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Prediction of composite suitability index for physical habitat simulations using the ANFIS method

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ABSTRACT

A physical habitat simulation is a useful tool for assessing the impact of river development or restoration on river ecosystem. Conventional methods of physical habitat simulation use the habitat suitability index models and their success depends largely on how well the model reflects monitoring data. One of preferred habitat suitability index models is habitat suitability curves, which are normally constructed based on monitoring data. However, these curves can easily be affected by the subjective opinion of the expert. This study introduces the ANFIS method for predicting the composite suitability index for use in physical habitat simulations. The ANFIS method is a hybrid type of artificial intelligence technique that combines the artificial neural network and fuzzy logic. The method is known to be a powerful approach especially for developing nonlinear relationships between input and output datasets.

In this study, the ANFIS method was used to predict the composite suitability index for the physical habitat simulation of a 2.5 km long reach of the Dal River in Korea. *Zacco platypus* was chosen as the target fish of the study area. A 2D hydraulic simulation was performed, and the hydraulic model was validated by comparing the measured and predicted water surface elevations. The distribution of the composite suitability index predicted by the ANFIS model was compared with that using the habitat suitability curves. The comparisons reveal that the two distributions are similar for various flows. In addition, the distribution of the composite suitability index of the Dal River is computed by the ANFIS method using monitoring data for the other watersheds, namely the Hongcheon River, the Geum River, and the Chogang Stream. The monitoring data for the Chogang Stream, correlation pattern of which was the most similar to that of the Dal River, yielded the distribution of the composite suitability index, which was very close to that obtained using data for the Dal River. This is also supported by the mean absolute percentage error for the difference in the weighted usable areas.

1. Introduction

The construction of hydraulic structures as dams and banks for flood protection and water supply are common in modern societies, and these structures can affect the environment of a river in various ways. The impacts of individual hydraulic structures were studied extensively in the past [1–5]. In 1992, a UN Conference on Environment and Development [45] proposed the concept of Environmentally Sound and Sustainable Development (ESSD) and various techniques have since been introduced, in attempts to mitigate the negative impact of such structures on natural environments, including rivers [6].

With river environments attracting so much attention, it became necessary to investigate the impact of hydraulic structures on river ecosystems and to resolve the resulting problems caused by such construction [7]. For example, in the United States, if a certain type of river work needs to be done, the impact of the altered discharge on the river environment must first be assessed and solution to minimize its impact should be given a priori [46].

The physical habitat simulation is a useful tool for assessing the impact of a change in flow on the ecosystem of a river. A physical habitat simulation is based largely on the concept of the Instream Flow Incremental Methodology (IFIM) [8–10]. This technique can be used to determine the discharge required to keep the potential productivity of the river related to the biodiversity [46]. PHABSIM,

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based on the IFIM concept, is a technique that is used to evaluate habitat suitability caused by a change in flow. This technique, in general, combines the hydraulic and habitat models and relates the flow conditions to the suitability of physical habitats for the target species in the river ecosystem [11–15]. Thus, the technique can provide the appropriate flow range needed to maintain specific species in the river.

In order to obtain quantitative results for a physical habitat simulation, the composite suitability index (CSI) should be computed. The CSI is a combination of the suitability of each habitat variable such as velocity, flow depth, and substrate. In general, the CSI can be constructed based on either a knowledge-based model or a data-driven model [47]. The knowledge-based model is the conventional approach and the evaluation results are heavily dependent on the individual habitat suitability index (HSI) and the methods used to calculate the CSI from each HSI [16]. The knowledge-based models assume that the correlations between physical habitat variables are negligible and spatial connectivity between habitats can be ignored [48]. However, for example, in reality, the flow depth and the velocity are related by the hydrodynamic principle and each HSI model does not include the geographic or spatial information regarding the river. In order to overcome this weakness, data-driven models, using artificial intelligence techniques such as artificial neural network [17], fuzzy logic [18–20], statistical methods [21], and genetic algorithm [22–24], have been proposed.

Specially, Fukuda et al. [25,26] introduced various data-driven models to assess the fish habitat suitability in the river. The models include artificial neural networks, classification and regression trees, fuzzy habitat suitability models, generalized additive models, generalized linear models, random forests, and support vector machines. Fukuda et al. [25,26] compared the predicted results and concluded that these data-driven models can be useful in the evaluation of habitat suitability.

Recently, hybrid type artificial intelligence techniques such as the fuzzy neural network (FNN) model and the adaptive neuro fuzzy inference system (ANFIS) model, were introduced and were reported to yield better results compared with individual artificial intelligence technique [49–52]. For example, fuzzy neural network models were used to construct the HSI model [27,28,53,54], indicating that fuzzy neural network models are appropriate for considering the uncertainty inherent in complicated ecosystems.

In this study, the ANFIS method was utilized to predict the CSI for a physical habitat simulation. The novelty of the present study is the application of a powerful data-driven approach, the ANFIS method to the prediction of the CSI directly using the monitoring data. A physical habitat simulation was carried out for a reach in the Dal River in Korea, and the adult *Zacco platypus* was chosen as the target fish. A 2D hydraulic model was used for the flow analysis. The distribution of the CSI predicted by the ANFIS method was compared with that obtained from habitat suitability curves. The CSI predicted using monitoring data in other watershed areas are given and the results are compared. The resulting weighted usable areas (WUAs) are also provided and discussed.

2. Study area

Fig. 1 shows the study area of the Dal River, Korea. The study reach is 2.5 km long, ranging from the Sujeon Bridge located downstream from the Goesan Dam to the Daesu Wier. The flow and physical habitat conditions of the study reach are heavily affected by the discharge from the Goesan Dam [29,55]. The Goesan Dam discharges 5–20 m^3/s at irregular intervals for hydropower generation, and the flow is kept constant by the downstream weir even if the dam does not discharge water.

The watershed area of the Goesan Dam is 675.2 km^2 and the design flood is 1750 m^3/s for a 50-year return period. For the study reach, the discharges for drought flow (Q_{355}), low flow (Q_{275}), normal flow (Q_{185}), averaged-wet flow (Q_{95}) are 1.82, 4.02, 7.23, and 17.13 m^3/s, respectively [30]. Here, Q_n denotes the average value of the recorded discharge over n days of the year. The slope of the reach is approximately 1/650, and the bed materials are composed of cobble, gravel, and sand. The median size of the bed material is 137 mm, indicating that it can be classified as a gravel-bed river [29]. Field investigations revealed that a riffle is present in the straight reach upstream of the bend and pools are located before and after the riffle. The presence of the pools and riffle is also supported by the distribution of bed materials. That is, coarse and fine particles are present at the riffle and pools, respectively [29].

Float-type, sonar, and radar water gauges are installed at the Sujeon Bridge, where various measurements of water levels can be made. For this reach, a long period of hydrologic and fish monitoring data have been accumulated through Government R&D projects [31,32].

Fish monitoring revealed that the dominant species in the study area is the minnow (*Zacco platypus*), followed by dark chubs (*Zacco temmincki*) and swiri (*Coreoleuciscus splendidus*) [32]. Detailed data are given in Fig. 2. In the present study, the adult minnow was selected as the target fish for the physical habitat evaluation. Adult *Zacco platypus* grows to about 0.08–0.12 m and normally lives in the riffles in the midstream or downstream reach of rivers. In particular, they adapt relatively well to artificial changes in a river environment such as various river works, the collection of aggregates, and water pollution, and thus are the most common freshwater fish species in Korea [33].

Kang [34] collected fish monitoring data in the Geum River basin, and developed habitat suitability curves for *Zacco platypus*. Fig. 3 shows the habitat suitability curves for flow depth, velocity, and substrate [34].

3. Physical habitat simulation

In this section, the hydraulic model was introduced for the flow analysis and the ANFISF method is presented for predicting the CSI. How the weighted usable area is calculated is then described.

3.1. Hydraulic simulation

For the flow analysis, the River2D model proposed by Steffler and Blackburn [35] is used in the present study. The model is based on the two-dimensional shallow water equations such as

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x}(Uq_x) + \frac{\partial}{\partial y}(Vq_x) + \frac{g}{2} = gH(S_{0x} - S_{fx}) + \frac{1}{\rho}\left\{\frac{\partial}{\partial x}(H\tau_{xx})\right\} + \frac{1}{\rho}\left\{\frac{\partial}{\partial y}(H\tau_{xy})\right\} \qquad (2)$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x}(Uq_y) + \frac{\partial}{\partial y}(Vq_y) + \frac{g}{2}\frac{\partial}{\partial x}H^2 = gH(S_{0x} - S_{fx}) + \frac{1}{\rho}\left\{\frac{\partial}{\partial x}(H\tau_{yx})\right\} + \frac{1}{\rho}\left\{\frac{\partial}{\partial y}(H\tau_{yy})\right\} \qquad (3)$$

which are depth-averaged continuity and x- and y-momentum equations, respectively. In Eqs. (1)–(3), H is the flow depth, U and V are the depth-averaged velocities in the x- and y-directions, respectively, q_x and q_y are respective discharges per unit width ($q_x = HU$,