Preliminary Study on the Impact of Flow Rate and Sediment Load to the Geometry Formation of Meanders in a Meandering River

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ABSTRACT

This study demonstrates the development of meanders with respect to different flow rate and sediment load. The knowledge on meanders is important, not only because it changes the geometry of the river but it also can cause threats to the people and properties. With more than 150 rivers throughout Malaysia, the knowledge on meander behavior is vital to avoid problems associated with poor planning of the development at riverside. Eight sets of experiments have been conducted using Armfield S12 MKII Advanced Hydrology Study System at the Faculty of Engineering, UNISEL Bestari Jaya Campus. The experiments was conducted under controlled environment with flow rate and sediment load as the variable parameters while the other factors that can affect meander growth and migration are kept constant. The changes in cross section were measured and 3D surface was generated using Surfer 9 to analyze the effect of variation in flow rate and sediment load to the erosion, transportation and deposition processes that involved in meander meander growth and migration. The relationship between flow rate and sediment load with the migration and growth pattern of meanders are discussed well in this paper. This study is meant to be continued further to come out with suitable equations in predicting meander migration.

Key words: *meandering; river sinuosity; erosion; sediment transport capacity*

Introduction

Growth and migration of meanders not only change the river geometry but also posed threats to the people and structure. It may continuously erode the bank thus affect the properties and human activities along the floodplain area. In some scenarios, the deposition of eroded sediments can reduce the river carrying capacity and cause flooding, which normally occur at the river bend. Problem to maintain the stability of roads and bridges may also become a concern when the meanders migrate downstream over time as the erosion scours its foundation. In order to reduce the possibility of flood occurrence, one of the widely used mitigation measures is to come out with channel improvement by straightening, widening and deepening the river or by reducing its surface roughness. However, it is well understood that the meanders are natural phenomenon that act as the energy dissipater for river flow thus disturbing it might affect the natural characteristic of the stream. To ensure that the channel migration did not cause losses to the human being and to avoid channel modification from affecting the ecosystem negatively, good understanding on meander growth and migration are crucial. Acknowledging the importance of meanders, large numbers of studies has been conducted to explore the causes and impact of river meandering, for example it is now accepted that secondary circulation can cause meanders as it erodes one river bank and deposit the sediments at the toe of the others.

However, until now there is no established method to predict river migration, it is dynamic and there are many factors that can influence the process. Even though many studies were conducted worldwide, in Malaysia, there is still no research available focusing in meander migration. Therefore, this study will focus on the fundamental effect of two governing factors which are flow rate and sediment load to the geometry formation of meanders. The experiment was conducted using Armfield S12 MKII Advanced Hydrology Study System at the Faculty of Engineering, UNISEL Bestari Jaya Campus. Further investigations are required to correlate the growth pattern and migration of meanders with respect to different value of flow rate and sediment load.

Background

There are several literatures discussed about meander growth and migration, some of them are using flume test while other studies based on field data from real rivers. Meander growth can be defined as the change in meander dimensions over time, for example its radius of curvature, amplitude and width. Whereas, meander shift is the displacement of the bend in either downstream or upstream direction, most of the time it will shift downstream.

The growth of meanders involves changes in its dimension. As the meander become larger, its amplitude and width increases. The same goes to the radius of curvature of the bend. To do research on meanders, knowledge on river geometry is crucial. Usually channel bends are treated as arcs; the parameters to describe meander geometry are shown in Figure 1.

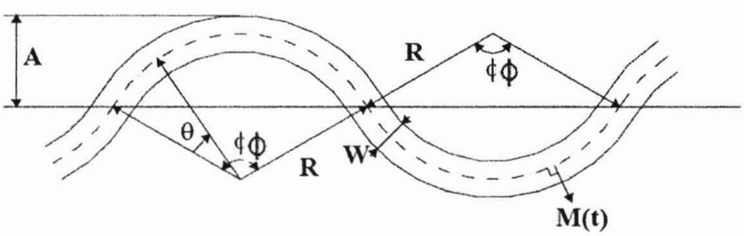

Figure 1: Parameters Defining Meander Geometry (Briaud et al., 2007)

The definitions of these parameters are as follows:

A = meander amplitude
W = channel width
M = channel migration distance
R = radius of curvature
ϕ = bend angle
θ = relative angle ($0 \leq \theta \leq \phi$) within each bend
t = time

Since 1970s, study on meander migration has become the interest of the researchers in river engineering field. Soil-water interaction and geometry are widely studied in various ways to come out with the best prediction of meanders. These approaches can be divided into three categories:

i. Time-sequence maps and extrapolation
ii. Fundamental modeling
iii. Empirical equations

Generally, the findings are not successful due to the complex characteristics of the river geometry and the dynamic of the flow. For the time-sequence map and extrapolation method, the researchers usually gather the series of topographic map and aerial photographs throughout the study period. These maps and aerial photographs can be obtained from local libraries and even websites such as the Google Earth. The method is quite simple and the study is based on a full-scale observation of real data, however, the disadvantages of this method are the maps and photographs might be limited to certain developed areas, and the assumption that the future flow and soil conditions will remain the same, which is not suitable due to development.

Fundamental modeling consists of erosion process modeling at the interface between soil and water. This will then be projected by using future hydrographs. Fundamental modeling can mimic the actual phenomenon at a specific site, and it can be utilized to model erosion at the particle level. However the disadvantages of using this method is that it requires site-specific measurement of soil properties, which is complicated and make it unique to that site only (Wang, 2006).

An example of the empirical equation method of Keady and Priest (1977) for the estimation of migration rate correlates the downstream migration to the free surface slope of the river and meander amplitude as shown in Equation 1.

$$\frac{V}{\sqrt{gA}} = \phi(s) \qquad \text{(Equation 1)}$$

where:

V = migration rate, (ft/yr)

g = acceleration of gravity, (ft/sec2)

A = meander amplitude, (ft)

s = free surface slope

Ø = function of s

The limitation of this formula is that it did not consider the rainfall that is one of the governing factors for flow condition. Rainfall can affect the flood peak and it is well understood that flood can result to a rapid and significant meander migration.

Hooke (1980) equation predicts bank erosion rate using regression analysis. Equation 2 shows the formula proposed by Hooke which considers the area of catchment for different scenarios with respect to surface runoff, precipitation, infiltration and evaporation rates which are functions of location, climate and type of soil.

$$Y\ (m/yr) = 8.67 + 0.114\ A \quad (r=0.73)$$

$$Y\ (m/yr) = 2.45\ A^{0.45} \quad (r=0.63) \qquad \text{(Equation 2)}$$

where:

Y = bank erosion rate

A =catchment area(km^2)

Interest on meanders can be seen in the 21^{st} century where there are increasing numbers of research papers published. For the field-based study, the researchers are looking at the interaction between the rivers flow with the evolution of planform and bed morphology over long run (Harrison et al., 2011; Hooke, 2008; Guneralp and Rhoads, 2009, 2010). While for the laboratory-based study, the researchers generally investigating on the flow and sediment transport behaviour in curved channels (Peakall et al., 2007; Termini, 2009 and Braudrick et al.,2009). Studies on real rivers usually are not preferred, as it require years of observation, and involved many unpredictable factors that make it difficult to forecast the future rates of meander migration. Nevertheless, most of the researchers agreed that the migration rates would slow down as the channel approaches a state of near stability. Other than the field and laboratory based investigation, some researchers preferred the theoretical and numerical modeling of meander morphodynamics (Luchiet al., 2011; Bolla et al., 2009 and Crosato, 2009) which involve complex modeling of the parameters. In 21^{st} century, the researchers also show interest on submarine meandering, where they are focusing on the effect of turbidity current to the growth and migration of meanders and also the interchannel-sedimentation patterns (Amos et al., 2010; Parsons et al., 2010 and Abad et al., 2011).

Zhang and Shen (2008) and Fu et al. (2009) also involved with the numerical simulation to investigate the growth and migration of meanders. They established a 3D simulation that was based on finite volume method. Although the correlation between natural and computed channel deformation can be achieved after the calibration of numerical models, it is not necessarily suitable to be applied to another river due to the varieties of influential factors.

Rapid interest in meander migration can be seen where a lot of research has been conducted worldwide. This involved both the study based on field and laboratory data, which look at the effect of flow pattern and sediment transport to the meanders evolution. Generally, for a meandering channel, the centreline (not the thalweg) follow sine-generated curves, its Froude number is small, the flow is turbulent and the channel ratio of width over depth is large. The variation of deflection angle, θ along the channel centreline, l_c and the channel sinuosity, σ can be expressed as shown in Equation 3 and 4 (Dai, 2008).

$$\theta = \theta_0 \, cos(2\pi \frac{l_c}{L}) \qquad \text{(Equation 3)}$$

$$\sigma = \frac{L}{\Lambda} = \frac{1}{J_0(\theta_0)} \qquad \text{(Equation 4)}$$

where:

θ_0 = value of θ when $l_c = 0$

Λ = meander wave length

L = meander length (measured along l_c)

$J_0(\theta_0)$ = Bessel function for first kind and zero-th order of θ_0

Using this equation, Dai and Tang (2010) come out with a mathematical model to simulate and predict the migration and expansion of meander loops. From their findings, it shows that for small θ_o ($0<\theta_o<=30^0$), migration of meanders is the main deformation that will occur in a meandering channel while for large θ_o ($100^0<\theta_o<138^0$), the migration and expansion will reduce. They also suggest that more numerical and experimental investigation should be done in order to validate the multiplier function of the migration and expansion found by them.

Methodology

A. Equipment Setup

The main equipment used for this study is the Armfield S12 MKII Advanced Hydrology Study System. It is equipped with a water storage tank and pumping system where the flow can be set between 0 to 2.75 L/min. For the platform, the 2 m long x 1 m wide x 0.2 m deep stainless steel tank is also connected to the dual linked jacking system so that the slope can be varied between 0 to 5 %.

B. Experimental Works

Eight sets of experiments were conducted on a 2000 mm long, 40 mm wide and 20 mm deep channel, molded in the Armfield S12 MKII Advanced Hydrology Study System. The details of the parameters and apparatus used can be described as follows:

i. Size of sediments - Uniform sand was used to ensure homogeneity of the material. The median grain size, D_{50} for the sediments used in this study is 0.80 mm.
ii. Flow rate – The submersible pump used in this study able to cater the flow between 0 to 2.75 L/min. From the preliminary study, no bed movement can be seen for the flow below 2.00 L/min. Thus, four different flow rates were chosen as the variable parameter for this study which is 2.00, 2.25, 2.50 and 2.75 L/min.
iii. Slope – The channel slope is important to maintain a constant depth of water, based on the literature, meander develops at a less steep area thus the initial slope was set at 0.5 % for the entire tests.
iv. Sediment load – The sediment load is one of the variable parameter for this study where two conditions were provided, there is either no sediment load or gradual sediment load. The material used is the same with the bed material where the median grain size, D_{50} is 0.8 mm.

The flow rate and sediment load for all the eight sets of experiment conducted are shown in Table 1.

Table 1: Experimental Conditions

Case No.	Flow Rate (L/min)	Sediment Load
1	2.00	No sediment load
2	2.25	No sediment load
3	2.50	No sediment load
4	2.75	No sediment load
5	2.50	Gradual sediment load - 0.25 kg daily
6	2.75	Gradual sediment load - 0.25 kg daily
7	2.75	Gradual sediment load – 0.50 kg daily
8 (bend)	2.25	No sediment load

C. Data Analysis

The iso–profiles of the meander were established using Surfer 9, a contouring and 3D surface mapping program, using the data measured in X, Y and Z direction along the river model. The correlation between flow rate and sediment load to the migration of meander was discussed well to come out with suggestions for future investigation.

Results and Discussion

From the experiments conducted, it can be seen that straight channel with initial size of 2000 mm x 20 mm x 40 mm has gradually changed its shape and turn into braided channel and increase its sinuosity over time. The sinuosity for a meandering channel is usually greater than 1.50 while for this study, the maximum sinuosity recorded is about 1.20. The meandering channel is not properly developed in this case mainly because of the short valley length.

D. Influence of Flow Rate with No Sediment Load

To study the influence of flow rate, several tests have been conducted with four (4) different flow rates, which are 2.00, 2.25, 2.50 and 2.75 L/min. It is found that the flow has to pass the threshold value to ensure movement of soil particle, or else it did not cause growth and migration of meanders. The flow will cause erosion to its bank line continuously until it reaches the stable channel configuration. Figure 2, 3 and 4 shows the development of meanders for the tests conducted with flow rate of 2.00, 2.50 and 2.75 L/min.

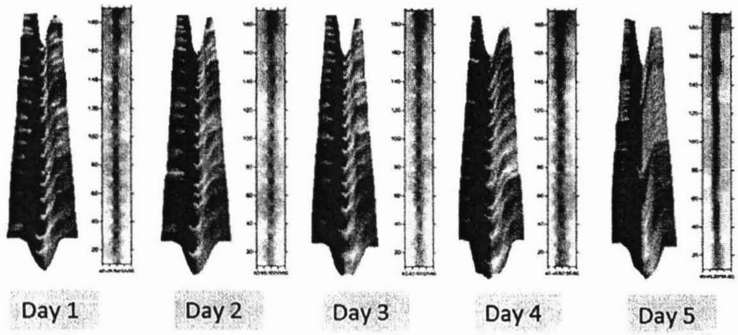

Figure 2: Development of Meanders using Flow Rate 2.00 L/min

In Figure 2 it can be seen that there is no significant formation of meanders even after 5 days of operation. Some particle movement can be seen along the bed, thus, it is expected that the flow intensities of 2.00 L/min is just above the threshold of motion for this study with D_{50} of 0.8 mm and initial slope, S_o of 0.5 %.

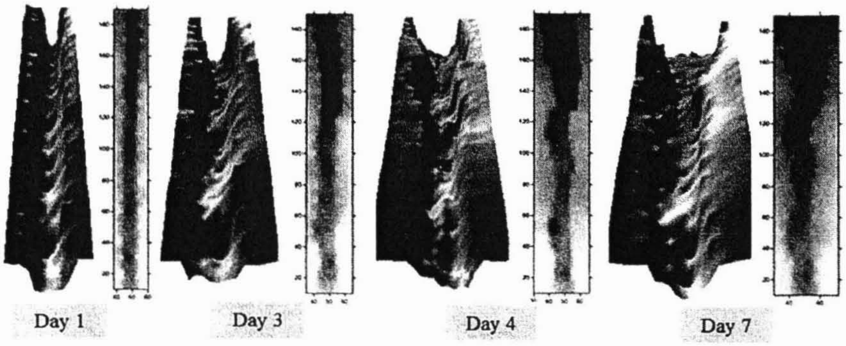

Figure 3: Development of Meanders using Flow Rate 2.50 L/min

For the other cases, the formations of meanders are quite significant. Higher flow intensities will have higher transport capacity; this can be translated into greater erosion and transportation of sediment material. Moreover, all these cases shows that the channel will undergo erosion, transportation and sedimentation processes until it achieve equilibrium and channel stability. Eventually, the migration will gradually decrease. Figure 3 and 4 shows that using 2.50 and 2.75 L/min flow rate, it took about seven and three days for the channel to reach its stability respectively.

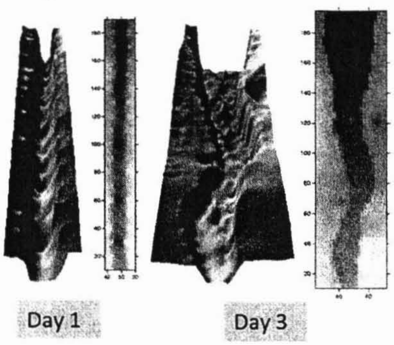

Figure 4: Development of Meanders using Flow Rate 2.75 L/min

It can be learned that a higher flow rate will produce higher shear stress, which resulted into higher erosion rate and increased in sediment transport capacity. By comparing Figure 3 and 4, it is clear that the one with higher flow rate took less time to reach its stability. Moreover, it recorded higher erosion and sediment transport compared to the one with lower flow rate. The deposition of bank failure is not apparent at higher flow rate due to higher energy and transportation capacity, which make it easily transported downstream.

This explains why during flooding, where the river is under very high flow rate, there will be significant shift in its plan form geometry because the stream erodes its bank line and reworks the flood plain rapidly. The occurrence of erosion, transportation and sedimentation processes will cause expansion of the river width and the down valley translation of bank line that makes the river become more sinuous. The increase in length will increase the frictional force between channel boundaries thus reduces the flow velocity. Once it reaches equilibrium, the channel planform will remain unchanged.

E. Influence of Sediment Load

Sediment load is one of the important factors that can affect meander growth and migration. Sediment load is highly associated with the concept of sediment transport capacity. In reality, it is hard to determine the amount of sediment supplied to a stream from the watershed due to the spatial and temporal variation of the parameters, for example it is hard to determine the eroded material induced by rainfall and bank erosion process at upstream.

For this study, the sediment load has been released daily and the amount varied accordingly. Figure 5 and 6 shows the difference in meander development for two experiment setups with the same 2.75 L/m flow rate and different amount of sediment load. The first one is loaded with 0.5 kg sediments daily while the second one is loaded with 0.25 kg sediments daily.

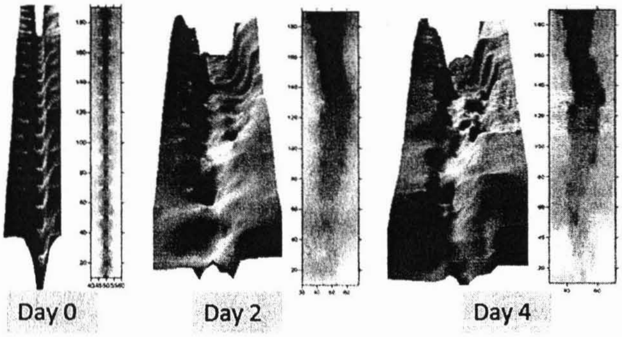

Figure 5: Case 7, Flow 2.75 L/min, Sediment Load 0.5 kg Daily

It is clear that for the one with 0.5 kg sediment load daily, aggradation occur rapidly because the stream unable to transport the sediment loads entering the reach, this case is known as capacity limited. Aggradation can lower the channel carrying capacity thus cause serious flooding to the nearby area. This can illustrate the real scenario occurring especially at upstream, once the sediment load increases rapidly such as due to deforestation, aggradation will occur and reduces the channel depth, this can affect its water carrying capacity and cause flooding. At a lower area downstream, meanders will develop as the flow balance, caused by the slope steepening.

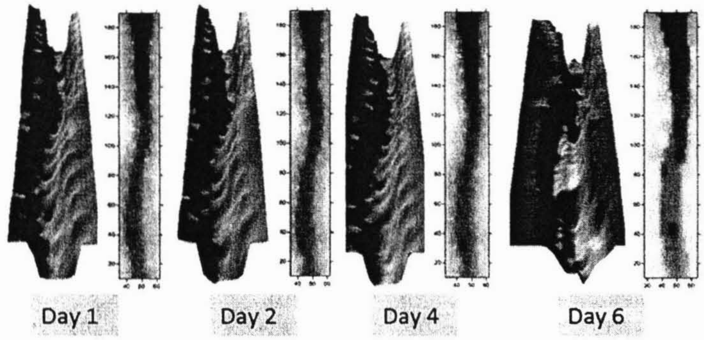

Figure 6: Case 6, Flow 2.75 L/min, Sediment Load 0.25 kg Daily

At a lower sediment load, as shown in Figure 6, it seems that the stream has sufficient sediment transport capacity to cater it. Thus, the shapes did not change rapidly from Day 1 to Day 4. However, as the sediments deposited day by day, the transport capacity might reduce. In Day 6 (six) scenario, when the river bank fails, there are more sediment load entering the reach, aggradation seems to occur which means that the amount of sediment load from the bank failure in addition to the normal 0.25 kg sediment load released daily is higher than its sediment transport capacity.

In order to know the relationship between sediment transport and the discharge, another experiment has been conducted as shown in Figure 7. This channel was run with 2.50 L/min flow rate and 0.25 kg sediment load released daily. By comparing Figure 6 and 7, it can be observed that aggradation is more apparent for the one with lower flow rate. Thus, it agrees that a higher flow rate will provide a higher sediment transport capacity for a stream.

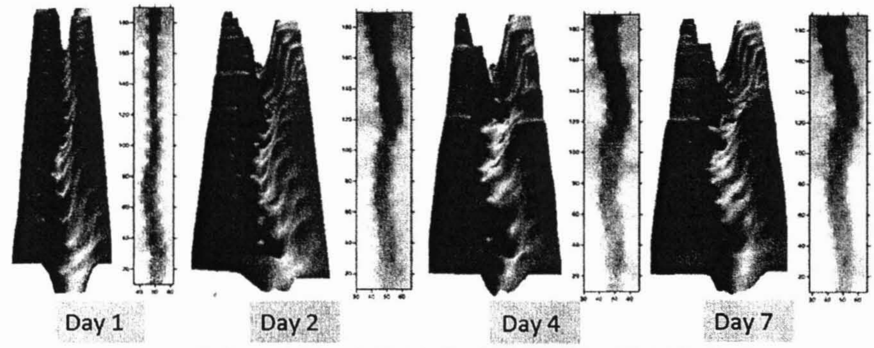

Figure 7: Case 5, Flow 2.50 L/min, Sediment Load 0.25 kg Daily

Conclusion and Recommendations

From the analysis of the data obtained, it can be concluded that river flow rate and sediment load are some of the important parameters involved in the growth and migration of meanders. Meanders formation is highly related to the erosion, transportation and sedimentation process, which can be affected by flow rate and sediment supply. The higher the flow rate, the higher will be the frictional force between water and the soil surface thus it will increase the soil erosion rate. Moreover, the sediment transport capacity will also increase as the flow rate increase. This implies that with higher flow rate, the river will be able to transport more sediment downstream. Other than that, sufficient sediment load is important to assist the meander development. If the sediment load is too low, severe degradation will occur, this will hinder the meander development as the erosion and sedimentation did not balance. The same goes when there is too much of sediment load; aggradation will occur along the channel that causes flooding to the neighboring area. When the water re-enter the river downstream, this will promote meandering. From this study, some recommendations are proposed to improve the analysis of the meander growth and migration. Firstly, it is suggested to use a bigger and longer river model, this can enhance river feature development and ease the data collection. This can assist the measurement of radius of curvature, bend angle, relative angle within each bend, channel width and channel migration distance which are important for better analysis. Secondly, more set of experiments should be conducted to have more comparison for better analysis. And lastly, it is good to have more frequent data collection and video recording for better view of the growth pattern.

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References

Abad, J.D., Sequeiros, O.E., Spinewine, B., Pirmez, C., Garcia, M.H., and Parker, G. (2011). Secondary current of saline underflow in a highly meandering channel: experiments and theory. *Journal of Sedimentary Research 81* (11–12), 787–813.

Amos, K.J., Peakall, J., Bradbury, P.W., Roberts, M., Keevil, G., and Gupta, S. (2010). The influence of bend amplitude and planform morphology on flow and sedimentation in submarine channels. *Marine and Petroleum Geology 27* (7), 1431–1447.

Bolla Pittaluga,M., Nobile, G. and Seminara, G. (2009). A nonlinearmodel for river meandering. *Water Resources Research 45*, W04432. doi:10.1029/2008WR007298.

Braudrick, C.A., Dietrich, W.E., Leverich, G.T., and Sklar, L.S. (2009). Experimental evidence for the conditions necessary to sustain meandering in coarse-bedded rivers. *Proceedings of the National Academy of Sciences of the United States of America106* (40), 16936–16941.

Briaud, J.L., Chen, H.C., Chang, K.A., Chung, Y.A., Park, N., Wang, W., and Yeh, P.H. (2007). *Establish guidance for soil properties-based prediction on meander migration rate*. Texas Transportation Institute Report No. 4378-1 for Texas Department of Transportation. The Texas A&M University, Texas.

Crosato, A. (2009). Physical explanations of variations in river meander migration rates from model comparison. *Earth Surface Processes and Landforms 34* (15), 2078–2086.

Dai, W.H., and Tang, H.W. (2010). A mathematical model of migration and expansion of meander loops. *Journal of Hydrodynamics 22* (2), 214-220.

Dai, W.H. (2008). *On the simulation and prediction of bed morphological adjustments of equilibrium in alluvial meandering streams*. PhD Thesis, Queen's University, Canada.

Fu, C.Q., Jiang, H.M., and Yin, H.J. (2009). Finite volume method for simulation of viscoelastic flow through an expansion channel. *Journal of Hydrodynamics 21* (3), 360-365.

Guneralp, I., and Rhoads, B.L. (2009). Planform change and stream power in the Kishwaukee River watershed, Illinois: geomorphic assessment for environmental management. In James, L.A., Rathburn, S.L. & Whittecar, G.R. (Eds.), *Management and restoration offluvial systems with broad historical changes and human impacts* (pp. 109–118). Geological Societyof America Special Papers. Geological Society of America, Boulder, CO.

Guneralp, I., and Rhoads, B.L. (2010). Spatial autoregressive structure of meander evolution revisited. *Geomorphology 120* (3–4), 91–106.

Harrison, L.R., Legleiter, C.J., Wydzga, M.A., and Dunne, T. (2011). Channel dynamics and habitat development in a meandering, gravel bed river. *Water Resources Research 47*, W04513,doi:10.1029/2009WR008926.

Hooke, J.M. (2008). Temporal variations in fluvial processes on an active meandering river over a 20-year period. *Geomorphology 100* (1-2), 3-13.

Hooke, J.M. (1980). Magnitude and distribution of rates of river bank erosion. *Earth Surface Processes 5* (2), 143-157.

Keady, D.M., and Priest, M.S. (1977). The downstream migration rate of river meandering patterns. *Proceedings of 12th Mississippi Water Resource Conference, Mississippi*, 29-34.

Luchi, R., Zolezzi, G., and Tubino, M. (2011). Bend theory of river meanders with spatial width variations. *Journal of Fluid Mechanics 681*, 311–339.

Parsons, D.R., Peakall, J., Aksu, A.E., Flood, R.D., Hiscott, R.N., Beşiktepe, Ş., and Mouland, D. (2010). Gravity-driven flow in a submarine channel bend: direct field evidence ofhelical flow reversal. *Geology 38* (12), 1063–1066.

Peakall, J., Amos, K.J., Keevil, G.M., Bradbury, P.W., and Gupta, S. (2007). Flow processes and sedimentation in submarine channel bends. *Marine and Petroleum Geology 24* (6-9), 470-486.

Termini, D. (2009). Experimental observations of flow and bed processes in large-amplitude meandering flume. *Journal of Hydraulic Engineering 135*, 575–587.

Wang, W. (2006). *A hydrograph-based prediction of a meander migration.* PhD Thesis, Texas A&M University, Texas.

Zhang, M.L., and Shen, Y.M. (2008). Three dimensional simulation of meandering river based on 3D RNG κ-ε turbulence model. *Journal of Hydrodynamics, 20* (4), 448-455.

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