh soils. Field findings from surveys indicate that low-density plant populations in the study area experienced adverse effects due to high-salinity soil conditions. Although this research measured the impact of potential situations on wetlands, substantial ambiguity arising from applying the 2D model to represent gates diminishes the accuracy of hydrological and connectivity characteristics. To enhance estuary evaluations, subsequent efforts to assess wetland ecosystems should include 3D hydrodynamic modeling alongside water temperatures and salinity levels.

Conclusion

7 of the 14 typhoons that transpired in the Pacific Ocean affected the IW in the river to varying degrees. The delta was impacted for half the period of these eight hurricanes. In the affected periods, the distance from the delta to the hurricane center ranged from 460 to 2100 km, with maximum wind speeds at the typhoon center from 22 to 65 m/s. Typhoons that failed to affect the River were either too far (> 2100 km from the river) or extremely feeble (< 25 m/s in maximum wind speed around the storm core). The hurricanes affecting the delta augmented wind speed (12.1 m/s at the most significant impact compared to 5.1 m/s on average without storm influence), water height (3.62 m versus 2.8 m), length of tidal flooding (7.5 hours versus 7.9 hours), wave height (1.4 m versus 0.3 m), and current speed (0.658 m/s versus 0.4 m), thereby intensifying bed shear stresses due to the combined effect of winds and waves (0.74 N/m^2 versus 0.30 N/m^2) and leading to sediment suspension forces (16.4 kg/m^3 versus 3.9 kg/m^3 in near-bed suspended sediment concentration). During significant typhoons, the mudflat underwent substantial net erosion. In contrast, the primary marsh underwent quick deposition, and the low marshes were covered by a fine-sand washover, resulting in the silting of a nearby creek. The research determines that the hydrodynamic, fossilized, and erosion procedures in intertidal marshes can be substantially affected by typhoons, even when they occur hundreds or possibly thousands of kilometers distant. These findings enhance understanding of the degree to which storms and hurricanes can impact IWs, which is essential for coastal planning.

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