An overview of riverbank erosion prediction techniques applied to the Mekong Delta, Vietnam

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Abstract. In recent times, the Mekong Delta has been experiencing severe riverbank erosion, causing significant damage to property, homes, land, and riverside infrastructure. The region is facing increasing intensity of erosion events, attributed to the impact of climate change and the effects of hydropower dams and water control systems upstream on the Mekong River. This paper discusses five key methodologies currently applied for riverbank erosion prediction in the Mekong Delta: digital map overlay, historical topographic data analysis, geophysical and terrain change analysis, physical phenomenon simulation using analogous conditions, and empirical formula-based prediction. Each method's theoretical foundation, procedural steps, and potential limitations are explored in depth.

1 Introduction

Formed over millennia by sedimentation, the Mekong Delta spans 13 provinces and cities in southwestern Vietnam. This crucial region contributes significantly to the national economy, accounting for 50% of rice production, 65% of aquaculture, and 17% of GDP. However, the past two decades have seen the delta face increasing threats from erosion, particularly due to decreased sediment accumulation.

Riverbank erosion [1] and riverbed sedimentation are intrinsically linked natural phenomena crucial to the formation and development of river systems. These complex processes interact as both causes and consequences of the constant dynamic between river flow and its channel. Identifying commonalities and general trends in these processes across an entire river system, over long stretches, or even within short periods and specific locations can be challenging. However, consistent monitoring enables us to establish patterns and relationships between riverbed erosion, sedimentation, and various influencing factors. These factors include spatial and temporal elements, hydrological conditions, and regular human activities affecting the river channel [2]. Additionally, irregular influences can trigger dynamic changes within the river channel. Therefore, understanding these patterns, regular responses, and relationships forms the basis for future predictions. Predicting riverbank erosion is a complex task demanding diverse techniques to account for the multitude of influencing factors.

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These publications present a diverse array of methodologies and models for predicting riverbank erosion. Ashraf [3] introduces a predictive model combining a numerical model with the excess shear stress approach. Azlinda [4] develops a streambank erosion prediction model using an Artificial Neural Network Autoregressive Exogenous (ANNARX) approach. Hasanuzzaman [5] focuses on estimating and predicting riverbank erosion susceptibility and shifting rates using the DSAS, BEHI, and REBVI models. Varouchakis [6] suggests a statistical tool based on logistic regression to assess the likelihood of riverbank erosion. Several other studies [7-16] have introduced various techniques and models for predicting and understanding riverbank erosion. These findings offer valuable insights for land use planning, management strategies, and protective measures. Accurately predicting sedimentation and other natural phenomena empowers decision-makers with the knowledge to make informed choices and take timely actions to mitigate their impacts. These actions might include building protective structures, developing early warning systems, establishing evacuation plans, and formulating sustainable land-use policies, ultimately reducing disaster risk. Additionally, this enables more efficient resource allocation, targeted relief efforts in most at-risk areas, and enhanced preparedness and resilience in vulnerable communities. This also allows scientists and researchers to study and understand the underlying causes and patterns of these natural events, contributing to further advancements in disaster management strategies. In summary, forecasting sedimentation and other natural disasters is crucial for saving lives, protecting property, and minimizing the economic and environmental impacts of these events. By empowering societies to prepare, respond effectively, and adapt to the challenges posed by nature, forecasting becomes an essential cornerstone of disaster risk reduction and management.

2 Situation of landslides in the Mekong Delta

Prior to 1990, the Mekong River annually transported an average of 160 million tons of fine silt and 30 million tons of sand and gravel, replenishing the river, sea, and over 30,000 km of man-made channels in the Mekong Delta for thousands of years, signifying its critical scientific and ecological role. However, this dynamic shifted when the sedimentation-erosion rate reached equilibrium in 1990. By 2005, erosion began to dominate, exemplifying the changing environmental balance in the region. According to the Water Resources Department of Dong Thap province, from the beginning of 2023 to the present, there have been 19 consecutive erosion incidents within the provincial boundaries. Erosion is not limited to the Tien and Hau rivers but has also expanded to the internal channels of Chau Thanh, Cao Lanh districts, and Sa Dec city, with an erosion length of nearly 1 km, affecting 15 households and resulting in an estimated damage of close to 2 billion VND. Current data from relevant agencies indicates that the total length of riverbanks at risk of erosion in Dong Thap has reached over 130 km. Similarly, in An Giang, successive erosion incidents have occurred over the past month. From the beginning of the year to June 16th, there have been 36 instances of erosion, subsidence, and land fissures along riverbanks and channels, spanning more than 1.6 km in length, affecting 65 houses and resulting in damages exceeding 2 billion VND. Upon assessment, An Giang's relevant authorities have identified 56 riverbank sections flagged for erosion risks, with a total length of approximately 181.4 km, and around 20,000 households situated within the impacted areas.
In Vinh Long province, over the past approximately six months, 82 erosion sites have been recorded across seven districts and towns. The responsible agencies in this province have allocated nearly 5 billion VND for mitigation efforts related to these erosion incidents. Notably, a significant erosion event in December 2022 resulted in the loss of 5 hectares of land and the submersion of 12 houses in Binh Thuan 1, Hoa Ninh commune, Long Ho district.

The city of Can Tho has not been exempt from these issues. Since the beginning of the year, there have been 26 instances of erosion, representing an increase of 19 incidents compared to the same period in 2022. These occurrences spanned various districts including Cai Rang, Binh Thuy, O Mon, Thot Not, Thoi Lai, Phong Dien, and Vinh Thanh, with a combined length exceeding 930 meters. Consequently, 26 houses have collapsed or sustained damage, with estimated losses surpassing 20 billion VND.

3 Causes of erosion in the Mekong Delta

3.1 The geological and topographical factors of the Mekong Delta

The Mekong Delta, one of the world's youngest alluvial plains, rests not on solid bedrock like the Southeastern Region or other plains, but on sediment deposits dating back millions of years. Unlike the flooded areas in Dong Thap Muoi and Tu Giac Long Xuyen, which formed 4,000 to 6,000 years ago based on C14 analyses, the majority of the area was deposited during the early Pleistocene period (approximately 1.2 to 2 million years ago). This distinct geology results in limited stability throughout the foundation. Surface soils in areas like Dong Thap Muoi, Tu Giac Long Xuyen, and the U Minh peat swamp are primarily silty alluvium, formed from a thick layer of decomposed organic matter. Along the riverbanks lies a band of soft, fluffy alluvium, while sandy soils with decreasing cohesion dominate the coastal regions. These characteristics contribute to the high natural erosion potential of the Mekong Delta's surface soils, limiting their consolidation and resilience against river flows.

3.2 Impact of river flow dynamics

During the average flood season, the project area experiences high flow velocities ranging from 0.8 to 1.1 m/s and peaking at 1.5 to 2 m/s. These velocities consistently exceed the permissible averages for preventing erosion: 0.55-0.65 m/s for riverbanks and 0.3-0.5 m/s for riverbeds. This sustained high velocity over the extended flood season (5-6 months) presents a highly significant potential for erosion of the riverbed and banks, impacting adjacent roads and protective materials.

At river confluences, the flow dynamics become complex due to high velocities, particularly near tidal junctions. This complexity leads to intricate flow patterns and the formation of water eddies, which create deep erosion pits in the riverbed. When these unstable pits approach the bank, they can trigger landslides.

3.3 Erosion in the river sections near the sea, particularly at river mouths

River mouths, as transitional zones between oceans and rivers, exhibit complex flow patterns influenced by tides, upstream flows, coastal currents, and offshore waves. Human activities like shipping, fishing, and aquaculture further complicate these dynamics,
contributing to constant changes in riverbed morphology through erosion, sedimentation, and landslides. The river mouths flowing into the East Sea experience significant tidal variations (approximately 3-3.5 meters). During low tide, wind-driven waves and ship movements erode the base of the riverbanks, reducing their counterweight and increasing their susceptibility to erosion. The greater the tidal fluctuation, the more severe the base erosion, leading to faster erosion rates and larger landslides.

3.4 Impact of topography and riverbed morphology

Meandering river sections feature unique flow patterns due to their curved shape. These bends generate helical flows, where surface water travels from the outer convex bank towards the inner concave bank, while bottom flow moves in the opposite direction. The high velocity and impact force of the surface flow erode the concave bank, compromising its soil structure and potentially leading to bank collapse. This eroded material is then deposited on the convex bank by the bottom flow. Higher water levels occur on the concave side due to centrifugal forces, creating a lateral water surface gradient that drives horizontal flows known as 'helical currents.' These intense, single-direction currents combine with the main flow to form a spiral pattern. During floods, increased water velocity and force intensify these eddy currents within concave banks, leading to deeper and wider scour holes.

3.5 The impact of upstream exploitation

According to the strategic environmental assessment report by the International Centre for Environmental Management (commissioned by the Mekong River Commission), dam construction on the main river course could "devastate the Mekong River's ecosystem." China's dams in the upstream areas have "already partially affected the ecosystem." If a series of dams are added downstream, the threat is unimaginable. Data from the strategic environmental assessment report indicates a 75% reduction in sediment load (annual sediment deposition to the Mekong Delta reduced from 26 million tons to 7 million tons, and nutrients carried with the sediment annually reduced from over 4,000 tons to just over 1,000 tons). Approximately 2.3 - 2.8 million hectares of agricultural land (primarily in Vietnam and Cambodia) will become barren. Exploiting the upstream will alter the river's flow. The flood season's flow will become irregular, and the dry season's flow will tend to decrease, causing water levels to drop, increasing the risk of severe bank erosion.

3.6 The impact of upstream exploitation

Calculations for several rivers in the Mekong Delta region indicate that ships and boats with a load capacity of over 5 tons, when operating on the river, create a reverse current with a flow velocity greater than the sediment's initiation velocity in the riverbed ($v = 0,3 – 0,6$ m/s). For the reverse flow, boats with a load greater than 15 tons have the highest velocity near the bank, 1.5 - 5.0 times greater than the sediment's initiation velocity. This is also a cause of erosion and riverbank collapse, as well as damage to bank protection structures. Ship waves are a major factor in the erosion of riverbank systems. These waves do not cause immediate erosion but erode the banks over time. Waves can be caused by wind or by the movement of boats on the river. In the inland waterway system of An Giang province
and on the Hau river, waves are primarily caused by boats. In recent years, the Mekong Delta in general and An Giang in particular have seen strong socio-economic development, leading to increased transportation needs between regions. To meet the growing demands for transportation and goods movement, the number and speed of water transport vessels have increased. This increase in both the number and speed of vessels operating on the waterways has generated strong waves hitting the banks, causing alarming levels of erosion in many channels and canals.

3.7 The impact of sand mining on rivers

Given the Mekong Delta's geologically young nature, sand extraction activities result in the formation of vast depressions on the riverbed. These actions almost permanently modify the river's morphology and its inherent hydrodynamic characteristics. Researchers suggest that it takes centuries for sand deposits in rivers such as the Tien and Hau to form and stabilize as they currently appear. Considering the declining sediment influx due to upstream dam constructions, the anticipation of natural replenishment and restoration of these sand deposits post-extraction is implausible.

3.8 Riverbank erosion caused by excessive loading

The riverbank is initially stable, but during construction activities such as building houses, depositing materials, filling soil, and dredging riverbed sediments onto the bank, we inadvertently increase the forces that induce sliding. While these actions might not immediately disrupt the bank's stability under smaller loads, they can lead to significant erosion under larger loads. Structures encroaching into the river's channel, combined with the destruction of the bank's structural integrity, result in the formation of longitudinal and transverse cracks (due to uneven settling between adjacent structures with differing weights). The following figures illustrate the process of riverbank erosion at locations where structures are constructed along the riverbank's edge.

3.9 The impact of land subsidence

Land subsidence is an often overlooked factor when explaining erosion in the Mekong Delta. According to monitoring results from both domestic and international organizations, including findings from the "Rise and Fall" project (a collaboration between Can Tho University and Utrecht University in the Netherlands) and the Norwegian Geotechnical Institute (NGI), the average subsidence rate of the Mekong Delta stands at 1-2 cm/year in rural areas, and 2.5 cm/year for urban and industrial zones.

The primary cause of this land subsidence is the economic development and population boom, which have led to rampant groundwater extraction and rapid infrastructure expansion, exerting significant pressure on the soil. When the soil subsides, the top layer, which has a low cohesion, gets compressed and comes into contact with river currents and seawater. Consequently, the processes of erosion and landslides become more prevalent and tend to occur in a "domino effect" pattern. This means that when one area erodes, water quickly infiltrates the adjacent areas, leading to subsequent erosion pits.
4 Methods of forecasting riverbank, canal, and stream erosion

4.1 The method of map overlay

To understand the long-term changes in river courses over several decades, it is essential for the planning and development of important infrastructure and regions along these rivers. With the advent of scientific and technological advancements, digital tools for forecasting spatial developments are now commonly used both globally and domestically. These tools rely on digitization and the superimposition of non-photographic maps and satellite images spanning multiple years.

By superimposing multi-year maps, the pattern of changes in the river sections of interest can be identified. This forms the basis for predicting future changes in the river course over the forecast period. For instance, by determining the average displacement speed of a river section over several years, its future position and the necessary prediction times can be anticipated.

The implementation process begins with the digitization of multi-year images. These digitized maps are then superimposed based on fixed landmarks on the terrain in the captured images. Subsequent steps involve executing algorithms to calculate displacement distances and rotation angles over different periods. The final step involves determining the position of the riverbank after the forecast period. Figure 1.9 illustrates the superimposition of digitized maps used to determine the pattern of changes in the Mekong River over time.

Various methods, ranging from traditional to technologically advanced ones employing cutting-edge information technology, are available for predicting the erosion of riverbanks, canals, and streams. This article aims to delve into a few notable methods.

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With a simpler approach, but the accuracy is not high when using Google Earth software with images taken at different times, depending on the location of the study areas. The limitation of this prediction method is its low accuracy, it only predicts on a plane without indicating the time period when erosion occurs.
4.2 Analyzing terrain documents of the riverbed over many past years

This forecasting method is constructed based on the exploitation and analysis of terrain measurement data of the river over many years. Through the process of analyzing and calculating this data, the patterns of the entire river, individual river sections, or specific areas on the plan, longitudinal and cross-section can be determined. On the basis of these discovered trends, we are able to predict future trends over preset time periods.

Firstly, it is necessary to collect data on the riverbed terrain (including the plan, longitudinal and cross-section), hydrological information, flow, silt, spatial data, and images from the Global Positioning System satellites of the river sections being studied. Based on these data, the pattern of the riverbed on the plan, longitudinal and cross-section is determined by constructing the evolution diagrams of the deep lines and cross-section for all documented years, as well as for a number of years with similar common characteristics.

Next, the relationship between the riverbed evolution on the plan, longitudinal and cross-section with factors such as hydrology, flow, the physical characteristics of the soil forming the river bed and bank, wave factors, and many other factors are also established. The hydrological flow regime during the time period required to forecast erosion and deposition is also predicted. In case of difficulties in predicting the hydrological flow regime, the hydrological flow regime of a typical year can be chosen as a reference.

Finally, based on the identified evolutionary laws and analysis of actual trend evaluations, the speed and scale of erosion and deposition for each required time point will be forecasted.

This method offers the significant advantage of providing a detailed visual image of the river's morphological changes over different periods, the shifts and deformations of channels and rivers, and more. However, it also has drawbacks such as a lack of long-term data, inconsistency in map measurement ratio, unevenness in coordinates, especially the sinking situation of the current posts. Therefore, the forecast results may encounter large errors.

4.3 The forecasting method based on the changes in the riverbank structure

This is a novel method capable of predicting riverbank erosion and construction subsidence by preemptively identifying soil defects such as: sand leakage, termite nests, heterogenous soil composition, mud pockets, poor soil layers, plastic deformation zones, and so on. This method is entirely capable of accurately determining the location and size of defect zones in the soil up to a depth of 30 m, yet to assess the stability level and potential for erosion and subsidence, there remain several difficulties. Generally, long-term monitoring or the combination with other supplementary research methods is required.

Georadar (GPR) is a geophysical exploration method; hence, for various survey objects, it should be combined with very low frequency (VLF) electromagnetic methods, multi-electrode electrical methods, seismic exploration, etc., to investigate the geology of works on dyke routes, embankment roads in erosion areas, and building foundations.

GPR is a geophysical method applying principles of high-frequency electromagnetic waves (12000MHz) to study the structure and characteristics of substances underneath the ground without excavation. The most advanced devices currently used in Vietnam include the pulse EKKO100, Ramac/GPR, and Ingegneria Dei Systemi (IDS) Detector Duo. The final result from GPR is a high-resolution cross-section of the real-time structure of the substance beneath the ground, from which the geological formation of soil layers and defects or
abnormalities of the soil layer can be analyzed and evaluated, thereby predicting the stability potential of riverbanks or protective construction works.

4.4 The forecasting method based on changes in geomorphological features

Before a riverbank erodes, cracks often appear, and houses and trees start to lean or shift positions. These are the foundations for specialists to monitor at-risk areas of riverbanks and estimate when erosion might occur. The stability or instability (erosion) of a riverbank depends on the relationship between resisting and driving forces. If the driving force is greater than the resisting force, the riverbank will erode, and vice versa. Therefore, when there is heavy rain, and the riverbank becomes water-saturated, and the river level drops at low tide, erosion can occur. Based on this principle, if we carefully observe and monitor the riverbank area, understand the tidal pattern, and forecast significant early-season rainfall, we can accurately predict the location, timing, and scale of the erosion.

4.5 The mathematical modeling approach

The method of predicting erosion using mathematical models is a method that employs mathematical tools, with the aid of electronic computers, to simulate the erosion process in a particular area or location under the influence of a continuous stream over a period of time. This method then uses this simulation to predict future erosion for that particular area or location.

The general requirements for studying and forecasting riverbed changes with a mathematical model are: a computer with large memory and high processing and calculating speed; the boundary conditions, initial conditions, and model verification documents must be accurate; the mathematical model must be robust and accurately simulate the actual conditions and evolution process; it must have documentation predicting the flow, including its magnitude and continuous evolution process. In cases where there is no forecast documentation available, one can choose the flow mode of typical years, or repeat the evolution process for several consecutive years in the past.

The method of predicting erosion with a mathematical model is a modern method based on logical scientific theory. However, the field of sediment transport, sedimentation, and morphological changes is one of the complex scientific areas with many unresolved issues. To date, deterministic theories aimed at describing the physical processes of sediments, especially cohesive sediments, that are governed by natural laws have not been fully developed due to the vast array of external forces acting simultaneously on these complex physical processes. Current mathematical descriptions of erosion/deposition processes are merely empirical, even though they are constructed based on "given" foundations that are deemed to be physically law-based. These empirical formulas often come with numerous parameters related to sediment layer characteristics such as sediment layer thickness distribution, bottom sediment particle composition, suspended sediment, bed shear stress to erosion/deposition threshold, etc. However, the actual measurement data are very limited, so these parameters must be considered as model calibration parameters. Even the sediment boundary of the model is mostly constructed from very scattered actual measurement data series and also needs to be considered as a model calibration parameter. For the reasons mentioned above, the sediment transport model and morphological evolution always potentially contain large errors. Therefore, regardless of whether the model has been
validated or not, users must always consider whether the simulation results are consistent with (the trend of) reality. Currently, there are many mathematical models simulating the morphological evolution process of rivers and seas such as: the MIKE model family of the Danish Hydraulic Institute (DHI Water & Environment), the American HEC model, the WROCLAW model of the Warsaw University of Agriculture (Poland), etc. Some notable models include: the SWAT hydrological and watershed erosion model; the 1D model simulating hydraulics, sediment transport and morphology of the river system (MIKE11-ST...); the 2D/3D models simulating morphological evolution, erosion evolution in detail areas (Sobek/Delft3D; MIKE21C, MIKE21/3 FM ST/MT).

4.6 Physical modeling method

Similar to its mathematical counterpart, the physical model bases its methodology on conditions of similarity between the real-life flow conditions in rivers or channels and a downscaled representation in a laboratory setting. This process involves meticulous measurement and monitoring of the evolution of the experimental river section, subsequently leading to an analysis and projection of potential future scenarios. The experiment with a physical model can be performed using either a fixed-bed or a movable-bed model. Although the latter can yield highly accurate predictions that closely mirror real-world situations, it comes with significant cost implications.

4.7 Empirical formula forecasting method

The result of this method is the development of an empirical formula for calculating the rate of channel bed evolution, based on actual measurement data or locating a suitable domestic or global empirical formula that can accurately evaluate the evolution process for application. Finding an appropriate formula for application is by no means straightforward. Therefore, in this study, we may present two empirical formulas for calculating the erosion rate of riverbanks for each river cross-section in two regions with data - Thườn Phoccer and Sa Đéc. These are also the two regions with the highest riverbank erosion rates in the Mekong Delta.

Simulating the process of riverbank erosion using mathematical formulas is a complex challenge. Riverbank erosion depends on many factors, with intricate relationships and dependencies amongst them, which are difficult to assess and distinguish clearly. If we denote Bx as the rate of lateral riverbank erosion over time, it can be represented as:

\[ B_x = f (\text{Streamflow, seepage, channel bed, waves, bank load...}) \]

If we only consider the two main factors, which are streamflow and the channel bed, the expression to calculate the rate of lateral erosion is not any simpler because: Streamflow can only be fully evaluated when its magnitude, direction, structure, and duration are known; The channel bed factor affecting erosion depends on many aspects of channel bed shape, physical properties, particle composition, distribution of soil layers constituting the channel bed...

Despite recent scientific advancements worldwide, the calculation of the bank erosion rate still applies empirical formulas. For example, the empirical formula for calculating the bank erosion rate for curved river sections proposed by Ibadzade is still in use:
in which:
\(B_x\): Lateral erosion rate (m/year) at cross-section \(i\);
\(B_{xo}\): The highest lateral erosion rate (m/year) in the studied section in the past;
\(R_i\): Radius of curvature at cross-section \(i\) (m);
\(B_i\): River width at cross-section \(i\) (m);

The empirical formula for calculating the erosion rate by Popov, constructed from data sources that track erosion patterns over several years on rivers in Central Asia:

\[
B_{xi} = B_{xo} \cdot \exp \left( -\alpha \frac{R_i}{B_i} \right)
\]

in which:
\(F\): The area of the eroded riverbank over the time period of \(T\) years (m\(^2\));
\(L\): Length of the eroded riverbank for each phase (m);
\(T\): Duration of erosion (years);
\(H_{maxi}\): Maximum depth at the \(i\)th cross-section (m);
\(H_{max}\): Maximum depth of the studied erosion segment (m);
\(H_o\): Stable depth (at the cross-section beyond the limit) (m).

Several formulas have been further refined or augmented with additional variables, such as velocity and the temporal extent of velocity sustenance, as well as adherence to the conduit's prescribed non-erosive velocity limit, among others.

5 Conclusion

Riverbank erosion in the Mekong Delta is extensive, severe, and worsening. This phenomenon results in significant losses of human life, property, and economic potential, thereby constraining the region's socio-economic development.

Several factors contribute to riverbank erosion in the Mekong Delta, including geological and topographical factors, upstream water resource management, waterway transportation activities, sand mining, changes in sediment load, and land subsidence.

Predictive methods for riverbank erosion in the Mekong Delta include the map overlay technique, analysis of historical riverbed data, forecasting based on changes in riverbank composition and geomorphological characteristics, mathematical modeling, physical modeling, and application of empirical formulas.

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