AN HYDRO-MORPHOLOGICAL STUDY WITH A PHYSICS-BASED NUMERICAL MODEL

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The impact of physical habitat change on the river ecology has increasingly caused concerns in both academic and engineering communities. The hydro-morphological integrity is considered as a key issue because it affects both the ecological structures and functions. Due to its complexity, the relationship between the morphological and ecological processes is not fully understood, although many efforts have been made by researchers in related disciplines, including geologists, ecologists, geo-morphologists, hydraulic engineers etc. In this study a physics-based mathematical model has been developed to simulate the fluvial morphological processes. In this model, two dimensional shallow water equations are solved using a TVD (Total Variation Diminishing) scheme, which is suitable for a wide range of flow conditions. A non-uniform sediment transport model is applied to simulate the evolution processes of an alluvial river, in which the sediment sorting process can be predicted. By using the present model, a braided river pattern is reproduced against a laboratory experiment. The model river shows a complex morphological planform and dynamic evolution characteristics, and contains a multi-thread stream which split off and re-joint each other. As the substrate and habitat to the aquatic ecology system, eco-environmental factors along morphological units have been investigated using the present model, including the sediment properties on pools and bars, the velocity distributions and the changes in riffles and bends. The effect of perturbation, such as the bed disturbance due to organisms, on morphological development of channel are further investigated.

1 INTRODUCTION

As a dynamic element in the planet surface, rivers have been concerned by geologists, ecologists, geo-morphologists, hydraulic engineers and so on. In recent decades, the fluvial environments have been influenced or altered in a global scale by external forces including the humanity activities and climate changes. For example, huge dams have been built for water conservancy along rivers, in which a large amount of sediment deposits in the formed reservoir, while the clear water scours the downstream reaches. The morphological changes in a river play an important role on multiple aspect, including inland navigation, flood control, eco-environments conservation and so on.

The fluvial morphological units are basis of the ecological structures and functions in rivers, since they provide the basic substrate and flow conditions for eco-system, such as the vegetation and fishes. The impact of physical habitat change on the river ecology has increasingly caused concerns in both academic and engineering communities [13-14, 21]. The hydro-morphological integrity is considered as a key issue because of the basic roles, and efforts have been made by researchers at the interface of this interdisciplinary. However, due to the complexity, the relationship between the morphological and ecological processes is not fully understood.

The braided river is a river pattern with complex planform appearances and dynamic evolution properties, which contains a network of multi-thread streams that split off and re-join each other. Although many efforts have been made by scientists in relative disciplines, the mechanism of braided river evolution is not fully known due to the complexity [2]. The dynamical elements of braided rivers, such as the bars, bifurcations and confluences, have been observed and investigated both in fields and in laboratories. In recent years, both the cellular models with reduced-complexity method [10, 18] and physical-based models [6, 11-12, 15] have been attempted to simulate the dynamic processes of braided channel patterns. In most of these numerical simulations, disturbances were widely introduced into the initial or boundary conditions: the perturbation of white noise in the initial bed elevation or the disturbance of an initial bar at the inlet. Although there are full of uncertainty existing in real world, such as uneven sandy bed, the uncertain arrangement of sands and disturbance due to organism, most of the disturbance are used as an artificial approach in previous models to induce the braiding pattern. However, the effect of disturbance in the development of braided pattern has not been clear so far.

2 HYDRO-MORPHOLOGY MODEL

In order to simulate the evolution of morphological units and investigate the effect of perturbation for braided rivers, a physical-based model is applied [16]. This model is built according to the property of natural braided rivers. Natural braided-type channels are attributed to interconnected factors, including the flow regimes, non-uniform bed material and complex interaction mechanisms between flow and sediment.

2.1 Hydro-dynamic model

The governing equations of the hydrodynamic model are depth-integrated shallow water equations, including continuity equation and the momentum equations:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial p}{\partial x}+\frac{\partial q}{\partial y}=0 \tag{1}$$

$$\frac{\partial p}{\partial t}+\frac{\partial(\beta pU)}{\partial x}+\frac{\partial(\beta pV)}{\partial y}=-gH\frac{\partial \zeta}{\partial x}-\frac{gp\sqrt{p^2+q^2}}{H^2C^2}+\varepsilon\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial p}{\partial t}+\frac{\partial(\beta pU)}{\partial x}+\frac{\partial(\beta pV)}{\partial y}=-gH\frac{\partial \zeta}{\partial x}-\frac{gp\sqrt{p^2+q^2}}{H^2C^2}+\varepsilon\left(\frac{\partial^2 p}{\partial x^2}+\frac{\partial^2 p}{\partial y^2}\right) \tag{3}$$

In these equations, ζ is the water elevation (m), H is the water depth (m), U and V are the components of depth-averaged velocity (m/s) in the x and y directions, respectively, $(p,q)=(HU,HV)$ are the water fluxes per unit width (m^3/s/m) in the x and y directions, respectively, β is the momentum correction factor, g is the gravitational acceleration (m/s^2), C is the Chezy roughness coefficient ($m^{1/2}$/s) and ε is the depth-averaged turbulent eddy viscosity (m^2/s).

As braided rivers often exist near mountainous regions, the flow regime is complex and both sub- and super-critical flows and trans-critical flows may occur. In the present study, a TVD–MacCormack scheme has been applied to solve the SWEs, which is second-order accurate in both time and space [7-8]. The scheme combines a symmetric TVD scheme with the standard MacCormack scheme.

2.2 Sediment transport model

In this sediment transport model, non-uniform sediments are taken into account which can be represented by a suitable number (N) of size classes. For each class, the governing equation of bed load transport is applied:

$$\frac{\partial\left(q_{bk}/u_b\right)}{\partial t}+\frac{\partial\left(\alpha_{bx}q_{bk}\right)}{\partial x}+\frac{\partial\left(\alpha_{by}q_{bk}\right)}{\partial y}=\frac{1}{L_s}\left(q_{bk}-\hat{q}_{bk}\right) \tag{3}$$

where k = 1, 2, …, N, q_{bk} is the transport rate of the kth size class of bed load, u_b is the bed load velocity of the kth class, α_{bx} and α_{by} denote the bed-load transport direction, L_s denotes the adaption length of the sediment movement, $\hat{q}_{bk}=p_k q^*_{bk}$ is the equilibrium sediment transport rate, which can be determined using van Rijn's formulae [19-20], p_k is the fraction of size class k in the mixing layer of the bed material and q^*_{bk} is the potential equilibrium transport rate.

The sediment transport equation is solved using a third-order accurate QUICKEST (Quadratic Upstream Interpolation for Convective Kinematics with Estimated Streaming Terms) scheme with the ULTIMATE (Universal Limiter for Transient Interpolation Model of the Advective Transport Equation) algorithm [9]. The numerical scheme has the advantage of avoiding the artificial spurious oscillations. This is an important feature for the prediction of sediment transport in rapidly varying flows.

2.3 Bed level change

The bed level changes due to the overall effect of sedimentation or erosion. The bed changing rate corresponding to the kth size class is written as

$$\left(1-p'\right)\left(\frac{\partial z_b}{\partial t}\right)_k=\frac{1}{L_s}\left(q_{bk}-q_{b*k}\right) \tag{5}$$

where p' is the porosity of bed material. The total bed variation is

$$\frac{\partial z_b}{\partial t} = \sum_{k=1}^{N} \left(\frac{\partial z_b}{\partial t} \right)_k \tag{6}$$

The selective sediment transport for different size fractions is an important process in the natural channel processes. From field and laboratory studies, it has been found that the effect of selective movement works both in the initiation and transport processes of sediment movement. The exposure effects of non-uniform sediment particles are modelled by modifying the critical shear stress through a correction factor. To simulate the bed sediment sorting process in the numerical model, a three layers model is used.

Bank and bar erosions are key morphological processes affecting the channel evolution. In natural rivers the erodibility of banks and bars depends upon many factors, such as the soil saturation and vegetation density. In this study, these processes are modelled based on the submerged angle of repose since non-cohesive sediments are dominant in natural braided rivers.

3 SETTING UP

The model is set up for laboratory scale scenarios against the laboratory experiment conducted by Egozi and Ashmore [4, 5]. The flume was 18 m in length, 3 m in width, 0.3 m in depth and was filled with a 0.15 m thick sand. The grain size of the bed sediment ranged from 0.18 mm to 8 mm, with the standard deviation being approximately 2.6. The mean grain size (d_{50}) was 1.2 mm and d_{90} was 3.6 mm. The total flume slope was kept at 0.015. To investigate the effect of perturbation, a rather wide and shallow initial channel was set with the width being 0.5 m and the depth 0.015m, while the discharge was set 5.6 l/s. At the downstream end the sediment was re-circulated from the tail tank and then fed back into the flume after separating excess water. In the numerical model, the horizontal domain was divided into square cells of 2 cm by 2 cm. Three types of cells were used in the simulation: the boundary zone, the erodible bed cells and the rigid bed. The sediment feed rate was determined using the integrated sediment transport at a downstream section. To represent the size gradation, the non-uniform sediment was classified into 11 groups, with the size boundaries being 0.18, 0.25, 0.35, 0.50, 0.71, 1.00, 1.40, 2.05, 2.81, 4.00, 5.50, 8.00 mm. The space beneath the bed floor was divided into three layers.

4 RESULTS

Figure 1 shows the model predicted channel evolution process within 50 hours, with time intervals being of 5 hours and 10 hours for a general display. It can be seen from Figure 1 that a braided pattern developed from an initial single straight channel. In this model river, basic morphological units can be found, including bars, sub-channels, confluences and bifurcations.

Key stages of channel evolution can be identified from the model prediction as shown in Figure 1. The channel was straight and flat at the initial time t = 0 hours. Until time t = 5 hours, sequenced central bars can be found due to the distribution of sediment transport induce by flow. When the central bars emerged above the water surface, the channel in this stage could be regarded as the multi-thread because the flow was divided. Limited bank erosions can be found along the channel. At time t = 10 hours, more spindle-shaped bars formed, which grew continually with time. The water flow was in narrow sub-channels constrained by the bars and banks. A main channel can be seen, which eroded banks slightly. With the flow being increasingly concentrated, the curvature of channel increased, and some bars grew by connecting or combining each other, see pictures at time t = 20 hours. Some characters can be found at time t = 30 hours, including bars, sub-channels, bifurcations and confluences. The braided river developed further over time with an increasing complexity of braided pattern.

As shown in Figure 1 that, during the period from the initial straight channel to a braided pattern, the bed and bank deformation near the inlet was limited, while the channel evolved more freely in the middle and down reaches. Therefore, the test section is chose as the reach from x = 5 m to x = 17 m. In the same reach, the channel shapes were measured from the physical experiments by Egozi and Ashmore [4, 5]. The total braiding intensity (BI) is usually used to measure the general complexity of braided pattern [2, 4]. In this study, the BI value was calculated over the test section by using data at every computational grid. Figure 2 shows the comparison of model predicted and experimental measured braiding intensity. It can be seen that the model prediction agrees generally well with experimental measurements. Both BI values increased obviously before the time t =40 hours, while after that time the increasing rate of became generally small. It was about 3 at the end.

In summary, for both the channel planform and the BI value, the model and experimental results agree generally well. The agreements indicate that the principle mechanisms of water flow and sediment transport were predicted well, which are crucial factors to the formation and evolution of braided patterns.

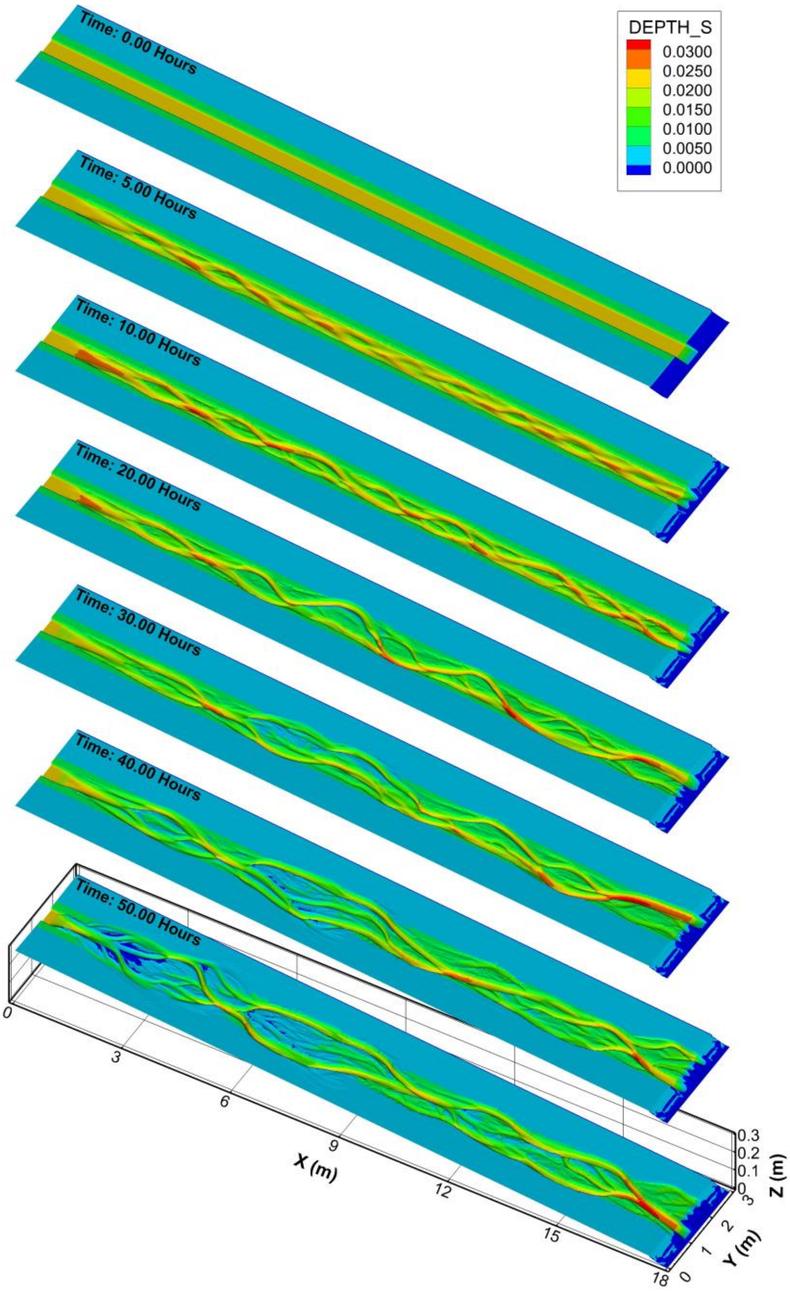

Figure 1. Model predicted braided channel evolution processes

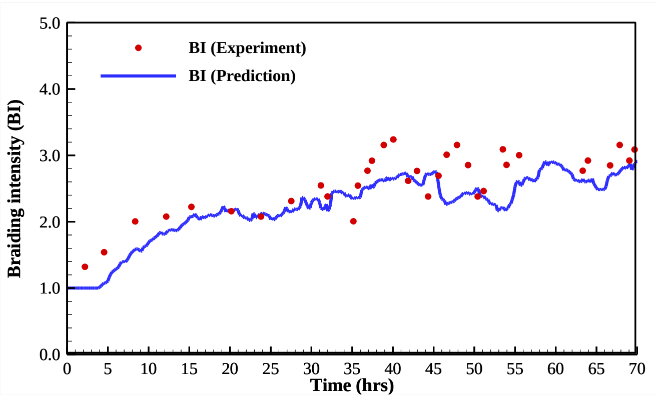

Figure 2. Comparison of model predicted and experimental measured braiding intensity

5 DISCUSSIONS

5.1 Local morphological units

Figure 3 shows an example of local vision of morphological units and the related flow field and sediment flux. It can be seen from Figure 3(a) that about three sub-channels emerged in this local site, and a complex local network formed with sub-channels splitting off and re-jointing each other. Even in one sub-channel, there was velocity distribution along the cross section. These flow regimes can provide a variety of environments for fluvial organisms. The sediment flux vectors, shown in Figure 3(b), present the local bed load intensity and direction. It can be found that the distribution of sediment flux differs from that of flow field. The most obvious phenomenon was that there was a main active channel in which the sediment transport rate was rather larger than others, while the difference of velocity was not so much as shown in Figure 3(a). The reasons are multifold. Firstly, the sediment transport rate depends upon flow flux in a nonlinear pattern. Secondly, the composition of the bed material is the source of bed load, while it usually changes in morphologic processes such as sediment sorting.

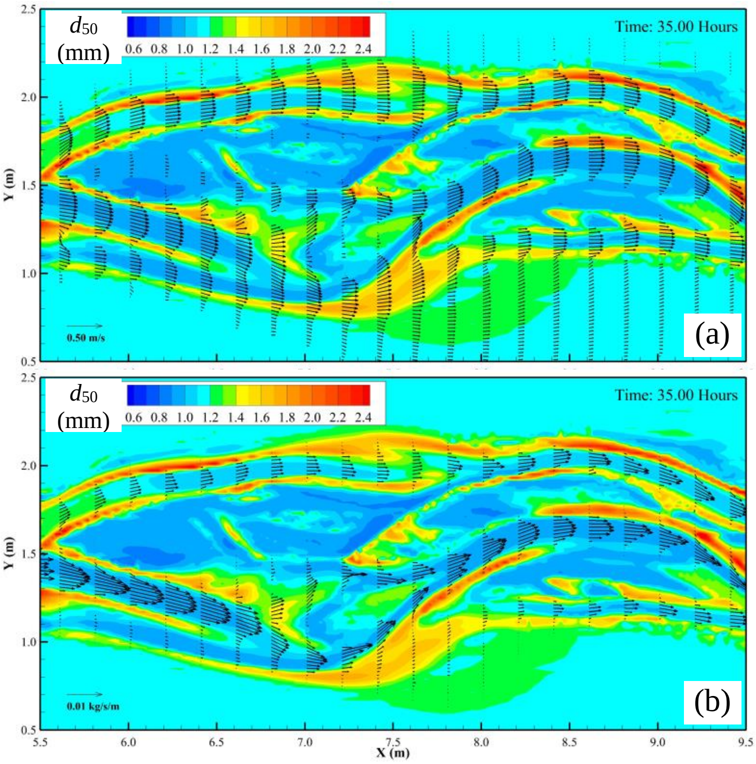

Figure 3. Local vison of morphological units together with flow field and sediment flux

The distribution of median grain size at bed surface is also given in Figure 3(a) and (b) for investigating the bed material composition. It can be found that the value of bed grain size varied significantly along sub-channels and their sections. This indicated the effect of sediment sorting. The sediment flux was larger in areas with finer bed material, which was usually at the central areas of sub-channels, than those near the banks with coarser sediments. In some areas the bed was rather coarse, then the sediment flux was very small, even close to zero, although the \water velocity was not so weak. In these areas, local armouring formed, which was also found in the experiments by Egozi and Ashmore [5].

In armouring zones, the banks became hard to be eroded due to large sediment particles. This is an important factor in the braided channel evolution. Deposition of coarse sediment at bar fronts has been observed in laboratory experiments by Ashworth et al. (1992a, b) and Pyrce and Ashmore (2003, 2005), while more detailed information and processes can be provided and analyzed by using model predictions. In addition, the coarsening of sediment toward the concave bank, which has been observed in curved channels both in field and laboratory conditions (Jackson, 1975; Yen and Lee, 1995; Clayton, 2010), can be predicted rightly by using the present model.

To summarize, the model can predict the complex flow fields, sediment transport and bed material distributions, which are basic environmental elements for fluvial biomass. While the existing of biomass can influence the water flow and sediment movement in return. For example, the deposition of fine material provides necessary substrate for colonization of vegetation, and the growth of vegetation can increase the flow resistance and accelerate sediment deposition [1, 3, 17]. Therefore, further efforts showed be focused particularly on incorporating these interactions and further investigating the mechanisms.

5.2 Effect of perturbation

In previous studies, when the dynamic processes of braided channel patterns were attempted to be simulated by using either the cellular models with reduced-complexity method [10, 18] or physical-based models [6, 11-12, 15], perturbations were commonly introduced into numerical models. Perturbations, such as a white noise on bed elevation, were just used as an artificial force to induce the braiding pattern. In the present study, it can be found that the braiding pattern has been simulated without any additional perturbations. This could indicate that the additional perturbation is not always a necessary prerequisite in numerical models.

However, there are real disturbances existing in real world, such as uneven sandy bed, the uncertain arrangement of sands and disturbances due to organisms. In this study, the effects of perturbation on braiding channel evolution were investigated by applying a random noise as perturbation in the initial channel bed. The range of the random component of bed elevation was the dimension of mean grain size, D_{50}, which was a small value for the channel shape. In this scenario analysis, to identify the changes due to perturbations, the initial channel width is set to 2m and discharge per unit width is kept constant.

Figure 4 shows the model predicted channel evolutions: one without any perturbation, and two with different perturbations being loaded. It can be seen that there were differences among these predictions with and without perturbations. First of all, the layouts of sub-channels were different significantly, such as the locations of bank erosion and courses of main channel were rather different each other. This indicated that despite the tiny magnitude of the perturbation, it did not attenuate over time, but worked on the braided channels. Secondly, there was a symmetric triangular zone in the upstream reach for the scenario without perturbation, see Figure 4(a), while the bed elevation in that area is asymmetric more or less, see Figure 4(b) and (c). In a summary that the perturbation is capable of altering the detailed bed elevation of braided channels. However the general braiding pattern was not changed, especially in the downstream reach where the channel was fully developed. This indicated that the perturbation in the initial bed do not alter the intrinsic braiding properties, at least in statistics meanings, which is consistent with the viewpoint of a recent study [15].

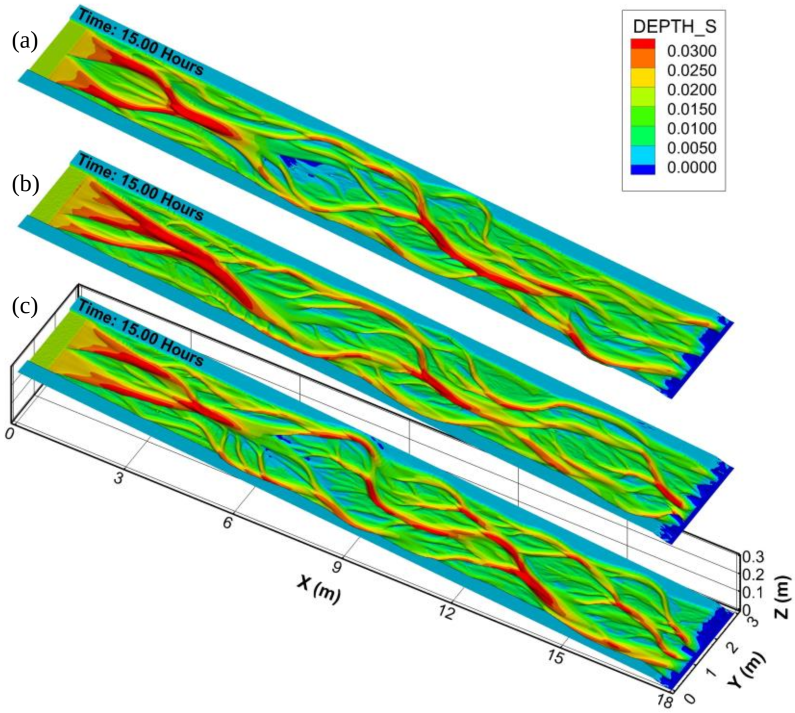

Figure 4. Comparison between numerical predictions with different initial perturbations
(a) Without perturbation, (b) with perturbation R1 (Random noise 1), (c) with perturbation R2 (Random noise 2)

The BI values of three scenarios with or without perturbations are shown in Figures 5 for comparison. It can be seen from this figure 5, that there are the same sequenced stages in channel development for each cases. Before time t = 5 hours, the BI was kept unit indicating the change of channel bed was such small that the channel pattern was not altered. From time t = 5 hours to time t = 8 hours, the averaged BIs in the test section increased rapidly from 1 to 3.5. After time t = 8 hours, the values of BIs increased continually but more mildly and with small oscillations. Until time t = 15 hours, the BIs were almost stable with the BI values being about 4. For the scenarios with and without perturbations, the values and variations of BIs were very close which revealed that the influence of perturbations on the channel pattern evolution was small in the meaning of statistics.

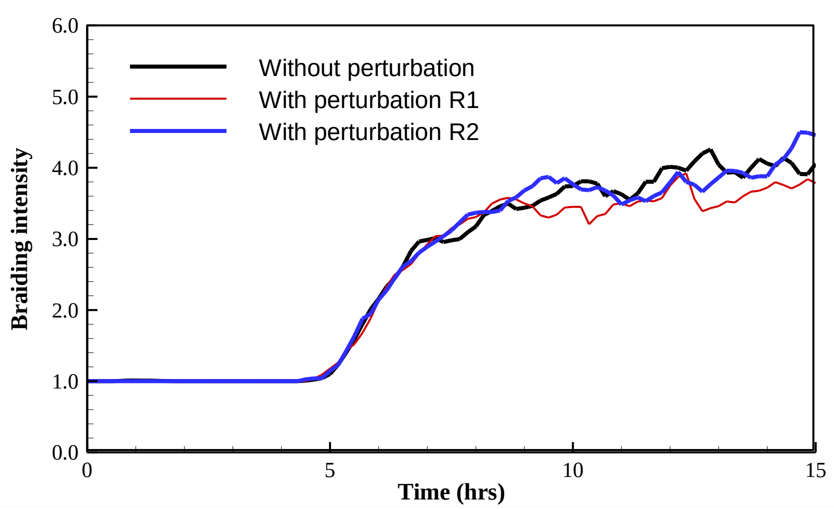

Figure 5. Temporal variation of braiding intensity in model predicted channels in three cases

6 DISCUSSIONS

A physics-based model has been applied to simulate the morpho-dynamic processes of braided channels. Attentions are paid to the formation and evolution of braided channel pattern, the variety of flow and sediment distribution and the effect of perturbation on channel evolutions. The model are verified against physical experiments, while scenarios with different perturbation have been investigated. The main results of this study can be summarized as follows:

1) Using the present physics-based model, the braided channel pattern can be reproduced and the predicted braiding intensity agrees generally with the experimental measurements.
2) The distributions of water flow, sediment transport and bed material provide a variety of environments for fluvial organisms, such as bed sediment distributions providing a variety of substrates for vegetation and benthic animals.
3) The perturbations can play an important role on the detailed evolution of braided channels: the locations of bank erosion and courses of main channel. However, in the meanings of statistics, the general braiding patterns are not altered.

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