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A numerical model for river habitat restoration: a case study of the Chin-sha River in China

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Abstract

Currently, the ecosystem is being damaged in many rivers and subsequently the fish species living there are also facing decline or even extinction. This situation urges to model the habitat and to design suitable restoration strategies in order to increase the capabilities of ecological modeling. In this paper, we proposed a numerical model to assess the ecosystem habitat situation and investigated the impacts of two ecological restorations strategies for the target fish species. The model includes a hydrodynamic model, a habitat model and habitat restoration schemes. The hydrodynamic model simulated the flow properties while sediments in the riverbed were also surveyed. Based on these parameters and fish preference curves, the habitat suitability indices were calculated. In order to analyze the river habitat quality, the weighted usable areas and overall suitability index were also calculated and the effects of the restoration strategies on selected fish species (Freshwater Reeves shad - *Tenualosa reevesii*) in the Chin-sha River were evaluated. The two ecological restoration strategies: addition of side-channel (Scheme I) and riverbank reconstruction (Scheme II) enhanced the Freshwater Reeves shad habitat suitability level, with the high suitability index proportion increasing from 19.5% to 33.1% for Scheme I and to 36.1% for Scheme II. Based on the modelling results, we concluded that our numerical model could potentially provide suitable scenarios for successful fish habitat restoration.

Keywords: River restoration strategy, ecohydraulic simulation, Chin-sha River, habitat suitability, side-channel, riverbank reconstruction.

1. Introduction

It is well established that aquatic ecosystems of rivers and streams are linked by physical processes at spatial and temporal scales. Habitat modelling has incorporated hydrodynamics and a large number and wide variety of eco-hydrodynamic models developed over the last decades are indicating a strong interest in river and habitat restoration (Rutschmann *et al*., 2014; Yao *et al*., 2014a, 2017; Frainer *et al.,* 2018). The scientific interest in understanding fundamental processes in the river and habitat restoration can be traced back to 1980s when the physical habitat models were used as important tools for river management (Bovee, 1982; Bovee, 1986). Another importance of eco-hydrodynamic models is to be used as predictive tools supporting inter-disciplinary ecosystem management and predicting the effectiveness of river restoration schemes (Yao *et al*., 2014; 2017a, b). The decline or extinction of aquatic species has raised great interest in habitat restoration. Therefore, it is important to use numerical models in order to assess the impact of habitat suitability levels and restoration strategies.

The river and habitat restoration is an attempt to recoup some of the ecosystem services which are being lost in the recent past. To achieve this, a more long-term effective and economical way is to use technological fixes such as sewage or sludge treatment plants (Palmer *et al*., 2007). Currently, to restore river ecosystems, restoration strategies and planning projects are in progress. Examples include, the United States have spent a large sum of financial resources on the restoration of aquatic habitats and many endangered species (Bernhardt *et al*., 2005; Yao *et al*., 2015). Since 2010, China has implemented most strict water management rules to protect and restore river ecosystems (Chen, 2007). Australia, on the other hand, has completed more than 2,200 stream restoration projects which include riparian management projects, bank stabilization, in-stream habitat improvement, and habitat monitoring projects (Brooks and Lake, 2007). In all successful and effective stream restorations, hydrodynamic and riverbed substrates survey are the key factors (Bond and Lake, 2003; Wang and Lin, 2013). Thus, to provide a scientific basis for effective stream restoration, it is important to link the hydrodynamic and substrates characteristics of the stream system to a habitat model and subsequently to evaluate and improve the levels of stream systems using an integrated eco-hydraulic model.

In order to examine relations between restoration schemes, and habitat improvement, we evaluated the current habitat suitability level and investigated two river restoration strategies, namely, addition of side-channel (Scheme I) and riverbank reconstruction (Scheme II). The Chin-sha River and the Freshwater Reeves shad (*Tenualosa reevesii*) were selected to study river and target fish restoration by the local Water Conservancy Bureau for restoration. We utilize measured hydrological and topographical data as a current condition to simulate the water velocity and depth for the study domain. We then used these results and surveyed substrates to calculate the fish habitat quality. The habitat conditions for the Freshwater Reeves shad were also quantified by combining hydrodynamic models and the fish suitability index.

2. Problem definition and modeling

2.1. Study area

We proposed the eco-hydraulic model on the Chin-sha River, which has a length of 564 km with eight hydraulic power stations namely, the Longpan, the Two family, the Pear, the Areva, the Jin'anqiao, the Longkaikou, the Ludila and the Guanyinyan. The Chin-sha River basin is stretched from the Sichuan Province to the Yunnan province. The abundant water resources in the Chin-sha River play a vital role for the sustainability of the ecological system of approximately 25 fish species living there. The eco-hydraulic model used in this study is a 9.4 km long river reach located between the Pear and the Areva power stations (Figure 1). The width of the river reach is ranged from 438 to 923 m and the maximum river depth are 4.94 m. The model data of the river obtained by field survey and interpolation. As the domain is a natural spawning site with high ecological requirement for the fish species living there, the effects of restoration strategies need to be investigated. The Freshwater Reeves shad was selected as target fish species to test the restoration strategies. The preference curves of the spawning Freshwater Reeves shad are shown in Figure 2 which are based on literature review and field work.

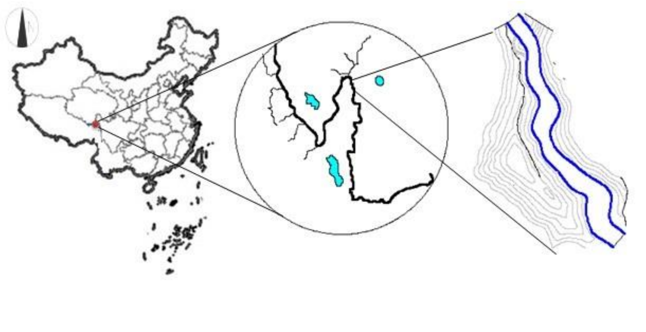

Figure 1. The Chin-sha River location and the computational domain

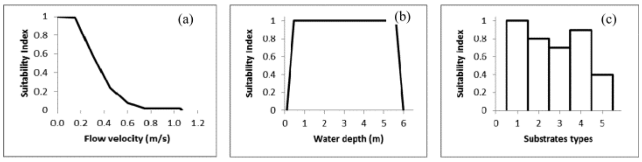

Figure 2. Suitability index of freshwater Reeves shad (*Tenualosa reevesii*): a) effect of velocity, b) effect of water depth, c) effect of substrate type (1 = clay; 2 = sand; 3 = cobbles; 4 = gravel; 5 = boulders)

2.2. Mathematical modelling

The numerical model consists of three parts; (1) a hydrodynamic model with riverbed substrates survey, (2) a habitat model, and (3) restoration strategies evaluation. For the hydrodynamic model, three assumptions were made; the Boussinesq approximation, the eddy viscosity concept, and the shallow water (Yao, 2016).

2.2.1. Hydrodynamic model

Continuity equation

$$u\frac{\partial h}{\partial x}+v\frac{\partial h}{\partial y}=0 \tag{1}$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial \eta}{\partial x}+\frac{1}{h}\left(\frac{\partial h\chi_u}{\partial x}+\frac{\partial h\chi_u}{\partial y}\right) \tag{2}$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial \eta}{\partial y}+\frac{1}{h}\left(\frac{\partial h\chi_v}{\partial x}+\frac{\partial h\chi_v}{\partial y}\right) \tag{3}$$

where x and y are the two horizontal coordinates; *u, v* are the velocity in the x and y directions, respectively; η is the water surface elevation; *h* is water depth; χ_u and χ_v stand for the depth integrated Reynolds stresses which are calculated by using the k-–ε turbulence model.

The k–ε model is an empirical model, which contains the turbulence kinetic energy (*k*) and its dissipation rate (ε).

Turbulent kinetic energy equation

$$u\frac{\partial k}{\partial x}+v\frac{\partial k}{\partial y}=\frac{\partial}{\partial x}\left(\chi_k\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\chi_k\frac{\partial k}{\partial y}\right)-\varepsilon-G_b+G_k \tag{4}$$

Turbulent dissipation rate equation

$$u\frac{\partial \varepsilon}{\partial x}+v\frac{\partial \varepsilon}{\partial y}=\frac{\partial}{\partial x}\left(\chi_\varepsilon\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\chi_\varepsilon\frac{\partial \varepsilon}{\partial y}\right)-\frac{C_2\varepsilon^2}{k}-C_1C_3G_b\frac{\varepsilon}{k}+C_1\frac{\varepsilon}{k}G_k \tag{5}$$

where χ_k and χ_ε are diffusion coefficients; G_k and G_b are terms of turbulent kinetic energy generation by mean shear and buoyancy, respectively; C_1, C_2, and C_3 are constants of the model; where the other parameters are the same as previous.

2.2.2. River bed survey

According to the river bathymetric survey sampling and subsequent interpretation, five types of sediments dominate in the study area; clay, sand, gravel, cobbles, and boulders. The sediments distribution of the riverbed and its suitability index are shown in Figure 3.

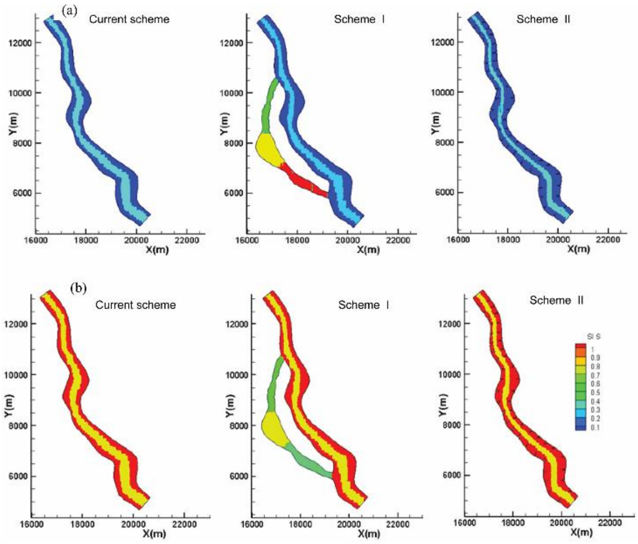

Figure 3. River bed substrate types (a) and the Freshwater Reeves shad suitability index (b) for the five substrate types (SI S = suitability index of substrates). (■ = clay; ■ = sand; ■ = cobbles; ■ = gravel; ■ = boulders)

2.2.3. Habitat model

Based on preference suitability curves, water velocity and depth, and substrates were selected as variables for the calculation of the habitat suitability index. The habitat suitability index (HSI), the weighted usable area (WUA) and overall suitability index (OSI) were calculated. The values of HSI ranged from 0 to 1, with 0 for the lowest and 1 for the highest suitability.

$$HSI = \left(SI_v \times SI_d \times SI_s\right)^{1/3} \tag{6}$$

$$WUA = \sum_{i=1}^{M} A_i \times HSI_{i,t} \tag{7}$$

$$OSI = \frac{\sum_{i=1}^{M} A_i \times HSI_i}{\sum_{i=1}^{M} A_i} \times 100\% \tag{8}$$

where M is the total number of grid meshes; A_i is the area of the single mesh; SI_v is the suitability index of water velocity; SI_d is the suitability index of water depth; and SI_s is the suitability index of substrates. The index HSI is categorized as low (0-0.3), moderate (0.3-0.7) and high (0.7-1.0).

2.2.4. Habitat restoration strategies and model setup

We evaluated three habitat suitability schemes: current scheme, addition of a side-channel (Scheme I), and river bank reconstruction (Scheme II) (Figure 4). To solve the partial differential equations, the finite volume method was used in all three numerical model applications. Three types of boundary conditions, inlet, outlet and solid boundary, were applied in the model. The convergence, which is based on the maximum errors in global mass and energy balances, was ensured using maximum errors less than 10^{-9} criteria in order to guarantee the high accuracy of the numerical model (Yao *et al.*, 2014). A systematic grid independence study was conducted for the model setup. The final grid nodes were 11,055 for the current scheme, 14,780 for Scheme I and 10,784 for Scheme II. The grid sizes were 21,190, 28,173 and 20,008, respectively. The numerical model setup was integrated a hydrodynamic, habitat and habitat restoration module. The hydrodynamic codes were obtained from open source software Telemac2d (Hervouet, 2000), while the habitat and habitat restoration module were developed by the authors.

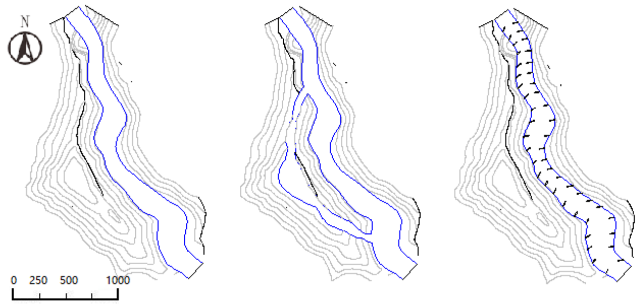

Figure 4. Current scheme, restoration Scheme I, and restoration Scheme II for the computational domain in the Chin-sha River, China

3. Results and discussion

The numerical model was applied to assess the habitat qualities of the current scheme and two restoration schemes (Scheme I, and Scheme II). Based on the values of water depth and velocity, and substrates, the habitat suitability index distributions were calculated as shown in Figure 5. Habitat sensitivity and comparison of the three schemes was also performed.

3.1. Current scheme

The Freshwater Reeves shad habitat suitability index distribution at current scheme is shown in Figure 5. It is noted that the Chin-Sha River branch would not be suitable for the Freshwater Reeves shad. Most of the river branches have low HSI values with only the downstream near-shore and backwater nursery areas, which provide suitable habitat conditions for refuge and nursing areas. The percentages of the high, moderate and the low habitat suitability for the Freshwater Reeves shad are 19.5%, 3.9% and 76.6%, respectively (Table 1). The corresponding areas for the high, moderate and low habitat suitability are 1.2 million m^2, 0.24 million m^2 and 4.6 million m^2. The WUA and OSI for the Freshwater Reeves shad in the Chin-sha River are 1.55 million m^2 and 25.6%, respectively.

Table 1. Comparison of the HSI distribution in the Chin-sha River

	Current (%)	Scheme I (%)	Scheme II (%)
Low	76.6	62.0	59.9
Moderate	3.9	4.9	4.0
High	19.5	33.1	36.1

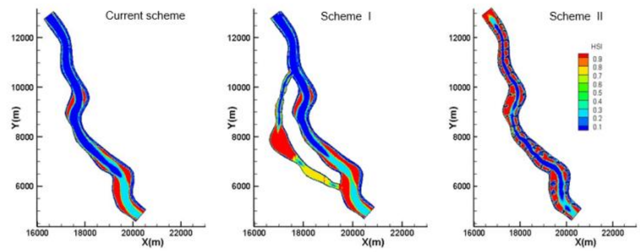

Figure 5. Habitat suitability index distributions of Freshwater reeves shad (*Tenualosa reevesii*) under current scheme, restoration Scheme I and Scheme II

3.2. Scheme I: addition of side-channel

The suitability index distribution for Scheme I (addition of side-channel) was calculated and it is also shown in Figure 5. Comparing with the current scheme, it is noted that the habitat level in the main stream of the study area was improved. It is also noted that the habitat suitability level in most areas of side-channel were high. Comparison with the current scheme's habitat condition shows that the percentage of the low and moderate habitat suitability for the Freshwater Reeves shad decreased to 62% and 4.9%, while the high habitat suitability increased from 19.5% to 33.1%. The WUA and OSI were increased to 3.1 million m^2 and 37.5%, respectively which is significantly higher than that of corresponding value at current scheme.

3.3. Scheme II: addition of side-channel

Scheme II (the riverbank reconstruction) were also performed. It is clearly shown that in overall, the fish habitat conditions were significantly improved along the river bank of the Chin-sha River, except in the middle of the river areas. In Scheme II, the proportions of the high, moderate and low habitat suitability for the Freshwater Reeves shad are 36.1%, 4.0%, and 59.9%, respectively. The corresponding WUA and OSI values are 2.4 million m^2 and 41.2%, respectively.

3.4. Comparison of restoration schemes

A comparison of the habitat conditions (between the two restoration schemes and the current condition) showed that the values of the WUA, OSI and the high habitat suitable areas for the restoration strategies, namely, Scheme I and Scheme II are much higher than the current condition. According to the values of highly suitable areas, the restoration strategy of Scheme II is better than that of Scheme I.

Although, evaluating the river restoration strategies also rely on both the pre and post-monitoring data, this data of the Chin-sha River at current stage has hampered progress in practical understanding of the physical processes. However, as numerical modelling has successful improved the river restorations (Zhang *et al.*, 2016, 2016a; Yao *et al.*, 2018), the overall accuracy and performance of our numerical model gives confidence in the numerical model.

4. Conclusions

In this study, a numerical model was proposed to investigate the Freshwater Reeves shad habitat suitability and two restoration strategies in the Chin-sha River. We evaluated the habitat and ecological situation on three different scales and assessed the habitat situation improvement for two proposed restoration schemes. We have emphasized the importance of the river restoration strategies, which can improve the physical-species-habitat relationships in the field. With the numerical modelling, the ecological status and the available knowledge on the habitat parameters were considered. The numerical model also potentially provided suitable scenarios for successful fish habitat restoration. Although our study is specific for the Chin-sha River and can also be used to evaluate habitat conditions in other cases.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

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