*Int. J. Environ. Res., 10(2):227-236, Spring 2016*
*ISSN: 1735-6865*

# Using an Eco-hydrodynamic Model to Simulate the Impact of Trunk Dam Construction on Kraal River Fish Habitat and Community

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Received 22 April 2015; Revised 22 Jan. 2016; Accepted 29 Jan. 2016

**ABSTRACT**: Dam construction provide benefits to local communities including hydropower generation and flood protection, but also harms fish species by altering physical habitat and providing pollution during the construction process. Evaluating river reaches habitat suitability level may know how the habitat and which extent affected by dams. This study used a systems analysis approach to preliminarily evaluate habitat suitability level at before dam construction and during dam construction in Kraal River. A habitat model which included hydrodynamic and pollution transport was used to evaluate the Garra fish (*Garra pingi*) habitat suitability level affected by pollution produced by dam building system and living waste water. Flow velocity, water depth, riverbed substrates and pollution concentration were selected as suitability indicators. Numerical model simulations were undertaken as follows: Firstly, the water depth and velocity were simulated and the substrate distributions were also surveyed. The pollution concentration was simulated and the corresponding suitability indexes were calculated based on the fish preference curves. After that, the HSI distributions in both before dam building and during dam building were obtained and compared. The results shown that the pollution from dam building system were severely influenced the Garra fish habitat. It is worth noted that the habitat suitability can be recover when the discharge pollution concentration could reduce lower than 800mg/L.

**Key words**: Eco-hydraulic; Habitat module, Pollution concentration, Kraal River, Garra fish (*Garra pingi*)

## INTRODUCTION

Dam building was bustling over the past 50 years in order to maximize the hydropower energy and dams bring significant benefits to modern society, including produce electricity, irrigation, flood control and navigation (Yi, et al., 2014; McCully, 1996; Fu and Qing, 1998). Besides, hydropower is also very convenient, very efficient and the leading source of renewable energy. It provides more than 97% of all electricity generated by renewable sources worldwide. Other sources including solar, geothermal, wind and biomass account for less than 3% of renewable electricity production (Breeze, 2014; Sener and Fthenakis, 2014). However, dam building receive lots of criticism and there are some drawbacks which are including riverbed substrates change, pollution during construction, habitat loss and reduce fish species diversity (Yao et al., 2014, 2016; Yang et al., 2015; Dudgeon, 2000; Zhang et al., 2016;). The pollution during the construction could severely reduce or destroy fish spawning rate and the fish spawning sites could also either been altered or severely wrecked (Hall et al., 2011; Postel and Carpenter, 1997). It is noted that freshwater ecosystems in Yangtze River, Lancang River and many other rivers are becoming very vulnerable due to dam construction (Li et al., 2007; Gan et al., 2003; Gui, 2007). It has also become apparent that the spawning habitats for migratory fish are decreasing significantly in Couesnon River, Snake River and Columbia River and also many streams and rivers of North America (Johnson and Moursund et al., 2000; Marston, et al., 2005; Martignac, et al., 2013; Benke., 2014). In addition, dam construction causes direct changes to flow velocity, water depth and the suspended sediment which are direct change Physical habitat in rivers. Thus, the impact of dam construction in natural rivers on fish species suitability level deserves system research and it is significant and meaningful to evaluate how the habitat and which extent affected by dam constructions.

Dam evaluation has been seen as an ecologically friendly way to guide the dam construction and aquaculture in river systems (Zheren, 2006; Gao et al., 2007). Dam evaluation principle can provide

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suggestions for dam building and provide more suitable habitat suitability level for freshwater fishes as well as remain the river ecosystem diversity. It is noted that the ecosystem in Kraal River is vulnerable and the Trunk Dam which are planned and start to build on the Kraal River. However, there is no research evaluate the fish species' habitat suitability level at before dam construction and during dam construction in that River. There is a need to system analyze and evaluate the impact of dam construction on river ecological function. One habitat approach is needed that could combine fish preference function with river hydrodynamic module and pollution transport module for simulating hydraulic processes and physical habitat quality for target fishes (Yao et al., 2014).

The habitat approach is particularly useful for ecological impact evaluation of dam construction and operation, analysis the effects of dam building on fish abundance, determine the suitable environmental discharge as well as evaluate the influence on surrounding environments (Huang et al., 2010; Ligon et al., 1995). The first habitat model was developed in the 1970s by the United States Fish and Wildlife Service (USFWS, 1980; Tomsic et al., 2007). Later on, many other physical habitat simulation model are also developed which are including PHABSIM, CASiMiR, MesoHABSIM, River2D, EVHA and HABSCORE (Bovee, 1982, 1986; Ginot, 1995; Alfredsen and Killingtveit, 1996; Jorde and Bratrich, 1996; Parasiewicz, 2001). More recently, physical habitat model has become an indispensable tool for river management and dam operations. Take PHABSIM for example, PHABSIM is developed by USGS (U.S. Geological Survey) Fort Collins Science Center and it is now used worldwide which enables the quantitative prediction of suitable physical habitat in a river reach for target species and life stages under different river flow scenarios, hydraulic calibration, and species physical habitat preferences (Gan and McMahon, 1990; Huusko and Yrjänä, 1997; Spence and Hickley, 2000; Gibbins et al., 2002; Koljonen et al., 2013; Natkhin et al., 2013; Klaar et al., 2014). Yao took account of hydrodynamic, pollution transport, sediment transport, heat transfer on habitat and population model to assess the ecological effects and fish abundance by dam building based on previous habitat model (Yao et al, 2014). Kraal River is chosen as target river in this study which has abundant water resource and unique freshwater ecosystem. However, the Trunk Hydropower Plant program has been proposed in 2004 and started to build since 2013 based on the industry requirement (Gui, 2010, Zhang, 2014). Therefore, it is significant to assess the habitat suitability level in there and find an approach that could minimize the negative influence of dam construction.

The aim of this paper is to use the habitat model proposed by authors (1) to evaluate the habitat suitability level at before Trunk dam building trunk dam building stage in the Kraal River aquatic ecosystem. Garra fish (*Garra pingi*) was selected as the target fish species. (2) The simulated velocity, water depth and 2 types of pollution are verified by the measured data. (3) The target fish habitat suitability level during -dam periods was assessed and comparison with habitat suitability level before Trunk dam building were also made. (4) In order to reduce the adverse effects on river ecosystems, the suitable pollution concentration discharge standard for Trunk Dam was also investigated based on 6 hypothetical pollution concentrations.

## MATERIAL & METHODS

The Kraal River is a tributary of Chin-sha River which located in the northwest of Guizhou and boarder of Yunnan. The Kraal River originates in the Linchang of Yunnan and extends 415 km. The Kraal River has 13787km$^2$ drainage basins and 1725m elevation drop with huge hydraulic resources. Our study areas is sited on this downstream of the Kraal River with length of 3.5 km (E103°05'; N25°36') and the Trunk Dam will build on the middle our study areas (Fig. 1). The cross-sectional geometry of the Kraal River was measured in 1990 and updated in 2005 by China Hydropower Cooperation. The cross sections of the river are narrow, with steep slopes on both river banks with a "V" shape or "U" shape in the Kraal River Canyon. The riverbed slope is 4‰ with the average values. The average annual discharge is 128m$^3$/s and the average annual sediment bed load is $1.2 \times 10^7$ t. the water temperature is range from 9 to 25 °C with lowest temperature happened on January and highest temperature occurred in July respectively. The air temperature on surrounding is 3 °C higher than the water temperature (Gui, 2007, 2010). According to the survey results, the Kraal River also plays an important role in aquatic ecosystems and provides diverse habitat conditions for fish species. However, the proposed Trunk Dam started built since 2013 which affected the whole freshwater ecosystem on during-dam building period. For example, during the Trunk Dam construction, the pollution from the dam building system and the living waste water are affecting the water quality in the river and the fish species habitat suitability level. In order to fulfill the ecological quality assessment, the target fish, which is the fish species that is predominant in the river or an endangered fish, should be surveyed and the factors influencing this fish species were also considered. Garra fish (*Garra pingi*) was selected as target fish because its plays a majority role in the Kraal River and flow velocity, water depth, river bed substrates and concentration of pollutants were considered (Fig. 2).

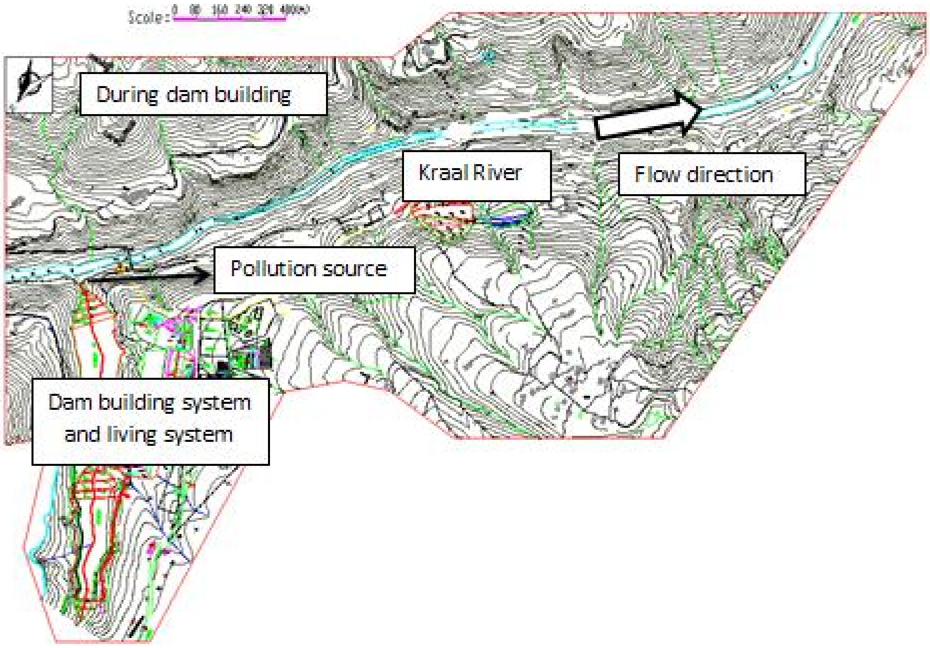

**Fig. 1. Location of the Kraal River and the schematic diagram of (a) before dam construction and (b) during dam construction**

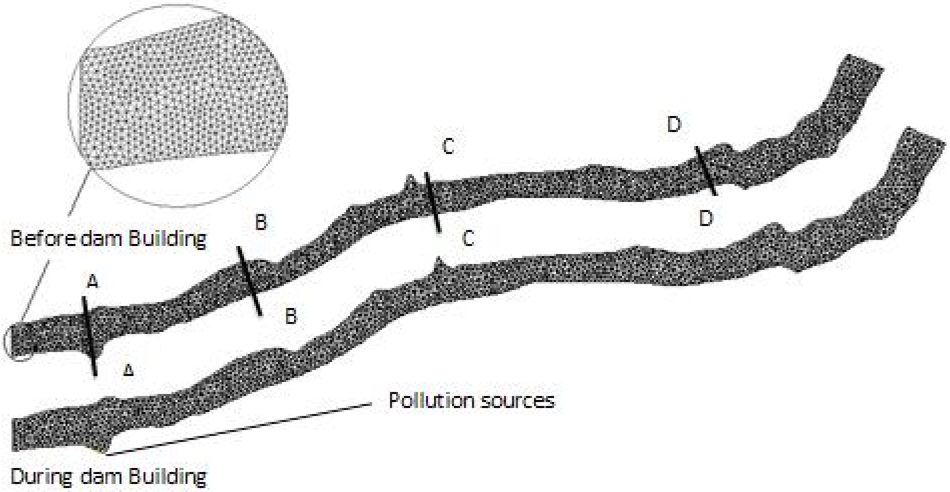

**Fig. 2. The generated mesh and boundary conditions for hydrodynamic and pollution transport calculation on Kraal River (A-A, B-B, C-C and D-D are the cross section)**

The model contains 3 parts which are habitat suitability module, hydrodynamic module and pollution transport module. The structure of the model is show in Fig. 3.

The variables which affect abundance, survival of Garra fish (*Garra pingi*) in Kraal River were considered in the habitat suitability module. Four main ecological factors were considered and selected as for habitat module which is flow velocity, water depth, river bed substrates, and concentration of pollutants. The suitable ranges from 0 to 1 and the SI (suitability index) curves of the 4 main ecological factors were determined based on fish species data survey, literature review, professional judgment and previous research (Fig. 4) (Gui, 2007, 2010; Yao et al., 2014). Individual velocity ($I_v$), depth ($I_d$), substrate ($I_s$), concentration of pollutants ($I_p$) and suspending sediment density ($I_{ss}$) suitability were defined for each of the Kraal River computation domain mesh and each time steps. The habitat suitability index (HSI) was calculated using a geometric mean of these main ecological factors.

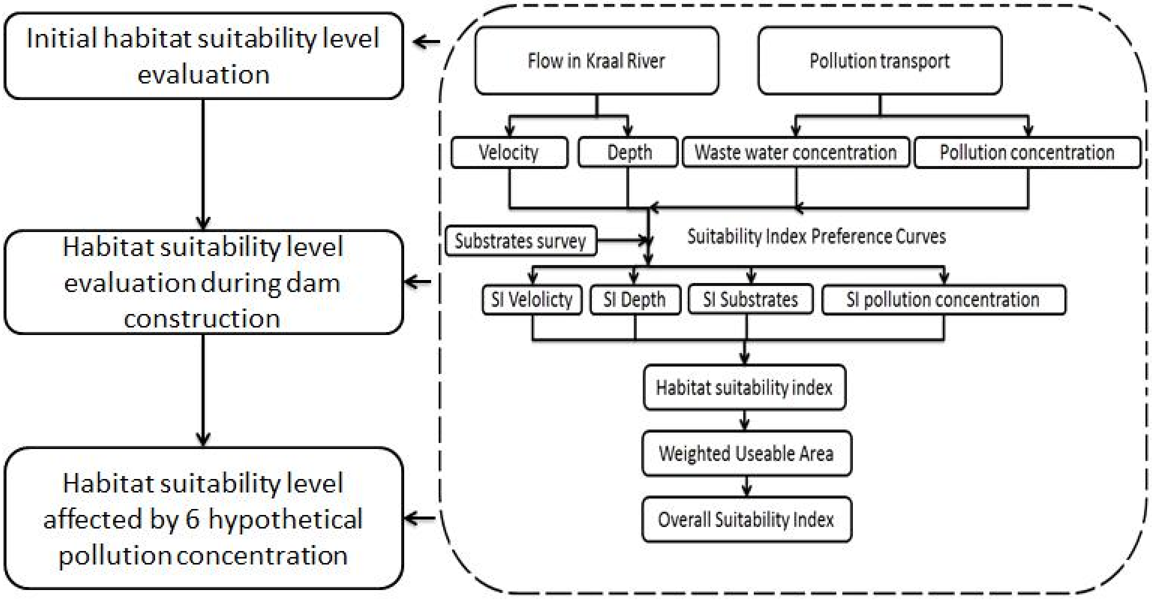

**Fig. 3. Flow chart of the eco-hydrodynamic model for assessing the impact of Trunk Dam construction on Kraal River**

Weighted usable area (WUA) and overall habitat suitability index (OSI) were also analyzed in Kraal River at Pre- and during- dam build period. The functions are defined as follows:

$$HSI_{i,\,t} = (SI_{1} \times SI_{2} \times SI_{3} \ldots SI_{n})^{1/n} \tag{1}$$

$$WUA_{t} = \sum_{i=1}^{M} A_{i} HSI_{i,t} \tag{2}$$

$$OSI = \frac{\sum_{i=1}^{M} A_i HSI_i}{\sum_{i=1}^{M} A_i} \times 100\% \tag{3}$$

Where $SI_1$, $SI_2$ and $SI_n$ are the related suitability indices obtained from the fish preference curves which is represented velocity, water depth, pollution density, and substrates types (Fig. 4) (Zhang, 2014). $A_i$ the horizontal surface of cell *i*; $HSI_i$ the habitat suitability index of cell *i* and *M* be the number of meshes in the river stretch under study.

Separate models were used to create HSI values for the Kraal River and Garra fish (*Garra pingi*). Flow velocity, water depth and concentration of pollutants were calculated from hydrodynamic module while pollution transports were determined by pollution transport module.

The shallow water equation was used in this study for hydrodynamic modeling which including continuity equation and momentum equation. The K-[ turbulence model is also applied in the hydrodynamic module.

Continuity equation

Momentum equation

K-[ turbulence model

$$\frac{\partial h}{\partial t} + \frac{\partial (Uh)}{\partial x} + \frac{\partial (Vh)}{\partial y} = 0 \tag{4}$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} = -g\frac{\partial \text{¦}}{\partial x} + \frac{1}{h}\left(\frac{\partial h2_{xx}}{\partial x} + \frac{\partial h2_{xy}}{\partial y}\right) - \frac{2_{bx}}{\circ h} + f_{Cor}v \tag{5}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} = -g\frac{\partial \text{¦}}{\partial y} + \frac{1}{h}\left(\frac{\partial h2_{yx}}{\partial x} + \frac{\partial h2_{yy}}{\partial y}\right) - \frac{2_{by}}{\circ h} - f_{Cor}u \tag{6}$$

$$\frac{\partial k}{\partial t} + U\frac{\partial k}{\partial x} + V\frac{\partial k}{\partial y} = \frac{\partial}{\partial x}\cdot\left(\frac{v_t}{\pm_k}\cdot\frac{\partial k}{\partial x}\right) + \frac{\partial}{\partial y}\cdot\left(\frac{v_t}{\pm_k}\cdot\frac{\partial k}{\partial y}\right) + P_h + P_{kv} - \pounds \tag{7}$$

$$\frac{\partial \pounds}{\partial t} + U\frac{\partial \pounds}{\partial x} + V\frac{\partial \pounds}{\partial y} = \frac{\partial}{\partial x}\cdot\left(\frac{v_t}{\pm_{\pounds}}\cdot\frac{\partial \pounds}{\partial x}\right) + \frac{\partial}{\partial y}\cdot\left(\frac{v_t}{\pm_{\pounds}}\cdot\frac{\partial \pounds}{\partial y}\right) + C_1\frac{\pounds}{k}\cdot P_h + P_{\pounds v} - C_2\frac{\pounds}{k} \tag{8}$$

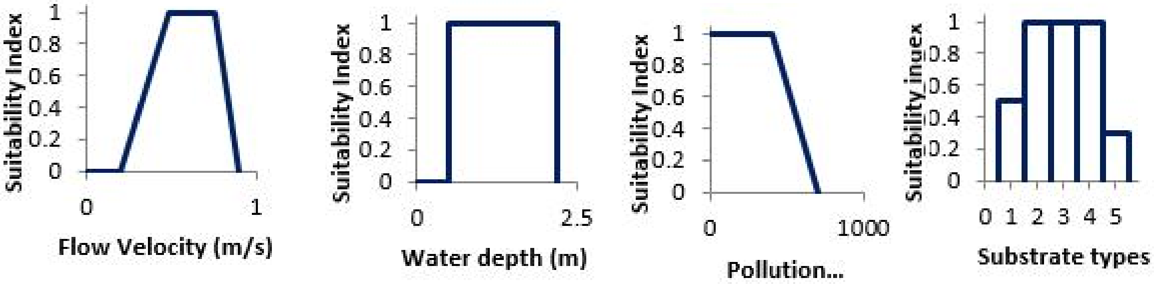

**Fig. 4. Suitability preference curves for Garra fish (*Garra Pingi*). (Substrates types: 1 = fine sand (particle size < 0.062), 2= coarse sand (particle size 0.062-2.000 mm), 3= gravel (particle size 2.0-64.0 mm), 4= cobble (particle size 64.0-250.0 mm), 5= rock (particle size 250.0-4000.0 mm))**

Where $U$, $V$ is the velocity (m/s); $g$ is the gravity (m/s$^2$); $\rho$ is water density (kg/m$^3$); $h$ is water depth (m); t is time (s); $\tau_{xx}$, $\tau_{xy}$, $\tau_{yx}$, and $\tau_{yy}$ are the turbulent stresses and calculated based on k-epsilon turbulence model; $\tau_{bx}$ and $\tau$by are bed shear stresses; $\eta$ is water surface elevation; $f_{cor}$ is the Coriolis parameter; $Ph$ is production of turbulent kinetic energy due to shear stresses with horizontal mean-velocity gradients; $P_{kv}$ and $P_{\varepsilon v}$ are value estimation of $k$ and $\varepsilon$ respectively;

$C_1=1.44$, $C_2=1.92$, $\sigma_k = 1.0$, $\sigma\varepsilon=1.3$, $\sigma_k=0.7$.

$$\frac{\partial\Phi}{\partial t}+\frac{\partial U\Phi}{\partial x}+\frac{\partial V\Phi}{\partial y}=\frac{1}{\circ}\left(\frac{\partial}{\partial x}\left(2_u\frac{\partial\Phi}{\partial x}\right)+\frac{\partial}{\partial y}\left(2_v\frac{\partial\Phi}{\partial y}\right)\right)+S \tag{9}$$

Where $S$ is the source term; $\Phi$ is the pollution concentration density (mg/L); $2_u$, $2_v$ are the diffusion coefficient on x and y direction.

The governing equations for shallow water equations and sediment transport are solved numerically by Finite volume method (FVM) with non-orthogonal grid. Flow velocity and water surface elevation are calculated from the 2D shallow water equations which include the effects of bed friction and turbulence. The bed shear stresses are determined by the quadratic friction law. The turbulent stress terms are calculated based on the depth-averaged version of k-[ turbulence model (Ferziger and Peric, 1996; Yao et al., 2014). The riverbed evolution and suspending sediment concentration was computed from sediment transport module. The pollutant transfer density distribution is calculated based on the depth averaged convection-dispersion equation. HSI, WUA and OSI are computed based on equation 1, 2 and 3.

Four types of boundary conditions including inlet, outlet, free surface as well as side wall boundary conditions were used in this model. At the inlet boundary the flow discharge rate was given and the water elevation at outlet boundary was specified. At the water surface and side wall, symmetry condition and solid wall condition were applied (Yao et al., 2014, 2015).

## RESULTS & DISCUSSION

The Kraal River reach is shown in Fig. 1. The whole computation domain was divided into 11186 meshes and 21088 nodes and the bed elevations were interpolated from surveyed data ($3.5\times10^5$ m$^2$). The computation areas of the hydrodynamic and habitat for Garra fish were analyzed to verify the velocity, water elevation, substrates, pollution concentration as well as habitat suitability index. The corresponding sensitive of habitat were quantified by WUA and OSI. Fig. 5 shows simulated velocity, water depth as well as simulated 2 pollution concentration distributions. It is noted that the average velocity in the Kraal River was 1m/s. The maximum velocity value and the maximum water depth were 1.8m/s and 3m respectively. Selected cross-sections flow velocity and water surface elevation in longitudinal section of Kraal River were simulated by the hydrodynamic module. The measured data on computation domain used to validate the velocity and water elevation. The surveyed results of the velocity at 4 cross-sections and water elevation along the river were compared with the simulated results and the comparison indicated that the simulated results agree well with the corresponding measured data (Fig. 6).

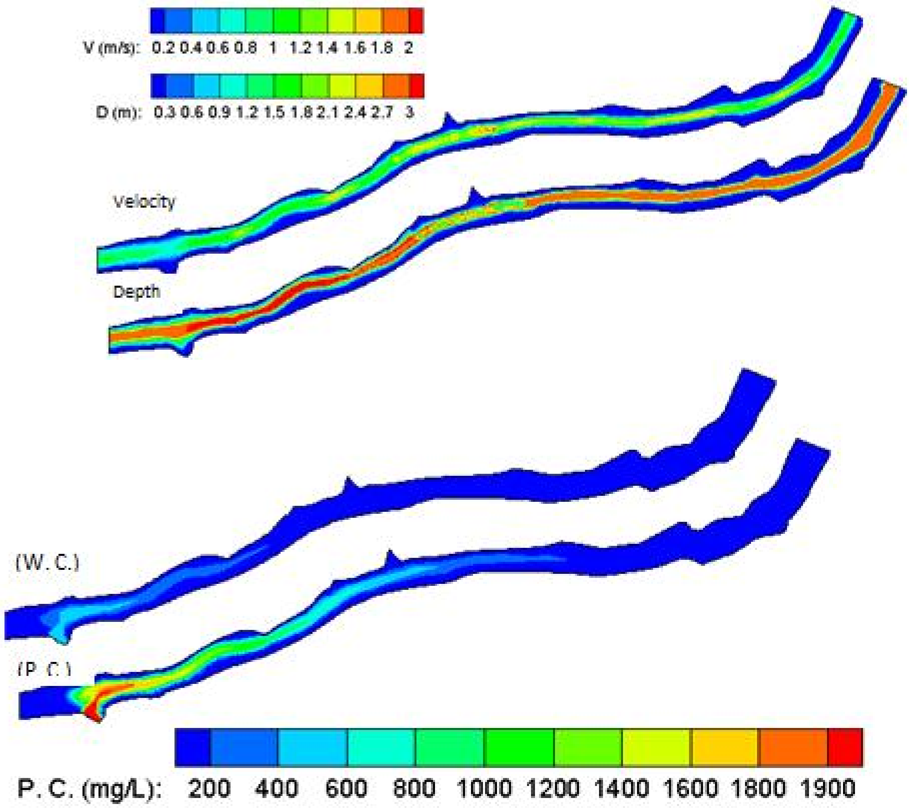

**Fig. 5. Model simulated velocity, water depth and 2 pollution concentration distribution in Kraal River (P. C. = pollution concentration from dam building system, W. C = waste water from living place)**

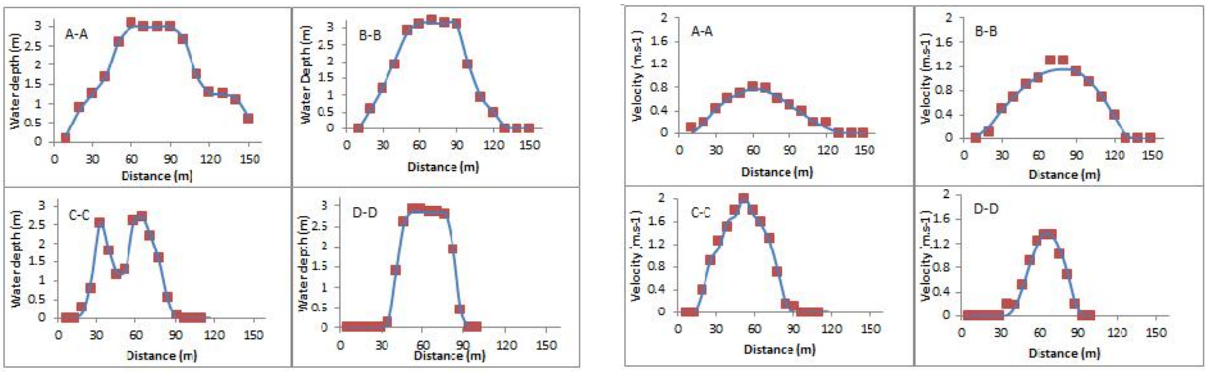

**Fig. 6. Comparison of computed and measured velocity and water depth on A-A, B-B, C-C and D-D cross sections ( — simulated data; 🟥 measured data).**

The maximum waste water concentration from dam building system and maximum living waste water density were 2000mg/L and 500mg/L respectively. It is noted that the living waste water can only affect the nearby place while the waste water from dam building system will affect the section of A-A, B-B and C-C. To assess the simulated accuracy of the pollution transport, measured pollution data was used for comparison (Fig. 7). These contrasts show that the simulated pollution densities were agreed well with the measured data. Therefore, it is indicated that the parameters setting are reasonable and model simulation results are reliable.

Fig. 8 shows the simulated HSI distributions before dam building, affected by waste water from dam building system and affected by waste water from living. As Fig. 8 shows that the habitat distribution

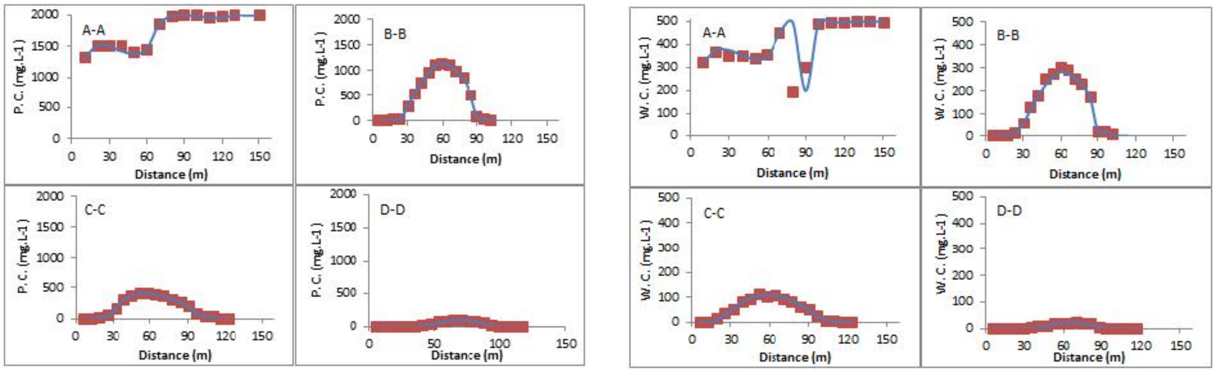

**Fig. 7. Comparison of simulated and measured pollution concentration on selected cross sections ( — simulated data; ■ measured data), (P. C. = pollution concentration from dam building system, W. C = waste water from living place).**

before the dam building periods were suitable for Garra fish to living with over 30% of the computation domain's HSI values are bigger than 0.7. Especially the upstream of river was found to be generally more suitable for the fish to living, while the downstream reach of the river are relatively less than ideal. During the dam construction, the living waste water had little effects on the HSI distributions, while the waste water from dam building system affected the whole upstream HSI distribution. The computation domain's HSI values which bigger than 0.7 were less than 20%. It is noted that before the dam construction, the WUA and OSI for Garra fish were $1.26\times10^{5}$m$^{2}$ and 36%. However, the corresponding WUA and OSI were reduced to $7.35\times10^{7}$m$^{2}$ and 21% during dam construction due to affect by waste water from dam building system. It is also noted that the pollution from dam building system was the main factor for the low habitat suitability level. It is recognized that a high pollution concentration can be stressful to Garra fish in Kraal River. The numerical simulations also indicate that a high pollution concentration from dam building system is the main reason for the poor habitat suitability level in the upstream of Kraal River. Therefore, an approach was considered to determine how the pollution concentrations affect the Garra fish habitat. In the current study, 6 hypothetical pollution concentrations from dam building system were set to simulate the effects on HSI distribution and the simulation results were presented in Fig. 9. From this figure it can be seen that the predicted HSI values are significantly improved after the pollution concentration reduced to 800mg/L. A comparison between the simulated 6 hypothetical conditions and the WUA and OSI level during the construction is shown in Table. 1. The OSI

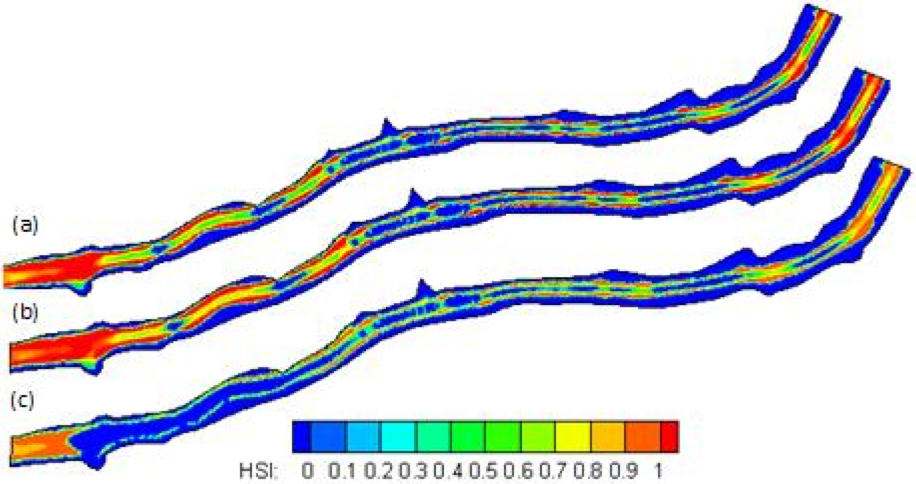

**Fig. 8. Model simulated habitat suitability index (HSI) distribution under (a) before Trunk Dam construction, (b) during Trunk Dam construction affected by W. C. and (c) during Trunk Dam construction affected by P. C. in Kraal River (P. C. = pollution concentration from dam building system, W. C = waste water from living place).**

is increased from 26.5% to 31.3% when the pollution concentration is decreased from 1800mg/L to 1000mg/L. The corresponding WUA are $9.28\times10^4$ and $1.10\times10^5$. The WUA and OSI have little increase when the pollution concentration is low then 800mg/L. It is means that if the waste water pollution concentration from dam building system could reduce below 800mg/L, then there are no negative effects for Garra fish in Kraal River.

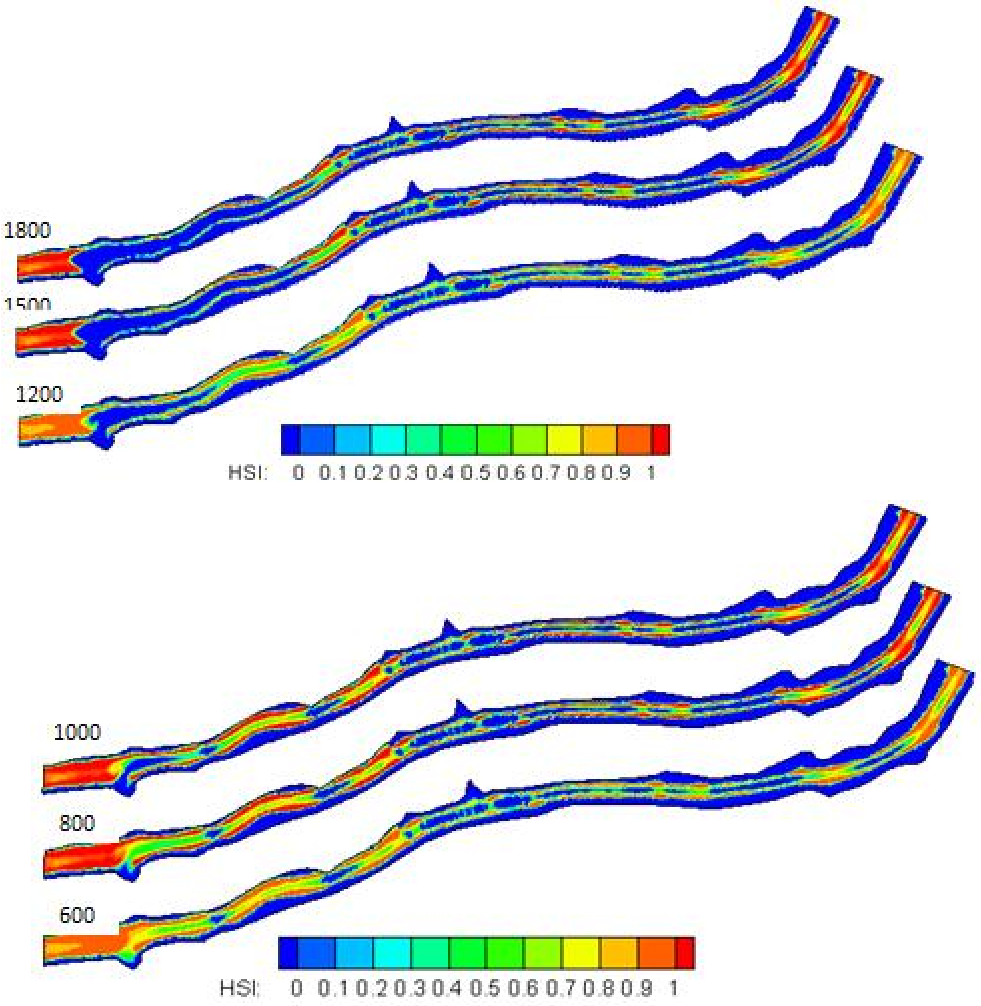

**Fig. 9. Model simulated the habitat suitability index (HSI) distribution affected by 6 hypothetical pollution concentrations which are 1800, 1500 , 1200 , 1000 , 800 and 600 mg/L**

**Table 1. Comparison the WUA and OSI under the 6 hypothetical pollution concentration**

| **Pollution concentration (mg/L)** | **WUA ($m^2$)** | **OSI (%)** |
|---|---|---|
| Before dam building | $1.25\times10^5$ | 35.6 |
| 1800 | $9.28\times10^4$ | 26.5 |
| 1500 | $9.77\times10^4$ | 27.9 |
| 1200 | $1.04\times10^5$ | 29.7 |
| 1000 | $1.10\times10^5$ | 31.3 |
| 800 | $1.21\times10^5$ | 34.7 |
| 600 | $1.24\times10^5$ | 35.5 |

The features and the application of the habitat model indicated that reducing the pollution concentration below to 800mg/L could significantly reduce habitat loss. The simulated model used in here could be used to determine whether the fish's habitat has been affected by pollution and how much proportion of the habitat been affected. This approach can also help to determine pollution discharge standard. It can also provide guidelines for pollution monitoring and fish abundance monitoring program. Based on the model simulation we could know how to select the monitoring sites in rivers. It should be noted that the fish preference curves need to be adapted when applied this model to other rivers or other fish species.

## CONCLUSIONS

Pollution produced by dam building system may significantly cause habitat loss and may have profound impacts on river ecosystems. The habitat suitability for Garra fish in the Kraal River reduced following the Trunk Dam construction. To evaluate the effect of the pollution from Trunk Dam building on fish habitat, an integrated model was developed and a series analysis and discussion were performed. The model results of Kraal River showed that the living waste water has little effects on the Garra fish habitat and the pollution from dam building system is the main contribution to the low habitat in upstream. The results also indicated that the fish habitat could recover in upstream if the pollution concentration could reduce lower than 800mg/L.

Habitat model can be a powerful way to understand how the fish species and river ecosystems affected by pollution produced by dam construction or other human alterations. This eco-hydrodynamic model is a corn concept to both hydraulic and ecological engineering including river fish habitat evaluation, river restoration assessment, dam operation optimization, dam construction and dam removal. Further development of the eco-hydrodynamic model could advance in the field of fish habitat and population abundance affect by hydrodynamic as well as habitat evolution.

## ACKNOWLEDGEMENT

The work was financially support by China hydro cooperation, Guiyang (DJX2208-2014), China CSC funding support (No.201163003). We thank the editor and anonymous reviewers.

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