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Experimental Study on the Effect of Flow Velocity and Slope on Stream Bank Stability (Part II)

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Abstract

Erosion significantly contributes to the instability of riverbanks. The current study considers the issues of instability and erosion that plague the banks of the Al-Muwahada channel. It was a large irrigation channel located west of Baghdad, Iraq. A laboratory flume was constructed to gain a comprehensive understanding of the erosion process on riverbanks. This flume serves as a scaled-down replica of the Almowahada channel. The main structure of the flume consists of a 3-meter steel construction with dimensions of 1 meter in width and 0.6 meters in height. In order to reduce the high flow velocity, it was periodically linked to quieting tanks with dimensions of 1 meter in width, 1.5 meters in height, and 0.4 meters in thickness. The flume's sidewalls are constructed with plexiglass that is 4 mm in thickness. Furthermore, a water reservoir with a capacity of 1800 liters was introduced into the flume. A riverbank was constructed with two slope angles, one at 45º and the other at 60º. The bank was then subjected to five different velocities. The experimental results indicate the velocity of flow and slope angle of the riverbank are the primary factors that influence the stability of the riverbank. The tipping point between erosion and deposition rises increasingly as the flow velocity increases. The majority of the sediment at the bottom, particularly on the near side of the bank, is the result of bank erosion. As the slope angle of the riverbank approaches 37°, it becomes more stable. The erosion-induced deformation in the riverbank with a slope angle of 45º is greater than that in the riverbank with a slope angle of 60º. The investigation demonstrated that the 45° angle is more susceptible to erosion caused by the flow velocity than the 60° angle.

Keywords: Erosion; Riverbank; Slope Angle; Velocity of Flow; Sediment Deposition.

1. Introduction

Soil erosion on riverbanks is the result of the water's ability to remove or wear away soil from the banks of a river. There are numerous factors that can contribute to this, including the volume and velocity of the river's water flow, the type of rock or sediment that composes the riverbank, and human activities such as deforestation or construction adjacent to the river [1]. Widening of the river channel, land loss, ecosystem devastation, and even changes in the river's course can all result from erosion. Although erosion is a natural process that happens over time, human activity can increase it and hasten its pace. There was aggradation downstream of the test segment and leveling of the entire cross-section at the end of the test section. On the other hand, in the instance of the vegetated riverbank, the initial bank profile remained nearly the same at the same upstream sand pit and flow discharge [2]. The pit region exhibits an increase in bed particle mobility in the downstream and downward directions of the longitudinal turbulent kinetic energy fluxes and the vertical turbulent kinetic energy fluxes for both the inner and outer layers. In contrast, the bed particle mobility is only present in the inner layer at the upstream section. A modified equation for bed load transmission has been established to account for the geometry of pits in alluvial channels impacted by sand mining [3]. There are several strategies to stop or lessen erosion along riverbanks, such as growing vegetation to stabilize the soil, building revetments or riprap to protect the

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bank, and enacting laws to restrict activities that worsen erosion. To save property, infrastructure, and the environment, it is crucial to control riverbank erosion.

Abbass et al. [4] and Julien [5] mentioned that the current global landscape is a result of ongoing natural processes of sedimentation and erosion that have occurred throughout geological time. Riverbank erosion leads to the degradation of the riverbed and the discharge of sediment into the receiving water body. Factors such as sediment deposition during high flows, soil fall from upper bank sections onto lower erosion pins, soil surface loosening, soil mass expansion and contraction caused by temperature and moisture content changes, movement of the erosion pin within the bank, and human interference are all considered [6]. The movement of water would cause the bed form and riverbank particles to separate from their interlocking. At the downstream portion of a river segment, the transportable particles would then begin to travel and deposit. Inadequate monitoring programs could lead to serious environmental and engineering issues in this process. According to the past research, two major agents of erosion were found: water and wind [7, 8].

Water is often regarded as the primary cause of soil erosion on a worldwide level. One facet of water's influence as an agent is the degradation of seashores, landforms, and river basins. Soil is eroded by water and delivers soil particles from higher elevations to places with lower elevations, causing soil erosion. Water has been identified as a significant cause of soil erosion, in comparison to wind [9, 10]. Soil erodibility, or the ability of soil to withstand erosion, is a property that is largely dependent on several variables, including organic matter content, infiltration levels, and soil structure. Riverbank erosions may cause sediment to build up, which exacerbates issues with river pollution. The rate at which sediments flush depends on the flow rate of the river. The interaction of velocity, bed form characteristics, and kinetic energy at the riverbed strongly predicts the beginning of sediment movement [11]. Researchers have spent the last decade studying cohesive soil and developing different formulas for critical shear stress that consider mechanical, chemical, biological, and environmental aspects that were given extra consideration [12**,** 13]**.** A few indices were created to relate the stability of riverbanks to erosions rather than a critical shear stress. The most noteworthy contributions to the development of the index were made by Maatooq & Hameed [14] and Kimiaghalam et al. [15]. A comprehensive comprehension of the river basin management process is necessary to elucidate the physical characteristics of rivers. An evaluation of the river planform, floodplain land cover, and geometry is necessary to understand the river's hydrodynamics and biological functions. Soil erosion refers to the deliberate disintegration of soil structure caused by the forces of wind and water. There are three types of features as:

- ***Sheet erosion***: The most common and less damaging erosion.
- ***Rill erosion***: This type of erosion can be classified as a moderate type of erosion and ranges between sheet and gully. The soil erodes downward and may extend into the subsoil, leading to a gully in a short time.
- ***Gully erosion***: The most erosive process compared to sheet and rill erosion. Gully mostly causes a great amount of soil loss and then contributes to shaping the earth's surface (see Figure 1) [16].

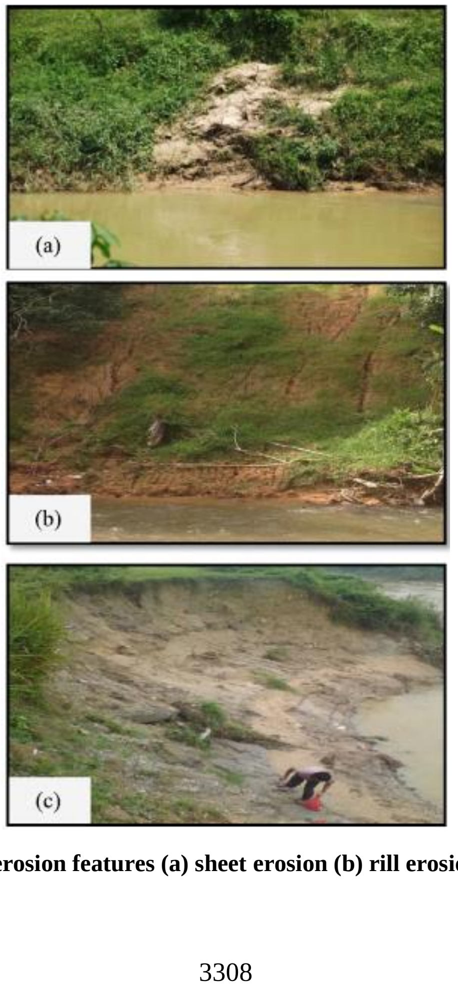

Figure 1. Types of erosion features (a) sheet erosion (b) rill erosion (c) gully erosion

The data indicate that the rate of bank erosion varied both vertically and along the channel, and that there was no correlation between local bank erosion and any hydrodynamic parameter [17]. The present study investigates the extent to which erosion affects the riverbank when it is subjected to varying flow velocities and a 45° and 60° slope angle in a laboratory environment.

2. Experimental Work

This study aims to investigate the state of the Al Muwahada channel and determine the factors that contribute to the instability and erosion of its banks. The Al Mowahada Channel, a substantial irrigation channel situated to the west of Baghdad, Iraq, it receives water from the Euphrates River upstream of the al-Fallujah barrage. The Al Mowahada Channel is used as the case study for this paper. The case is to be studied in the laboratory by simulating the channel's dimensions and the flow state. The geometric feature of the channel is characterized by a maximum water depth of 5 meters, a minimum water depth of 1.35 meters, a bottom width of approximately 20 meters, and a top width of 40 meters (Figure 2). The maximum and minimum discharge rates are 140 and 35 m^3/s, respectively. The water table frequently fluctuates between 1.35 and 5 m as a result of the functional mechanism of the channel, increasing to 5 m for five days and then descending to 1.35 m for an additional five days [18]. The phase of dropping is illustrated in Figure 3.

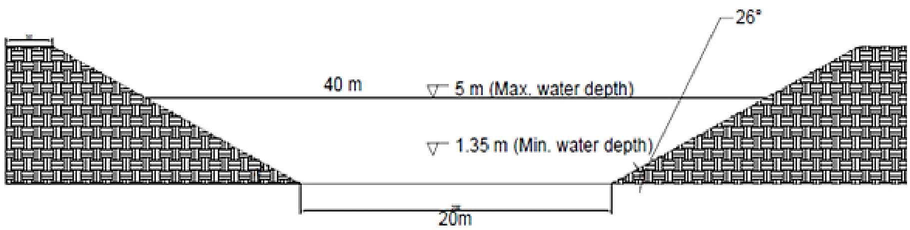

Figure 2. Design geometry of prototype channel

Figure 3. Slope instability of the channel bank during dropping period

2.1. Laboratory Flume

The experimental investigations were conducted using a laboratory flume. The flume was being manufactured to create a physical model that more closely resembles the natural channel under controlled conditions. The main structure of the flume is a steel frame with dimensions of 3 m in length, 1 m in width, and 0.6 m in height. It also periodically connects to quieting containers that are 1 m wide, 1.5 m high, and 0.4 m thick to dissipate the high flow velocity. The sidewalls of the flume are constructed from Plexiglas that is 4 mm thick. A water storage tank of 1800 liters was also incorporated into the system of flume to conserve flow water. The pumping apparatus was connected to the flume using a four-inch diameter pipe. Water is pumped into a flowmeter (Rotameter type) by a three-horsepower pump, which then measures the discharge inputs to the quieting tank (Figure 4). The dimensions of the flume are determined by modeling the actual dimensions of the original channel (prototype). The geometric similarity entails that the ratios of the prototype characteristic lengths to the model lengths are Lr equal to 1/45. The Froude number of the prototype must be equivalent to the Froude number of the model to confirm the validity of the modeling [19].

Figure 4. Laboratory flume

The rectangular, fully contracted, sharp-crested weir, as illustrated in Figure 5, was used to conduct the calibration procedure for the flow meter device [20]. By simultaneously operating the weir and the flow meter and recording 10 readings for each. The actual discharge of the flow meter ($Q_{\text{flow meter}}$) was then plotted, and the regression equation that follows is the result of the calibration illustrated in Figure 6.

$$Q_{actual} = 0.7535\ Q_{\text{flow meter}} + 1.6032 \tag{1}$$

where Q_{actual} is the discharge of weir.

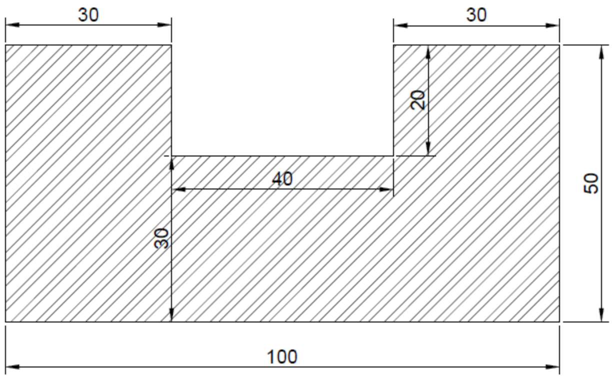

Figure 5. Rectangular fully contracted sharp crested weir (all Dimensions in cm)

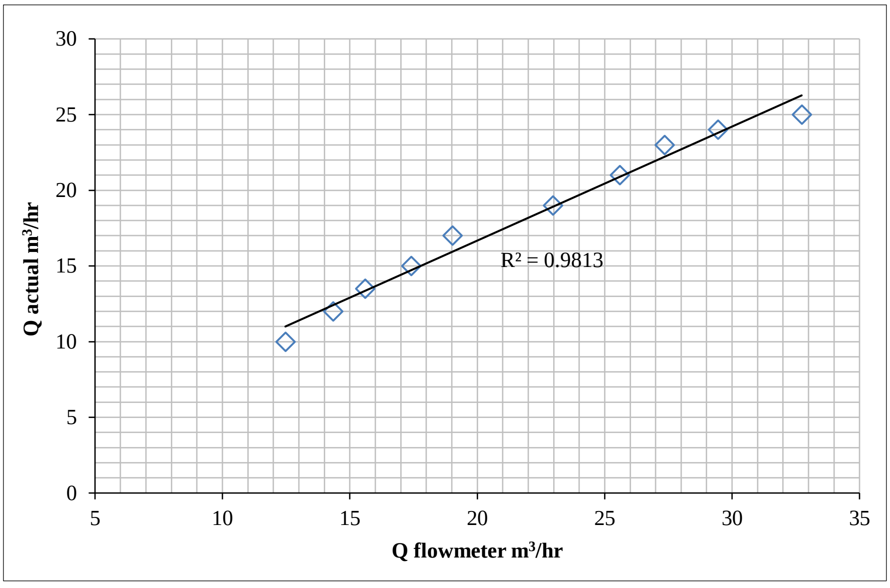

Figure 6. Calibration curve of the flow meter

2.2. Material and Methods

The flume model was designed to accurately replicate field conditions and parameters in a laboratory environment. To construct the riverbank in a laboratory environment, the original bank soil of the Al-Mowahada channel is being used, with the essential soil properties, embankment geometry, and water table within the embankment factors considered. A borehole was excavated at a depth of 12 meters to investigate sediments along the riverbank, as illustrated in Figure 7. Both the flow rate and the water depth in the laboratory flume were under control. The investigation involves the simulation of a model in a flume to conduct laboratory tests, as partially illustrated above. Finally, construct riverbanks with a slope angle of 45º and 60º, as illustrated in Figures 8 and 9. The water content, dry unit weight, and specific gravity of the soil are all taken into consideration.

Figure 7. Soil investigation of the embankment

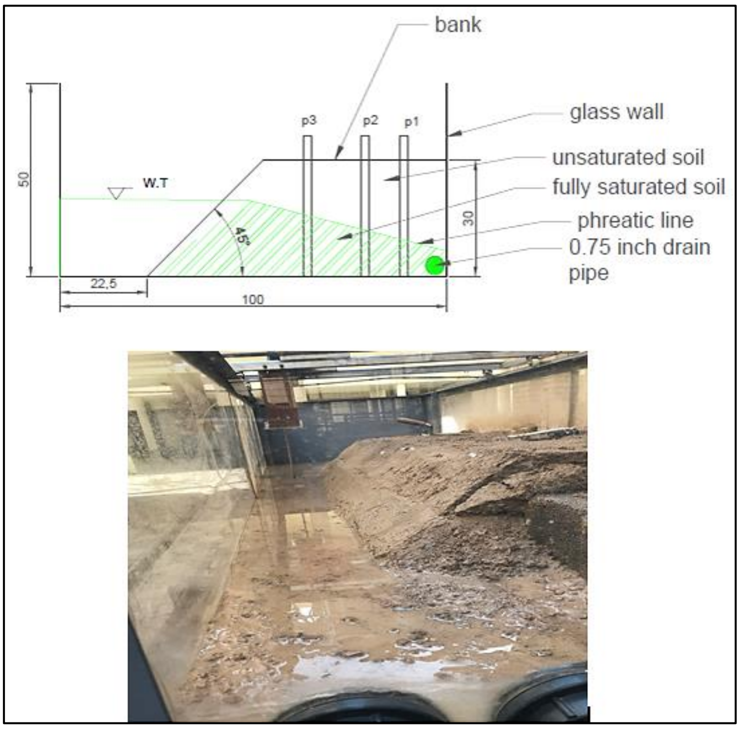

Figure 8. Geometry of bank in Lab. flume with 45̊ slope angle and p1, p2, and p3 are piezometers (dimensions in cm)

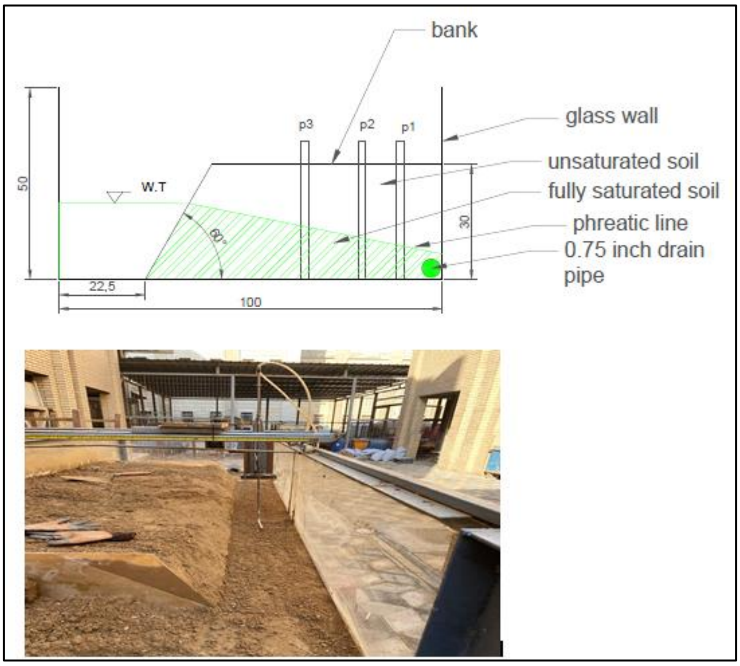

Figure 9. Geometry of bank in Lab. flume with 60° slope angle and p1, p2, and p3 are piezometers (dimensions in cm)

2.3. Preparation of Soil

The soil preparation was the most critical aspect of the work in the laboratory. It was divided into four stages as follows:

Stage 1: Soil sampling: A soil sample was collected from a location on the bank channel side that was in contact with the failure region, 1.5 meters below the surface and 0.5 meters above the bank soil's uppermost stratum. The upper stratum consisted of five meters of silty sand soil. Soil is dried by spreading a sample of soil on a nylon sheet that has been enveloped in a single, approximately 10-cm-thick layer and allowed to air dry.

Stage 2: Gradient of soil: To ensure that the gradient in the soil sample remains constant. The soil sample was crushed using an iron rod and subsequently filtered using a 4.5 mm filtration equipment.

Stage 3: Soil water content: The soil water content in the laboratory should be identical to the actual conditions. The sample's water content decreased to 13% after the soil was air-dried, where the soil layer's field water content is 32.7%. To achieve the field water content of soil samples, a specific volume of water must be introduced. The weight of the soil sample after multiple attempts indicates that the required water ratio is 25.2% [21, 22].

Stage 4: Riverbank configuration: the dimensions of the bank are shown in Table 1.

Table 1. Geometry of the laboratory model of bank

Slope angle of bank (°)	Length of bank (cm)	Width of bottom (cm)	Width of top (cm)	Height (cm)
45	200	77.5	47.5	30
60	200	77.7	60.18	30

3. Experimental Setup

A laboratory riverbank was constructed at an angle of 45 degrees and 60 degrees with silty sand soil to conduct the studies on erosion. The experiments examined five different water velocities, starting with the minimum velocity of water of the prototype channel and ending with the maximum velocity of it. Table 2 displays the laboratory angles and their related experiment velocities, which were modeled based on the actual velocities observed in the field.

The deformation of embankment was observed at three-hour intervals, and this process was repeated for a duration of 12 hours for each velocity. The monitoring was conducted by measuring the erosion in the cross-section of the bank using laser scanner at two stations along the flume. The first station was located 120 cm from the inlet of the flume, while the second station was located 170 cm away. The flume glass walls are impervious barriers; hence they do not accurately replicate the bank's behavior in the field. Thus, to accurately replicate reality, a water drainage system within the bank is employed to remove seepage and establish a non-horizontal phreatic line across the bank. The function of this system is to create a negative pressure at the end of the tube that is greater than the positive pore pressure in the bank while the flume is operating. The drainage system utilized gravity to create a suction force inside the bank, allowing water to be withdrawn without the need for piping.

Table 2. The laboratory angles and corresponding velocities of the physical models

No.	Angle	Velocity (m/s)				
		EXP.1	EXP.2	EXP.3	EXP.4	EXP.5
1	45°	0.101	0.116	0.12	0.13	0.135
2	60°	0.101	0.116	0.12	0.13	0.135

4. Results and Discussion

This section will provide a detailed discussion on the effect of flow velocity and slope angles of 45° and 60° on the stability of the stream bank.

4.1. Riverbank Erosion at a Slope Angle of 45°

The evolution and mutual adaptation of the flow of the river along its banks and the sediment conditions lead to changes in the riverbed and its landform. The study findings indicate that the slope angle, flow velocity, and soil type are the primary factors that significantly influence riverbank erosion. The riverbank underwent a continuous transformation due to the increase in flow velocity at a constant slope angle. The alteration in the bank's configuration became evident during the initial three hours of the experiment, when the flow velocity reached 0.101 m/s. The lower third part of the bank base accumulated significant amounts of deposited sediments. Over time, the deformation gradually acquired a more streamlined form. The tipping point between erosion and deposition was centered approximately at the upper end of the lower third of the bank, as shown in Table 3 and Figure 10-a. The figure indicates that the ends of the curves begin to decrease due to the deformation of the channel cross section with a constant discharge. This behavior leads to a change in the depth of the water in the channel and the effect of erosion transfer from the water surface level at 12.1 cm to 11.4 cm approximately. The negative sign in the tables indicates the value of deposition, while the positive sign indicates erosion.

Table 3. Deformation of riverbank for a velocity of 0.101 m/s with slop angle 45° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.33	0.90	0.57
0.00	2.05	2.05
0.55	3.20	2.65
2.45	3.70	1.25
4.65	5.00	0.35
6.65	6.65	0.00
8.55	8.40	0.15
10.50	9.85	0.65
12.80	10.80	2.00

When the flow velocity reached 0.116 m/s, the natural of erosion has been changed, resulting in an increase in the amount of sediment. Furthermore, the tipping point between erosion and depositions was increased and concentrated at 5.2 cm from the channel bed. The increase in flow velocity resulted in an increase of the drag force exerted on soil particles and an increase in the magnitude of shear stress, so causing an increase in erosion in the upper part of the bank. The increase in the drag force and shear stress in the friction zone between the soil of bank and the flow sheet leads to the lifting of larger soil particles. The particles, because of their significant mass, do not continue their movement and settle at a close distance from where they were uprooted. The bank's overall shape following the end of the experiment at 37° is formed as illustrated in Table 4 and Figure 10-b.

Table 4. Deformation of riverbank for a velocity of 0.116 m/s with slop angle 45° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	0.90	-0.90
0.20	2.25	-2.05
0.75	3.30	-2.55
2.65	3.85	-1.20
4.85	5.05	-0.20
6.85	6.65	0.20
8.75	8.45	0.30
9.95	10.00	-0.05
13.00	11.55	1.45

At a velocity of 0.12 m/s, the erosion process became more consistent, and the tipping point between erosion and deposition also increased, as depicted in Table 5 and Figure 10-c.

Table 5. Deformation of riverbank for a velocity of 0.12 m/s with slop angle 45° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	1.90	-1.90
0.20	3.10	-2.90
0.75	3.65	-2.90
2.65	4.35	-1.70
4.85	4.95	-0.10
6.85	6.75	0.10
8.75	8.60	0.15
9.95	10.60	-0.65
13.00	10.75	2.25

For a velocity of 0.13 m/s, at a depth of 6.2 cm, the tipping point between erosion and deposition moved to the top. The tipping point between erosion and deposition increases as the flow velocity increases. The inclination angle of the riverbank was altered from 45° to approximately 37° to serve as a reminder that the flume is straight. The deformation and morphological changes are illustrated in Table 6 and Figure 10-d.

Table 6. Deformation of riverbank for a velocity of 0.13 m/s with slop angle 45° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	1.75	-1.75
0.20	2.85	-2.65
0.75	3.60	-2.85
2.65	4.10	-1.45
4.85	6.00	-1.15
6.85	6.85	0.00
8.75	8.40	0.35
10.9	10.55	0.35
13.00	12.50	0.50

At a velocity of 0.135 m/s, the deposition continues to increase, and ripples develop at the bottom of the channel. The most amount of sediment observed at the bottom of the bank, particularly close to the side of the bank, is a result of bank erosion. As shown in Figure 10-e, for a velocity of 0.135 m/s, it appears that the shape of the bank gradually approaches the actual configuration of the original channel. This can be seen in Table 7 and Figure 10-e, specifically during the last three hours of operation.

Table 7. Deformation of riverbank for a velocity of 0.135 m/s with slop angle 45° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	4.10	-4.10
0.20	4.60	-4.40
0.75	5.10	-4.35
2.65	4.85	-2.20
4.85	5.30	-0.45
6.85	5.60	1.25
8.75	7.20	1.55
10.9	8.95	1.95
13.00	12.45	0.55

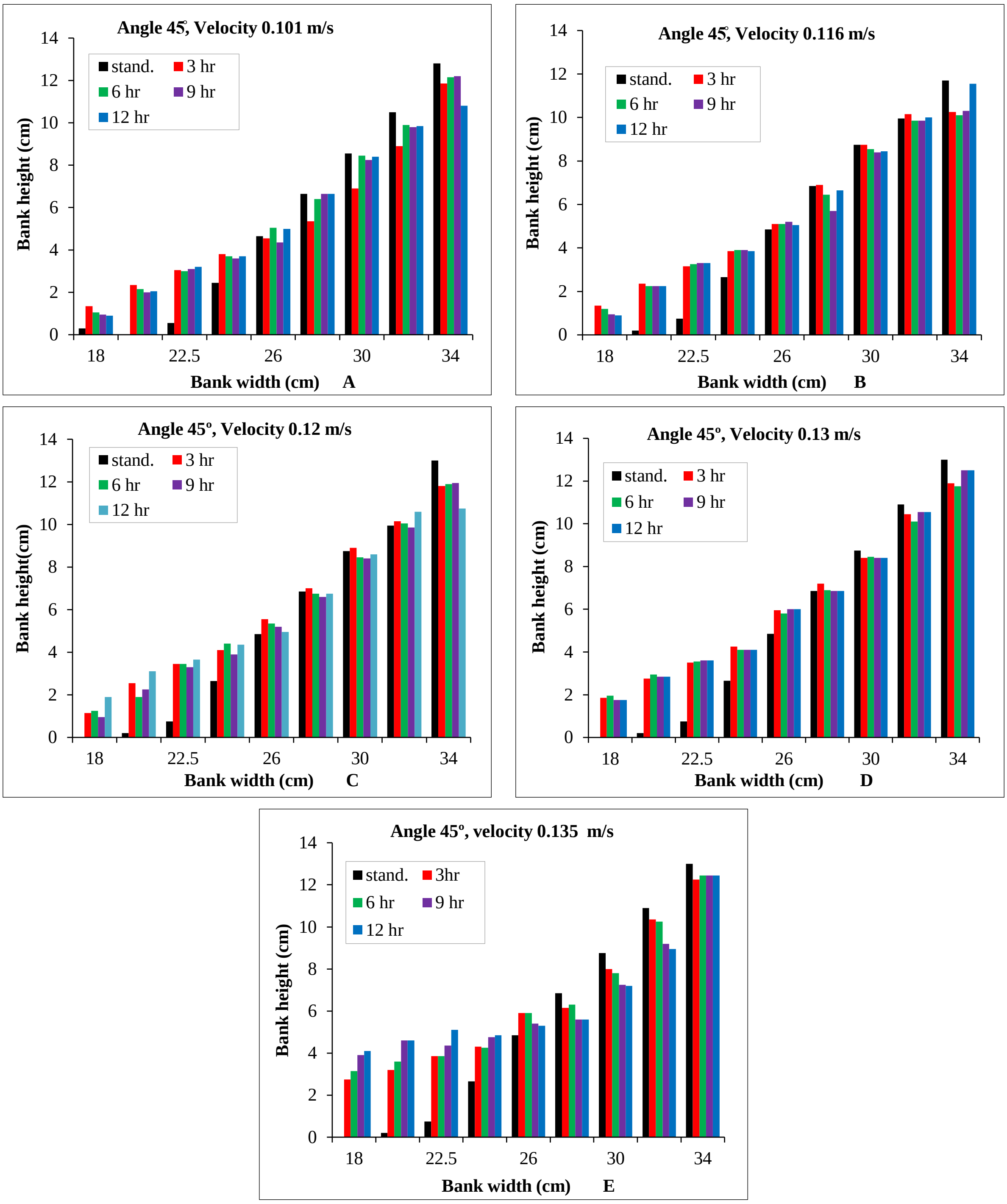

Figure 10. Behavior of riverbank soil under effect of flow velocity with 45° slope angle

4.2. Riverbank Erosion at a Slope Angle of 60°

As previously mentioned, the objective of each experiment has been to demonstrate the effect of the flow velocity, soil type, and bank slope angle on the stability of the riverbank under the effect of erosion. This section involves the results of an erosion test that was conducted on a riverbank with a slope angle of 60°. The flow velocity exhibited variability in ascending order during the five trials conducted at this angle. The first experiment was conducted at a flow rate of 0.101 m/s for a duration of 12 hours. Measurements were recorded at two sites along the flume at three-hour intervals. The friction between the water sheet in contact with the bank and the soil particles of the bank had an impact on the behavior of the bank. When the bed shear velocity value is scarcely greater than the critical value of initiation of motion, the bed material particles will remain in constant contact with the bed and roll and/or slide [20].

As illustrated in Table 8 and Figure 11-a, in the first three hours, the amounts of eroded soil were in equilibrium with the deposited soil in the bank. The reason for the drop in water velocity as it approaches the bottom of the channel is the location of the dividing point between the sedimentation and erosion processes, which is 6 cm from the bottom. Large soil particles fall to the bottom of the channel due to momentum loss.

Table 8. Deformation of riverbank for a velocity of 0.101 m/s with slop angle 60° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	2.60	-2.60
0.00	3.70	-3.70
3.40	5.15	-1.75
6.35	6.15	0.20
8.50	6.85	1.65
9.55	7.80	1.75
11.75	8.60	3.15
13.40	9.25	4.15
14.80	10.35	4.45

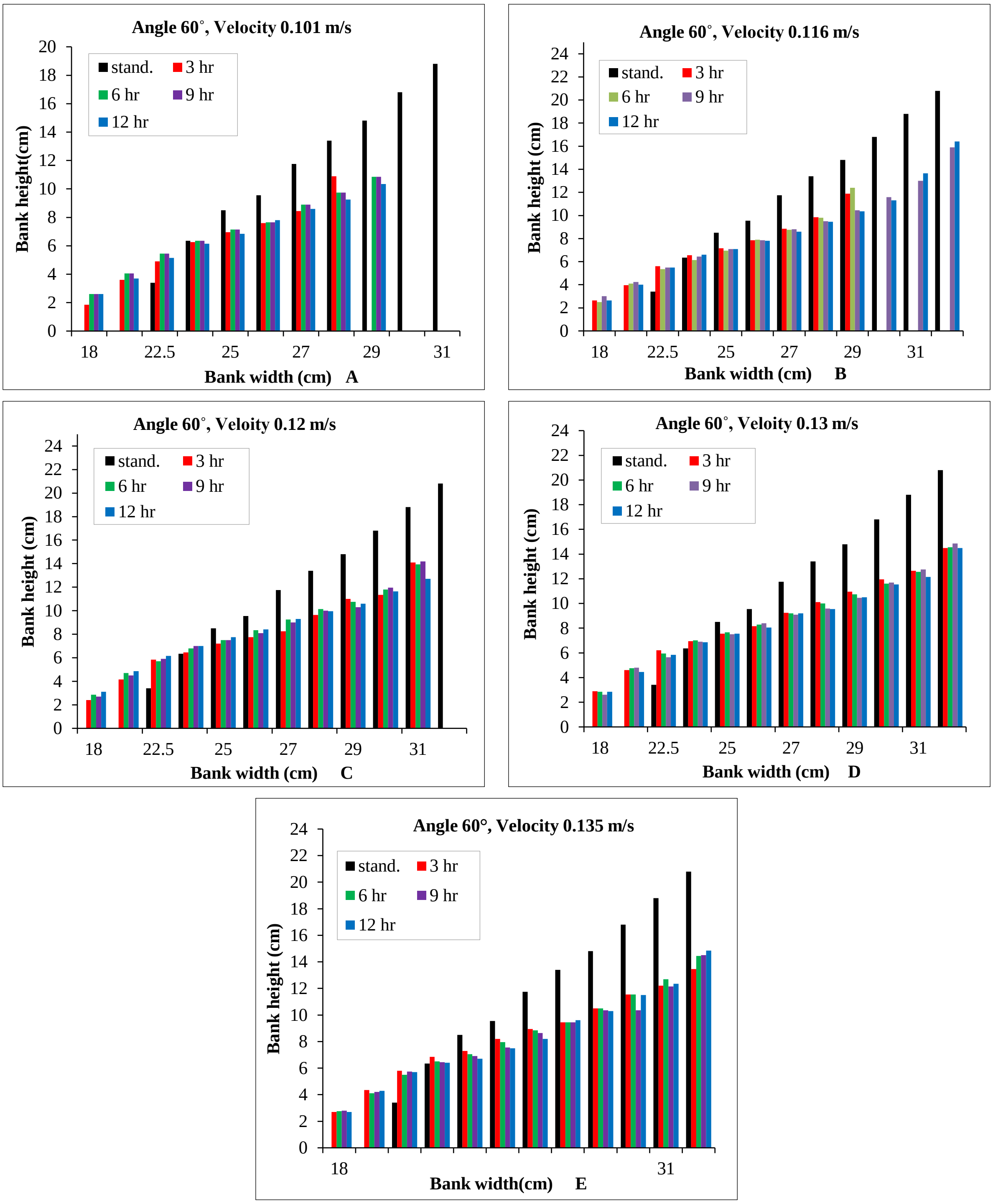

Figure 11. Behavior of riverbank soil under effect of flow velocity with 60º slope angle

The sedimentation area at the toe of the bank recedes when the flow velocity increases to 0.116 m/s, and the quantity of erosion increases directly (Figure 12). The tipping point between erosion and sedimentation exceeded the previous point and approached a depth of 6.25 m from the bottom of the channel (see Table 9 and Figure 11-b).

Figure 12. Erosion of the channel bank with slop angle of 60°

Table 9. Deformation of riverbank for a velocity of 0.116 m/s with slop angle 60° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.0	2.65	-2.65
0.0	4.00	-4.00
3.40	5.50	-2.10
6.35	6.60	-0.25
8.50	7.10	1.40
9.55	7.80	1.75
11.75	8.60	3.15
13.40	9.45	3.95
14.80	10.35	4.45
16.80	11.30	5.50
18.80	13.65	5.15
20.80	16.40	4.40

Table 10 and Figure 11-c illustrate the behavior of the bank, which was subjected to a flow velocity of 0.12 m/s. The deformation of the channel bank produces a new angle that is more stable than the present bank angle and approaches the 45° angle. The collapse occurs because of tension cracks that develop on the surface of the bank as a result of the shoulder's prolonged exposure to flow, as illustrated in Figure 13.

Figure 13. Tension crack phenomenon

Table 10. Deformation of riverbank for a velocity of 0.12 m/s with slop angle 60° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	3.10	-3.10
0.00	4.85	-4.85
3.40	6.15	-2.75
6.35	7.00	-0.65
8.50	7.75	0.75
9.55	8.40	1.15
11.75	9.30	2.45
13.40	9.95	3.45
14.80	10.60	4.20
16.80	11.65	5.15
18.80	12.70	6.10

In contrast to the velocities observed before, the velocity of 0.13 m/s resulted in a sedimentation depth of 4.45 cm and an erosion depth of 6.65 cm, which were the highest values recorded as shown in Table 11. The difference between the two amounts is caused by suspended sediment that is transported over the length of the channel section. Generally, the amount of deformation in the bank of the channel at this velocity and during a 12-hour period is approximately similar as shown in Figure 12-d. The results indicate that the velocity of 0.13 m/s has a limited or steady effect on the angle of the riverbank with slop angle of 60°.

Table 11. Deformation of riverbank for a velocity of 0.13 m/s with slop angle 60° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0.00	2.85	-2.85
0.00	4.45	-4.45
3.40	5.85	-2.45
6.35	6.85	-0.50
8.50	7.55	0.95
9.55	8.05	1.50
11.75	9.20	2.55
13.40	9.55	3.85
14.80	10.5	4.30
16.80	11.55	5.25
18.80	12.15	6.65
20.80	14.50	6.30

Figure 13-e depicts the erosion and deposition amounts during a period of 12 hours for a slope bank with an angle of 60˚ and a velocity of 0.135 m/s. The data indicates that the deposition begins at the channel bed and extends up to a height of 6.35 cm on the bank as shown in Table 12. The erosion initiated at a vertical distance of 6.35 cm above the bed and extended up to the surface of the water. After a duration of 3 hours from the start of flowing, the highest amount of sediment deposition occurred in the channel bed, namely at approximately 4.3 cm below the bed level. Conversely, the highest level of erosion in the upper part of the banks measured approximately 6.45 cm simultaneously. For all other durations of 6, 9, and 12 hours, the erosion and deposition appear to be insignificant.

Table 12. Deformation of riverbank for a velocity of 0.135 m/s with slop angle 60° (in cm)

Bank scan prior to operation	Bank scan after operation	Deformation
0	2.7	-2.7
0	4.3	-4.3
3.4	5.7	-2.3
6.35	6.4	-0.05
8.5	6.7	1.8
9.55	7.5	2.05
11.75	8.2	3.55
13.4	9.6	3.8
14.8	10.3	4.5
16.8	11.5	5.3
18.8	12.35	6.45
20.8	14.85	5.95

The amount of sedimentation rises as the flow velocity increases, with the exception of flows at velocities of 0.13 and 0.135 m/s and a slop angle of 60°, as illustrated in Figure 14. At a high flow velocity, the lifting force increases, leading to the lifting of large soil particles, which settle at a short distance from their original location due to their relatively large weight.

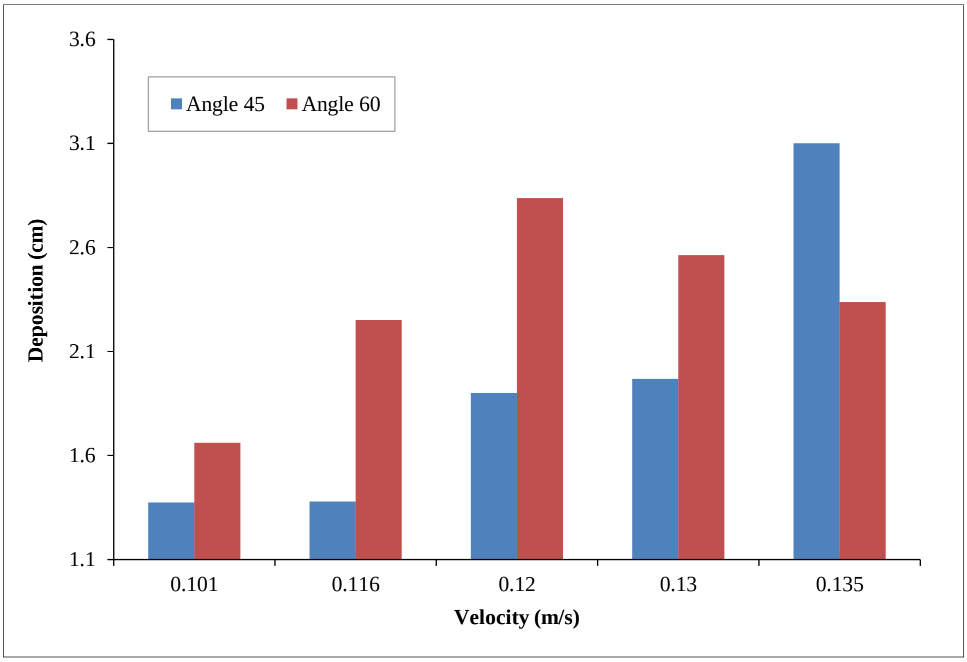

Figure 14. Relationship between the flow velocity and amount of deposition

As a result, the main source of sediment in the canal is bank erosion, which is approximately 86%. Furthermore, as the flow velocity increases, the tipping point position (T.P.P.) between erosion and deposition moves upward, as shown in Figure 15.

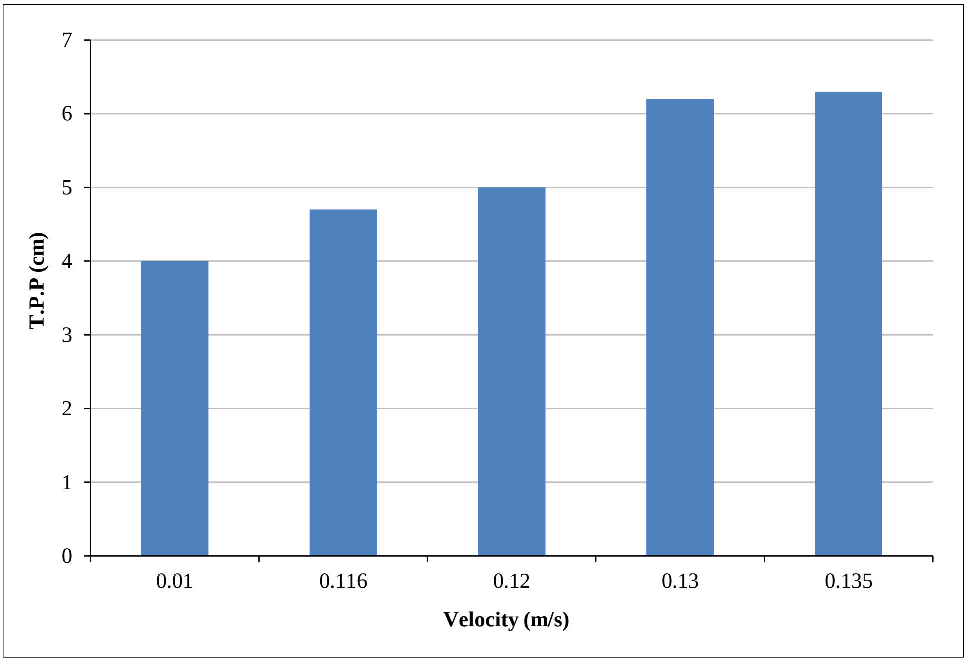

Figure 15. Relationship between the flow velocity and position of tipping point

The movement of sediments on the channel bed and on the bank differ. This distinction was evident in the findings of the present study and is dependent upon three primary variables: the shape and dimensions of the sediment particle, the velocity of flow, and the slope angle of the bank.

5. Conclusions

This study deals with the behavior of the riverbank and the amount of erosion and deposition resulting from river hydraulics and the effect of the bank inclination angle on this behavior. To explain that behavior, a laboratory flume has been designed and manufactured in the Civil Engineering Department at the University of Technology, Iraq-Baghdad. Also, riverbanks with two different slope angles (45º and 60º) were designed and configured. Five flow velocities (0.01, 0.116, 0.12, 0.13, and 0.135) were supplied for each riverbank angle. The experiment is run by supplying the flow on the bank for 12 hours at each velocity, and the bank is scanned transversely at two stations to measure the deformation resulting from the flow, as well as the amount of sedimentation. The results of this research revealed the following:

- The velocity of flow and slope angle of the riverbank were the major factors that influenced the stability of the riverbank.
- The tipping point position (T.P.P.) between erosion and deposition moves upward as the flow velocity increases.
- Bank erosion is responsible for most of the sediment present at the bottom, particularly on the near side of the bank.
- The erosion in the slope angle of 60º was less than that in the slope angle of 45º, as illustrated in figure 14. The soil particles experience an increase in shear stress as the slope angle increases. At a 45° slope angle, the shear stress is greater than at a 37° slope angle, resulting in enhanced downslope movement of soil particles and hence increased erosion. At a higher angle of 45°, the gravitational forces exerted on the soil particles are more powerful in comparison to a shallower angle of 37°.
- The slope angle of the riverbank becomes more stable at 37°.

6. Declarations

6.1. Author Contributions

Conceptualization, J.K.M. and H.A.H.; methodology, J.K.M. and H.A.H. formal analysis, J.K.M.; investigation, J.K.M., H.A.H., and S.F.A; resources, J.K.M.; data curation, J.K.M.; writing—original draft preparation, J.K.M.; writing—review and editing, J.K.M. and S.F.A; visualization, J.K.M.; supervision H.A.H. and M.Q.W.; funding acquisition, J.K.M. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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6.5. Conflicts of Interest

The authors declare no conflict of interest.

7. References

[1] Das, T. K., Haldar, S. K., Sarkar, D., Borderon, M., Kienberger, S., Gupta, I. D., ... & Guha-Sapir, D. (2017). Impact of riverbank erosion: A case study. Australasian Journal of Disaster and Trauma Studies, 21(2), 73-81.

[2] Arora, S., & Kumar, B. (2024). The riverbank vegetation for mitigating the adverse effects of sediment dredging. Ecohydrology, 17(5), e2656. doi:10.1002/eco.2656.

[3] Barman, B., Kumar, B., & Sarma, A. K. (2019). Impact of sand mining on alluvial channel flow characteristics. Ecological Engineering, 135, 36–44. doi:10.1016/j.ecoleng.2019.05.013.

[4] Abbass, Z. D., Maatooq, J. S., & Al-Mukhtar, M. M. (2023). Monitoring and Modelling Morphological Changes in Rivers Using RS and GIS Techniques. Civil Engineering Journal (Iran), 9(3), 531–543. doi:10.28991/CEJ-2023-09-03-03.

[5] Julien, P. Y. (2010). Erosion and sedimentation. Cambridge University Press, Cambridge, United Kingdom. doi:10.1017/CBO9780511806049.

[6] Maatooq, J. S., & Adhab, B. A. (2017). Effect of Distance of the Submerged Vanes from the Outer Bank on Sediment Movement within 180° Bend. American Journal of Engineering and Applied Sciences, 10(3), 679–684. doi:10.3844/ajeassp.2017.679.684.

[7] Nama, A. H., Abbas, A. S., & Maatooq, J. S. (2022). Field and Satellite Images-Based Investigation of Rivers Morphological Aspects. Civil Engineering Journal (Iran), 8(7), 1339–1357. doi:10.28991/CEJ-2022-08-07-03.

[8] Couper, P., Stott, T., & Maddock, I. (2002). Insights into river bank erosion processes derived from analysis of negative erosion-pin recordings: Observations from three recent UK studies. Earth Surface Processes and Landforms, 27(1), 59–79. doi:10.1002/esp.285.

[9] Musa, J. J., Abdulwaheed, S., & Saidu, M. (2010). Effect of Surface Runoff on Nigerian Rural Roads (A Case Study of Offa Local Government Area). AU Journal of Technology, 13(4), 242–248.

[10] Abdulwahd, A. K., & Maatooq, J. S. (2023). Experimental investigation of local scour under two oblong piers of a bridge crossing a sharp bend river. Journal of Water and Land Development, 58, 129–135. doi:10.24425/jwld.2023.146605.

[11] Singer, M. J. & Munns, D. N. (1996) Soils: An Introduction (3rd Ed.). Prentice Hall, Upper Saddle River, United States.

[12] Abdulwahd, A., & Maatooq, J. (2023). Effect of Bridge Piers Locations and Flow Intensity on Morphological Change in a 180-Degree River Bend. Engineering and Technology Journal, 41(11), 1–11. doi:10.30684/etj.2023.140134.1455.

[13] Yang, C. T. (2006). Reclamation: Managing Water in the West Denver. Bureau of Reclamation, Technical Service Center, Sedimentation and River Hydraulics Group, US Department of Interior, Colorado, United States.

[14] Maatooq, J. S., & Hameed, L. (2019). Identifying the pool-point bar location based on experimental investigation. Journal of Water and Land Development, 43(1), 106–112. doi:10.2478/jwld-2019-0068.

[15] Kimiaghalam, N., Clark, S. P., & Ahmari, H. (2014). An experimental study on the effects of physical, mechanical, and electrochemical properties of natural cohesive soils on critical shear stress and erosion rate. International Journal of Sediment Research, 31(1), 1–15. doi:10.1016/j.ijsrc.2015.01.001.

[16] Muhsen, N. A. A., & Khassaf, S. I. (2022). The study of the local scour behaviour due to interference between abutment and two shapes of a bridge pier. Journal of Water and Land Development, 55, 240–250. doi:10.24425/jwld.2022.142327.

[17] Rosgen, D. L. (2001). A stream channel stability assessment methodology. Proceedings of the Seventh Federal Interagency Sedimentation Conference, 25-29 March, 2001, Reno, United States.

[18] Abidin, R. Z., Sulaiman, M. S., & Yusoff, N. (2017). Erosion risk assessment: A case study of the Langat River bank in Malaysia. International Soil and Water Conservation Research, 5(1), 26–35. doi:10.1016/j.iswcr.2017.01.002.

[19] Kozarek, J. L., Limaye, A. B., & Arpin, E. (2024). Comparing turbulent flow and bank erosion with controlled experiments in a field-scale meandering channel. Geological Society, 540(1), SP540-2023. doi:10.1144/sp540-2023-17.

[20] MOWR. (2022). Directorate of Water Resources of Abu-Ghareeb- Iraq. Ministry of Water Resources, Baghdad, Iraq.

[21] Chanson, H. (2004). Hydraulics of open channel flow (2nd Ed.). Elsevier, Amsterdam, Netherlands.

[22] Li, Q., Wang, L., Ma, X., & Nie, R. (2023). Experimental study of the effects of riverbank vegetation conditions on riverbank erosion processes. Environmental Fluid Mechanics, 23(3), 621–632. doi:10.1007/s10652-023-09924-2.