Ecohydraulic Assessment of Water Abstraction for Hydroelectric Power Generation in the Anegawa River, Japan

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Abstract: The influence of water abstraction for hydroelectric power generation on instream fish habitat was evaluated using a two-dimensional hydrodynamic simulation, the Habitat Suitability Index (HSI), Weighted Usable Area (WUA), and Weighted Suitable Area (WSA) in a midstream reach of the Anegawa River, Japan. The study reach is affected by upstream dam flow regulation and water withdrawal for hydropower generation. The unsteady two-dimensional hydrodynamic model was calibrated and validated with observed data from 2015 and 2016. The reach’s habitat quality was assessed for the adult goby (Rhinogobius flumineus) and dark chub (Nipponocypris temminckii) by combining computed hydraulic variables and suitability indices for the given species. Analysis of the spatial HSI distribution and the WUA and WSA variations under discharges ranging from 0.1 – 40 m³/s revealed that both WUA and WSA for goby tended to be larger than those of dark chub. Water abstraction had opposite effects on goby and dark chub during their spawning months. These results, including the flow curves developed here, could inform improved future management of the flow regime in this and other Japanese rivers.

Keywords: Hydropower plant; Habitat suitability; Hydrodynamic simulation; Fish; River

1 Introduction

Harmonizing fish habitat conservation with water-use activities in rivers has become a major issue recently for water managers worldwide in the pursuit of sustainable water use (Erlewein, 2013; Fanaian et al., 2015; Carolli et al., 2017b). In Japan, river water is used for various purposes, including agriculture, industry, daily life, hydropower generation, and fisheries. These water uses, as well as flood control, cause temporal variations in stream water discharge. Flow reductions and reduced water levels in fragmented river sections produced by large water withdrawals from the river tend to increase the water temperature and decrease the dissolved oxygen concentration, which leads to declines in fish species richness and changes in the fish assemblage composition (Singh and Agarwal, 2017). However, riverine flood control and water development have taken precedence over fish habitat conservation in Japan. Despite the enactment of the River Law revised in 1997, which regulates water use in rivers in order to harmonize ecological conservation and related water use activities, effective harmonization methods have not been identified.

The appropriate evaluation of fish habitat is crucial to sustainable water management. However, methods for the quantitative description of fish habitat in relation to anthropogenic water use are still under development. Richter et al. (1997) introduced the Range of Variability Approach (RVA), which is based on an aquatic ecology theory concerning the critical role of hydrological variability. Upstream discharge regulation based on the Instream Flow Incremental Methodology (IFIM) is a well-known method used to determine the minimum flow suitable for target fish species in a river (Tharme, 2013). Jowett and Biggs (2006) reviewed six New Zealand cases and showed that the modified flow regimes given by the minimum flow requirement approach largely succeeded in achieving the desired ecological outcomes. The Habitat Suitability Index (HSI) has been used widely to evaluate the quality of fish habitat in river sections (e.g., Yi et al., 2010; Fukuda et al., 2011, 2015; Maeda, 2013; Lange et al., 2015; Li et al., 2015; Zhang et al., 2017). Marsili-Libelli et al. (2013) proposed a fuzzy-based method for the assessment of fish habitat suitability using a Suitability Index (SI) for hydraulic and water quality parameters and applied this to two Italian rivers. Zhang et al. (2017) studied the distribution of the Chinese mitten crab in fragmented Yangtze River estuarine habitat patches using an individual-based model with HSI.

Recent studies combining hydrodynamic simulation models with HSI have revealed the stream discharges most favorable for given target fish species. For example, Li et al. (2013) showed that the Xiaowan Dam had an immediate and profound impact on fish in a section of the Lancang-Mekong River, China. Yi et al. (2014) examined the effect of the construction of the Manwan Reservoir on extinction risk for endemic fish species in the Lancang-Mekong River. Garbe et al. (2016) investigated the interplay between spawning brown trout and dependent variables (refugia and food) using one-dimensional hydraulic and habitat models in the River...
Nar in England. Yu et al. (2018) employed ultrasonic telemetry and a three-dimensional hydrodynamic model to build habitat suitability curves for four major species of Chinese carp in the Yangtze River, China.

Flow abstraction from a river for hydroelectric power generation is a common source of conflict between human economic activities and ecological conservation. Gorla and Perona (2013) analyzed both the ecological and economic efficiency of several flow release policies for a typical mini-hydropower plant in Switzerland. Boavida et al. (2015) investigated the effects of hydropoaking in Iberian barbel habitat in the Ocreza River, Portugal. Carolli et al. (2017a) proposed a method that used hydrological, hydraulic, and habitat models to quantify the impacts of water abstraction on ecosystem services in the upper Noce River, Italy. Carolli et al. (2017b) developed a method to evaluate white-water rafting suitability by integrating hydrological, hydraulic, and habitat suitability models. Erlewein (2013) explored the systemic limitations of environmental assessment for hydropower development in an Indian state, indicating that the concept of strategic environmental assessment may be able to overcome existing shortcomings. Santos et al. (2006) investigated the impact of small hydropower plants with fish passes on fish assemblages in medium-sized streams in Portugal. Singh and Agarwal (2017) studied the effect of a hydropower project on fish diversity in a river in India. However, few studies have addressed the applicability of two-dimensional (2D) simulation-based quantitative methods to comparatively narrow and steep river reaches influenced by upstream flow regulation and water abstractions. In addition, studies on water allocation planning for multiple water uses in Japanese rivers are rare.

The Anegawa River, which flows into Lake Biwa (the biggest lake in Japan), is representative of fluvial systems having hydroelectric and agricultural water uses as well as ecological importance. However, a target value for environmental flow (“E-flow”) in the river has not been explicitly defined by the Japanese government, only “normal water discharge”. E-flow is a concept that river flow for ecology should be prioritized under restriction of economic water use (Akiyama et al., 2012). The normal flow discharge refers to the discharge necessary for maintaining stream functions related to various in-stream human activities, downstream water uses, and water quality and ecology in drought; this was set as 1 m³/s at Imamurabashi Station in conjunction with operational rules for the Anegawa Dam (Nagahama Civil Engineering Office, personal communication) (Figure 1). Therefore, ecological water use in E-flow is more emphasized than that in normal water discharge. In this context, Maeda et al. (2019) investigated the influence of agricultural water withdrawal on the goby (Rhinogobius flumineus) and dark chub (Nipponocypris temminckii) in a 285 m midstream reach of the Anegawa River, demonstrating the importance of increasing in-stream discharge during the spawning period of the dark chub. However, the effect of water abstraction for hydroelectric power generation upstream of the reach remains unclear.

This study explored the influence of hydropower generation abstraction on instream fish habitat for a midstream reach of the Anegawa River, Japan using a 2D fish habitat evaluation method. The relationships between water withdrawal and fish environments, such as adult goby and dark chub habitats, were elucidated by integrating 2D hydrodynamic and HSI models. Flow analysis conducted under various assumed upstream current discharge values was used to estimate HSI distributions and determine suitable areas for the target fish species in the reach.

2 Method

2.1 Study area

The Anegawa River originates in the Ibuki Mountains of Japan and flows into Lake Biwa. The river is 39 km in length and has a watershed area of 103 km² (Figure 1). A river reach 380 m long and 23 – 50 m wide was chosen for the evaluation of fish habitat in this study. The reach is affected by two anthropogenic factors, namely outflow discharge control at the Anegawa Dam and water abstraction at the Magatani Dam (Figure 1). The Anegawa Dam reservoir, which was built in 2002, is located approximately 30 km and 8 km upstream from the river mouth and the study reach, respectively, and has a capacity of 7.6 × 10⁶ m³. The upstream Magatani Dam diverts river water into a long headrace tunnel for hydroelectric power generation at the Ibuki power plant, which has a maximum output capacity of 5.4 MW. The water used by the...
plant returns to the river downstream of the study reach. Annual precipitation at the Nagahama meteorological observation station (Figure 1) ranged from 1,320 – 2,056 mm from 2002 – 2016.

The study reach has a single-wave sinusoid shape and includes two clear pool-riffle-run sequences (Figure 2). Topographical surveys of the river bed were undertaken at five transverse cross-sections on July 27, 2015; the measured river bed slope was 1/118. The substrate composition in the reach was dominated by sand and gravel.

2.2 Discharge

Stream discharge fluctuations arise mainly from Anegawa Dam outflow regulation meant to control flooding, regulate the water supply, and maintain river flow during drought. However, the current regulation methods appear to require improvement in order to harmonize the various water uses. During 2002 – 2016, the mean daily outflow discharge from the Anegawa Dam varied from 0.0 – 27 m$^3$/s with an average of 2.2 m$^3$/s; water withdrawal from the river at the Magatani Dam has been observed to significantly decrease discharge at the river reach.

Discharge in the reach from 2014 – 2016 was evaluated to assess the impact of current water use on fish habitat in the river. Using the water level $H$ (m) measured by the Nagahama civil engineering office, and ten river discharge observations $Q$ (m$^3$/s) from 2015 and 2016 taken at the downstream end of the study reach, the relationship between water level and discharge was estimated to be $Q = (4.39H – 2.5)^2$. Using this $H$-$Q$ curve, the reported stream water level, and daily discharge data for water abstraction for the Iibuki hydroelectric power plant at the Magatani Dam upstream of the reach (provided by Kansai Electric Power Co., Inc.), natural discharge conditions (“natural” hereafter) can be evaluated by assuming no anthropogenic water withdrawal and no natural inflow or outflow within in the study reach.

Figure 3 shows the natural river discharge and that abstracted for hydropower generation; the actual discharge in the reach is expressed as the difference between the two flow curves in this figure. The mean daily water abstraction discharge ranged from 0.43 – 3.5 m$^3$/s in 2014, 0.91 – 3.5 m$^3$/s in 2015, and 1.0 – 3.2 m$^3$/s in 2016, constituting 1.2 – 45%, 71 – 77%, and 13 – 76% of the natural river discharge, respectively. The yearly-average actual daily discharge at the downstream end of the reach was estimated to be 4.0, 3.4, and 3.2 m$^3$/s in 2014, 2015, and 2016, respectively.

The characteristic actual instream discharge values are summarized in Table 1. The median discharge during the three years was 2.86 m$^3$/s on average, while the discharge’s 75th percentiles were approximately 4 – 5 m$^3$/s, much smaller than the maximum discharge values. Therefore, it is presumed that the stream discharge was almost always less than 5 m$^3$/s during the years of interest.

2.3 Fish

The target fish species included goby (*Rhinogobius flumineus*) and dark chub (*Nipponocypris temminckii*). These species were selected due to their existence in the reach and the availability of suitability index (SI) curves, or preference...
curves, for the fish species. The goby is omnivorous and ~4 – 6 cm in total length; this fish prefers areas with low current velocity and stays around plant roots and gravels on the river bed (Kawanabe et al., 1989). The goby is one of the predominant species in the midstream region of the Anegawa River, as found in our fish-capture survey, which was conducted in the pool-riffle-run in the downstream region of the reach on October 21, 2015. The dark chub is in the Cyprinidae family, is omnivorous, and measures ~15 cm in total length; this fish lives in low-current pools (Kawanabe et al., 1989).

2.4 Hydrodynamic simulation

Nays2DH (Nays2DH Development Team, 2011) was adopted to solve the unsteady 2D Reynolds-averaged Navier-Stokes equation and continuity equation in order to estimate the spatial distribution of hydraulic variables (i.e., water depth and current velocity) in the reach. Using the cross-sectional topography data from nine cross-sections prepared with the result of the topographical survey and aerial photographs taken on August 1, 2015 (via Google Earth), the river section was discretized into 7,700 quadrilateral cells with 8,106 nodes (Figure 2). The 2D hydraulic model was calibrated at 1.12 m/s with data on water depth and current velocity measured on October 18, 2015. The downstream boundary condition featured a water depth of 0.32 m in calibration. The time step was 0.05 s. The total computational time was 1,200 s, during which time the flow reached steady state. During model calibration, the values of the Manning’s roughness coefficients in the pool, riffle, run, bank vegetation, and bed protection were adjusted so that the computed hydraulic variables matched observed variables; the model was then validated at 1.48 m/s as measured on October 15, 2016.

The validated hydrodynamic model was run to estimate the distributions of current velocity and water depth, which were used as inputs to the HSI model under low (0.1 m/s) to high (40 m/s) discharge; the discharge range was determined based on historical data for outflow discharge from the Anegawa Dam. Here, uniform water depth was given in the downstream boundary condition.

2.5 Habitat Suitability Index (HSI)

The SI curves representing water depth and current velocity preferences for the adult goby and dark chub were obtained from Tsujimoto et al. (2000) and Kawamoto et al. (1999). The preference curves for the goby were created using an expert-based method, and those for the dark chub were estimated from a field survey in the Kibagawa River, Japan, conducted by Kawamoto et al. (1999). Based on these curves, the habitat SI ranged from unsuitable (0) to optimal (1) (Figure 4). Using the SI curves and the computed hydraulic variables (i.e., nodal water depth \( h_i \) and velocity \( v_i \)), the SI values at the \( i \)-th node for the \( f \)-th fish, \( \text{SI}_i^{f} (h_i) \) and \( \text{SI}_i^{f} (v_i) \), were computed. Then, the \( i \)-th nodal HSI value for the \( f \)-th fish was computed as the geometric mean of the SIs as follows:

\[
\text{HSI}_i^f = \sqrt{\text{SI}_i^{f} (h_i) \times \text{SI}_i^{f} (v_i)}, \quad \forall i, f
\]  

where \( f= 1 \) (goby), 2 (dark chub), and \( i= 1, 2, \cdots, 8,106 \). The geometric mean in Eq. (1) gives a more conservative estimate of habitat suitability than an arithmetic mean of SI, because the HSI value in Eq. (1) goes to zero if either of the SI values incorporated there is zero.

2.6 Weighted Usable Area (WUA)

The water surface area in the reach changes depending on the upstream discharge. The WUA can be used to comprehensively evaluate the quality and quantity of the fish habitat under temporal discharge variations. The WUA value for the \( f \)-th fish was calculated using an elemental HSI estimated from the four nodal HSI values in each cell:

\[
WUA_f = \sum_{j=1}^{N_E} w_j^f \text{HSI}_j^f \tag{2}
\]

where \( w_j^f \) is the area of the \( j \)-th element; \( \text{HSI}_j^f \) is the elemental HSI at the \( j \)-th element for the \( f \)-th fish; and \( N_E \) is the total number of elements in the reach, which is equal to 7,700 in this study. Note that the WUA is an area-weighted HSI and a function of discharge; it represents the overall effectiveness of the reach as habitat for the adult goby and dark chub.

2.7 Weighted Suitable Area (WSA)

The WUA can include areas of low HSI that are not ideal for fish habitat. In order to focus on the preferable (i.e., higher-HSI) elements, the Weighted Suitable Area (WSA) was also calculated in this study:

\[
WSA_f = \sum_{j=1}^{N_E} w_j^f \text{HSI}_j^f \tag{3}
\]

where \( w_j^f \) is the area of the \( j \)-th element for the \( f \)-th fish. Note that HSI\(_j^f\) values greater than 0.5 indicate that the associated \( j \)-th element is suitable for the \( f \)-th fish, and that the area of the element is substituted for \( w_j^f \).

3 Results

3.1 Calibration and validation

Due to the importance of hydraulic conditions, many previous studies on riverine fish habitat evaluation have employed hydrodynamic simulations with various assumed discharge levels. This study adopts this approach for the Anegawa
River study reach. At the beginning of the study, the Nays2DH hydrodynamic model was calibrated with data obtained at seven observation points in 2015. The computed water depths were consistent with the observed depths, while the computed current velocities tended to be underestimated. However, since the root mean square errors (RMSEs) of water depth and velocity were 0.11 m and 0.25 m/s, respectively, we concluded that the model appropriately reproduced the flow on the observation day. Figure 5 shows the computational result for water depth and velocity in the hydrodynamic model calibration, in which the estimated locations of pools and riffles are reproduced fairly accurately. The model was subsequently successfully validated with seven sets of measured water depth and velocity data from 2016 (RMSEs for water depth and velocity were 0.09 m and 0.41 m/s, respectively). Values of Manning’s roughness coefficient in Nays2DH were found as 0.04 – 0.10 m$^{-1/3}$s.$^{-3}$. 

3.2 HSI

Using the validated hydrodynamic model, spatial distributions of hydraulic variables were produced under given upstream discharges ranging from 0.1 – 40 m$^3$/s. Habitat suitability was evaluated for the goby and dark chub at each node in the reach, using Eq. (1) to express the nodal estimated fish preference. Next, the nodal HSI value was converted into an elemental value via calculation of the arithmetical mean of the four nodal HSIs on the boundary of the element. Finally, the WUA and WSA were computed for the given fish using Eqs. (2) and (3) with the elemental HSI.

Estimated distributions of the nodal HSI for the two fishes are shown at discharges of 0.1, 3, 9, and 30 m$^3$/s in Figures 6 and 7. Comparison of these figures clarifies the differences in the influence of discharge variation on the preferable area distribution for the two species. Regarding the goby, the area of high habitat suitability was concentrated in the river pools under lower discharge (e.g., 0.1 m/s). The location of high HSI shifted from higher-depth regions to the riverbanks as the discharge increased, which is attributed to the water
depth and velocity preferences defined in Figure 4. Because the velocity in the runs increased as the discharge grew from 3 to 30 m/s, the area of low HSI colored in blue expanded in and around the two riffles. For the dark chub, the changes in HSI distribution with discharge variation were similar to those for the goby. However, the high-HSI region locational shift began at smaller discharge values.

3.3 WUA
WUA is graphed as a function of discharge in Figure 8. For both fish species, the WUA increased with increasing discharge at low flow rates, reached a maximum at a particular discharge, then began to decline with further increases in discharge. The maximum WUA values for the goby and dark chub (termed WUA\textsuperscript{max} and WUA\textsubscript{2 max} ) were 7,020 and 4,730 m\textsuperscript{2} at discharges of 9.3 and 2.6 m\textsuperscript{3}/s, respectively. The goby attained the higher maximum WUA value.

It is noted that WUA includes cells of various HSI values that represent habitat quality as defined in Eq. (2). In order to find out the ratio of cell areas with high or low HSI to WUA at each discharge level, four-stage area-weighted HSI regions (“very suitable”, 0.75<HSI≤1; “suitable”, 0.5<HSI≤0.75; “unsuitable” 0.25<HSI<0.5; and “very unsuitable”, 0<HSI≤0.25) were also depicted for the goby and dark chub in Figure 8. This shows that the goby has a larger “very suitable” area than does the dark chub over the span of considered discharge.

3.4 WSA
The WSA/flow curves, which represent the regional magnitude of the area-weighted suitable HSI (i.e., HSI greater than 0.5), are given in Figure 9. The maximum WSA values for the goby and dark chub, WSA\textsuperscript{max} and WSA\textsubscript{2 max}, were 6,180 and 3,950 m\textsuperscript{2} at river discharges of 8.0 and 1.5 m\textsuperscript{3}/s, respectively. Note that the dark chub is more vulnerable to discharge increases above the peak value ( WSA\textsuperscript{max} = 3,950 at Q = 1.5 m\textsuperscript{3}/s) than the goby, even though their response to the discharge decrease from their peaks of WSA is similar. This indicates that the dark chub’s habitat is more sensitive to discharge variations than the goby’s. These results also match the fact that the dark chub quantity caught during the 2015 fish survey was much smaller than that of the goby.

4 Discussion
4.1 Impact of water withdrawal in the spawning period
The impact of water withdrawal for hydroelectric power generation from May to August, and the dark chub spawn, can be investigated via analysis of WUA variation and potential power generation in the study reach. Actual and natural daily river discharge (averaged over the four months) and the associated WUA\textsubscript{1} and WUA\textsubscript{2} values are summarized in Table 2. Water abstraction led to 3.8 – 8.8% declines in WUA\textsubscript{1} and 7.0 – 9.2% increases in WUA\textsubscript{2}. Although the river discharge decreases adversely affected both species during the spawning season, the sum of WUA\textsubscript{1} and WUA\textsubscript{2} remained almost constant. Water abstraction measured 1.67, 2.10, and 1.85 m\textsuperscript{3}/s in 2014, 2015, and 2016, respectively, corresponding to 47.6, 59.3, and 57.5% of the maximum withdrawn discharge, or almost half of the maximum abstraction during each year. In short, it appears that the current water intake policy causes low river water discharge, which negatively affects the goby and positively affects the dark-chub. This result indicates the importance of consider multiple species in the discharge control in the river.

4.2 Relation between normal water discharge and WSA
In Japan, the normal water discharge including water for animals and plants is generally planned based on drought-period water discharge that occurs once in ten years (Tamai et al., 1993). Since the normal water discharge in the Anegawa River is set only at the Imamurabashi Station (located far downstream of the study reach, Figure 1), there exists no method to evaluate the impact of water abstraction in the study reach. Drought-period water discharges from 2014 – 2016 in the study reach are estimated as 1.89, 0.47, and 0.61 m\textsuperscript{3}/s. If the three-year-averaged drought-period water discharge of 0.99 m\textsuperscript{3}/s is assumed to be employed as a target discharge for fish habitat conservation in the reach, WSA\textsubscript{1} and WSA\textsubscript{2} will decline up to 63 and 96% of their respective maximum values. Therefore, it is concerning that the current
method of setting the normal water discharge based on drought-period discharge leads to significant reductions in suitable habitat for the adult goby. In addition, dynamic water allocation between hydroelectric power generation and fish habitat conservation is crucial, because the WSA of the dark chub is sensitive to variations in river discharge. The WSA/flow curve determined here could contribute to the setting of more reasonable discharge control than current outflow management at the Anegawa Dam.

4.3 Selection of HSI model

Yi et al. (2014) compared the performance of habitat suitability models regarding the Chinese sturgeon based on the preference curve method, the expert knowledge-based fuzzy logic method, and the data-driven fuzzy logic method, concluding that (1) there were few differences in the results of the first two, and (2) the quality of the training dataset was very important for the third. Since obtaining sufficient data quantity and coverage (e.g., including very high and very low discharges) is difficult in reality, the preference curve method with expert knowledge, employed here, may remain effective for habitat suitability evaluation in the Anegawa River.

5 Conclusions

The effects of water abstraction for hydroelectric power generation on adult goby and dark chub habitat were analyzed quantitatively in a reach of the Anegawa River, Japan. The results of a hydrodynamic simulation using instream and outflow data from 2014 – 2016 were supplied to the HSI model, which produced WUA/flow and WSA/flow curves. The data showed that flow regulation upstream of the study reach significantly influenced the HSI, WUA, and WSA in the reach. Although further investigations of multifaced validity on habitat suitability evaluation are needed, this study indicated the effectiveness and importance of applying an ecohydraulic approach to determining the normal water discharge.

This study demonstrated quantitative, high-spatial-resolution, and close relationships between anthropogenic water withdrawal and instream fish habitat in a narrow, steep river in Japan. Although the study reach can provide larger desirable areas for the goby, the current typical discharge causes decreased suitable areas for this species. The dark chub has a lower habitat potential in the reach and may be more vulnerable to instream flow variations.

The analysis on the impact of water withdrawal for hydroelectric power generation in the fish spawning period using WUA indicated that the current water intake policy negatively and positively affected the habitat of goby and dark chub, respectively. The difference in the ecological influence demonstrates the importance of consideration of multiple species in the discharge control. Further study is necessary to determine the harmonized water abstraction in conflicting interests.

In the future, evaluation of habitat suitability should be improved through the consideration of other important factors, such as substrate, vegetation, and prey. Morphological variations in the river due to sediment transport should also be considered in fish habitat evaluations conducted from a long-term perspective.

Acknowledgements

The authors would like to thank Dr. Kazuhiro Sugahara and Professor Takuya Ohkubo for assisting with the fish survey. The topography survey was supported by the Kitai Sekkei Company. The morphological, hydraulic, and ecological information were provided for the Anegawa River watershed by the Nagahama Civil Engineering Office, Anegawa Coastal Land Improvement District, Kansai Electric Power Co., Inc., Upstream Anegawa Fisheries Cooperative, and Maibara City. We are grateful to the iRIC Project for supplying the Nays2DH hydrodynamic simulation model. This study was supported in part by JSPS KAKENHI Grant Number 26310301.

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