Evaluation of physical fish habitat quality enhancement designs in urban streams using a 2D hydrodynamic model

Joo Heon Lee a,⁎, Jun Teak Kil b,1, Sangman Jeong c,2

a Department of Civil Engineering, Joongbu University, Kumsan, Chungnam-Do 312-702, Republic of Korea
b Division of Water Resources, Korea Engineering Consultants Corps, Gauar-dong, Gwangan-gu, Seoul 462-805, Republic of Korea
c Department of Civil & Environmental Engineering, Kongju National University, Kongju, Chungnam-Do 330-717, Republic of Korea

⁎ Corresponding author. Tel.: +82 41 750 6744; fax: +82 41 750 6391.
E-mail addresses: leejh@joongbu.ac.kr (J.H. Lee), june79ms@paran.com (J.T. Kil), smjeong@kongju.ac.kr (S. Jeong).

1 Tel.: +82 2 2049 5252; fax: +82 2 2049 5111.
2 Tel.: +82 41 850 8628; fax: +82 41 856 7818.

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Contents lists available at ScienceDirect
Ecological Engineering
journal homepage: www.elsevier.com/locate/ecoleng

Abstract

Creating a habitat for a variety of forms of life, such as riparian plants and various fish, is a necessity for stressed river ecosystems. In this study, the hydraulic characteristics of a fish habitat in an urban channel were analyzed using River2D, which is a two-dimensional (2D) depth-averaged finite element hydrodynamic model, to improve the habitat of two target fish in the Daejeon Stream, Korea. These species are Pseudopungtungia nigra, which is an endangered species in the Daejeon Stream, and Zacco platypus, which is a dominant species. In addition, changes in the weighted usable area (WUA) were compared and reviewed as boulders were placed in the stream. The best method for improving the P. nigra's habitat is proposed. A simulation analysis was performed on urban rivers for fish habitats. As a result, a straight and monotonous urban river flow was found to be an appropriate habitat environment for Z. platypus. The WUA for Z. platypus was about 20 times greater than that for P. nigra. Three different fish habitat enhancement methods were evaluated by calculating the WUA for the target fish in the study channel. By calculating the WUA to create fish habitats, the V-type riffle method was found to increase the usable area of the habitat environment for P. nigra by 360%, and the step stone method and single boulder method did so by 60% and 8%, respectively. For the single boulder method, boulders were placed in the channel bed at 3.3-m intervals, which significantly increased habitat availability. Moreover, centralizing the flow pattern in the channel among several types of boulder placements greatly expanded the habitat for P. nigra. Thus, an appropriate placement interval and boulder location that considers the characteristics of the riverbed and target fish species should be researched and implemented.

1. Introduction

Rivers have an important role in sustaining riparian ecosystems and human communities. However, globally, rivers have been severely impacted by a variety of human activities that have resulted in the loss of many of their original ecosystem’s functions. Preserving an ecological habitat is a key requirement for riparian assets and endangered fish species; most studies are related to habitat modeling and generally focus on stable and natural channels (Hauer et al., 2007; Hauer et al., 2008). For example, Crowder and Diplas (2000) provided results that demonstrate the extent to which a boulder, or a series of boulders, can influence the predicted flow conditions and fish habitats in a natural stream using a two-dimensional (2D) hydraulic model. García and Gortazar (2006) evaluated the effectiveness of habitat enhancements, such as riffles and pools, with a 2D hydraulic model under different instream flow conditions in natural streams located in Spain.

Many researchers have demonstrated that improving the natural habitat of fish requires knowledge of the natural recovery process of river ecosystems (Cairns et al., 1977; Gore, 1983; Konrad, 2009; Nagaya et al., 2008; Shih et al., 2008). In particular, understanding the interaction between the physical habitat and the hydraulic habitat is essential to rehabilitate impaired river ecosystems. One approach to stream restoration that focuses on the physical fish habitat is the Instream Flow Incremental Methodology (IFIM), which is an example of how ecological characteristics can be applied to ecosystem restoration (Bovee, 1982; National Biological Service, 1995; Spence and Hickley, 2000; Lopes et al., 2004). In this approach, the Weighted Usable Area (WUA) for a fish habitat in...
the stream is applied to assess the influences of different instream structures to provide a hydraulic habitat.

In urban streams and rivers, the amount of fish habitats is severely limited because of the use of traditional flood control methods for river management. Urban rivers have been managed and exploited with an emphasis on both flood control and instream water use, leading to tremendous damage to the riparian ecosystem and river environment. In this study, we assessed the effectiveness of different obstacles, such as boulders, to create a fish habitat using the River2D model. Several traditional methods that have been used to artificially create fish habitats were compared and analyzed. As an alternative to eco-friendly methods, hydraulic and ecologic characteristics were analyzed after boulders were placed on the river bed, and the WUA was estimated using micro-habitats (depth, velocity, riverbed materials) to protect and maintain fish habitats. Instead of using traditional standardized methods to maintain rivers, an alternative, forward-looking and detailed method is proposed to create an environment that provides an eco-friendly habitat for fish.

2. Methods

2.1. Study site

The study reach is situated in Daejeon Metropolitan City in Korea. The basin area of the Daejeon Stream is 89.38 km², and the total length of the stream is 23.08 km. The Daejeon Stream is a typical urban stream that flows through the heart of Daejeon City. Most of the reaches of the Daejeon Stream that pass through the urban area have unchanging, straight flow patterns. Urbanization of the Daejeon Stream’s basin has not only changed the morphology of the stream but also has had a significant impact on the ichthyofauna of the river’s ecosystem. *Pseudopungtungia nigra*, which is a native fish, became endangered due to the lack of a proper habitat and instream flow (Hur and Kim, 2009). As a result of habitat degradation and the decline of *P. nigra*, *Zacco platypus* is the dominant species in the basin (CGRBM, 2005).

In this study, typical straight sections of urban streams that consist of very monotonous flow patterns were selected and used as basic modeling to analyze the current issues for fish habitats in urban rivers. The selected study reach is 100-m long, while the average width of the channel is 17 m; it is located mid-downstream of the Daejeon Stream (Fig. 1).

2.2. Model employed in this study

2.2.1. River2D

A two-dimensional numerical model was selected for the hydraulic simulation with low flow in the study reach. The 2D numerical model was found to be very effective in comparison to the 1D model, especially for spatially distributed phenomena, such
as patterns of sediment erosion and fish habitat quality under low discharge (Clark et al., 2006; Brown and Pasternack, 2008).

In this study, the hydrodynamic component of the River2D model uses the two-dimensional, depth-averaged St. Venant Equations, which are expressed conservatively. These three equations represent the conservation of water mass and the two components of the momentum vector. The depth and discharge intensities in the two respective coordinate directions are the dependent variables (Steffler and Blackburn, 2002).

Conservation of mass:

\[
\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0
\]  

Conservation of \(x\)-direction momentum:

\[
\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(U q_x) + \frac{\partial}{\partial y}(V q_x) + \frac{g}{2} \frac{\partial}{\partial x}(H^2) = g H(S_{0x} - S_H) + \frac{1}{\rho} \left( \frac{\partial}{\partial x}(H \tau_{xx}) \right) + \frac{1}{\rho} \left( \frac{\partial}{\partial y}(H \tau_{xy}) \right)
\]

Conservation of \(y\)-direction momentum:

\[
\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}(U q_y) + \frac{\partial}{\partial y}(V q_y) + \frac{g}{2} \frac{\partial}{\partial y}(H^2) = g H(S_{0y} - S_H) + \frac{1}{\rho} \left( \frac{\partial}{\partial x}(H \tau_{yx}) \right) + \frac{1}{\rho} \left( \frac{\partial}{\partial y}(H \tau_{yy}) \right)
\]

where \(H\) is the average depth of the flow; \(U\) and \(V\) are the averaged velocities of the \(x\) and \(y\) coordinates, respectively; \(g\) is the acceleration due to gravity; \(\rho\) is the density of water; \(S_{0x}\) and \(S_{0y}\) are the bed slopes of the \(x\)- and \(y\)-axes, respectively; \(S_H\) and \(S_H\) are the friction slopes; and \(\tau_{xx}, \tau_{xy}, \tau_{yx}\) and \(\tau_{yy}\) represent the components of the horizontal turbulent stress tensor.

2.2.2. WUA (Weighted Usable Area)

The main goal of this study is to apply the Weighted Usable Area (WUA) to evaluate available fish habitats in an urban stream. The WUA is the amount of physical habitat that is available for fish species at a given flow (Golder Kingett Mitchell, 2007). The fish habitat component of River2D is also based on the WUA (Bovee, 1982), which is a concept used in the PHABSIM family of fish habitat models. The WUA is calculated as an aggregate of the product of a composite suitability index (CSI, which has a range of 0.0–1.0). The habitat suitability index that is defined in River2D includes the preferences of the target species with regards to the flow velocity, depth, and channel properties. The criteria for the flow velocity and the depth reflect the assumption that lotic biota distributions, certain distribution phases, and certain life cycle phases are controlled by the hydraulic conditions within the water column (Gore and Hamilton, 1996).

The WUA in a stream reach was calculated by Eq. (5).

\[
WUA = \sum_{i=1}^{n} [f(V_i, D_i, C_i) \cdot A_i]
\]

where \(A_i\) is the stream area of the \(i\)th cell, and \(f(V_i, D_i, C_i)\) is the composite suitability index for \(A_i\), which is usually a product of the corresponding suitability weights for the flow velocity, depth and channel properties (Milhous et al., 1989).

2.3. Monitoring activities

2.3.1. Flow regime of the study reach

To analyze the flow regime of the Daejeon Stream, historical stream flow monitoring results from the Master Plan of Daejeon Stream Management (2008) were used. The Daejeon Stream’s natural flow regime that is presented in Table 1 was estimated from the flow duration curve of the Daejeon Stream basin (Fig. 2). For example, the drought flow (Q355) is an average value of the recorded discharge over a ten-year period that exceeded 97% of the total duration (i.e., 355 days of the year). The minimum instream flow of the Daejeon Stream was legally set to 0.5 m³/s. To ensure the minimum instream flow that is required for the Daejeon Stream’s ecosystem (even during drought periods), Daejeon Metropolitan City built a diversion pipeline from the neighboring watershed’s stream and a dam 9 km upstream from the Daejeon Stream’s outlet. Thus, 0.5 m³/s was set as the basic flow rate to implement the entire habitat modeling process, to reflect the legally ensured minimum flow rate of the study reach and to simulate the critical low flow conditions, which can be considered as the ecosystem’s base flow.
2.3.2. Target fishes and habitat suitability index (HSI)

In this study, *P. nigra* (an endangered fish species) and *Z. platypus* (the dominant species that inhabits most of the Daejeon Stream) were selected as the target fish to ensure fish diversity and an increased number of suitable fish habitats.

The habitat suitability index (HSI) indicates the suitability of habitats based on a single parameter, such as the velocity, depth and substrate. The preferred habitat environment for *P. nigra* and *Z. platypus* was monitored by Hur and Kim (2009) based on a field survey and fish collection. The HSI for the flow velocity, depth and channel index (substrate) were obtained from previous research on the same basin by Hur and Kim (2009). Fig. 3 shows the HSI curves of the velocity and depth for *P. nigra* and *Z. platypus*. The channel substrate’s HSI, which is shown in Fig. 3, indicates a favorable substrate for each target fish, which increases linearly in a range between Index 1 and Index 4. Channel Indices 1, 2, 3 and 4 represent silt (>0.1 mm), sand (0.1–1.0 mm), fine gravel (1.0–50.0 mm) and coarse gravel (50.0–100.0 mm), respectively.

2.3.3. Velocity and depth

The flow velocity and the depth of the reach were monitored by a field survey during base flow conditions. Using the observed data, a calibration process was conducted to accurately simulate the natural flow before performing a fish habitat simulation. The entire study reach was modeled using River 2D with 1-m finite element meshes; 65 measuring points were used to compare the observed and simulated hydraulic properties, such as the flow velocity and the flow depth in the channel.

Fig. 3. Habitat suitability index for target fishes.

![Fig. 3. Habitat suitability index for target fishes.](image)

Fig. 4. Measuring points and hydraulic simulation results of River 2D. (a) 65 Measuring points of study reach. (b) Result of hydraulic simulation.
The boundary conditions that were measured during the 0.5-m$^3$/s discharge were used in all of the model simulations presented herein. Therefore, the upstream boundary condition was given as a flow rate of 0.5 m$^3$/s; the downstream boundary condition was given in the form of the water surface elevation, which is equal to 49.6 EL.m; and Manning’s coefficient of 0.035 was applied to the entire study reach.

**Fig. 4** shows the location of the 65 measuring points along with the hydraulic simulation results, without any boulders in the study reach and with an upstream boundary condition of 0.5 m$^3$/s. **Fig. 5** illustrates the correlation between the simulated and observed data at 15 measuring points in the study reach. The model did a good job of simulating the velocity’s magnitude and depth at the 15 measuring points.

**Table 2** shows the 2D hydraulic simulation results without boulders placed in the channel. The correlation coefficient (R) and the coefficient of determination ($R^2$) of the velocity and the depth between the model and the observation are higher than 0.98 and 0.97, respectively. In addition, from the root mean square error (RMSE), we can see that the model can simulate the hydraulic characteristics of the study reach very well.

### 3. Results and discussion

#### 3.1. Habitat modeling results for the current conditions

The physical habitats for two target fish were simulated using a River2D model. Because WUA was estimated using the River2D model without boulders, the WUA of *P. nigra* was lower than that of *Z. platypus* by 95.28%, as shown in **Table 3**. The simulation results show that, under minimum instream flow conditions, the WUA provided a habitat environment that was much more advantageous to *Z. platypus* than *P. nigra* in the Daejeon Stream. **Fig. 6** shows the estimated results of the WUA for each target fish.

Because the study reach is relatively poor for *P. nigra*’s habitat due to urbanization, the diversity of fish in the study reach is low. This finding suggests that *P. nigra* has not returned to urban rivers, which are not appropriate habitats; however, a relatively high number of *P. nigra* are found in natural rivers. Thus, a variety...
of habitat environments for fish should be provided, and habitats for endangered as well as many other species must be created if they are to survive.

3.2. Evaluation of habitat enhancement design

Typical techniques for enhancing fish habitats in Korean rivers (MOE, 2002) were analyzed based on the results of habitat modeling in the study reach. Examples of fish habitat-enhancing techniques include the step stone method, the V-type riffle method, and the single boulder method (MOE, 2002). A simulation was performed using the River2D model to analyze the hydraulic effect on fish habitats, especially for both the target fishes. The typical methods for boulder placement and configuration are shown in Table 4 and Fig. 7. Because the four different fish habitat-enhancing methods were hypothetically modeled in River2D, the simulated results could not be validated with the observed data. However, the model's ability to capture variables in the channel was validated by the observed data; thus, the application of the River2D model in this study is appropriate.

The evaluation of the traditional fish habitat improvement methods that are based on the WUA are shown in Table 5. In V-type riffles, the flow in the channel is centralized, and the appropriate average flow velocity is estimated for the habitats of P. nigra. This improvement extended downstream, and habitats for P. nigra increased.

As for the single boulder method and the step stone method, diverse flow patterns occurred near boulders; however, the fish habitats for P. nigra did not improve as much as they did under the V-type riffle method.

The results of the simulation are presented in Table 6 and Fig. 8. The WUA of P. nigra increased in comparison to its level before the boulders were placed. However, the decrease in the habitat environment for Z. platypus was also observed.

3.3. Analysis of the effect of boulder placement

To capture the hydraulic and ecological effect of boulders on the physical fish habitats, different numbers of boulders and placement methods were compared, as shown in Table 6.

In Case A, the simulation results of the WUA were analyzed when boulders of the same size were placed in the middle of a channel at regular intervals. As illustrated in Table 7, additional boulders produce greater WUA increases. When four boulders were placed at 3.5-m intervals, the WUA increased at its highest rate.

In Case B, the WUA of P. nigra was analyzed contingent upon the placement type of the four boulders, which is the optimal number of boulders for the 17-m channel width at the studied reach. Habitat simulation with four boulders in different placements shows that B5 has the highest WUA (112.10 m²). The WUA increased for B1 to B4 and B6 was low, even though two of the boulders were placed similarly to B5 (Table 8 and Fig. 9).

The traditional method for improving fish habitats positively affected the habitat environment for P. nigra. The methods created an environment in which Z. platypus was also able to live. Even as the flow on the riverbeds diversified, ecosystem diversity was ensured.

3.4. Habitat simulation with four boulders in different placements

The WUA simulations that represent the effects of regularly spaced boulders across the study reach. The spatial WUA simulations are found in Fig. 8.

Table 4
Traditional fish habitat enhancement methods (MOE, 2002).

<table>
<thead>
<tr>
<th>Methods</th>
<th>Boulder type</th>
<th>Boulder diameter (mm)</th>
<th>Arrangement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step stone</td>
<td>Circular</td>
<td>700–800</td>
<td>Straight line</td>
</tr>
<tr>
<td>V-type riffle</td>
<td>Circular</td>
<td>700–800</td>
<td>110°</td>
</tr>
<tr>
<td>Single boulder</td>
<td>Circular</td>
<td>700–800</td>
<td>Straight line</td>
</tr>
</tbody>
</table>

Table 5
WUA results for three different habitat enhancement methods.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Pseudopungtungia nigra</th>
<th>Zacco platypus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>WUA (m²)</td>
<td>Difference (%)</td>
</tr>
<tr>
<td>None</td>
<td>51.82</td>
<td>-</td>
</tr>
<tr>
<td>Step stone method</td>
<td>83.16</td>
<td>60.5</td>
</tr>
<tr>
<td>V-type riffle method</td>
<td>240.60</td>
<td>364.3</td>
</tr>
<tr>
<td>Single boulder method</td>
<td>56.05</td>
<td>8.2</td>
</tr>
</tbody>
</table>

Table 6
Simulation scenario that uses boulders.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Boulder type</th>
<th>Distance between boulders</th>
<th>Number of boulder</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case A</td>
<td>Circular</td>
<td>Regularly spaced</td>
<td>1–9</td>
</tr>
<tr>
<td>Case B</td>
<td>Circular</td>
<td>Irregularly spaced</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 7
WUA simulations that represent the effects of regularly spaced boulders across the study reach.

<table>
<thead>
<tr>
<th>Scenario Boulder placement</th>
<th>WUA (m²)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>85.31</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>87.74</td>
<td>2.85</td>
</tr>
<tr>
<td>B3</td>
<td>86.91</td>
<td>1.88</td>
</tr>
<tr>
<td>B4</td>
<td>86.39</td>
<td>1.27</td>
</tr>
<tr>
<td>B5</td>
<td>112.10</td>
<td>31.40</td>
</tr>
<tr>
<td>B6</td>
<td>87.24</td>
<td>2.26</td>
</tr>
</tbody>
</table>

Table 8
WUA simulations that represent the effects of four irregularly spaced boulders across the study reach.

<table>
<thead>
<tr>
<th>Scenario Boulder placement</th>
<th>WUA (m²)</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>85.31</td>
<td>-</td>
</tr>
<tr>
<td>B2</td>
<td>87.74</td>
<td>2.85</td>
</tr>
<tr>
<td>B3</td>
<td>86.91</td>
<td>1.88</td>
</tr>
<tr>
<td>B4</td>
<td>86.39</td>
<td>1.27</td>
</tr>
<tr>
<td>B5</td>
<td>112.10</td>
<td>31.40</td>
</tr>
<tr>
<td>B6</td>
<td>87.24</td>
<td>2.26</td>
</tr>
</tbody>
</table>
Fig. 7. Design of traditional fish habitat enhancement methods (MOE, 2002). (a) Step stone. (b) V-type riffle. (c) Single boulder.

Fig. 8. Simulated WUA of *Pseudopungtungia nigra* (upper) and *Zacco platypus* (lower) based on 3 scenarios that represent different river habitat enhancement techniques, i.e., (a) and (b) step-stone technique, (c) and (d) V-type riffle method and (e) and (f) single boulder method.
4. Conclusion

This study applies the WUA concept to analyze the habitat quality enhancement design in an ecologically damaged urban river. The WUA of *P. nigra* and *Z. platypus* was 51.82 m² and 1098 m², respectively, in natural conditions in an urban stream. The WUA of *Z. platypus* was about 20 times higher than that of *P. nigra*. The monotonous flow pattern of urban rivers was deemed as appropriate for the habitation environment of *Z. platypus* but not for *P. nigra*.

As a result of evaluating the traditional fish habitat enhancement design, the WUA of *P. nigra* increased by 364.3%, 60.5% and 8.2% with the V-type riffle method, step stone method, and single boulder method, respectively. However, the WUA for *Z. platypus* decreased slightly after the boulders were placed.

An interval of 3.5 m between the boulders proved to be the most efficient design for single boulder placement to improve fish habitats in the studied reach. Additionally, the results that implemented the V-type riffle method and B5 suggest that habitats for *P. nigra* increased when the flow was centralized among several placement types. Thus, a boulder placement design to centralize flow should be reviewed by considering the characteristics of the riverbed and target species.

Revitalizing stressed and endangered fish species in severely impacted urban streams by providing a sufficient physical habitat is a fundamental step in river rehabilitation and restoration projects.

As an alternative to traditional fish habitat enhancement designs, such as riffles and step stones, a method that uses boulders and simulates physical habitats for endangered fish species was proposed to enhance the biodiversity of creatures in a riparian ecosystem.

To create suitable physical habitats for fish in an urban river restoration project, target species that are found to be in danger in the target river should be accurately reviewed, and their ecological characteristics should be carefully examined first.

References


