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Brief Communication: 2-D numerical modeling of the transformation mechanism of a braided channel

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Abstract

This paper investigates the controls on the transformation mechanism among different channel patterns. A 2-D depth-averaged numerical model is applied to produce the evolution of channel patterns with complex interactions among water flow, sediment transport, and bank erosion. Changes of the variables as discharge, sediment supply, and vegetation are considered in the numerical experiments, leading to the transformation from a braided pattern into a meandering one. What controls the transformation is discussed with the numerical results: vegetation helps stabilize the cut bank and bar surface, but is not a key in the transition; a decrease in discharge and sediment supply could lead a braided pattern to a meandering one. The conclusion is in agreement with various previous field work, confirming the two dimensional model's potential in predicting the transition between different rivers and improving understanding of patterning processes.

1 Introduction

The channel pattern refers to limited reaches of the river that can be defined as straight, meandering, or braided. However, there is a gradual merging of one pattern into another, they do not fall easily into well-defined categories. Knowledge of the mechanism of transformation is vital within practical engineering and yet, when compared to the wealth of literature upon formation of one channel pattern, it has been comparatively understudied. Laboratory studies and field data analysis of river patterns have contributed to the interrelationships of control factors (e.g. discharge, sediment supply, bank materials, vegetation), which influence the transformation between braided and meandering channels (Leopold and Wolman, 1957; Ackers and Charlton, 1971; Schumm and Khan, 1972; Ikeda, 1973, 1975; Ashmore, 1982, 1991). The review of the previous work can be seen in Bridge (1993). With the rapid developments of numerical methods in fluid mechanics, computational modelling has become an important tool for investigating dynamic interactions in evolving braid units. Cellular models and fluid dynamics models have been developed to model braided rivers (Murray and Paola, 1994, 2003; Paola, 2001; Thormas and Nicholas, 2002; Takebayashi and Okabe, 2009; Bridge and Lunt, 2005; Jang and Shimizu, 2009; Wang et al., 2010; Schuurman and Kleinhans, 2011). Although various computational studies on the formation of braided rivers are available, few preliminary numerical studies of the transformation process from braided to meandering pattern (Crosato and Mosselman, 2009) are offered, to discuss the impacts of control factors on the patterning processes.

The primary objective of this study is to investigate the effects of control factors on the transformation mechanism of braided channels. In the numerical experiment, a conceptual braided channel is established by a 2-D numerical model, which takes into account the impact of vegetation as a term into the momentum equation of the flow. The control factors as discharge, sediment supply, and vegetation are considered in the simulation of the transition from the braided into the meandering channel. Predictions agree well with previous work of field and theoretic research. It demonstrates that the numerical model can be applied to improve understanding of the patterning processes under different scenarios.

2 Numerical model

2.1 Model description

The 2-D numerical model is developed which takes into account effects of secondary currents, non-equilibrium sediment transport process, and bank failure process due to bed scour. Effect of secondary currents is considered following the method by Lien et al. (1999). The bank erosion model developed by Hasegawa (1981) is applied to calculate the bank failure processes. A moving grid system is applied in such simulations, and it can be very time-consuming to regenerate new grids in areas with complex boundaries, such as migrating island bars in multi-thread channels, especially in an orthogonal grid system. Detail on the numerical algorithms for incorporating the bank failure calculation into the 2-D simulation is described in Xiao et al. (2012), which allows this model to solve problems involving channel pattern changes.

The numerical solution is based on a finite difference method in the orthogonal curvilinear coordinate system. The finite difference equations corresponding to the differential equations are expressed in an alternating direction implicit form. All the discretization procedures are based on a second-order central difference scheme, except for the time differentials of water level in the continuity equation, which use a forward difference scheme. For the advective accelerations in the momentum equations, a combination of the first-order upwind scheme and second-order central difference can be used (Falconer, 1986) in the 2-D numerical model.

The model of water flow is verified using various laboratory experiments, including flow measurements in a laboratory channel with consecutive bends (Wang et al., 2010), the non-equilibrium sediment transport model is validated with field measurements on the changes of bed elevation of a 180° bend channel, and tested with the physical modeling of meandering channels by Friedkin (Xiao et al., 2012).

Based on the advances in numerical modeling and fundamental study of the physical mechanism of channel evolution, some researchers suggested the use of 2-D numerical models to study the cause-and-effect relationships between river patterns and various control variables. Meandering rivers (Mosselman, 1998; Duan, 2005, 2010) and braided channels (Nicholas and Smith, 1999; Jang and Shimizu, 2009; Schuurman and Kleinhans, 2011) have been replicated in idealized experiment conditions with the detailed data of river characteristics, respectively.Compared with the above numerical models, this simulation model is able to simulate planform evolution and channel pattern changes for various initial and boundary conditions in a conceptual alluvial channel, as shown in Wang et al. (2010).

2.2 Considering the influence of vegetation

The significance of riparian vegetation as a control of river form and process is increasingly being recognized in fluvial research, the 2-D numerical model takes into account the influence of vegetation with a vegetation stress term in the momentum conservation equation of flow.

The equilibrium equation for the riparian vegetation zones in the Cartesian coordinate system can be introduced by Ikeda and Izumi (1990) in the form:

$$\frac{\tau}{\cos\theta} = \rho g H S - D_r + \frac{\mathrm{d}}{\mathrm{d}y}\int_0^H \left(-\rho\overline{u'v'}\right)\mathrm{d}z \tag{1}$$

where τ is the total shear stress near the river bank (Pa); D_r is vegetation stress term (Pa); v', u' is fluctuating velocity in the longitudinal and transverse direction (m s^{-1}), respectively; S is the slope; H is the averaged depth (m), θ is the inclination of the location, often $\theta \approx 0$, Eq. (1) can be reduced to:

$$\tau = \rho g H S - D_r + \frac{\mathrm{d}}{\mathrm{d}y}\int_0^H \left(-\rho\overline{u'v'}\right)\mathrm{d}z$$

$$D_r = \frac{1}{2}\rho C_\mathrm{D}\overline{u}^2\frac{aH}{\cos\theta}. \tag{2}$$

Let $p^v = D_r$, the vegetation stress term in the i direction can be written as:

$$\frac{\partial p^v}{\partial x_i} = \frac{\partial\left(\frac{1}{2}\rho C_\mathrm{D}\overline{u}^2\frac{aH}{\cos\theta}\right)}{\partial x_i} = \frac{1}{2}\rho C_\mathrm{D}\frac{aH}{\cos\theta}\overline{u}u_i \qquad i = 1,2 \tag{3}$$

$$\overline{u} = \sqrt{\sum_i u_i^2} \qquad i = 1,2 \tag{4}$$

where $\overline{u}$ is the depth-averaged flow velocity (m s^{-1}); u_i is the flow velocity in the i direction (m s^{-1}); a is the vegetation density (m^{-1}), defined as $a = \mathrm{d}/(l_x l_y)$; d is the radius of the vegetation (m); l_x, l_y is the distance of vegetation in the longitudinal and transverse direction (m).

C_D is the drag coefficient of vegetation. Consider the influence range of the riparian vegetation, let $C_\mathrm{D} = 1.5$ when the vegetation zones near the river bank (Ikeda and Izumi, 1990),and the value of C_D decreases with the distance from bank. In this study, we assume the influence of vegetation is proportionate to the distance from the channel center in the form:

$$\begin{array}{ll} C_\mathrm{D} = 0 & x = l \\ C_\mathrm{D} = 1.5 - 1.5x/l & 0 < x < l \\ C_\mathrm{D} = 1.5 & x = 0 \end{array} \tag{5}$$

where l is the distance from the river bank to the channel center (m); x is the distance from the computed point to the river bank (m).

Due to the establishment of the 2-D numerical model is in the orthogonal curvilinear coordinate system, the vegetation stress terms can be rewritten as:

$$\begin{aligned} \frac{\partial p^v}{\partial \zeta} &= \frac{1}{2}\rho C_\mathrm{D} \frac{aH}{\cos\theta} \sqrt{U^2 + V^2}\, \frac{y_\eta h_1 U - y_\xi h_2 V}{J} \\ \frac{\partial p^v}{\partial \eta} &= \frac{1}{2}\rho C_\mathrm{D} \frac{aH}{\cos\theta} \sqrt{U^2 + V^2}\, \frac{x_\xi h_2 V - x_\eta h_1 U}{J} \end{aligned} \tag{6}$$

where h_1, h_2 are lame coefficients in the ξ, η direction; J is the Jacobian of the transformation, $J = h_1 h_2$; U, V are depth-averaged velocity components in the ξ, η direction; x_ξ, x_η, y_ξ, y_η are coordinate components in the Cartesian coordinate system.

3 The transformation process of a braided channel by the 2-D numerical model

3.1 Formation of a braided channel

The conceptual channel is 10 000 m long and 300 m wide. The initial bed is flat with a slope of 0.4 ‰; the medium grain size of bed and bank materials is 0.1 mm. The water discharge and the sediment feed rate are provided in Table 1, water level downstream is constant during the development of the channel. The computational time interval $\Delta t = 6$ s during the real time of 720 days.

Figure 1 depicts an unstable braided channel after 720 days. Two control factors contribute to the braided channel formation: large and sudden variation in discharge has resulted in broadened channel cross-sections; large sediment supply leads to aggradation up and down in the upper section of the channel; the initially symmetric inflow becomes almost asymmetrical and forms point bars or migrating central bars. It illustrates a fluctuation of the controls may cause the transformation of the braided channel pattern.

3.2 The evolution of the braided channel under different scenarios

Four numerical experiments are performed on the basis of the simulated braided channel. The 2-D numerical model is applied to consider the different control factors, such as the effects of discharge, sediment supply, and bank vegetation. The experimental condition and results are presented in Table 2.

Figure 2a–c show the final planform of the braided channel in runs No. 1, 2, 3. As shown in Fig. 2a, reduction of the discharge in run No. 1 leads to a weak sediment transport capacity, deposition takes place in the branch channel and a new main channel is formed in the upper section. With time processes, aggradation results in higher bed elevations above the initial bed profile in the upstream, the stream power downstream is increasing and a broad, island braided channel is formed. Compared with run No. 1, the braided channel in run No. 2 also transforms into a meandering one in the upstream through different mechanism: reduction of sediment load results in less aggradation and bed scour in the upper section, and may be a key in the formation of a straight channel pattern with no island-bars in the downstream (Fig. 2b). Figure 2c shows the riparian vegetation enhances the strength of banks, stabilizes the channel, holds on the sediment, and the planform seems like that of run No. 2. The number of branches decreases with time in the three numerical experiments.

Figure 3 shows the comparison of the bed deformations between runs No. 1–3 and the initial braided channel at the cross section of 6000 m. As decreasing the discharge and sediment load respectively in run No. 1 and 2, the main channel shifts to the right bank as the sand bars growing on the left bank; the shape of the cross section transits from "W" to "U". In run No. 3, the depth of the channel is deeper than that of run No. 1–2, and the width ratio is relatively smaller. It illustrates the vegetation can increase tensile and shear strength, give adequate time and conditions for development, such stabilization allows the existence of relatively steep cut banks and may hinder the lateral migration of channels (Bridge, 1993).

As shown in Fig. 4, the planform of run No. 4 is the contribution of the influence of discharge, sediment supply, and bank vegetation. It can be seen that the initial braided channel transforms into a single thread channel pattern, differing from the other three numerical experiments, especially in the downstream; the reach downstream is sketched, where the wetted and active branches are marked off.

The quantified parameters characterizing run No. 1–4 are obtained in Table 3. "Braided-channel ratio" B is used to describe the development of multiple channels from a channel belt to as follows (Friend and Sinha, 1993):

$$B = L_{\text{ctot}}/L_{\text{cmax}} \tag{7}$$

where L_{ctot} is the sum of the mid-channel lengths of all the segments of primary channels in a river, and L_{cmax} is the mid-channel length of the same channel.

Table 3 shows the braiding and meandering parameters from run No. 1–4 and the initial channel (Figs. 3–4). Because of the similar planform in run No. 2 and run No. 3,

Fig. 5 presents the sketch of the braided channel with the initial channel, and run No. 1, 2, 4.

Theoretically, if a river has only a single channel, with no braids, the braided-channel ratio of (B) would approach one while measurement of sinuosity (P) also has a minimum value of unity. One can see the values of P and B tend to correlate negatively with the reduction of breaches from Table 3. A large portion of branches exhibits morphological activity, with 7 branches in the initial reach as shown in Fig. 5a, the number of branches is reduced to 2 in run No. 4 while the channel pattern becomes the meandering (Fig. 5c). The results reflect that the value of P would decrease with the channel belts intersect each other, and the channel belts developing along the single-channel, meandering arm have higher sinuosity.

Bed profiles of the four experiments are compared in Fig. 6. In run No. 2, the profile is nearly linear when the channel is straight in the middle section of the channel. Pools and riffles occur in all the experiment channels, it reveals a similarity in the profiles of streams possessed of dissimilar patterns. The fluctuation is relatively stable in run No. 4: it may tend to the quasi-equilibrium state.

The flow field of run No. 4 is plotted in Fig. 7, including the velocity and bed elevation; it can be seen that reduction of the inlet discharge and sediment supply lead to a meandering flow path. The results demonstrate that the discharge and sediment supply play a significant role in the transformation mechanism of channel patterns, agree qualitatively with the existing theories of channel patterns (Table 4).

4 Conclusions

This paper investigates the transformation mechanism from a braided channel to a meandering one by numerical approach. A 2-D numerical model for hydrodynamic, sediment transport and river morphological adjustment is applied in the numerical experiments. A conceptual braided channel and its transformation with different control factors are simulated to study the mechanism of fluvial process. It demonstrates that the tendency of the research on the mechanism of fluvial processes may be regarded as a combination of the theoretical study with numerical models in future. Further studies are needed to study the fundamental equation that governs the evolutions of alluvial river which has not been fully understood to ensure the availability of the numerical model.

Supplementary material related to this article is available online at http://www.nonlin-processes-geophys-discuss.net/1/953/2014/npgd-1-953-2014-supplement.zip.

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Table 1. The experimental conditions.

Time step	Time (d)	Discharge ($m^3\,s^{-1}$)	The medium grain size (mm)	Sediment supply ($kg\,m^{-3}$)
1	360	150	0.1	1
2	360	300	0.1	5

Table 2. The experimental conditions and results.

No.	Discharge ($m^3\,s^{-1}$)	Sediment supply ($kg\,m^{-3}$)	Bank vegetation	Time (d)	Simulation results
1	150	5	No	600	The main channel is formed in the upstream part, a relatively braided channel remains in the downstream.
2	300	1	No	600	The main channel is formed in the upstream, a straight thread was created in the middle part.
3	300	5	Yes	600	Deep erosion in the upper channel, maintain the original plan view in the downstream.
4	150	1	Yes	600	The braided channel is transformed to the sinuous single thread channel.

Table 3. The parameters of the braided reach.

No.	Number of breaches	Braided-channel ratio (B)	Sinuosity (P)
Run No. 1	6	2.11	1.06
Run No. 2	5	1.9	1.00
Run No. 3	4	1.97	1.01
Run No. 4	2	1.22	1.35

Table 4. The transformation of channel with change of control factors (Chien et al., 1987).

Control factor	Direction of change	Channel pattern
Discharge	–	Braided-meandering
Sediment supply	–	Braided-meandering
Bank vegetation	+	Braided-meandering

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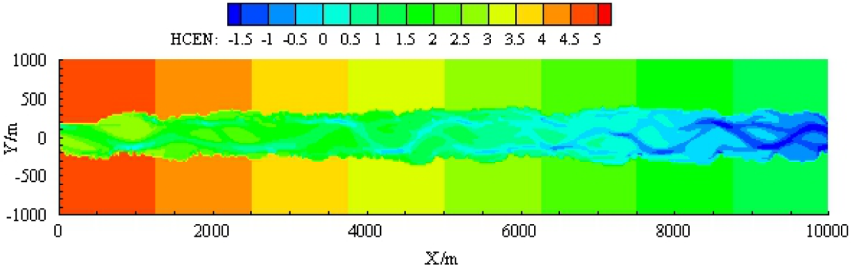
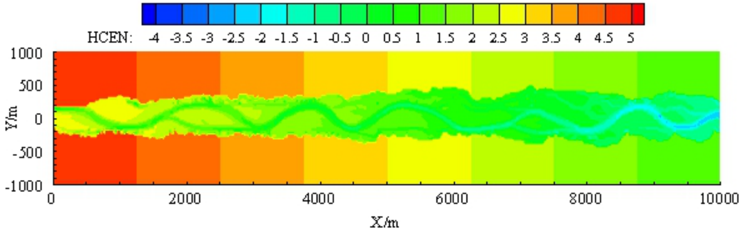
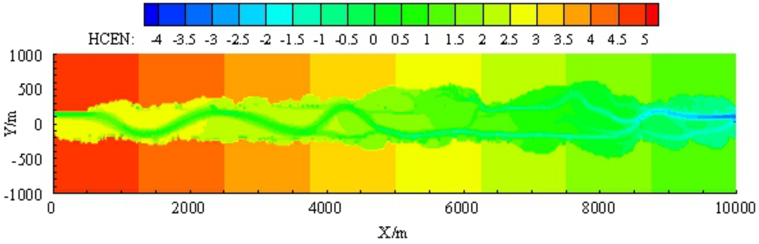


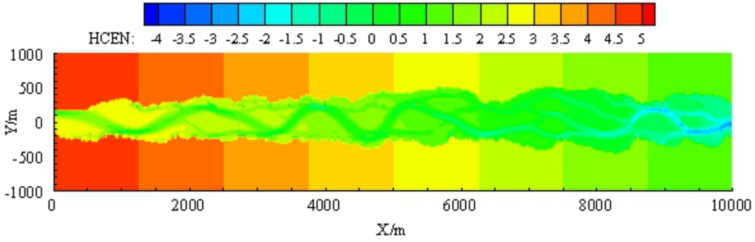
Fig. 1. Layout of the conceptual channel after 720 days.



(a) Run No.1



(b) Run No.2



(c) Run No.3

Fig. 2. Layout of the experimental channel after 600 days (run No. 1–,3).

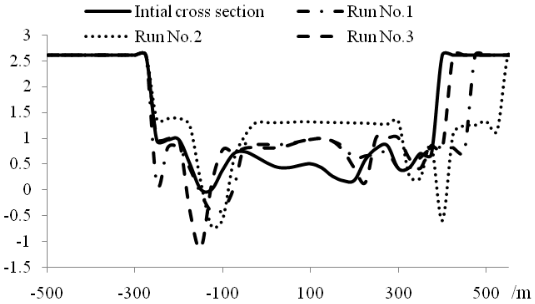


Fig. 3. Comparison of bed deformation at the 600 m cross-section.

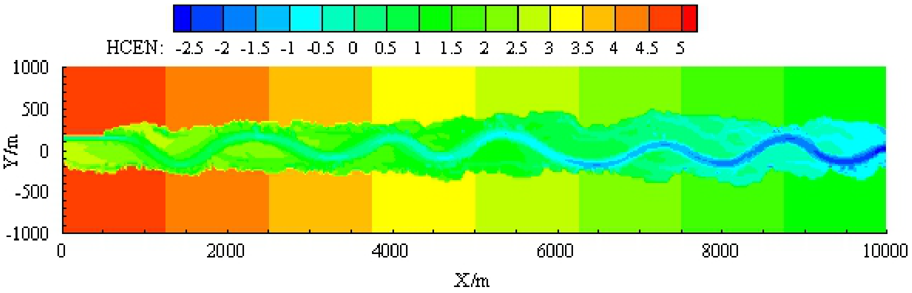


Fig. 4. Layout of the experimental channel after 600 days (Run No. 1–3).

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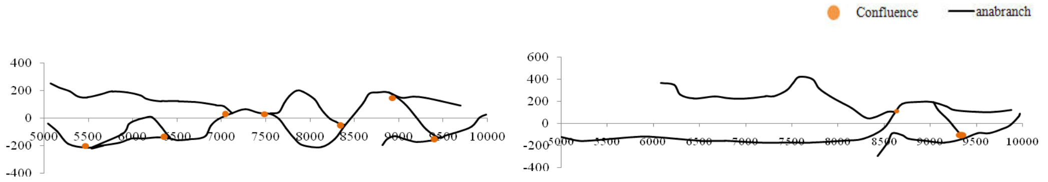
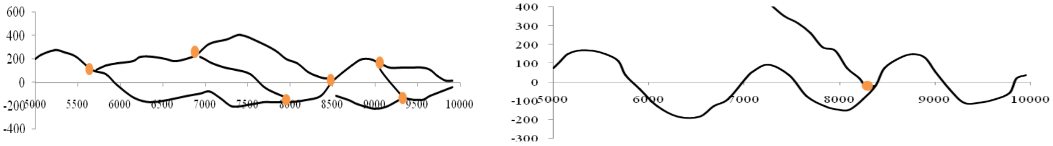


(a) Initial reach (c) Run 2



(b) Run 1 (d) Run4

Fig. 5. Sketch of the braided reach for initial and Run 1–4.

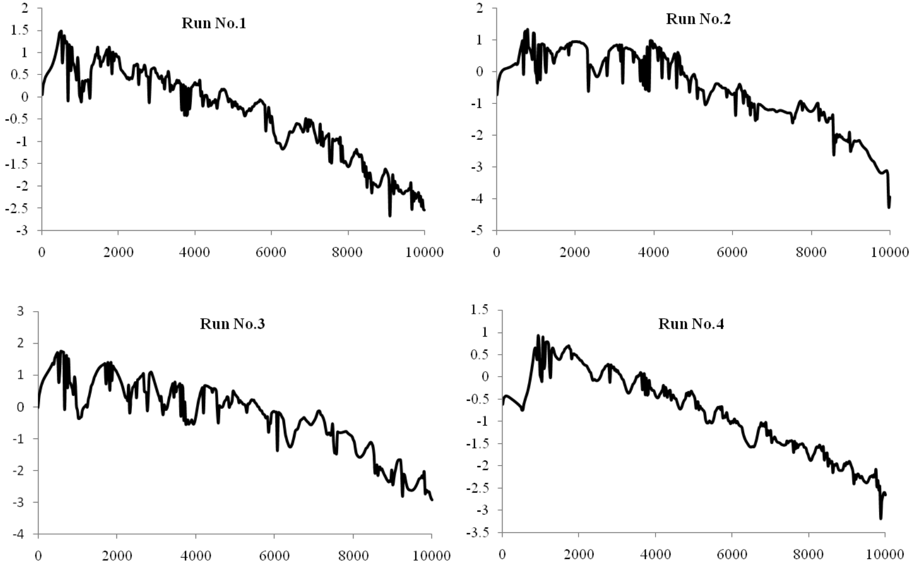
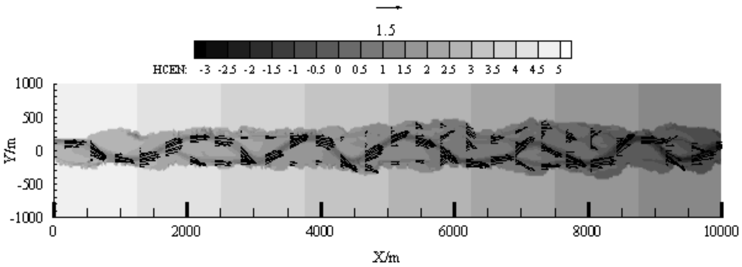
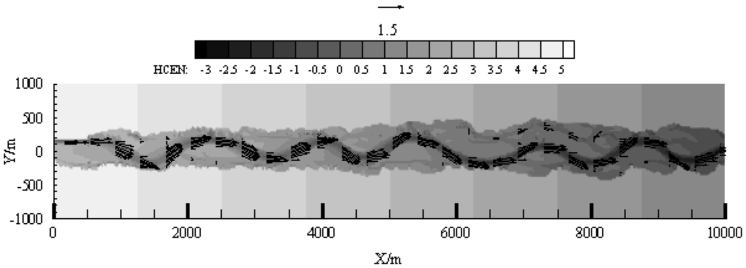


Fig. 6. Bed profile of the four experimental rivers.



(a) T=300days



(b) T=500days

Fig. 7. Temporal changes in flow field, including velocity and bed elevation of Run No. 4.