Flow and Sediment Matrix in Mid-Channel Bar Formation

Mat Salleh. M. Z.[1], Ariffin. J.[2]

Abstract— This paper presents the study on flow and sediment matrix to mid-channel bar formation. Aggradation and degradation contribute to the change in stream bed and stream banks in rivers. Sediment is the byproduct of these two processes. A study was carried out on a laboratory flume with fine grain sand of sizes D_{50} = 0.8 mm initially spread on the flume bed. Study had observed the initiation for formation of mid-channel bar through the combination of several small bars at location of minimum shear velocity. The formation occurred within the deposition zone. This study provides a basic knowledge on the relationship of flow and sediment to the formation of mid-channel bar.

Index Terms— Aggradation, Degradation, Mid-channel bar, River Bed, River Bank, Sediment Transportation, Shear Velocity.

1.0. INTRODUCTION

In the last two decades, the development of the fundamental issues related to river morpho-dynamics has been actively pursued. The developments consist of field observation, laboratory measurements, theoretical development and modeling simulation. The Findings help in enhancing and building knowledge on river morphology. Previous studies had adopted various approaches in demonstrating the varied pattern confirmation with respect to hydrodynamics and sediment interaction. One significant aspect would be on the bar formation in rivers. The instability of the river bed is due to the change of hydrodynamic force and sediment movement lead to spontaneous change in river morphology. These have resulted in the formation of bars (free bars and force bars) in rivers. This study aims to establish the profile of mid-channel bars under the influence of flow and sediment.

1.1. BASIC CONCEPT ON THE FORMATION OF MID-CHANNEL BAR

The formation of mid-channel bar derives from instability condition of erodible bed subjected to turbulent flow in all straight channels. It can be described as a process of interrelationship between flow and sediment in term of bed load, and suspended load. The process of formation started when bed load dominates the sediment transport process with steady flow condition of well sorted sediment. In these conditions the crucial parameter controlling the formation of bars is the width to depth ratio β of the channel. This was proven by [1], and [2] who concluded that a mid-channel bar would form if the threshold β is exceeded depending on both flow and sediment.

The second condition of formation of mid-channel bar would occur when a significant portion of sediment transport is carried as suspended load. [3] and [4] reported that the effect of suspended load could destabilizes the value of Shield stress. [5] found that the critical value of β for bar instability rapidly changes to infinity when the shield stress increases beyond the threshold value and with increasing particle Reynold Numbers.

1.2. BASIC CONCEPT OF EROSION AND SEDIMENTATION

The process of erosion and sediment transport are key components in measuring the formation of midland point bars. [6] categorized the fluvial river system into three zones (1) an erosion zones of runoff production and sediment sources, (2) transport zone of water and conveyance and (3) a deposition zones of runoff delivery and sedimentation.

In the first or upper zone the erosion process predominates and the stream and riverbeds are generally degraded. The streams join together at confluences and their slopes are generally steep. The second (middle) zone is characterized by near equilibrium condition between the inflow and outflow of water and sediment. The bed elevation in this equilibrium zone is fairly constant and the river generally flows in a single channel. The lower zone is characterized by net sedimentation and riverbed aggradations. There is branching of the river into channels and the slope of these channels is rather flat.

The mid-channel bar is usually initiated at the inflection section of river but it is not uncommon in river meanders [7]. The most mid channel bar are emergent parts of riffles or swallowing. The force of water is intricately connected to the dislodging of soil and rock particles and their conveyance. When the power of water becomes less, it is forced to deposit the particles on its way.

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The mid-channel bar can change during flood season as erosions are active due to high flow impacts bank. The deposition tends to increase after the event of flood with decrease in the velocity of flow. The formations of mid-channel bars involve the following with the effect of erosion and sedimentation. Alternate bars in river change to point bars and cause river to meander. With erosion and sedimentation of the point bars this promotes bifurcation in rivers. Bifurcation of channel changes to midland point bar with the dynamic change of flow and sediment. Erosion, sedimentation and flow govern the formation of point bars. Their impacts serve as important input to the formation of midland point bars.

1.3. IMPACTS OF EROSION AND SEDIMENTATION ON THE MEANDER GEOMETRY AND RIVER ADJUSTMENT

The erosion and sedimentation do not only affect the river bed but also geometry of river. [8] reported that an erosion process at outer bank caused widening of the channel and induced a bed deposition at most location in river. When the widening happen, shear stress was decreased and the large deposition of sediments and material occurred. This tends to happen in the centre of channel because of stream flow causes an effect of ripples condition.

The findings from[9], [10], and [11] revealed that a mid channel bar contributes to the bank erosion process on both sides of the channel with time. The flow of water dispersed at head of mid channel bar and re-direct the flow towards the sides of bars to create a bifurcation in channels. Erosion occurred at the bifurcation that causes widening of the bank channel. Thus, width changes could be seen as important sides function induced during the development of mid-channel bars.

According to [7], an initial formation of mid-channel bars in meandering rivers may result from two different mechanisms. First is the mechanism of width variation reproduced in straight channels and second is the contribution of nonlinear relationship between sediment and flow interaction interactions even the width is keep constant. These nonlinear effects induced erosion process that lead to the central deposition of material in a sinuous channel with constant width. All this mechanism is related to the erosion and sedimentation. The relationship between width and bedforms could be seen with a process of erosion and sedimentation that vitally need the account for dynamic relationship between them. These two parameters are deserved for attention in future studies to improve the understanding of meander morphodynamics.

In research on the change of Yangtze River channel by [12], the single branch channel in the Jianli River was separated into two branches which are north and south channels by mid-channel bar. The bar became attached to the southern bank of the Jianli bend. The North Channel was used as the navigation channel until cut-off event in 1971 when this sand bar became an island in the channel. The major changes of this river first came from the formation of mid-channel bars that occur through the process of erosion (erosion of channel banks supplies new portions of sediment into water flow) and sedimentation (continuous sediment deposition leads to channel aggradations and rise of water levels) form upstream and downstream channels respectively.

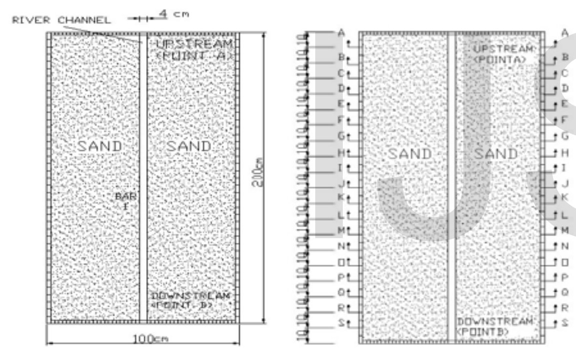
1.4. IMPACT OF MID-CHANNEL BAR FORMATION TO THE RIVER SYSTEM

Mid-channel bar are a normal mechanism occurs in river. Their impacts critically change the river ecology and characteristic. Based on [13] in a study of Jamuna River, stated that the braid bars occur in this river was originated from the formation of mid-channel bars. The mid-channel bar migrated and grew from lateral and downstream accretion. [14] proved that the deposit channel bars in Jamuna River were the cause for long cut of it bank during low flow stage. He described the deposit of sinuous crested dunes, ripples, and plane beds. The present of bar in river contributes to the channel morphology changes and usually it turn to meander or braid rivers. Bridge and Lunt, (2005) again proved that the present of mid-channel bar in river induced the higher rate of flow and in braided river it usually transported relatively coarse sediment as bedload. This river bank was also unstable. They also stated that the discharge variability for this river was very large as compared to others.

2.0. METHODOLOGY

The experiment was carried out on a laboratory flume of 2m long by 1m wide. (A channel constriction path was made at the centre to facilitate flow). Water is supplied from a tank using a submersible pump via a flume. A valve is used to regulate the flow. The types of material used in the experiment is sorted fine grain sand of sizes of D_{50} = 0.8 mm. The sand is compacted and water was made to flow into the flume to saturate the sand. All experiments were conducted in initially straight channel.

The flume was first marked in both horizontal and vertical by each 1 cm from upstream (point A) to downstream (point B) along the channel in order to investigate the changes. The flume gradient used was fixed at 0.5% in every experiment sufficiently steep to produce braiding by the imposed discharge. Data were collected along the 2 m flume starting from point 10 cm downstream of the entrance and 10 cm upstream end of channel. This is to make sure that the flow of water was uninterrupted from sediment feed effects on the channel pattern. The measurement was made at every 10 cm interval along the flume section until the end of the downstream channel. Twenty cross sections were established and measurements were taken at every section. This is to make sure the change of channel pattern was accurately identified. Data on channel pattern development were collected throughout the study by direct observation with subsequent shots taken daily. Changing indices were measured through daily observation. The change in the riverbed was made relative to the channel bank to facilitate observation on changes in the profile.



(a) (b)

Figure 2.1: (a) Flume dimension and (b) measurement points along channels

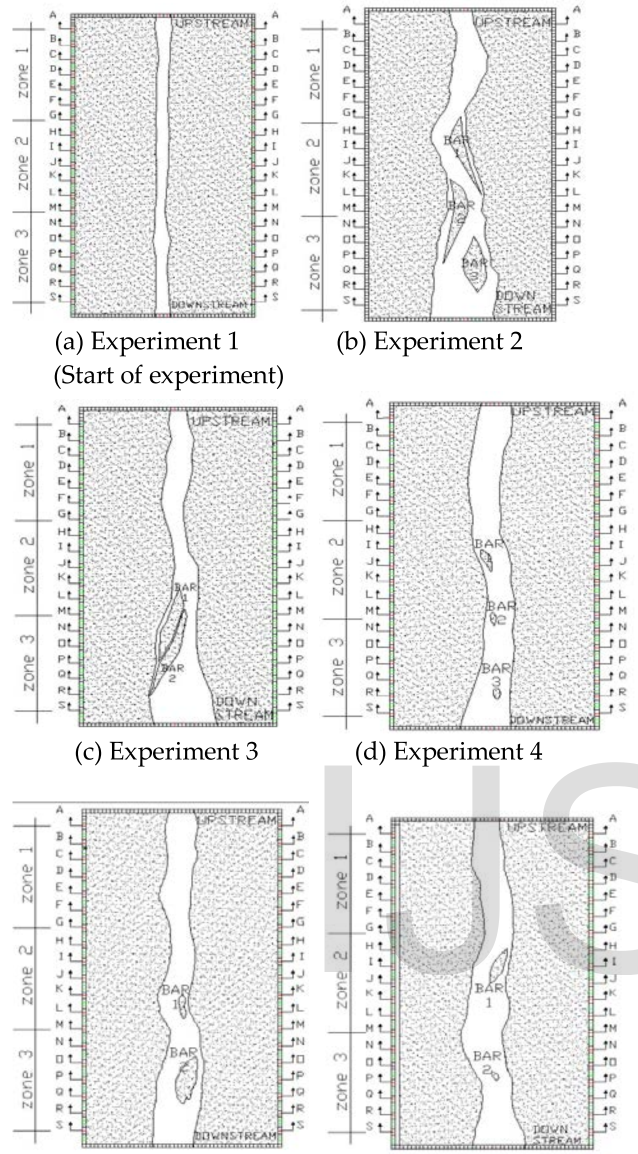
Six experiments were carried out using different matrix of flow and sediment release. Three experiments were carried out for different flow and without sediment release. The discharges used were 3.8×10^{-5} m^3/s, 4.2×10^{-5} m^3/s and 4.6×10^{-5} m^3/s. Another three experiments were established to measure the relationship between effects of sediment transport to the formation of mid-channel bar. In these experiments, the flow is constant to 4.6×10^{-5} m^3/s and different sediment release of 1 kg, 0.5 kg, and 0.25 kg were recorded. This was intended to measure the effect of flow rates and sediment release to the formation of mid-channel bars. Table 2.1 shows detail of parameters used in experiment.

Experiment	Discharge(m^3/s)	Sediment Released(kg)	Flume Length(cm)	Flume Slope (%)	Flume Width(cm)	Flume Depth(cm)	Duration (day)
1	3.8×10^{-5}	0	200	0.5	100	20	14
2	4.2×10^{-5}	0	200	0.5	100	20	5
3	4.6×10^{-5}	0	200	0.5	100	20	2
4	4.6×10^{-5}	0.25	200	0.5	100	20	7
5	4.6×10^{-5}	0.5	200	0.5	100	20	6
6	4.6×10^{-5}	1	200	0.5	100	20	4

Table 2.1: Detail of parameters for the experiment

3.0. RESULTS

Bar formation was observed in all experiments except for experiment no. 1. Erosion had initially occurred at the upstream and deposition was observed at the downstream end.



(a) Experiment 1 (Start of experiment)

(b) Experiment 2

(c) Experiment 3

(d) Experiment 4

(e) Experiment 5

(f) Experiment 6

Figures 3.1(a), (b), (c), (d), (e), (f): Final result for both experiments

Formation of two types of bars namely point bar and mid-channel bar were evident in the area of zone 2 (transported zone) and zone 3 (deposition zone). However, no bars were visible in zone 1.

The depth of zone 1 was found to be deeper followed by zone 2 and zone 3 respectively. The width of channel had widened in the deposition zone for both experiments.

3.1. Conditions of Different Flow

Results of experiments 1, 2, and 3 have shown that channels planform had changed into high sinuosity at every change of flow. Widths of channels in all experiments have shown to be larger at the downstream compare to the upstream end.

The bars were formed in bigger sizes. The locations of bar formations were close to each other and located on inner bank of channels. Most of the bars are formed from a cut-off point bar. It appeared in lunar and ellipse shapes. In term of geometry coordinates, all bars are formed in zone 2 and zone 3 and are actively formed in zone 3. The bed profile was flat. The scours and dunes were also not common but bars are actively formed.

3.2. Condition of Different Sediment Matrix

Based on the results of experiment 4, 5, and 6 it proved that a straight channel changed into meandering but it was less sinuous as compared to condition with different flows. The width of channels was also quite similar at all locations along the river. There was less difference of channel changes for different sediment presented.

Bars were observed to have formed in small sizes initially and cluster-like. Region of formation was observed to be some distance from the centre of sediment deposition within zone 2 and zone 3. Shape of bars observed takes the form of elliptical shape.

3.3. Relationship between Shear Velocity and Formation of Mid-channel Bar

3.3.1. Effect of Flow

Shear velocity is one of the main factors that contribute to the formation of mid-channel bar. In this study, the changes of shear velocity along the channel were being considered in terms of different stream flow without the presence of sediment. An analysis was made by looking at the changes of graph pattern at measurement points along the channel. **Figure 3.2** shows a graph of shear velocity profile for experiment 1 with channel discharge of 3.8×10^{-5} m^3/s. Values of shear velocity were generally increased from upstream to downstream of channel. Most values of shear velocity are above 1.00 m/s at all points. No bars are formed in this channel. The values of shear velocity were not stable with different changes at each point. The maximum and minimum value of shear velocity was at point 130 cm and 14 cm of channel respectively. The scours were visible at this point.

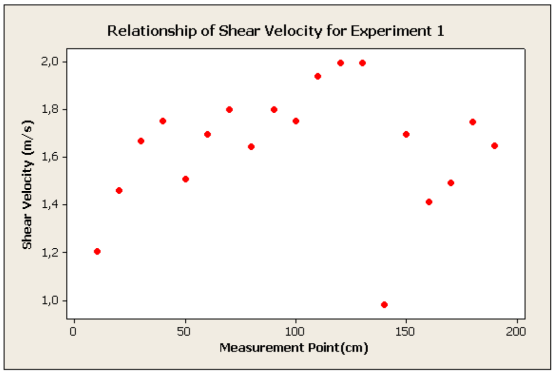


Figure 3.2: Shear velocity profile for experiment 1

Figure 3.3 shows a graph pattern of shear velocity and the location of bar formation in experiment 2 with channel discharge of 4.2 x 10^{-5} m^3/s. The values were generally descended from upstream to downstream. The graph profile shows that the channel was developed by an unstable condition with continuously changes of its values at each location. The maximum and minimum value of shear velocity was at point 20 cm and 170 cm respectively. The value dropped rapidly at zone 2 and started to stabilize at three different points of 80 cm, 120 cm and 170 cm with a value less than 1.00 m/s. The values were less different at these point and bars are formed. Bar 1 and Bar 2 are formed at location of stable values of shear velocity while Bar 3 is formed at minimum value.

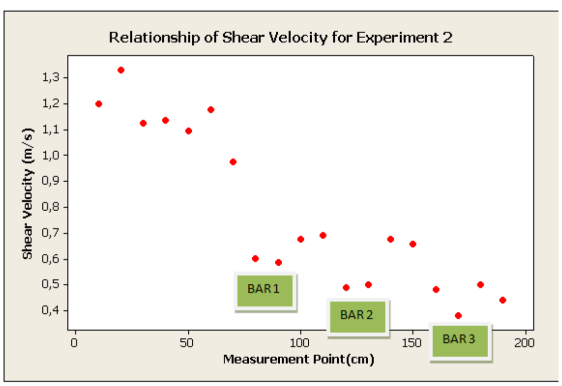


Figure 3.3: Location of bar formation at profile of shear velocity for experiment 2

Figure 3.4 shows the graph of shear velocity profile and location of bar formation in experiment 3 with channel discharge of 4.6 x 10^{-5} m^3/s. The channel was also developed by unstable condition. Its value was higher at upstream and descended at downstream similar to **Figure 3.3.** The value was the highest at point 90 cm and lowest at 180 cm of channel. Most of the shear velocity were higher at transported zone and started to decrease again at point of 100 cm. Bars are formed at points 120 cm to 180 cm of minimum shear velocity with a value under 1.00 m/s. There were no points of stable shear velocity in this graph. The values were differed at each point.

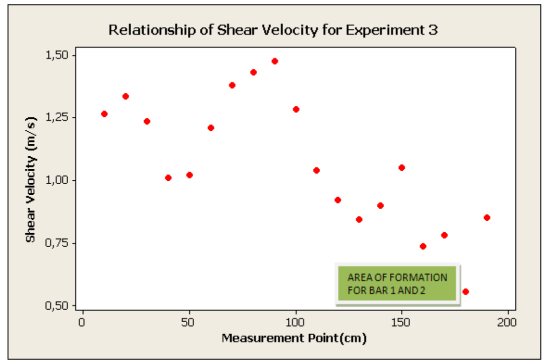


Figure 3.4: Location of bar formation at profile of shear velocity for experiment 3

3.3.2. Effect of Sediment Release

In earlier section, discussion was made based on the effect of shear velocity in terms of flow on bar formation. This section focuses on the effect of shear velocity for different sediment release. An analysis was made by looking at the pattern of graph changes in measurement points along the channel.

Figure 3.5 shows a shear velocity profile and location of bar formation for sediment release of 0.25 kg. The profile was not stable with continuous changes of values from upstream to downstream. The maximum and minimum value of shear velocity was at 40 cm and 10 cm respectively. There was no point of stable shear velocity along the channel. The bars are formed at points 90 cm, 130 cm, and 180 cm. These are the location of minimum shear velocity. Therefore the bars are formed at location with minimum shear velocity. The critical value of shear velocity was 1.1 m/s.

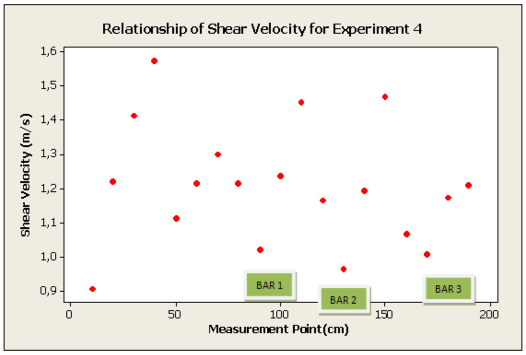


Figure 3.5: Location of bar formation at profile of shear velocity for experiment 4

Figure 3.6 shows a shear velocity profile and the location of bar formation for sediment release of 0.5 kg. The value of shear velocity was lower at zone 1 but started to increase in zone 2 and dropped again at zone 3. The profile was also not stable. The shear velocity dropped rapidly at zone 2 (80 cm – 120 cm) and started to stabilize in zone 3. The most maximum and minimum values of shear velocity was found at points 70 cm and 120 cm respectively. The stable values were at points 150 cm to 180 cm. The bars formed at these points with value of shear velocity under 1.0 m/s. Therefore bars are formed at stable values of shear velocity.

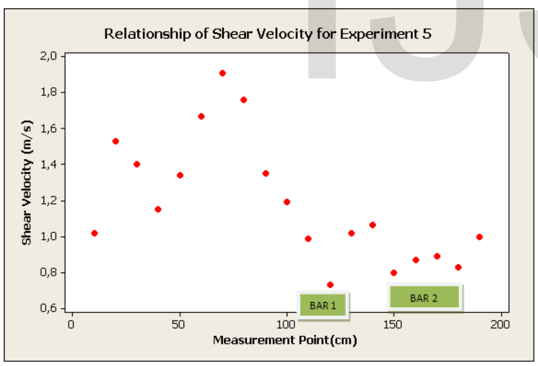


Figure 3.6: Location of bar formation at profile of shear velocity for experiment 5

Figure 3.7 below shows the shear velocity profile for sediment release of 1 kg, which was developed in unstable condition with different values of shear velocity at each point. The maximum and minimum shear velocity was at 70 cm and 190 cm respectively. The shear velocity started to stabilize at points 80 cm to 100 cm and 140 cm to 160 cm. Bar is formed at these points. The values were also higher at zone 2. It dropped again and started to stabilize at zone 3.

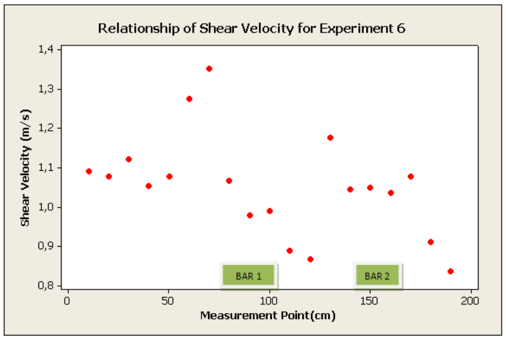


Figure 3.7: Location of bar formation at profile of shear velocity for experiment 6

4.0. DISCUSSION

The study of characteristic of geometry coordinates for mid-channel bar formation has been discussed. Mid-channel bars had only formed in zone 2 and zone 3 for both experiments. There were no bars visible in zone 1. This could be due to the erosion that existed in zone 1 and deposition at zone 2 and zone 3. The sediment from zone 1 was transported to zone 2 and zone 3 because of the local flow rate. Erosion was observed when higher flow rates were induced. As a result, there were evidences of erosions in zone 1 and it was noted that these sediments had been transported downstream in stages with respect to the flow induced. Pulses of flow had initiated the deposition. It was also proven in experiment 3 that with higher flow rate, bigger bars are formed at zone 3. The higher erosion rate at upstream caused more sediment to be transported downstream. Flow induced erosion and the pulses of flow initiated the bar formation. The lower flow rate reduced the erosion with less sediment being transported but at the same time initiates deposition. It was also proven in experiment 1 where no major changes of channels and bar formation were evident at very low flow.

The time it takes for a bar to form will be longer when lower discharge was used and shorter duration when the discharge was increased. The channel changes rapidly when flow increased due to changes of its bed and bank profile. This condition induced the process of formation for mid-channel bar. The highest flow was enough to degrade the bed and bank sediment in channel and produce much sources of sediment for deposition process. This was proven in experiment 3. When sediment acted on upstream of channel the flow of water was decreased due to the resistance of these sediments. Therefore much time was taken for mid-channel bar to form. This was shown in experiment 4 with a discharge of 4.6 x 10^{-5} m^3/s. Although same discharge was used in experiment 3 it was noted that it takes longer time for a bar to form because the experiment had only utilize 1 kg of sediment.

The bars are not actively formed when sediments were released in channels. It was shown in experiment 4, experiment 5, and experiment 6. The bars are formed in smaller size as compared to other experiments. The bars are also formed in zone 2 and zone 3 only. No bars were visible in zone 1. It was similar to the effect of flow. However, the deposition still happened at downstream although sediment was released at upstream. The sediments were transported to downstream, and they were deposited at these zones to produce bars.

The channels produced were in straight pattern before the experiments. All channels had gradually meandered except for experiment 1. Initially, it was widened before it started to meander. The channels were widened because of the erosion process. Thus, it proved again that some form of erosion and deposition had taken place. The bank was eroded, and its material collapsed on the bed. These materials and bed sediments acted as sediment sources in the deposition process. Erosion happened on the outer bank and sedimentation on the inner bank. When a flow acted in channel its planform was highly sinuous because the flow induced the process of erosion and sedimentation. This phenomenon was proven in experiment 2 and experiment 3. The channel became stable and changes were not significant when the flow was reduced as shown in experiment 1. It had started to meander upon sediment release with smaller sinuosity.

It was also observed that the sand bed showed gradual progress towards braiding upon sediment release. This is attributed to the sources of sediments that promote erosion and deposition process. Upon deposition the released sediment may get eroded and transported downstream. It was found that erosion and sedimentation of bed channel had actively occurred upon sediment release. Braiding was significant with higher sediment release as proven in experiment 6 at zone 1 and zone 2.

Bar profile was being investigated in this study. Two different shapes were noted namely lunar and elliptical. Results have shown that both flow and sediment have effect on the formed shape of the mid-bar. Lunar shapes were formed to the effect of different flows while elliptical shapes were formed to the effect of different sediment discharge. The bars formed from the effect of different flows were initially formed from the cut-off point bars. The formation was observed at the inner bank as proven in experiment 2 and experiment 3. Upon meandering, point bars had gradually formed. Some of the upstream sediments were deposited on the inner bank in zone 2, and others were deposited at downstream. The repeated process of deposition produced a large amount of sediment that promotes the point bar formation. Growth in the point bar had reached a threshold limit in growth which could be due to the extended length formed that crosses the flow path. The flow had finally cut-off the point bars to produce several longitudinal mid-channel bars.

In conditions of different sediment releases most of the bars takes the form of elliptical shapes. The bars were initially formed at the centre of the deposited sediment. Bars are also formed in smaller sizes as shown in experiment 4, 5 and 6. Thus, it was found that, sedimentation process is not the only factor that determines bar formation. Flow plays a significant role in bar formation and the shapes formed. Even with different sediment releases it was noted that about same numbers of bars were formed in each channel. Despite active deposition which had taken place, the bar formation were not visible due to weaker erosion process.

Shear velocity is critically related to the formation of mid-channel bars. All experiments have shown that the profiles had developed into unstable conditions at points of different shear velocity values. Results of the findings have shown that the channels changed dynamically with different mechanism of bar formation along channels. The findings also showed that when the values of shear velocity were low, the bars are formed and simultaneously happened in higher values of shear velocity. Shear velocity increases the erosion process. Bars are not formed when their values were higher. In Section 3.0, the shear velocity was found to be higher at the upstream and lower at the downstream. The points of low shear velocities coincide with the formation of bars at the downstream region. This has resulted in bars formed in zone 2 and zone 3 in channels. Bars are also formed at locations of minimum and stable shear velocity. It is also important to note that instability in the shear velocity will produced bar that is unstable and can be easily vanished by the erosive flow.

5.0. SUMMARY OF STUDY

From the study, it can be concluded that both flow and sediment are critical in determining the extent and shape of bar formation. Erosion and sedimentation process have substantial effect on the geometry formation of mid-channel bar. Shear velocity is significant to the profile of bar formation apart from the local matrix of flow and sediment in channels.

6.0. ACKNOWLEDGEMENT

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7.0. REFERENCES

[1] Colombini, M., Seminara, G., & Tubino, M. (1987). Finite-amplitude Alternate Bar. *Journal of Fluid Mechanic, 181*, 213-232.

[2] Shielen, R., Doelman, A., & Swart, H. E. (1993). On the Nonlinear Dynamic of Free Bars in Straight Channel. *Journal of Fluid Mechanic, 252*, 325-356.

[3] Fredsoe, J. (1978). Meandering and Braiding of Rivers. *Journal of Fluid Mechanic, 84*, 609-624.

[4] Kuroki, M. (1988). *Study of Flow and Bedform in River Alluvials.* Phd, Hokkaido Uni.

[5] Watanabe, Y., & Tubino, M. (1992). Influence of Bed Load and Suspended Load on Alternate Bars. *Proc. of Hydr. Eng., 36*.

[6] Leopold, L. B., & Langbein, W. B. (1962). Concept of entropy in landscape evolution. *US geological surver*(500 A).

[7] Luchi, R. (2010). Width variations and mid-channel bar inception in meanders. *Geomorphology, 119*, 1–8.

[8] Carling, P. A. (2006). The dispersion of magnetite bedload tracer across a gravel point-bar and the development of heavy-mineral placers. *Ore Geology Reviews, 28*, 402–416.

[9] Kim, Y. H., & Voulgaris, G. (2005). Effect of channel bifurcation on residual estuarine circulation: Winyah Bay, South Carolina. *Estuarine, Coastal and Shelf Science, 65*, 671-686.

[10] Cardenas, M. B. (2009). The effect of river bends morphology on flow and timescales of surface water-groundwater exchange across point bars. *Sedimentary Geology 191*, 3–36.

[11] Zu-lin, H., Li, G., & Ke-jian, C. (2009). Experiments of Three-Dimensional Flow Structure In Braided Rivers. *Journal of Hydrodynamics, 21*(2), 228-237. doi: 10.1016/S1001-6058(08)60140-7

[12] Li, L. (2007). River channel change during the last 50 years in the middle Yangtze River, the jianli reach. *Geomorphology, 85*, 185–196.

[13] Bridge, J. S., & Lunt, I. A. (2005). Depositional Models of Braided Rivers. 11-51.

[14] Bristow, C.S. (1993) Sedimentary structures exposed in bar tops in the Brahmaputra River, Bangladesh. In: Braided Rivers (Eds J. B. Best and C. S. Bristow), pp. 277-289. Special Publication 75, Geological Society Publishing House, Bath.