Technical Note

Two-Dimensional Numerical Investigation for Short- and Long-Term Effects of Spur Dikes on Weighted Usable Area of *Rhinogobius candidianus* (Goby)

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Abstract: The weighted usable area (WUA) is one of the popular metrics to quantify the stream physical habitat and the effects of instream structures. However, most habitat studies only considered existing or proposed channel geometries in their WUA computations and not how the channel will evolve over time. This study reports a numerical investigation for the effects of spur dikes on WUA along the Juanchiao levee, Touchien River, Taiwan. Seven virtual dikes were placed along the outer bend in the study reach and the *Rhinogobius candidianus* was selected for target species. The horizontal two-dimensional (2D) flow fields at various flows and the corresponding WUAs for *R. candidianus* were computed under four channel bathymetry configurations, including: (1) existing; (2) immediately after dikes are implemented; (3) after 10-year channel migration without dikes; and (4) 10 years after dikes are implemented. The WUA obtained from the first two bathymetry configurations aimed to investigate the short-term spur dikes effect, whereas the last two examined the long-term effect. The channel geometry after 10 years channel migration under the conditions of both with and without spur dikes were simulated through a 2D mobile bed model. The analyses of short-term effect showed the WUA of *R. candidianus*, shortly after the virtual dikes were placed, increases due to increased water depth near the dikes, especially in low-flow conditions. As for long-term effects, however, the WUA in the case with spur dikes are lower than the case without spur dikes, especially in relatively high-flow conditions. The adverse effects of spur dikes on WUA appeared in the long-term investigation and resulted from the ever-increasing water depth and flow velocity around the tip of spur dikes and the main channel. This study showed that the habitat quality and availability might be overestimated if the channel bed changes over time. When using the WUA approach to evaluate the effects of instream structure on physical habitat prior to actually placing them in the river, quantitative predictions of the long-term variation of channel geometry and the associated physical habitat conditions are important. **DOI: 10.1061/(ASCE)HY.1943-7900.0000789.**

CE Database subject headings: Levees and dikes; Channels; Rivers and streams; Taiwan.

Author keywords: Spur dike; Physical habitat; Channel migration; Weighted usable area (WUA).

Introduction

The spur dikes (or flow deflector) are one of the most widely deployed instream structures in river restoration projects due to their ability in increasing physical habitat heterogeneity. However, long-term field survey results from earlier researches (e.g., Peters et al. 1998; Shields et al. 1998) showed that the spur dikes might have adverse effects on the instream biota. Thus, the use of spur dikes should be adequately evaluated to determine their impact on physical habitat and aquatic species. Recently, sophisticated hydraulic simulation along with weighted usable area (WUA) (Milhous et al. 1989) computation, have been widely adopted to predict the effects of instream structures on the physical habitat prior to actually placing them in the river (e.g., de Jalon and Gortazar 2007; Shih et al. 2008; Remshardt and Fisher 2009; Boavida et al. 2011; Chou and Chuang 2011). Although the WUA can offer quantitative prediction of microscale physical habitat for chosen species and life stages, most researchers implicitly assumed the channel geometry to be invariant after project construction and only simulated the flow patterns under present or proposed channel geometry without considering the changes of channel geometry in a long-term period owing to spur dikes. Thus, the assessment results are only indicative of the changes of WUA shortly after the spur dikes were placed.

This study used horizontal 2D hydraulic and sediment transport simulation to investigate the short- and long-term effects of spur dikes on WUA for a target species. The study reach is the Juanchiao Levee located on the downstream portion of Shangping River, Taiwan. The investigation of short-term effect aimed at evaluating the change of WUA before and shortly after the placement of spur dikes. The long-term effect investigation examined the differences in WUA after 10-year channel migration between the conditions of with and without spur dikes. The importance of using modeling technique to predict the long-term channel migration in WUA computation was demonstrated from the results of short- and long-term spur dikes effects investigation.

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Materials and Methods

Study Site

Shangping River is located in the northern Taiwan which is one of the two upstream tributaries of the Touchien River. The other tributary is Yulo River which meets Shangping River in the Zhudong Township as shown in Fig. 1. The length and watershed area of Shangpin River are 23.97 km and 253 km^2, respectively. Shangping River is a mountainous river with bed slope varying from 0.02 (upstream) to 0.01 (downstream). The D_{50} of bed material ranges between 86 mm and 229 mm. The average annual rainfall in the watershed is 1,600 mm, and the floods with 2-, 50-, and 100-year return periods are 720, 3,530, and 4,300 m^3/s, respectively.

The study reach, Juanchiao Levee, is located in the downstream of Shangping River. The main channel in the study reach is a wide-radius bend with 384-m radius of curvature, and the width is 70 m. The Juanchiao Levee is located along the outer bend with the length of 460 m. As a result of the lack of riparian buffer between the Juanchiao Levee and the main channel, the levee frequently failed during flood events. To protect the levee, the river management office attempted to place seven spur dikes along the outer bend. According to the report issued from the river management office, the designed locations and geometry of the spur dikes are shown in Fig. 2. The spur dikes will be placed perpendicular to the flow, and the length and height are 10 m (15% main channel width) and 3 m (water depth under 2-year flood), respectively. The spacing between dikes is 30 m. The short- and long-term effects of these seven spur dikes on the WUA were investigated through this study prior to actually placing them in the study reach.

Analysis Framework

Four channel bathymetry configurations were modeled, including: (1) existing; (2) immediately after spur dikes are implemented; (3) after 10-year channel migration without dikes; and (4) 10 years after dikes are implemented. The 2D flow field and corresponding WUA were then computed for each of these channel geometries at various seasonal flows. The only difference between the first and second bathymetry configurations is that in the second configuration seven virtual spur dikes were placed on the study reach. Thus, through the comparison of WUAs obtained from the first two bathymetry configurations, the short-term effects of spur dikes can be investigated. To investigate the long-term effects, the channel geometry after 10 years channel migration under the conditions of both without and with spur dikes (i.e., the third and fourth bathymetry configurations) were derived from 2D sediment-transport modeling. Thus, similar to the short-term effects investigation, the WUAs obtained from the third and fourth bathymetry configurations were compared to investigate the long-term effects of spur dikes.

Hydraulic and Sediment Transport Modeling

The finite difference depth-averaged 2D mobile bed model, developed by Hsieh and Yang (2003) and Hung et al. (2009), was used to simulate the hydraulic characteristics and long-term channel

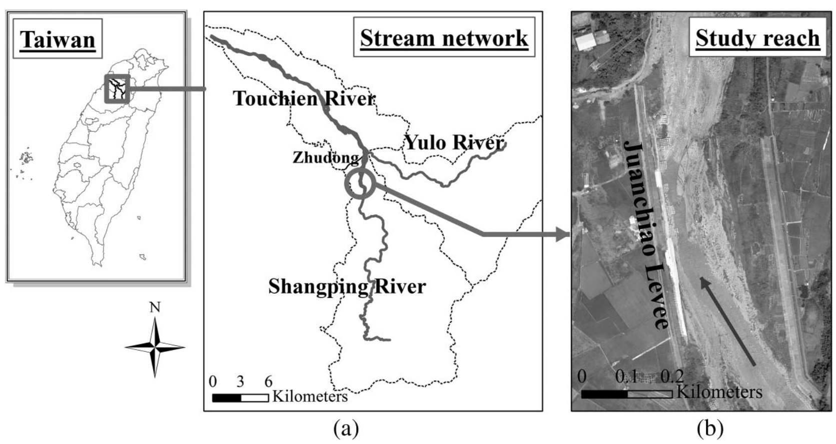

Fig. 1. Maps of the study area: (a) location of the Shangping River basin; (b) aerial photograph of the study reach, Juanchiao Levee (photograph courtesy of Second River Management Office, Water Resources Agency)

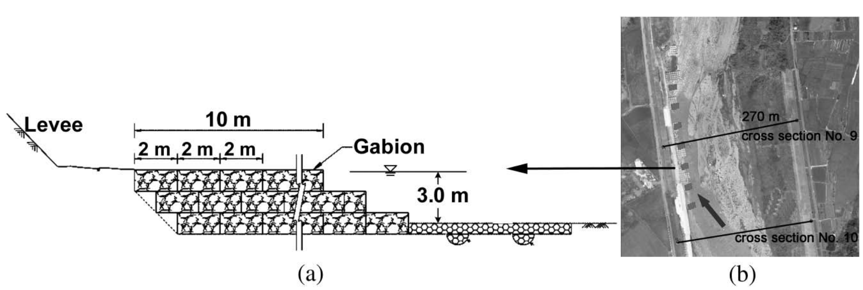

Fig. 2. Design of the spur dikes: (a) geometry and material; (b) location (photograph courtesy of Second River Management Office, Water Resources Agency)

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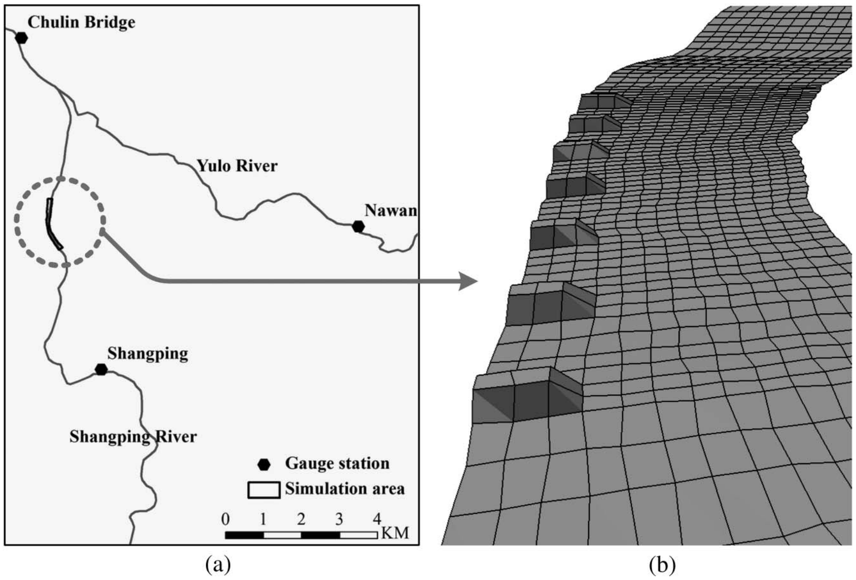

Fig. 3. Locations of the gauging stations and computer-simulated area: (a) map showing the gauging stations near the study reach; (b) quasi 3D rendering of the simulation area showing the simulation grid around the seven virtual spur dikes

migration under the condition of both with and without spur dikes. Fig. 3 shows the 2D hydraulic and mobile bed simulation area. The thalweg length of the simulation area is 1,400 m. The simulation grids located far from the virtual spur dikes are 20-m long and 5-m wide. The grid size around the spur dikes is 5-m long and 5-m wide. The mesh size around the spur dikes is 5 m because the native resolution of the topography data surveyed in 2008 is 5 m. Using 5-m mesh size avoids the process of interpolation. Besides, the differences in flow patterns at certain discharges between the conditions of 5-m and 1-m mesh size had been compared. The overall distribution of water depth obtained under 5-m and 1-m mesh size is similar except that the vortex between dikes at 5-m mesh size cannot be observed as vividly as the condition of 1-m mesh size.

In this study, the simulations can be classified as *hydraulic simulation only* and *mobile bed simulation*. The hydraulic simulation only simulated the flow patterns at certain discharges without considering the sediment transport. The outcomes were then used to calculate the WUA for the target species. On the other hand, the mobile bed simulation coupled the flow and sediment transport equations to predict the channel geometry after 10 years of channel migration. The outcome was adopted as input in *flow simulation only*, thereafter the WUA after long-term channel migration can be calculated. The modeling environment and input condition are listed below:

1. Channel geometry: For hydraulic simulation only, four channel bathymetry configurations were modeled as mentioned in the previous section. The first and second channel bathymetry configurations regarding the short-term investigation were derived from the topography data surveyed in 2008. The third and fourth channel bathymetry configurations regarding the long-term investigation were predicted by mobile bed simulation.
2. Discharges at farthest upstream section from the simulation area: For the hydraulic simulation only, 28 seasonal flows (95, 90, 80, 75, 60, 50, and 40% duration flows in four seasons) were modeled. For mobile bed simulation, recorded discharges during 1999–2008 were assumed to be repeated and were adopted as an inflow hydrograph. Six typhoon events induced over 720 m^3/s discharge (two-year return interval) within the 10-year period among which the largest discharge was 3,506 m^3/s (50-year return interval). All the inflows mentioned above were derived from the recorded data at the Shangping gauge station which is located 5.5 km upstream from the study reach.
3. Water-surface elevation at the farthest downstream section from the simulation area: The nearest gauge station downstream from the study reach is far away (i.e., 5 km) from the simulation area. Thus, the 1D model GSTARS 3.0 (Yang and Simões 2002) was used to determine the water-surface elevations at the farthest downstream section from the simulation area. To ensure that the results of 2D hydraulic and sediment-transport simulation around the virtual spur dikes are not sensitive to the uncertainty in specifying the downstream boundary condition, the location of the farthest downstream section is decided to be far from the Juanchiao Levee (i.e., 500 m).
4. Inflow sediment hydrograph at the farthest upstream section from the simulation area: The inflow sediment hydrograph is required for mobile bed simulation and was derived from a sediment rating curve. The curve was developed by the Water Resources Agency (2008b) based on the recorded suspended load at the Shangping gauge station.
5. Initial bed material size: A nonuniform grain-size distribution was used as initial bed-material composition in sediment routing (Fig. 4). The grain-size distribution was obtained from a field survey around the toe of Juanchiao Levee (left bank of cross section No. 9 in Fig. 2) in 2008.

Weighted Usable Area

The concept of weighted usable area (WUA) was proposed by Milhous et al. (1989) and Bovee et al. (1998) which can offer quantitative index of microscale physical habitat condition for chosen species and life stages. The WUA ratio in a reach is evaluated as

$$\text{WUA ratio} = \frac{\sum_j F[f(v_j), f(d_j), f(c_j)]A_j}{\sum_j A_j} \quad (1)$$

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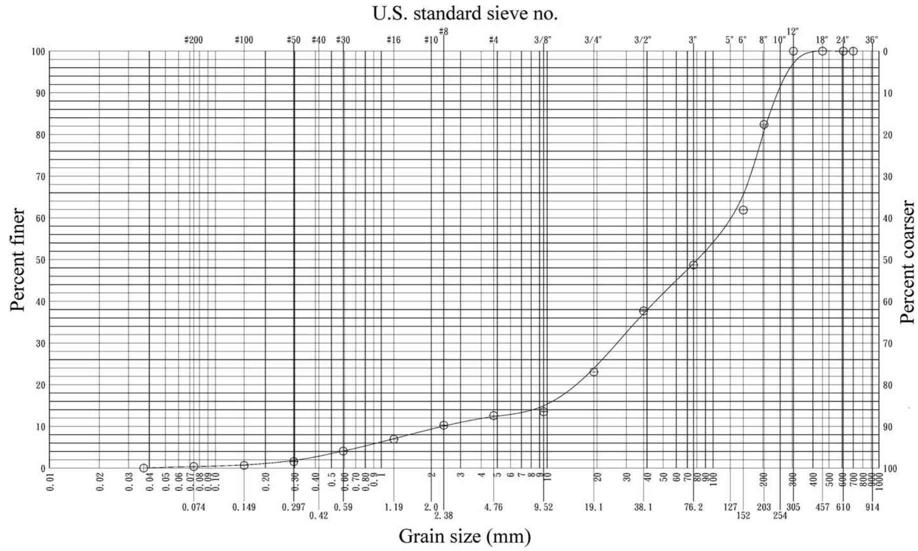

Fig. 4. Grain-size distribution at cross section No. 9

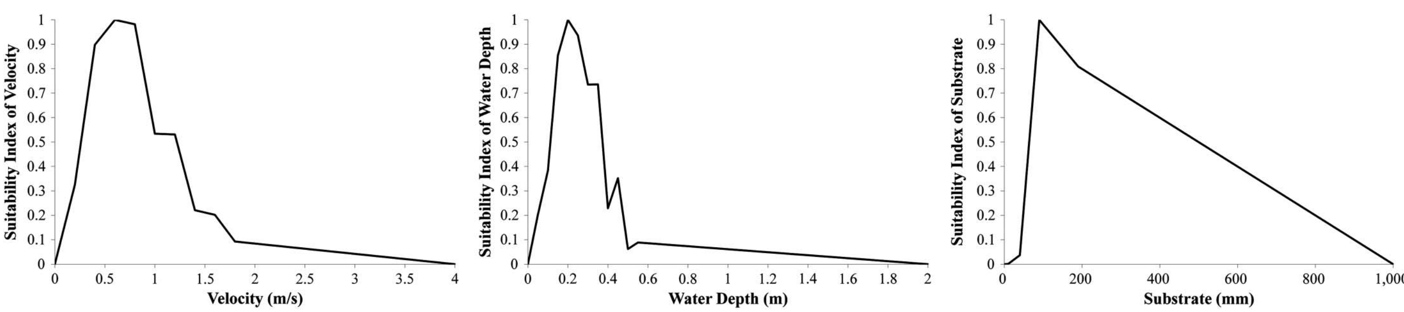

Fig. 5. Habitat suitability curves of the *R. candidianus* (data from Water Resources Agency 2008a)

where $f(v_j)$, $f(d_j)$, and $f(c_j)$ are the suitability indices of flow velocity, depth, and substrate, respectively, for a target fish species at the jth computation grid; A_j is the area of the jth computation grid; and F is composite function. The *R. candidianus* (goby) was selected as target species because it is the dominant species in the study reach and an endemic species of Taiwan. The habitat suitability curves (HSCs) (Milhous et al. 1989) of *R. candidianus* are shown in Fig. 5 (Water Resources Agency 2008a).

The value of the WUA ratio ranges between 0 and 1 which represents the quality of physical habitat for a target fish species. A higher value of WUA for a species implies a better physical habitat condition for the species. Thus, after the water depth and velocity were simulated through numerical modeling technique under the conditions of both with and without spur dikes, the WUAs can be obtained from Eq. (1) based on which one can analyze the effects of spur dikes on physical habitat. The D_{50} was used to calculate the suitability index of substrate for *R. candidianus*.

Results

Table 1 lists the relative difference of WUA ratio before and shortly after the placement of virtual spur dikes in the study reach. The relative difference of WUA ratio is defined as

Table 1. WUA Ratios of *R. candidianus* before and Shortly after the Spur Dikes are Placed

Discharge (m^3/s)	WUA ratio of *R. candidianus*: Without spur dikes	With spur dikes	Relative difference (%)
3.72	0.64	0.68	6.25
4.85	0.72	0.76	5.56
12.3	0.83	0.84	1.2

$$\text{Relative difference}(\%) = \frac{\text{WUA with dikes} - \text{WUA without dikes}}{\text{WUA without dikes}} \times 100 \quad (2)$$

The WUA ratios of the target species (*R. candidianus*) increase shortly after the spur dikes are placed, especially under low to median discharge. Fig. 6 shows the relations between water-surface area and water depth at 3.72 m^3/s (50% flow in winter) with and without the spur dikes. Compared with the case of no spur dike, the water-surface area with higher suitability index of water depth for *R. candidianus* significantly increases shortly after the spur dikes are placed. Thus, the increase of WUA ratio resulted from the creation of pools and increase of water depth at local grids owing to spur dikes. The results show that for the study reach, the spur dikes could have positive short-term effects on the WUA for *R. candidianus*.

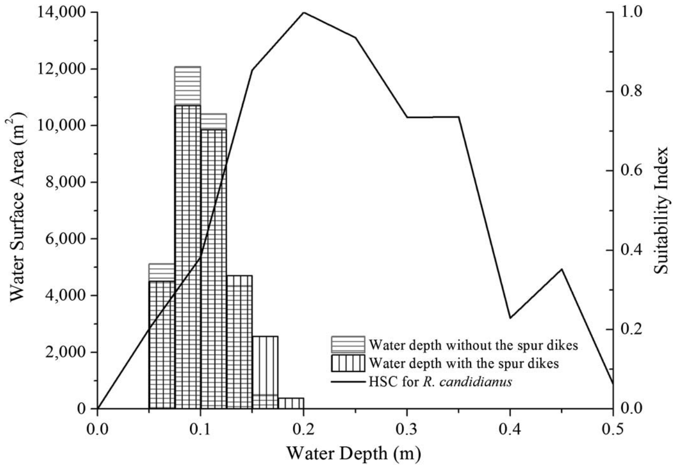

Fig. 6. Distributions of the simulated water depth at discharge of 3.72 m^3/s before and shortly after the spur dikes are placed

Fig. 7 shows the simulated accumulated scour and deposition depths from 2009 to 2018, considering both with and without spur dikes. In the case of no spur dikes, the overall scour depth within the study reach ranges from 0.5 to 1.5 m. Some local areas have higher scouring potential with the maximum scour depth of 2.0 m. These results indicate that the channel bed in the overall study reach is scoured if no other stream stabilization structures are placed. This explains why Juanchiao Levee failed several times under flood conditions. In contrast, the deposition of sediment occurs near the toe of Juanchiao Levee with the average deposition depth of 0.5 m if the spur dikes are placed. This means that the artificial riparian buffer formed between the levee and main channel protects the toe of Juanchiao Levee from scouring during floods. With spur dikes present, the scour depth in the main channel ranges from 1.0 to 2.5 m, which is larger than that without the dikes, a condition that can result in a maximum scour depth of 3.0 m.

Fig. 8 shows the WUA ratios of target species after 10 years of channel migration under the conditions of both with and without

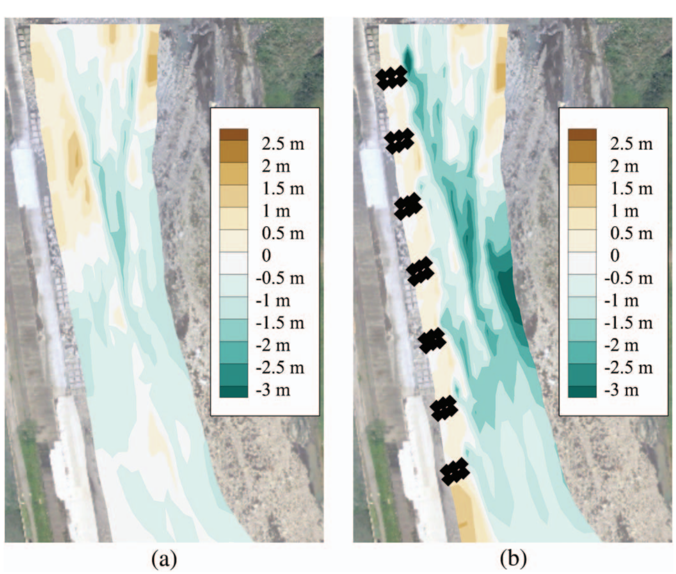

Fig. 7. (Color) Spatial distribution of simulated accumulative scour and deposition depths during 2009–2018 for (a) results without spur dikes; (b) results with the spur dikes

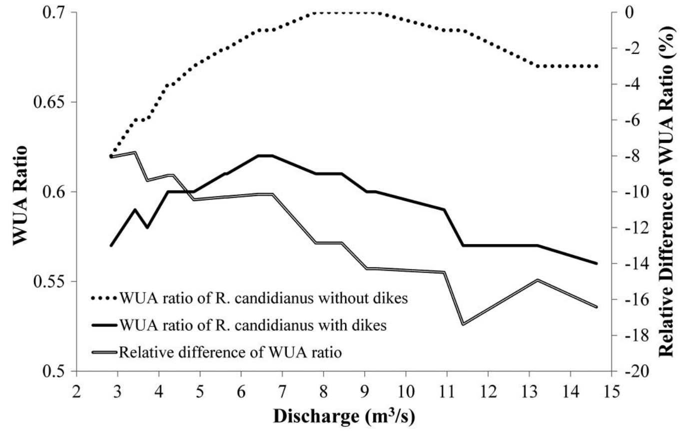

Fig. 8. WUA ratios of target species after 10 years of channel migration under the conditions of both with and without spur dikes

spur dikes. Fig. 8 also shows the relative differences of the WUA ratio after 10 years of channel migration; the WUA ratios of *R. candidianus* in the case with spur dikes are significantly lower than that without spur dikes, especially in relatively high-flow conditions. Figs. 9 and 10, respectively, show the percentages of water-surface area under different water depth and flow velocity at 50% flow in summer (13.2 m^3/s). Fig. 11 shows the boxplots of suitability index for *R. candidianus* at 13.2 m^3/s. From Figs. 9 and 10, one can observe three interesting results: (1) the habitat suitability curves of water depth and flow velocity for *R. candidianus* are monotonic decreasing functions when the water depth and velocity are greater than 0.2 m and 0.6 m/s, respectively; (2) the water depth and velocity at most grids in the case with spur dikes are higher than without spur dikes; and (3) parts of the increased water depth and velocity resulted from the presence of spur dikes are distributed over the monotonic decreasing part of the habitat suitability curves. The above three results lead to a decreased value of suitability index of water depth and velocity as compared with the case without spur dikes as shown in Fig. 11. This circumstance would be more significant under relatively high flow condition because the proportion that the increased water depth and velocity distributed over the monotonic decreasing part of the habitat

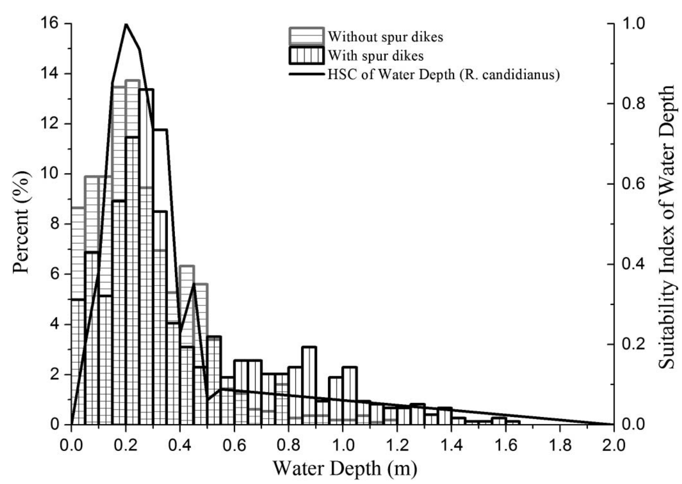

Fig. 9. Percentages of water-surface area corresponding to different water depth at discharge of 13.2 m^3/s for conditions of both with and without spur dikes

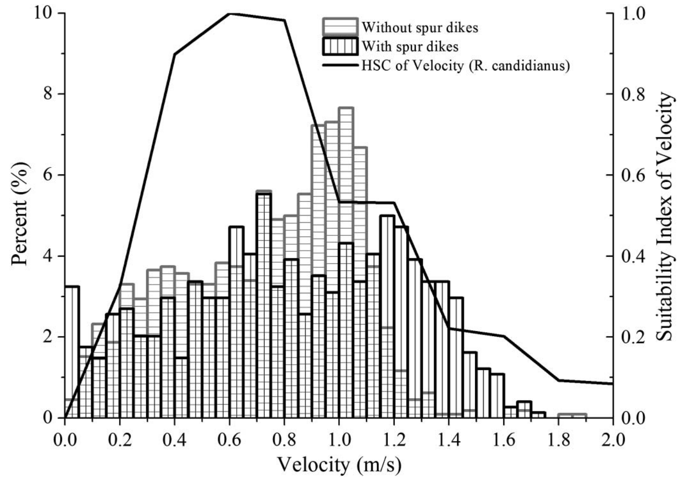

Fig. 10. Percentages of water-surface area corresponding to different flow velocity for conditions of both with and without spur dikes at a discharge of 13.2 m^3/s

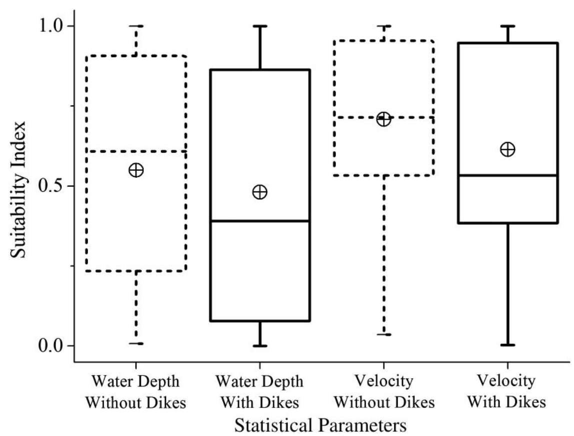

Fig. 11. Boxplots of water depth and flow velocity suitability indices for *R. candidianus* for conditions of both with and without spur dikes at a discharge of 13.2 m^3/s

suitability curves will increase with the increase in discharge. Thus, the WUA ratios of *R. candidianus* in the case with spur dikes are lower than the case without spur dikes, especially in relatively high flow conditions.

Conclusions

This study numerically investigated the short- and long-term effects of spur dikes on the WUA. The simulation results showed that the spur dikes could improve the stability of Juanchiao Levee because of the formation of a riparian buffer between the bank and main channel. Besides, the WUA ratio for *R. candidianus* increases shortly after the virtual spur dikes are placed. The planning for placing spur dikes along the study reach seems to be supported if only based on the results of the short-term effects investigated. However, the evaluation of the WUA after 10 years of channel migration showed that the WUA ratio for *R. candidianus* in the case with spur dikes is significantly smaller than that in the case without spur dikes.

This study showed that the implicit assumption of invariant channel geometry adopted by earlier researches regarding physical habitat modeling might lead to overestimation of habitat quality and availability because of channel-bed changes over time. When using the WUA approach to evaluate the effects of instream structure on physical habitat prior to actually placing them in the river, quantitative predictions of the long-term variation of channel geometry and the corresponding change of WUA are important.

Two concerns should be considered prior to adopting the proposed framework in investigating the effects of instream structure on physical habitat. The first one is the selection of hydraulic and mobile bed models. Hydraulic engineers often adopt 2D depth-averaged models because of their simplicity and ability in simulation under large-scale and long-term conditions. However, if the flow patterns within the simulation area are dominated by the vertical flow component (e.g., spiral flow motion in river bends and frontal downflow around bridge piers), results obtained from 2D models might lose important information, and a 3D model should be utilized. The second concern is the metrics used to assess the physical habitat. Although WUA was used in this study, other metrics, either qualitative or quantitative, may be adopted. What metrics are most appropriate depends on the biological goals of the project.

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