

## THE MEKONG RIVER TRAINING ALTERNATIVES FROM ENVIRONMENTAL FRIENDLY SOLUTIONS

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**Abstract:** *Due to the presence of a big river and alluvial geological conditions, the Vietnam Mekong delta (VMD) is prone to landslides, resulting in numerous vulnerable areas where erosion and land subsidence can occur frequently. In addition, the concentration of major cities and densely populated areas (such as Long Xuyen, Cao Lanh, Can Tho, Vinh Long, My Tho, Ben Tre) along rivers, which is often preferred due to their historical, economic significance, may pose a notable risk of riverbank collapse. Based on statistical data from 2019, approximately 393 areas in the VMD have been impacted by riverbank erosion, this has resulted in significant damages to both the economy and threatening human lives in the areas. Various river training alternatives for the Vietnam Mekong delta have been progressively implemented, starting with basic studies and the development of plans aimed at stabilizing river morphology. These efforts are geared towards ensuring river flow stabilization and promoting social-economic development. Among the interventions including both hard and soft solutions for river training in VMD, the article introduces a number of possible environmentally friendly solutions, such as, directing the flow, flow vortex solutions to adjust the sediment transport and riverbank protection measures. Each solution is accompanied by calculations and cost estimates, indicating their feasibility and potential for implementation.*

**Keywords:** *Mekong River, River training, riverbank environment, riverbank erosion*

### 1. INTRODUCTION

#### 1.1. The Vietnam Mekong Delta and the current status of riverbank erosion

The Mekong River has its source on the Tibetan plateau at an altitude of approximately 5,000 meters, and flowing through six countries, namely China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. At the end, it forms the Vietnam Mekong delta (VMD). The Mekong River ranks as the twelfth longest and tenth largest river in the world with the length of approximately 4,500 kilometres and an average annual water volume of around 475 billion cubic meters. The Vietnam Mekong Delta (VMD), which is inhabited by 18 million people, spans across an area of approximately 41,000 km<sup>2</sup>. Out of this, about 24,219 km<sup>2</sup> of

land is utilized for agriculture production, while 8,000 km<sup>2</sup> of deltaic area is designated for aquaculture. The aquaculture sector in VMD is estimated to yield nearly 2.7 million tons of production, accounting for approximately 70% of the national aquaculture output, as per the 2017 estimates (General Statistics Office Of Vietnam, 2020). The division of water flow between the main Mekong River and the Bassac River at the delta apex, also known as Chaktomuk junction in Cambodia territory, is uneven, with the majority of water flowing into the main Mekong. Within the VMD, the water fluxes at Tan Chau monitoring station, located along the main Mekong channel also named as Tien River, are considerably higher than those at Chau Doc monitoring station, situated along the Bassac River also named as Hau River. The main population centres in the Mekong Delta residing in riverside areas due to local customs such as

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Can Tho, Long Xuyen, My Thuan, and My Tho (Figure 1).

The erosion of riverbanks is a natural occurrence influenced by the balance between river morphology and sediment transport, with the riverbank being the focal point. When there is an instability imbalance, landslides may occur. This process happens continuously and is influenced by various factors such as ship waves, weak sand, soil load, lowering water level, and excavation for fish ponds. In this region, there are numerous locations where landslides pose a significant threat. According to findings from the Southern Institute of water resource research (SIWRR), as of 2019, the VMD river system had 123 points along the riverbank that were identified as dangerous landslide areas, spanning a total length of approximately 231 km. Out of these, 65 spots were particularly severe, covering a total length of 101 km. Recently, the pressure of socio-economic development and climate change has led to extensive sediment dredging, exploitation, and alteration of the river's main flow, further impacting the stability of riverbanks.

For example, the Intergovernmental Panel for Climate Change (IPCC) has identified the VMD as one of the most vulnerable areas globally to climate change. The study estimates that climate change could alter the hydraulic regime of the delta, leading to a potential increase of 16-19% in maximum monthly water discharge, while minimum monthly water fluxes could decrease by 26-29% (IPCC 2007). The report has also highlighted that if sea levels rise by 1m, half of the mangrove area in the delta (2,500 km<sup>2</sup>) could be lost, and nearly 1,000 km<sup>2</sup> of land used for agriculture and aquaculture could be converted to salt marsh. In addition to global climate change, there are growing concerns about the sustainability of the delta due to various human activities in the region. The Mekong River Commission (MRC 2015) reported that there are currently 37 hydropower dams either existing or planned on the Upper Mekong mainstem. Furthermore, in

the Lower Mekong basin, there are 164 hydropower dams that are either operational or proposed in the river mainstem and tributaries, with at least 88 dams planned to be commissioned by 2030 (ODM, 2020). This significant expansion of hydropower dams will have a significant impact on the flow dynamics of the system. It will increase water fluxes during the dry season and reduce flood peaks during the wet season, (Blackmore and Stein, 2004; Lauri et al., 2012). River impoundment, caused by the construction of dams, has significant impacts on sediment transport in the Mekong River Delta. Lu et al., (2014) showed that sediment load in the Mekong between 2008 and 2010 was drastically reduced to between 50 Mt/yr and 91 Mt/yr, compared to the pre-dam period estimates of 150-160 Mt/yr. This sediment supply reduction is further exacerbated by increasing rates of sand mining in the delta distributary channels. Jordan et al., (2019) estimated that sand extraction volumes were  $4.64 \pm 0.31 \text{ Mm}^3/\text{yr}$  ( $6 \pm 0.4 \text{ Mt/yr}$ ) in 2018 for a 20 km stretch of the Mekong River in My Thuan City, Vietnam. This extraction quantity is many times larger than the total amount of sand influx into the delta, which has been suggested to be as little as  $6.18 \pm 2.01 \text{ Mt/yr}$  (Hackney et al., 2020). The sediment deficit has resulted in increased erosion rates of the distributary delta channels, causing them to deepen by an average of 2.5 m since 1998 (Vasilopoulos et al., 2021). This channel deepening has led to an extension of the tidal limit inland, resulting in saltwater intrusion (Eslami et al., 2019) and riverbank instability (Hackney et al., 2020) posing threats to lives and infrastructure across the delta system. Despite this pressing issue, research on river training regulation has been limited, and there is a lack of comprehensive planning and enforcement mechanisms to ensure the safe development of river corridors. Although some urgent measures have been taken, unfortunate incidents have occurred due to inadequate design and implementation of these efforts.

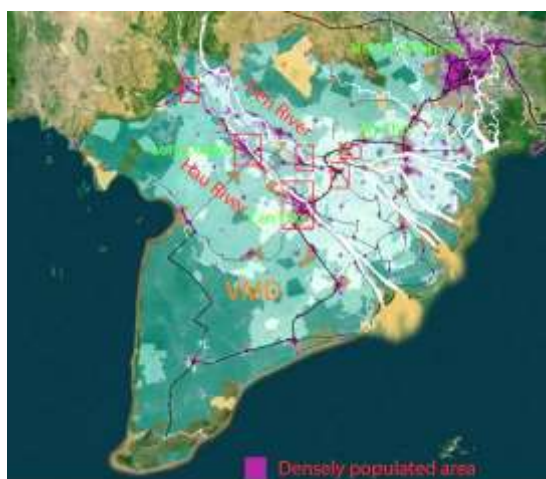


Figure 1: Concentrated residential areas in the Vietnam Mekong Delta



Figure 2: Overview of riverbank collapses areas in the Mekong Delta as of 2019 (source: VNDMA)

Table 1: Statistics of erosion areas on the river, canal and canal system in the VMD (source: VNDMA, 2019)

No.	Province	River bank erosion area			Riverbank deposition area		
		Number of river erosion locations	Length (km)	rate min-max (m/year)	Number of river deposition locations	Length (km)	rate min-max (m/year)
1	Dong Thap	59	15,5	1-20	14	14,5	0,5-5
2	Long An	21	24,6	0,5-10	11	35,5	0,5-3
3	Tien Giang	35	77,3	0,5-6	9	23,8	0,5-40
4	Vinh Long	25	61,8	1-10	11	31	1-6
5	Ben Tre	20	27,8	1-11	17	38,1	0,5-50
6	Can Tho	36	27,7	0,5-15	5	6,5	4-24
7	Hau Giang	20	31,1	1-6	10	25,1	0,5-3
8	Tra Vinh	32	74,9	0,5-30	16	31,3	0,5-5
9	An Giang	45	69,5	0,5-15	8	10,7	5-20
10	Kien Giang	10	22,5	1-10	12	39,9	0,3-1
11	Ca Mau	48	109,6	1-30	14	97,8	0,3-1
12	Bac Lieu	24	14,5	1-30	14	49	0,5-2
13	Soc Trang	18	24,1	0,5-5	9	28	0,5-15
14	<b>Total</b>	<b>393</b>	<b>581</b>		<b>150</b>	<b>431</b>	

## 2. CURRENT STATUS OF RIVER REGULATION IN THE WORD AND PARTICULARLY IN VMD

### 2.1. Global river embankment development

Throughout history, river embankment has been a topic of interest, particularly in

civilizations located near major rivers such as the Yellow River, Yangtze River, Rhine River, Mississippi River, and Volga River. Over time, there have been two main approaches to river governance: traditional and modern. Traditional river management involves using corrective measures based on the natural

evolution of river beds to control the flow and channel of the river, aiming to stabilize the river and implement safety regulations for flood prevention, water transport, and river crossing. On the other hand, modern river governance focuses not only on achieving traditional goals, but also on integrating the ecological environment and landscape, creating spaces for recreation and relaxation, ensuring ecological balance, and promoting ecotourism services. Traditional river governance typically involves bank protection measures such as embankment reinforcement

to protect against floods and landslides. River cut-offs and creek sealing are often employed in river bends, while dredging, clearing, and breaking shallow thresholds are used in sections with complicated channels to adjust the channel size accordingly. From a modern perspective on river management, the focus is on creating living spaces and preserving the cultural environment that are adapted to water. River management works are now designed with multiple goals and functions, aiming for environmentally friendly solutions that yield positive outcomes.



a) Concrete riverbank



b) Concrete riverbank protection combined with landscape

*Figure 3: River management works are based on different points of view:  
a) traditional view, b) modern point of view*

One of the most influential factors on the ecological system in river management works is the structure located at the interface between the water and the riverbank. This area serves as a crucial habitat for animals for feeding, sunbathing, laying eggs, and growing aquatic plants and other vegetation. Therefore, the use of fully concreted structures can have a significant impact on this ecosystem. Conversely, clever design choices such as incorporating stone blocks or concrete blocks can minimize the environmental impact. River governance today no longer solely relies on the natural evolution of riverbeds, but rather recent studies indicate

a trend towards direct intervention in river structures to address issues such as erosion caused by secondary flows. Underground works have been explored by various groups of researchers as a means to alter these structures, mitigating landslide damage while also preserving the natural landscape. In developed countries such as the USA, Netherlands, Japan, and France, there is a growing trend towards protecting and restoring the functions of rivers that have been previously hardened. On the other hand, developing countries like Bangladesh, Vietnam, and Brazil tend to prioritize exploiting rivers for economic purposes

without much consideration for their natural functions. In either case, investments required for protecting or restoring river functions can be substantial.

In developed countries, the 21st century is being hailed as the era of river renaissance. Notably, efforts to restore the river by removing old dams and implementing various measures such as welding mines, U-shaped and V-shaped embankments to protect shoals and regenerate the ecosystem have been carried out vigorously. For example, The Netherlands is a low-lying country with a history of managing water due to its vulnerability to river and sea flooding. With climate change and increasing risks of extreme weather events, such as heavy rainfall and river discharge, there was a need to develop a sustainable and adaptive flood risk reduction strategy. The project "room for river" is implemented by the Holland government with a total length of about 725km, the total value of this program is more than 2.3 billion Euro implemented in the period from 2000-2015. The project is based on the principle of "living with water" rather than "fighting against water," and it employs a multifaceted approach that includes river widening, dike relocation, excavation of floodplains, and creation of retention areas to store excess water during floods. The project involves a combination of engineering and nature-based solutions to achieve flood risk reduction, ecological enhancement, and spatial quality improvement. By creating additional room for rivers to flood, the project aims to increase flood safety for people and infrastructure, while also improving the ecological and recreational value of river area (source : Henk Nijland; <https://urbannext.net/room-for-the-river/>; <https://www.dutchwatersector.com/news/new-tap-splits-rhine-highwater-with-great-accuracy-over-two-rivers>).

The Yangang Creek basin, located in a

highland drainage area, was prone to potential flood disasters. Prior to the restoration efforts, the creek suffered from insufficient drainage sections, excessive meandering, overgrown vegetation, and severe siltation. As a result, frequent flooding occurred during heavy rainfall events. To address this issue, the project conducted by AEC geosynthetics company aimed to eliminate flooding disasters by widening the channel. The restoration approach adopted a combination of aesthetic landscape design and eco-friendly construction methods to achieve a harmonious and balanced relationship between the project and the natural environment. Two types of revetments were utilized based on site conditions: simple reinforced concrete and stacked ACEModule™. Its precast concrete structure and hollow design made construction easier and offered significant advantages in terms of safety, simplicity, landscape enhancement, and eco-friendliness (<https://www.geoace.com/>).

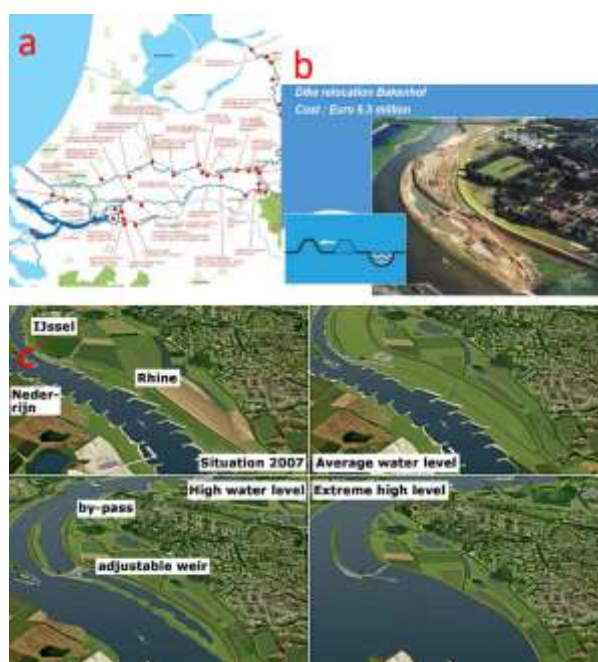


Figure 4: (a) The "room for river" project (Source: Ruimte voor de rivier

official organisation); (b) Dike relocation at Bakenhof (source : Henk Nijland);



(c) Effective flood prevention and landscape creation of the project



Figure 5: the applied the ACEModule™ technology for riverbank protection (a) the construction was building and (b) after the project is completed. (<https://www.geoace.com/>)



Figure 6: The globally built modern river regulations, (a) Huangpu river banks, Shanghai, China ; (b) The combined torch system creates favorable conditions for the development of aquatic species in the Yodo River, Japan; (c) Vegetative cover over dyke structure (Germany); (d) Soldering iron combined with landscape on the Rhine - The Netherlands; (e; f) Corrective design combining landscape on Fox River (USA).

It can be asserted that riverbank protection techniques are now being designed with greater flexibility, incorporating both

structural and non-structural solutions to minimize investment costs while maintaining stability in river morphology. Permanent infrastructure is typically only constructed in areas where urban protection, population, key cultural and infrastructure assets are located, while temporary measures such as dredging through the sea can be used in less populated areas. Moreover, riverbank protection efforts are now more mindful of delineating urban areas and ecological zones, and prioritize preserving the aesthetic appeal of the river. In many urban areas, efforts are made to enhance the water surface and landscape design, with the use of various architectural elements to add to the overall beauty of the river.

## 2.2.Existed technical solutions for riverbank protection in the VMD and the limitation

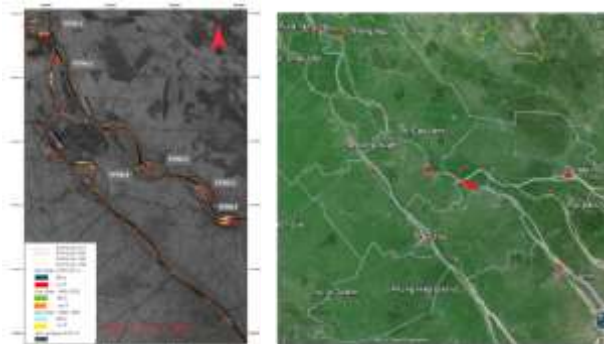


Figure 7: Bank erosion areas (left) and bank protection embankment areas (red areas) (right) for the year 2021 (Source: SIWRR)

Up to now, the riverbank protection works

along the Tien and Hau rivers are very few compared to other rivers in our country. Due to the significant width and depth of these rivers, the cost of implementing riverbank protection measures is substantial. Therefore, the primary focus is on safeguarding densely populated urban areas. Some areas that have been protected along the Tien River include Hong Ngu, Sa Dec, Vinh Long, My Tho, and some parts of Tra Vinh and Cua Tieu Tien Giang; and along the Hau River, there are Chau Doc, Long Xuyen, and Can Tho (Figure 7).

The solutions currently applied in VMD are mostly inclined or partially inclined revetments, with typical structural types as shown below:

Type 1. Inclined roof embankment, applied at: Tan Chau, Hong Ngu, Vinh Long. This type of embankment is used mostly on Tien and Hau rivers because of their ease of construction, suitable for domestic construction conditions, and current conditions of construction equipment and human resources. However, embankment protection in this deep river area, filling the erosion hole to create stable embankment foot is very expensive, accounting for more than 50% of the cost of the project (Figure 8).

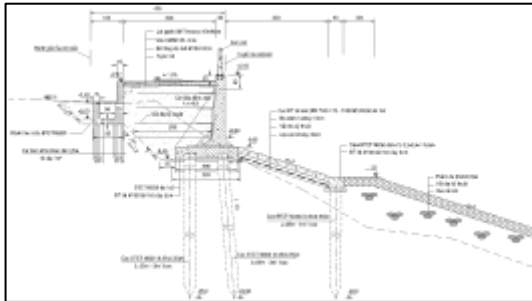
Type 2. Embankment protection half vertical, half inclined, applied in Can Tho and a few places in Long Xuyen, Vinh Long. The typical structure of this embankment is shown in Figure 8. With this structure, the top wall is made with the form of an earth retaining wall placed on a pile system, and the outside is protected by a sloped embankment. Most of the cost of the structure is in the corner wall. This type of structure has been built in many places, especially in small and medium-sized rivers and canals, where the population is densely populated.

Type 3. Prestressed vertical wall embankment.

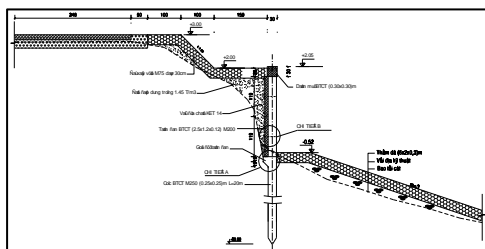
With the advantage of prefabricated piles, it ensures that the construction quality is controlled at the place of production, construction is fast, and there is little need for site clearance. The vertical wall prestressed embankment has been applied on the Tien River, the section passing through the My Tho city. The most difficult condition for calculating this type of embankment is the calculation of the length of the pile and the prediction of the lateral load capacity of the pile, under normal working conditions or under erosion of the building's toe. This structure has been used a lot in the system of rivers and canals, My Tho is the first place to use this type of construction to protect the banks of the Tien River (Figure 8). Although prestressed embankments offer benefits such as effective quality management, accelerated construction, and lower site clearance costs, their overall cost is significantly higher due to the expenses associated with materials and material transportation.

Type 4: Welding pile embankment. Australian experts have been utilizing a special underground structure since 2002 to provide stable protection for the river section near the My Thuan bridge. This structure, known as a pile welding torch system, consists of 12 welding torches spaced 200m apart, with each torch measuring 100m in length. The concrete piles used are 45cm in diameter, and the distance between the piles is 1.125m. Additionally, a stone fall protection system has been implemented at the foot of the piles to prevent local erosion. This bank protection project, based on the (Tilleard and Ladson, 2014) structure, was the first of its kind to undergo physical modeling at the Institute of Water Resources research (SIWRR) and be applied in the Tien and Hau river areas. After three surveys conducted by the Australian team of experts, it was found that the area's

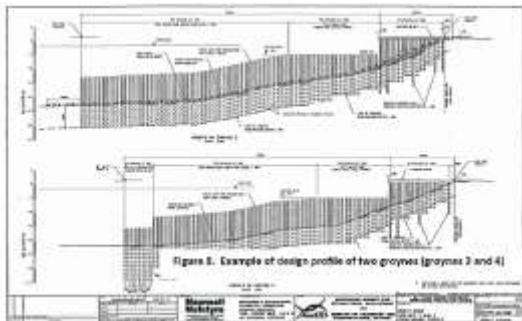
landslide situation had ceased, and shore stability had been restored. This project serves as an important case study, providing



Cross section of Embankment Type 1, 2



Cross section of Embankment Type 3



Cross section of Embankment Type 4

*Figure 8: The current technical solutions for riverbank protection in the VMD*

However, there are currently limited bank protection works to prevent and mitigate landslides on Tien and Hau rivers, particularly on river bifurcation. Investing fully in erosion areas, as identified from remote sensing images, would be costly and impractical given the country's current socio-economic conditions. Most of the existing protection constructions are embankments with inclined roofs, which are relatively low cost and easy to construct. However, there is a lack of effective evaluation and detailed study after their implementation. These embankments

detailed insights and solutions for stabilizing riverbank.



The location applied (Tan Chau, Dong Thap Province)



The location applied (Rach Mieu, My Tho)



The location applied (My Thuan Bridge)

are not environmentally friendly and are prone to subsidence when eroded, similar to the current semi-vertical and semi-slanted structures. The use of prestressed embankment works with anchor rows inside may not be advantageous in terms of reducing ground clearance costs, as the stability of the embankment depends greatly on the strength of the mooring line. Additionally, this type of construction is not environmentally friendly. The pile welding project, which has shown promising results, requires detailed study and application in

specific locations. While it has moderate costs, good shore stability, and ease of construction without requiring ground clearance, the calculation and design techniques can be complex. Non-structural solutions, which provide long-term strategies to adapt to landslides and gradually mitigate them, have not been thoroughly applied or given sufficient attention due to limited resources in the country. These solutions include planning and planting landmarks to restrict activities in the landslide corridor.

### **3. PROPOSING NEW SOLUTION FOR RIVER TRAINING**

#### **3.1. Basic view to propose solutions to regulate and stabilize the river**

- The realignment of the river must be done in accordance with the natural river position, avoiding obstructions that could significantly disrupt the flow patterns of the main tributaries.
- The chosen river realignment route should serve as a key waterway traffic axis, functioning as an "efficient water transport axis" throughout the seasons, in order to optimize socio-economic development in various sectors and regions.
- Efforts should be made to minimize investment in infrastructure works and mitigate any adverse effects on existing built infrastructure caused by landslides.
- Islets with established populations and livelihood activities should be protected, while younger islets can be dredged to regulate the flow.
- The river realignment plan should be carefully balanced and calculated for each specific period, taking into consideration factors such as climate change and upstream exploitation, while also considering the inheritance and updating of properties.

#### **3.2. Proposing solutions for riverbank protection**

Compliance with the master river management plan is essential for

construction investments. However, as the master river management plan is not yet available, it is necessary to develop a comprehensive plan for river management. Without proper planning, the design work cannot ensure optimal benefits for all economic sectors. Making investments in inappropriate projects may result in conflicts with other objectives in the future, particularly in terms of river morphology and unfavourable changes in the channel bed. Furthermore, due to the lack of an established correctional route, the project's scale may not be reasonable. For instance, extending the work both upstream and downstream may be necessary to ensure its effectiveness or completion. However, such changes in the channel after the investment is completed could render the project ineffective and result in wastage. Therefore, a thorough study of the historical development of the river section or calculations using mathematical or physical models is necessary to determine the appropriate investment location and scale for economic viability.

##### ***3.2.1. Design of dredging and river widening***

When shoals converge in a creek, they can disrupt the flow in curved rivers with V-shaped cross-sections that are skewed to the left or right. Additionally, banks in the middle of young dunes can cause sedimentation, narrowing the channel and obstructing navigation while altering the flow. To address these issues, dredging and clearing solutions must be implemented based on calculations of width, length, and dredging depth that take into account a stable cross-section and ensure a smooth flow. In the Tien and Hau river systems, shoals are frequently observed. Therefore, when dredging, it is crucial to prioritize environmental pollution control to prevent any negative impact on aquaculture areas. It is essential to calculate and evaluate changes in flow before and after dredging to ensure optimal results. Monitoring and measuring sediment return during the process

of maintaining flow is also necessary, as this area often experiences sediment accretion. Stabilizing the river potential is crucial in mitigating these issues. The areas where rivers diverge, confluence, and form distributaries are prone to high sediment accumulation, as depicted in the picture. Sedimentation can alter the rates of distributaries and confluence, negatively impacting the overall river morphology. Hence, dredging and clearance are necessary to maintain stability in these areas and mitigate the effects of sedimentation. When conducting dredging in these river sections, careful consideration must be given to the impact on flow dynamics, as well as the prevention of post-dredging landslides.

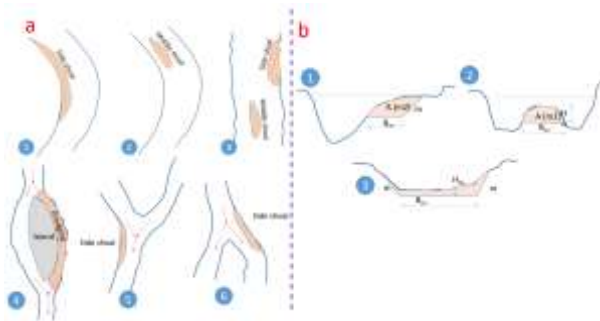


Figure 9: (a) The areas that require dredging are the convergence and bifurcation points where sediment accumulates and (b) Types of dredging in Tien and Hau rivers

For Type 1 dredging, which involves side-shore dredging, various parameters need to be calculated, including dredging length ( $L_{nv}$ ), width ( $B_{nv}$ ), dredging area ( $A$ ), height  $H_{nv}$ , and slope coefficient ( $m$ ), to prevent landslides. Similarly, for Type 2 dredging, which involves adjusting the river section, calculations must be made to assess the changes in flow before and after the adjustment. Dredging parameters and design water level must be determined to ensure the safe participation of floating vehicles in the dredging process. Type 3 dredging, which may involve the use of dredges or suction vessels, requires stability calculations for the roof coefficients. Additionally, the dredging route must be checked for obstructions such as bridges,

culverts, and pumping stations to avoid disruptions during dredging operations.

### 3.2.2. Underground dam works

Underground dams have been utilized on the Mississippi River to adjust the distributive ratio of river creeks, particularly in areas with low demand for navigation. These dams are designed as sunken concrete embankments, strategically placed in specific river tributaries to regulate the distributive ratio. The advantage of this project is that it can take effect immediately after completion, allowing for adjustments to the distributive rate based on different water seasons, such as floods and dry periods. However, the construction, installation, and stability calculations are complex. Currently, there are no similar works in the Mekong Delta River system. Nevertheless, they could potentially be used in certain river sections to improve water sources and adjust the flow distributive axis for navigation, particularly in brackish areas where freshwater and saltwater sources fluctuate throughout the year, and where the flow regime is moderate with changing creek depths.

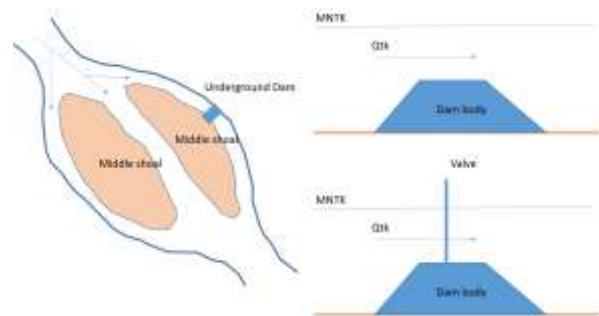


Figure 10: Application of underground dams to regulate flow distributive

### 3.2.3. Bottom vanes construction

The bottom fan is a concrete slab that is positioned on the riverbed, designed to obstruct the movement of bottom sand and facilitate natural clearance by coordinating erosion in the propeller area. It leverages the flow of water to cause erosion in the channel, redistributing sediment without the need for

equipment such as traditional dredging. The advantages of this approach include natural sediment redistribution following the water flow, and prevention of deep erosion. However, experimental calculations need to be conducted to determine its effectiveness, and this technology has not been applied in Vietnam yet. Nevertheless, it has been studied and applied in various locations around the world, such as Bangladesh and the Netherlands. The main purpose of this technology is to create turbulent flows near the riverbed to erode downstream, thus improving the natural distribution of sand in the deposited currents. This approach aims to avoid dredging and sand mining, which result in loss of sand without replenishment to the river system, particularly downstream where erosion may be severe. Currently, there are many ongoing research and physical model testing of this technology worldwide.

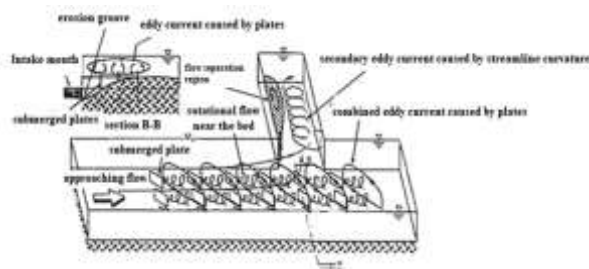


Figure 11: Bottom vanes structure (Serajian et al. 2020)

- Structure: This type of structure is installed on river beds to modify the direction of bottom flow. It is commonly used to adjust the flow of mud, sediment, and alluvium in rivers, with the purpose of controlling river bank erosion and changing the cross-section of the river bed. The structure is typically designed as a concrete casting and can be either flat or equipped with scour holes.
- Size and arrangement: The structures are

positioned to create an angle  $\alpha$  with the direction of flow, typically ranging from 100 to 300 degrees. Placed on river beds, these structures induce eddy currents by altering the balance between lateral pressure and suction force. These eddies, in turn, cause changes in the downstream slope of the river bed. As such, these structures are utilized to modify the cross-section of the river bed.

When performing calculations, it is essential to conduct experimental calculations with varying heights and angles in different flow directions to determine the most optimal design for the project.

In this study, the MIKE 3D model is utilized to simulate the implementation of the construction method applied at the head of Tan Loc Island in the Hau River, Can Tho city. MIKE 3D is a numerical modeling software developed by DHI Group, a global leader in water and environmental management solutions. DHI Group provides a wide range of software tools, for hydrodynamic, hydrological, and water quality modeling. MIKE 3D is commonly used for simulating and analyzing complex three-dimensional flow and water quality processes in rivers, lakes, coastal areas, and other aquatic environments. The chosen structure is a flat plate with dimensions of  $L \times B \times H = 100 \times 20 \times 2$  (m), comprising of 6 structures arranged in 3 rows as shown in the figure, suitable for a flow direction at an angle of 200 degrees. The model simulated the construction work during the flood season of 2013, spanning from August to November. The comparison of peak flow velocity values during ebb tide and flood tide periods was done for two domain models: one without bottom vanes and the other with bottom vanes. The results of this comparison are depicted in Figure 13.

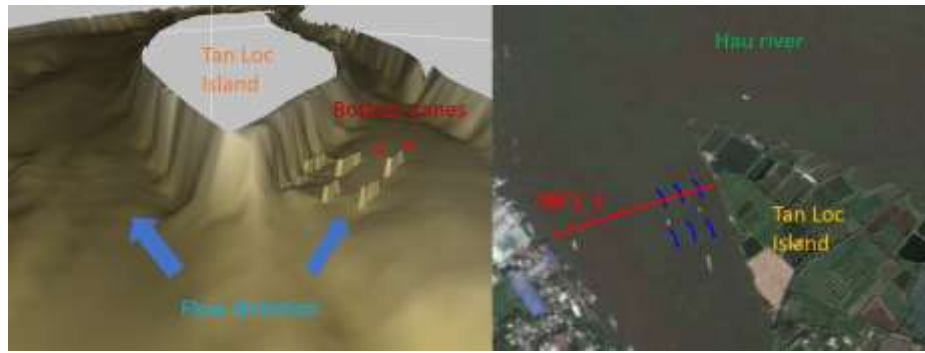


Figure 12: Simulation of Bottom Vanes construction on river bottom in 3D model,

(b) The schematic shows the location of the bottom vanes and the calculated cross section

During ebb tide (strongest river velocity), the horizontal and vertical velocity (Y, Z components: vector values) of the current were generally very small, with a maximum speed of about 0.3 m/s. However, in the presence of structures such as bottom vanes, the horizontal and vertical velocities increased significantly, with a maximum speed of about 1 m/s. Furthermore, the flow has a tendency to bypass the lower vanes, directly impacting the soil layer beneath the river, leading to gradual erosion of the soil layers and increased depth in the local topography. This phenomenon could potentially result in the expansion of the smaller downstream channel and contribute to the stability of the bifurcation. The results obtained in this study also supported by the findings of Thomas et al., (2011) in their physical modelling. They observed that in asymmetrical bifurcations, secondary flow cells form near the bed of the bifurcate channels, which can help maintain the subordinate bifurcate open despite reduced water discharge. Similarly, Marra et al., (2013)

demonstrated that secondary flow cells exist near the bed upstream of the nodal point, causing a larger portion of near-bed flow to enter the dominant downstream branch. This results in more sediment being directed towards the dominant channel, potentially leading to aggradation and driving the bifurcation towards symmetry. These findings collectively suggest that asymmetrical bifurcations may exhibit stability under a wider range of conditions and greater resilience to perturbations, as indicated by these two studies.

Therefore, in addition to the solutions already implemented and listed above, the implementation team is also exploring environmentally friendly solutions with reduced investment costs. The calculation details for pile and bottom vanes technologies have been obtained using 3D models, but further physical experiments may be necessary to establish a scientific basis and identify suitable locations for experimental application.

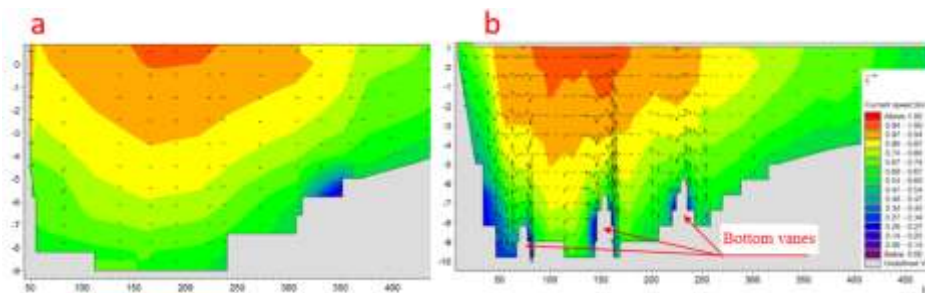


Figure 13: The velocity on section 1-1 at ebb tide (17h 00 1/9/2013); (a) without Bottom Vanes; (b) With Bottom Vanes. The colour present the the magnitude of the velocity in the direction

of flow (X component) while the magnitude of the vector represents the magnitude of the velocity in the horizontal and vertical directions (Y, Z components).

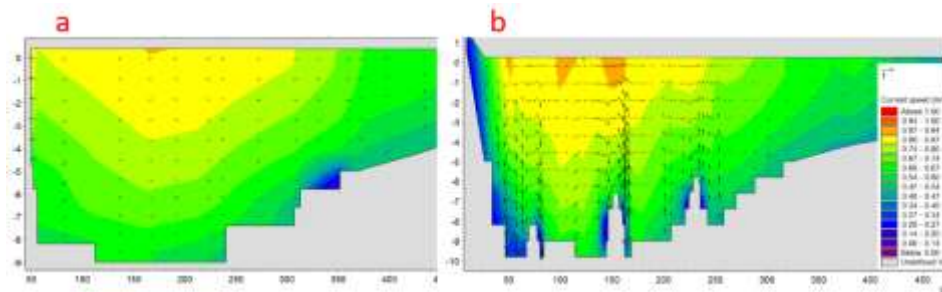


Figure 14: The velocity on section 1-1 at flood tide (0h 00 02/09/2013)

### 3.2.4. Floating fish houses

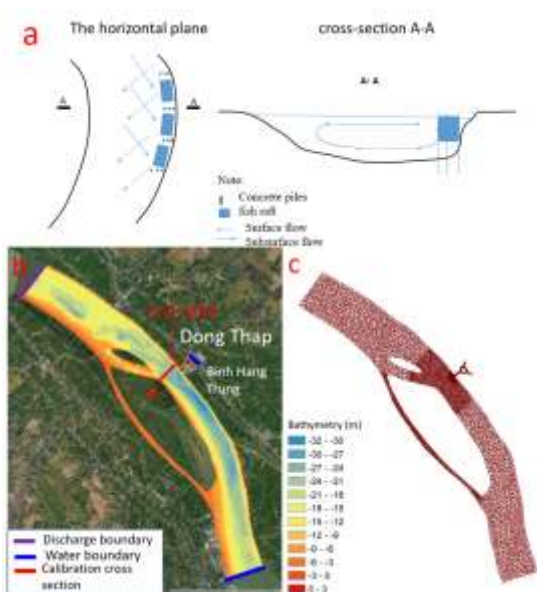


Figure 15: (a) Outline of fish raft arrangements and effects on the river velocity; (b) Study area with topography of the channel and simulated boundaries, (c) mesh used in the modelling

Due to the characteristics of the Mekong River cross-section, such as its wide riverbed, vertical slopes on both sides, and loose bank soil, the use of pile-supported fish rafts can provide advantages in mitigating riverbank erosion. The stability of the fish rafts in terms of anchors, electricity, and water supply is crucial for supporting daily life and maintaining an optimal aquatic environment for fish. However, due to limitations in investment for anchoring infrastructure, many households tend to choose shallow river sections with low velocity flow, which can result in increased risks of disease and

pollution in the environment. Based on actual investigations in farming areas with flow velocities of 0.3-0.5 m/s (after considering the resistance of the fish rafts), it has been observed that such conditions can promote better fish development and limit the occurrence of diseases. Therefore, considering the need for riverbank protection and the desire to create safe and adaptable fish farming areas, this study proposes and analyses solutions for mooring fish rafts, using computational modelling to determine appropriate locations. The fish houses were specifically applied to the Binh Hang Trung river section in Cao Lanh district, Dong Thap province, where there is a need to relocate fish rafts and prevent serious landslides in the region. The MIKE 3D model was utilized to simulate the functioning of fish houses, as detailed in the Journal of Science and Technology Water Resources No.72, ISSN: 1859-4255. The setup, calibration, and validation of the model were described in the publication.

Fish houses are currently positioned within the convex bank of the meandering river, resulting in strong currents passing through the left bank and causing significant erosion. To ensure stability for fish farmers and minimize landslides, we propose a solution that involves implementing fish rafts and dredging to clear the concave bank (Figure 15). This approach will provide stability to the area. In the modelling, the rearing area is divided into three groups of rafts, with each cluster consisting of 18 individual rafts that are 8m long, 6m wide, and

3.5m high. The entire cluster, when combined, has dimensions of 48m in length, 18m in width, and 3.5m in height, with 0.5m above the water surface and 3.5m submerged. The water resistance coefficient (denoted as "f") is 1.0 mean no allow the water flow through the fish house. The ponds are situated as shown in the diagram, with the clusters of rafts arranged along the length of the riverbank and the width (18m) acting as a circulation embankment with a depth of 3m from the water surface (Figure 15).

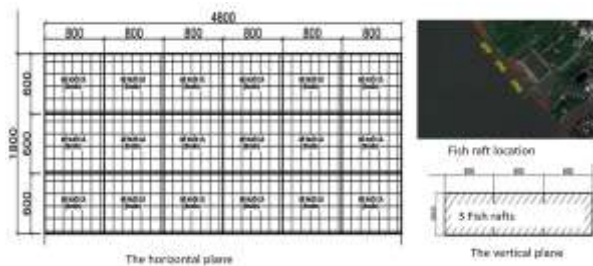


Figure 16: Size of fish rafts and small cages (18 fish rafts)

The simulation scenarios were configured to model the operation of fish rafts during the high flood season in 2011 including:

- HT0: Calculation for current flow (without fish rafts)
- KB1: Calculation for flow with fish rafts with drag coefficient  $f=0.3$  (allowing 70% of water flow through the vertical surface of the fish raft)
- KB2: Calculation for flow with fish rafts with drag coefficient  $f=0.5$  (allowing 50% of water flow through the vertical surface of the fish raft)
- KB3: Calculation for flow with fish rafts with drag coefficient  $f=0.7$  (allowing 30% of water flow through the vertical surface of the fish raft).

This extracted velocity is then combined with the surface flow direction relative to the riverbank direction to assess how the area with the fish rafts changes. Flow rates are extracted at positions on these cross-sections, corresponding to the top, middle, and bottom layers, as illustrated below (Figure 17). To analyze the impact on the velocity in the river

where the fish raft cluster settle, three cross-sections are selected for calculation, including:

- Cross section MC1-1: representing the fish raft head area.
- Cross section MC2-2: representing the area between fish rafts.
- Cross section MC3-3: representing the area at the end of the fish raft.

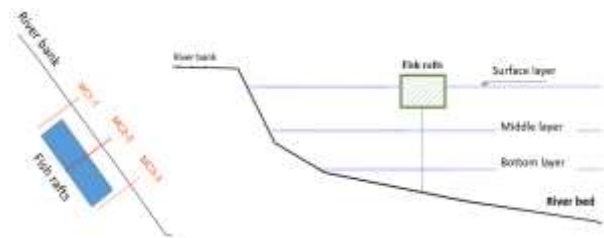


Figure 17: The cross-sectional positions evaluate the change of velocity flow

The figure below clearly demonstrates the effect of reducing the flow near the river bed as calculated on the 3D model. It indicates that a higher drag coefficient results in a greater ability to reduce water velocity, but this also means a larger investment in anchor piles. Therefore, it is important to choose the appropriate flow resistance coefficient based on specific conditions. When the drag coefficient is set to 0.7, allowing 30% of the water to pass through the raft barrier, it has a significant impact on the mainstream by pushing it away from the shore. However, the reduction in regional velocity may not guarantee sufficient oxygen and fitness for fish, as the decrease in velocity is also strong.

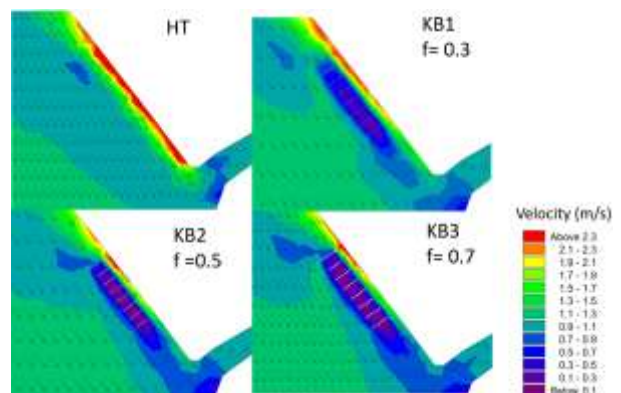


Figure 18: The change of bottom flow in each scenario

The calculation results reveal that the flow velocity in the area in front of the raft remains relatively unchanged, while the resistance coefficient increases. This suggests that a vicious current is likely to form in front of the embankment, causing an increase in inshore flow, as illustrated in the figure below. These results were observed during ebb tide (highest velocity)

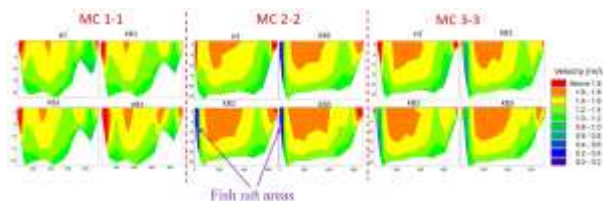


Figure 19: The simulated flow velocity at cross sections at ebb tide (September 16, 2011)

At section MC 2-2, located in the middle of the raft, it was observed that in the absence of fish rafts, the mainstream pressing close to the shore was pushed towards the middle of the river. Additionally, the nearshore current significantly decreased. However, the speed of the right bank on the side increased, depending on the size of the drag coefficient of water flow. At section MC 3-3, the results indicate that the fish raft has an effect on directing the current. This causes the main current to be farther from the shore behind the raft, resulting in a significant reduction in flow close to the riverbank.

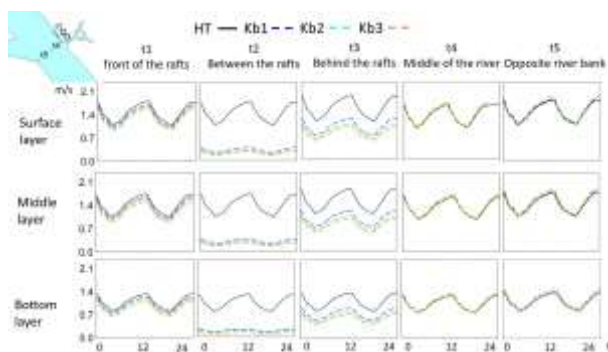


Figure 20: The simulated flow velocity at areas study in difference scenarios (September 16, 2011)

The figure depicted above illustrates that the velocity in front of the raft, between the river

and the opposite bank, does not exhibit significant changes across the water layers. However, noticeable changes in flow are simulated in the area between the raft and behind the raft. Specifically, the velocity decreases from 1.4 m/s to 0.5 m/s, depending on the specific location within that area. The calculations using 3D models demonstrate that a cluster of fish rafts can be utilized as an embankment to alter the flow direction and redirect the mainstream away from the riverbank. However, it is important to carefully consider the resistance coefficient, as a high coefficient may negatively impact the currents upstream of the fish raft. To achieve an effective effect with minimal impact on the head erosion of the fish raft area and downstream of the raft area, a current resistance coefficient of approximately 0.3-0.5 is recommended. The presence of fish rafts reduces the flow velocity close to the shore, which in turn helps protect the banks in curved river sections.

#### 4. CONCLUSION

The evolution of riverbeds and riverbanks is a continuous process influenced by both natural and human factors, with both positive and negative impacts that researchers aim to understand and manage. Over the years, scientists in this field have proposed various structural and non-structural solutions to control and mitigate these impacts. In recent decades, with the increasing pressures of economic development, climate change, river morphological changes have become more severe. To effectively tackle the challenge of riverbank stability while considering landscape aesthetics, environmental sustainability, and compatibility with modern living standards, a range of solutions have been proposed globally. In this study, several river management options were proposed that prioritize environmental sustainability, regional economic development, and cost-effectiveness, which could potential apply for the VMD. These options aim to achieve long-term flow stabilization and have the potential to be implemented in various areas in VMD. Detailed summaries of these options are provided below.

- Various alternative environmental solutions have been introduced, offering multiple choices for addressing riverbank erosion and deposition areas through training and protection measures. These options can be carefully selected and applied to effectively manage and mitigate the impacts of erosion and deposition along riverbanks.
- Dredging can potentially improve water distribution in the branches area of rivers. However, it may also lead to imbalances in sediment transport, as excessive dredging in deposition areas could contribute to higher erosion rates. Therefore, careful consideration should be given to the budget and location of dredging activities, taking into account the sediment dynamics and erosion rates in order to achieve a more balanced approach.
- The constructions like Bottom Vanes is not yet applied in the delta, however, it would be good to pilot for an area to access the real value of this alternatives.
- The fish house floating in the delta has good application and propose to be expend for many other places, however, this have to be taken into account for the water quality and master plan for aquaculture development along the river.

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