Identifying Flow Eddy Currents in the River System as the Riverbank Scouring Cause: A Case Study of the Mekong River

Tanh T. N. Nguyen 1,2,*, Dong-Sin Shih 3, Lloyd HC Chua 4, Huyen N. Kieu 1,2, Linh H. Ha 1,2, Linh H. Nguyen 1,2, Ninh V. Luu 5, Thai V. Huynh 6, Linh M. Duong 1,2, An T. Ngo 1,2, Hoa V. Nguyen 1,2 and Chau N. Tran 1,2

1 Faculty of Engineering, Technology, and Environment, An Giang University, Long Xuyen City 880000, Vietnam
2 Vietnam National University-Ho Chi Minh City, Ho Chi Minh City 700000, Vietnam
3 Department of Civil Engineering, National Yang Ming Chiao Tung University, Taipei City 112304, Taiwan
4 School of Engineering, Faculty of Science Engineering & Built Environment, Deakin University, 75 Pigdons Road, Waurn Ponds, VIC 3216, Australia
5 An Giang Province Hydro-Meteorological Center, Long Xuyen City 880000, Vietnam
6 An Giang Province Department of Environment and Natural Resources, Long Xuyen City 880000, Vietnam
7 Faculty of Information Technology, An Giang University, Long Xuyen City 880000, Vietnam
* Correspondence: ntntanh@agu.edu.vn; Tel.: +84-918-752-344

Abstract: River morphological change is the complex evolution of riverbed states, which can lead to serious riverbank failures, and is a worldwide concern. However, revealing the cause of the evolution, in particular, the potential morphological scouring by eddy currents, is difficult. Accordingly, we propose a comprehensive combination of 2D and 3D simulations to reveal the eddy currents. We selected the Vam Nao, part of the Mekong River, with semi-tidal effects and confluence flows as the case study. We created two unstructured 40 m × 40 m triangular meshes using inverse distance interpolation. This study used the Saint–Venant equations (TELEMAC2D) and Navier–Stokes equations (TELEMAC3D) to reveal the eddy currents for 2009, 2017, and 2018. TELEMAC2D (the simplified form of TELEMAC3D) was assessed for 15 days, 3 months, and 1 year, which met a satisfactory level. The eddy currents' appearance was verified by local knowledge. We found recirculating currents near the riverbank to the East (right at the riverbank failures), whose velocity was approximately half and 1/3–1/4 of the mainstream flow velocity in the dry and flood seasons, respectively. Our study approach performed well in revealing the eddy currents, which can aid in assessing potential riverbank failures and can be applicable to similar contexts.

Keywords: riverbank erosion; 2D and 2D hydrologic modeling; eddy currents

1. Introduction

Morphological change is a common phenomenon in river systems. It is a worldwide concern [1] due to its adverse effects on livelihood and human activities, i.e., agriculture, transportation, and navigation. One major cause for this change is river flow [2,3]. When the morphology changes, it will alter the river flow [4]. The morphology and water flow interact with each other, resulting in continuous morphological evolution. This change may include the processes of sediment filling and scouring [5], of which the latter is a critical concern due to its adverse effects.

Numerical modeling can help reveal flow patterns and aid in the study of morphological change, as well as reveal hydrologic phenomena. For instance, MIKE 11 is beneficial for water flow simulation in river systems [6,7], which has performed well in studies of the Nzhelele River in South Africa [8], Acheelos River in Greek [9], and the Mekong [10]. Another model iSIS is capable of flow estimation [11], i.e., demonstrated on the Avon River (Anh) [12] and Hunter River (Australia). The popular HEC can be applicable to support...
hydrologic computation [13,14]. Alternatively, TELEMAC-2D can help simulate flow patterns efficiently [15] due to its capacity for parallel computation [16] (a high-performance computation).

Water flow is the driving force for the scouring. In many cases, the interactions between river flow and morphology can result in forming scouring holes, as the flow washes sediments away from the river bottom [17]. Recent studies have revealed the scouring with many demonstrations. In river systems, the eddy currents can cause scouring in a certain area [18,19]. However, the understanding of eddy currents is limited, although they potentially have significant effects on morphological changes in natural river systems.

The review of the literature showed that studies of eddy currents are needed to better understand their behavior. Thus, we conducted this research on the Mekong River where many of them exist. We focused on revealing the eddy currents and assessing their potential effects on riverbank failures. We selected the Vam Nao area (Figure 1), a complex river system with flow confluence and semi-tidal effects, in the Mekong River system in Vietnam, as a case study. This system is unique with two high tides and two low tides per day. The Mekong River with its natural regulation is formed by the dry and rainy seasons in Vietnam and there are strong flood effects in the rainy season [20]. Water flow in the study area is affected by hydrological variation due to upstream hydropower [21], the floodplains in Cambodia [22], and the tide. Sediment filling/scouring and eddy currents are the main phenomena on the River. Our research question is how the eddy currents move and potentially affect the riverbank.

![Figure 1. Study area.](image)

2. Materials and Methods
2.1. Study Site Selection

This study area lies in the Mekong River Delta, Vietnam, with boundaries defined at four hydrometeorological stations, Tam Chau (TC), Chau Doc (CD), Cho Moi (CM), and Long Xuyen (LX), the so-called CD-TC-CM-LX. In this area, water from Cambodia enters Vietnam at CD and TC to form the Hau River and Tien River. respectively. These two rivers come together in the Vam Nao area. Our study area is the upstream of the Mekong River in Vietnam, which has a mean discharge of 15,000 m$^3$/s (10th largest river in the world) [23]. The discharge varies by season (rainy and dry), and the discharge at TC is approximately four times greater than that at CD [23]. The Mekong River in Vietnam has many riverbank failure cases (including the Vam Nao area) [24], which have caused serious livelihood loss and infrastructure damages.
2.2. Mesh Generation

We created two triangular meshes of 40 m × 40 m using inverse distance interpolation weighting (IDW) from bathymetry data for each year of 2009, 2017, and 2018. The first was a CD-TC-CM-LX mesh with 11,490 ha, 89,930 nodes, and 169,951 elements for TELEMAC2D and the second was a NG-VN-BT mesh with 941.5 ha, 6711 nodes, and 12,681 elements for TELEMAC3D. The equation of IDW is [25,26]:

\[ z_j = \frac{\sum_i \frac{z_i}{d_{ij}}}{\sum_i \frac{1}{d_{ij}}}, \quad j = 1, \ldots, N \]  

where \( i \) is the point to be interpolated adjacent to \( j \), and \( N \) is the number of points to be interpolated; \( z_j \) is the value of the points to be interpolated; \( z_i \) is the value of the points adjacent to \( z_j \); \( d_{ij} \) the distance between \( z_j \) and \( z_i \), and \( n \) is the coefficient of the distance weight adjustment.

2.3. Saint–Venant Equations

We applied the finite element method to solve the Saint–Venant equations using the TELEMAC2D platform as follows [27]:

Continuity:

\[ \frac{\partial h}{\partial t} + u \cdot \nabla (h) + h \text{div}(u) = S_h \]  

Moment by \( x \):

\[ \frac{\partial u}{\partial t} + u \cdot \nabla (u) = -\frac{g}{h} \frac{\partial Z}{\partial x} + S_x + \frac{1}{h} \text{div}(hv_t \nabla u) \]  

Moment by \( y \):

\[ \frac{\partial v}{\partial t} + u \cdot \nabla (v) = -\frac{g}{h} \frac{\partial Z}{\partial y} + S_y + \frac{1}{h} \text{div}(hv_t \nabla v) \]  

where \( h \) is the water depth (m); \( u, v \) are the velocity components (m/s); \( \nabla \) is the gradient; \( g \) is the accelerated gravity (m/s\(^2\)); \( v_t \) is the diffusive coefficient (m\(^2\)/s); \( Z \) is the water elevation (m); \( t \) is the time (s); \( S_h \) is the source (m/s), and \( S_x, S_y \): sources (m/s\(^2\)).

TELEMAC2D is a platform supporting parallel computation. This model has been applied widely in studies of water flow and morphological changes [28], i.e., flood prediction on the Severn River, England from 1998 to 2000 [29]. TELEMAC2D was able predict the flow in Paston, Brazil [30]. In this study, we ran TELEMAC2D with the timestep of 4 s to obtain the velocity (m/s), water elevation (m), and vector directions of the eddy currents.

2.4. Navier–Stokes Equations

This study applied TELEMAC3D to simulate the water flow and the eddy currents. TELEMAC3D solved the Navier–Stokes equations using the volume limit in the nonhydrostatic state [31]:

\( \text{div}(U) = 0 \) 

Moment:

\[ \frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial x} + v \Delta (U) + F_x \]  

\[ \frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} + W \frac{\partial V}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial y} + v \Delta (V) + F_y \]  

\[ \frac{\partial W}{\partial t} + U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial z} - g + v \Delta (W) + F_z \]  

where \( p \) is the pressure, \( g \) is the accelerated gravity, \( v \) is the viscosity, and \( F_x \) and \( F_y \) are the sources (i.e., Coriolis) and component velocities of \( U \) with \( U(t, x, y, z) \). The input discharge at Nang Gu and the input water elevation at Binh Thuy were extracted from the outcome.
of TELEMAC2D, while the input discharge at Vam Nao station was measured data. In this study, we ran TELEMAC3D with the timestep of 4 s to obtain the major outputs of velocity (m/s), water elevation (m), and the eddy currents’ directions by layer.

2.5. Model Assessment

This study computed the Nash–Sutcliffe index (NSE) of water elevation for the model assessment of TELEMAC2D. The NSE equation is:

\[ \text{NSE} = 1 - \frac{\sum_{i=1}^{n} (D_{\text{obs},i} - D_{\text{sim},i})^2}{\sum_{i=1}^{n} (D_{\text{obs},i} - \overline{D_{\text{obs}}})^2} \]  

(9)

where \( D_{\text{sim},i} \) is the simulated water elevation, \( D_{\text{obs},i} \) is the observed water elevation, and \( i \) is hour. We expected to obtain the computed NSE (hourly) at 15 days, 3 months, and a year greater than 0.6, which indicates a satisfactory model [32]. The model performance was assessed for water elevation at the Vam Nao station. Because the simplification of TELEMAC3D is TELEMAC2D, the model assessment for TELEMAC2D also represents TELEMAC3D. The eddy currents and depth-averaged velocity vector directions can be directly and mathematically computed from TELEMAC2D and TELEMAC3D. The quality of the eddy currents depends upon the performance of TELEMAC2D and TELEMAC3D. This study verified the existence of the eddy currents confirmed by two local people who live in the area.

2.6. Equipment and Tools

We used BlueKenue [33] for the mesh generation and input preparation for TELEMAC2D; TELEMAC2D solved the Saint–Venant equations; we also used Google Earth; QGIS [34]; and the programming languages of Fortran [35], Python [36], and R [37]. We used Workstation E5-2699V4 (44 cores × 2) (high-performance computation) for the simulation.

3. Results

3.1. Model Calibration and Assessment

This study found the friction coefficient was the driving parameter affecting the simulated water elevation. Thus, we varied the coefficient values in TELEMAC2D and then estimated the NSE values. The results reported that the computed values of NSE (hourly) in 15 days were 0.55, 0.64, and 0.016 for the frictions of 0.008, 0.01, and 0.016, respectively. For models simulating outcomes that result in the values of NSE > 0.6, they were considered satisfactory [32]. Our simulation showed that the friction of 0.016 resulted in the good fit of observed to simulated water elevation (Figure 2). This friction also fell in the friction range (0.016–0.035) of the Mekong River in Vietnam as reported by Tri and Hue [38]. Next, for the friction of 0.016, we conducted a model assessment for TELEMAC2D for a longer period and obtained the NSE of 0.97 and 0.98 for the flood season (8–10/2009) and the whole year 2009, respectively. The results from the model assessment indicated the good performance of our model and that it could be applied to the study.

3.2. Eddy Currents

Flow regulation in the Vam Nao area is affected by the mixing flow of that from the Vam Nao River and the Hau River. The results showed that the velocity in the confluence was about 0.4–0.85 m/s in the flood season, which was much lower than the mean velocity of Hau River. Our simulated outcome was similar to the previous report (0.74 m/s in Binh Thuy) [39].
In particular, we determined the eddy currents in the region that previous studies have not addressed. They are exhibited with flow directions (arrows), cursors (bold line), and magnitudes (colored) in the figures below. In 2009, the eddy currents appeared to the East in the flood season (Figure 3) and to the West (Figure 4) in the dry season of the mainstream South–North. The eddy currents (confirmed by local people) occurred in the same area as that simulated. In 2017, they occurred mostly on the East side (Figures 5 and 6) right at the riverbank failure. Although the flow velocity in the eddy currents was less than 2 m/s most of the time, the eddy currents flowed anti-clockwise and caused the bank scouring. In this case, it was a gradual scouring, since the velocity was not high. In the dry season and the same period, the velocity of the currents was about 0.6–0.99 m/s in 2009 to the West, while it was 0.32–0.64 m/s to the East in 2017. These results showed that in 2017 and later in 2018 (Figures 7 and 8), the velocity reduced, but the eddy currents continued to occur and potentially scour the riverbank.

**Figure 2.** Simulated and observed water elevation $H$ over 15 days for the friction of 0.016 (m). Notes: $H_{obs}$ is the observed and $H_{sim}$ is the simulated water elevation.

**Figure 3.** Average flow velocity (VELOCITY UV) in the flood season in 2009 (m/s).
Figure 3. Average flow velocity (VELOCITY UV) in the flood season in 2009 (m/s).

Figure 4. Average flow velocity (VELOCITY UV) in the dry season in 2009 (m/s).

Figure 5. Average flow velocity (VELOCITY UV) in the flood season in 2017 (m/s).
Figure 6. Average flow velocity (VELOCITY UV) in the dry season in 2017 (m/s).

Figure 7. Average flow velocity (VELOCITY UV) in the flood season in 2018 (m/s).
Figure 8. Average flow velocity (VELOcity UV) in the dry season in 2018 (m/s).

To better understand the flow regime in the eddy currents area, we simulated the water flow using TELEMAC3D with five layers of flow velocity. The results showed that the eddy currents occurred in all the layers. For demonstration, we present in Figures 9 and 10, for 2017 when the failure occurred. Several months after the bank failure, in the flooding season, the eddy currents continued to exist at both the surface and bottom (Figures 11 and 12) in the same location. These results indicated a formation of a temporally stable state of the eddy currents, which did not significantly vary after the bank failure event in this context.

Figure 9. Average flow velocity (VELOcity UV) in the dry season in 2017 at the bottom (m/s).
Figure 10. Average flow velocity (VELOcity UV) in the dry season in 2017 at the surface (m/s).

Figure 11. Average flow velocity (VELOcity UV) in the flood season in 2017 at the bottom (m/s).
3.3. Discussion

In the confluence area, the study results showed that the river flows consisted of the mainstream and the flow along the riverbank (Figures 3–8). The results above reported that the eddy currents existed adjacent to the riverbank, which potentially caused the gradual riverbank scouring. By comparing the eddy currents in 2009, 2017, and 2018, we found that the currents occurred in the East. This was combined with water level fluctuation to co-scour the bank. Comparing the eddy currents between 2017 (with the bank failures) and 2009 (without the bank failures) can help identify potential scouring sites leading to bank failures. Indeed, after eight years, on the East side, the eddy currents occurred along with the bank failures.

The simulation results reported that the velocity of the eddy currents was about 0.32 m/s, which is half of the mainstream. This showed that the eddy currents could potentially contribute to gradual bank scouring. The additional analysis with TELEMAC3D showed that the flow regime had eddy currents in all layers by depth. When the upstream discharge was dominant, the flow tendency was the upstream–downstream direction, and since this area is tide-influenced, the tide rise contributed to flow direction changes. These results indicated that the eddy currents were affected by upstream flow and the semi-tide.

The formation of the eddy currents in the research area is a natural phenomenon driven by upstream flow and tide. The results from our study reported that the application of comprehensively numerical modeling can help reveal the eddy currents and their potential scouring effects, which agreed with Dike et al. [40]. As the eddy currents continue to be in place, they would form local scour holes nearby [40]. Our results are similar to the case of the Ohio River, where the flow separation occurred in the area adjacent to the riverbank, which led to eddy current formation [41]. We also found a similarity in the flow propagation of the eddy to the case of Leifer [42]. In our study, the replacement of the eddy continuously occurred, particularly in the flood season, along with the variation in the water level, which partly contributed to bank scouring in the study area.

The development of eddy currents is complex. Their formation depends upon both flow and river geometry as stated by Sharma [43]. Combined with the weak shearing resistance of soil, permeability, and water level variation, they can cause bank erosion [44]. Booth [45] reported that in addition to the eddy currents, the low-flow periods when backwaters are lost can also lead to the scouring. In our case, due to the semi-tidal effects, the Mekong River has two times of water-level rise and fall per day; thus, this tide
significantly affects the scouring. Youdeowei and Abam [46] reported that undercutting of
the bank’s toe and the shoaling of river eddy currents could lead to steepening bank slopes
and cause bank failures. In other words, revealing the eddy currents can help identify
potential scouring on riverbank, but this needs to be combined with other factors such as
backwater, water level fluctuation, and soil structure to fully address the scouring effects
and the bank failures. The eddy currents in our study are a natural phenomenon of river
systems, and the outcome from this study can provide the additional knowledge of the
eddy currents in this context.

4. Conclusions

Revealing the natural eddy currents in river systems is necessary for understanding
river systems’ behaviors and effects. This study introduced an approach of revealing the
eddy patterns, which potentially contributes to riverbank protection and management. We
determined the movement of eddy currents from the West to the East in the study area,
which can cause scouring and thus bank failures. The scouring due to the eddy currents
occurs over many years. This study reported the appearance of eddy currents in both the
river surface and bottom. The eddy currents occurred due to the interaction between the
upstream flow, semi-tide, and river shapes.

This study reported that the application of TELEMAC2D and TELEMAC3D can help
to clearly reveal the eddy currents, viewed with directions and magnitudes under 2D
and 3D lenses. In particular, this study revealed the variation in the eddy currents, which
contributes to assessing the potential effects of the currents on the scouring. This technology
can be applicable to similar study contexts.

The case study for this research was the eddy currents in the Mekong River, Vietnam,
where they exist but have not been well-studied. Thus, our study can aid providing addi-
tional knowledge of the currents, which potentially contributes to hydrological planning
and engineering in the region. We noted that the eddy current vectors also depended upon
mesh sizes, and thus, future studies in this field should consider this aspect.

Author Contributions: Conceptualization, D.-S.S., L.H.C., T.T.N.N., N.V.L. and T.V.H.; methodology,
H.N.K., L.M.D. and T.T.N.N.; software, H.V.N. and L.M.D.; validation, D.-S.S., L.H.C., T.T.N.N.,
L.H.H. and L.H.N.; formal analysis, L.H.H. and L.H.N.; investigation, L.H.H. and L.H.N.; resources,
T.T.N.N.; data curation, T.V.H., N.V.L. and L.H.H.; writing—original draft preparation, H.N.K. and
T.T.N.N.; writing—review and editing, D.-S.S., L.H.C., C.N.T. and T.T.N.N.; visualization, L.H.H.
and L.H.N.; supervision, T.T.N.N.; project administration, L.M.D. and T.T.N.N.; funding acquisition,
A.T.N. and T.T.N.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VIETNAM NATIONAL UNIVERSITY-HO CHI MINH CITY,
grant number A2020-16-0.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Some or all data, models, or code that support the findings of this
study are available from the corresponding author upon reasonable request. They are the codes of
TELEMAC2D and TELEMAC3D.

Acknowledgments: We thank Vietnam National University-Ho Chi Minh City for sponsoring this
research, An Giang University, An Giang Hydro-Meteorological Center, An Giang Department of
Environment and Natural Resources, and An Giang Department of Science and Technology for
support (Research Contract 28/HD-KHCN on 21/12/2017).

Conflicts of Interest: The authors declare no conflict of interest.
References

1. Das, T.K.; Haldar, S.K.; DAS Gupta, I.; Sen, S. River Bank Erosion Induced Human Displacement and Its Consequences. Living Rev. Landsc. Res. 2014, 8, 1–35. [CrossRef]

2. Izumi, N.; Parker, G. Linear stability analysis of channel inception: Downstream-driven theory. J. Fluid Mech. 2000, 419, 239–262. [CrossRef]

3. Roth, G.; Siccardi, F.; Rosso, R. Hydrodynamic description of the erosional development of drainage patterns. Water Resour. Res. 1989, 25, 319–332. [CrossRef]

4. Cao, Z.; Pender, G.; Wallis, S.G.; Carling, P. Computational Dam-Break Hydraulics over Erodible Sediment Bed. J. Hydraul. Eng. 2004, 130, 689–703. [CrossRef]

5. Simpson, G.; Castelltort, S. Coupled model of surface water flow, sediment transport and morphological evolution. Comput. Geosci. 2006, 32, 1600–1614. [CrossRef]

6. Alaghmand, S.; Abdullah, R.B.; Abustan, I.; Eslamian, S. Comparison between capabilities of HEC-RAS and MIKE11 hydraulic models in river flood risk modelling (a case study of Sungai Kayu Ara River basin, Malaysia). Int. J. Hydrol. Sci. Technol. 2012, 2, 270–291. [CrossRef]

7. Kadam, P.; Sen, D. Flood inundation simulation in Ajoy River using MIKE-FLOOD. ISH J. Hydraul. Eng. 2012, 18, 129–141. [CrossRef]

8. Makungo, R.; Odiyo, J.; Ndiritu, J.; Mwaka, B. Rainfall-runoff modelling approach for ungauged catchments: A case study of Nzhelele River sub-quanternary catchment. Phys. Chem. Earth Parts A/B/C 2010, 35, 596–607. [CrossRef]

9. Moussoulis, E.; Zacharias, I.; Nikolaidis, N.P. Combined hydrological, rainfall–runoff, hydraulic and sediment transport modeling in Upper Acheleos River catchment. Desalination Water Treat. 2016, 57, 11540–11549. [CrossRef]

10. Talchabhadel, R.; Shaka, N.M.; Dahal, V.; Eslamian, S. Rainfall runoff modelling for flood forecasting (a case study on west rapti watershed). J. Flood Eng. 2015, 6, 53–61.

11. Lin, B.; Wicks, J.M.; Falconer, R.A.; Adams, K. Integrating 1D and 2D hydrodynamic models for flood simulation. Proc. Inst. Civ. Eng. Water Manag. 2006, 159, 19–25. [CrossRef]

12. Baban, S.M.; Foster, I.D. Modelling water flow and quality: An evaluation of the ISIS model in the River Avon, United Kingdom. West Indian J. Eng. 2002, 24, 1–15.

13. Gross, E.J.; Moglen, G.E. Estimating the Hydrological Influence of Maryland State Dams Using GIS and the HEC-1 Model. J. Hydrol. Eng. 2007, 12, 690–693. [CrossRef]

14. Hydrologic Engineering Center. Introduction and Application of Kinematic Wave Routing Techniques Using HEC-1. US Army Corps of Engineers. Available online: http://www.hec.usace.army.mil/publications/TrainingDocuments/TD-10.pdf (accessed on 30 June 2021).

15. Hervouet, J.M. TELEMAC, a hydroinformatic system. Houille Blanche 1999, 85, 21–28. [CrossRef]

16. Hervouet, J.M. A high resolution 2-D dam-break model using parallelization. Hydrol. Process. 2000, 14, 2211–2230. [CrossRef]

17. Warren, L. Scour at Bridges—What’s it All About? Open File Report 93-W0487; Geological Survey (U.S.): Reston, VA, USA, 1993.

18. Holton, J.R.; Hakim, G.J. An Introduction to Dynamic Meteorology. Am. J. Phys. 1973, 41, 752–754. [CrossRef]

19. Charles, C.D.; Ify, L.N.; Levi, C.U. Prediction of Eddy current and scour hole positions along river beds. PENCIL Pub. Phys. Sci. Eng. 2015, 1, 1–10.

20. Dutta, D.; Alam, J.; Umeda, K.; Hayashi, M.; Hironaka, S. A two-dimensional hydrodynamic model for flood inundation simulation: A case study in the lower Mekong river basin. Hydrol. Process. 2007, 21, 1223–1237. [CrossRef]

21. Kuenzer, C.; Campbell, I.; Roch, M.; Leinenkugel, P.; Tuan, V.Q.; Dech, S. Understanding the impact of hydropower developments in the context of upstream–downstream relations in the Mekong river basin. Sustain. Sci. 2013, 8, 565–584. [CrossRef]

22. Fujii, H.; Garsdal, H.; Ward, P.; Ishii, M.; Morishita, K.; Boivin, T. Hydrological roles of the Cambodian floodplain of the Mekong River. Int. J. River Basin Manag. 2003, 1, 253–266. [CrossRef]

23. Leprung, T.; Li, Q.; Li, Y.; Vukien, T.; Nguyenthai, Q. Morphology Evolution of Cuadai Estuary, Mekong River, Southern Vietnam. J. Hydrol. Eng. 2013, 18, 1122–1132. [CrossRef]

24. van Tho, N. Coastal erosion, river bank erosion and landslides in the Mekong Delta: Causes, effects and solutions. In Geotecnics for Sustainable Infrastructure Development; Springer: Berlin/Heidelberg, Germany, 2020; pp. 957–962.

25. Achenleos, G. The Inverse Distance Weighted interpolation method and error propagation mechanism—Creating a DEM from an analogue topographical map. J. Spat. Sci. 2011, 56, 283–304. [CrossRef]

26. Bartier, P.M.; Keller, C. Multivariate interpolation to incorporate thematic surface data using inverse distance weighting (IDW). Comput. Geosci. 1996, 22, 795–799. [CrossRef]

27. Ata, R.; Goeyry, C.; Hervouet, J.M. TELEMAC Modeling System 2D Hydraulics TELEMAC2D Software-User Manual; EDF R&D: Paris, France, 2014. Available online: http://www.opentelemac.org/downloads/MANUALS/TELEMAC-2D/telemac-2d_user_manual_en_v7p0.pdf (accessed on 21 January 2021).

28. Meyer-Peter, E.; Müller, R. Formulas for bed-load transport. In IAHSR 2nd Meeting, Stockholm, Appendix 2; IAHR: Madrid, Spain, 1948.

29. Horritt, M.; Bates, P. Evaluation of 1D and 2D numerical models for predicting river flood inundation. J. Hydrol. 2002, 268, 87–99. [CrossRef]
30. Fernandes, E.H.; Dyer, K.R.; Niencheski, L.F.H. Calibration and validation of the TELEMAC-2D model to the Patos Lagoon (Brazil). J. Coast. Res. 2001, 470–488.
31. EDF R & D. TELEMAC Modeling System: 3D Hydrodynamics TEELMAC3D Software 7.1/Operating Manual; Pham, C.-T., Joly, A., Eds.; EDF R & D: Paris, France, 2016. Available online: http://www.opentelemac.org/downloads/MANUALS/TELEMAC-3D/telemac3d_user_manual_v7p1.pdf (accessed on 20 January 2021).
32. Moriasi, D.N.; Arnold, J.G.; van Liew, M.W.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 2007, 50, 885–900. [CrossRef]
33. Canadian Hydraulics Centre. Blue Kenue Reference Manual; Canadian Hydraulics Centre, National Research Council: Ottawa, ON, Canada, 2011.
34. QD Team. QGIS Geographic Information System, Open-Source Geospatial Foundation Project; QD Team: Norwich, UK, 2016.
35. Chivers, I.D.; Sleightholme, J. Introduction to Programming with FORTRAN; Springer: Berlin/Heidelberg, Germany, 2006.
36. Lutz, M. Learning Python: Powerful Object-Oriented Programming; O’Reilly Media, Inc.: Sebastopol, CA, USA, 2013.
37. R Core Team. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing: Vienna, Austria, 2013.
38. Tri, D.Q.; Hue, L.T. Modeling and forecasting water flow in Vietnam’s Mekong River. In Proceedings of the Scientific Conference on Meteorol-Hydrology and Oceanography, Hanoi, Vietnam, 27 October 2016.
39. Huy, P.D.A.; Tu, T.T. Assessing variation of riverbank in Vam Nao. Sci. Technol. Dev. J. 2015.
40. Dike, C.C.; Nwaogazie, I.L.; Onochie, O. Eddy current propagation: A case study of the Nun River. PENCIL Publ. Phys. Sci. Eng. 2015, 1, 11–20.
41. Hubbs, S.A. Changes in Riverbed Hydraulic Conductivity and Specific Capacity at Louisville. Riverbank Filtr. Hydrol. 2006, 60, 199–220. [CrossRef]
42. Leifer, I. A Synthesis Review of Emissions and Fates for the Coal Oil Point Marine Hydrocarbon Seep Field and California Marine Seepage. GeoFluids 2019, 2019, 4724587. [CrossRef]
43. Sharma, H. River dynamics and Hydraulic Structures: River Dynamics for transitional stage rivers with case study of Sharda River near Lakhimpur or variable flow patterns. EasyChair Preprint 2020, 1–14.
44. Pavoni, J.L.; Stein, D.E. Environmental Impact of Riverbank Revetment; University of Louisville: Louisville, KY, USA, 1975.
45. Booth, E. Sediment Response to Construction and Recent Adaptive Management of Glen Canyon Dam, Colorado River, Arizona; American Geophysical Union: Washington, DC, USA, 2017.
46. Youdeowei, P.O.; Abam, T.K.S. Local engineering practices of erosion control in the coastal areas of the Niger Delta. Environ. Earth Sci. 1997, 31, 231–235. [CrossRef]