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ORIGINAL ARTICLE

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Abstract This study attempted to analyze flow duration in a basin using a method to estimate environmental flow developed by the International Water Management Institute, and simulate the effects of runoff characteristics unique to a river and flow variability due to basin developments on aquatic ecosystems. To do so, KModSim, a simulation model for basin-wide water distribution, was used to assess flow duration in the Geum River basin, one of the four major river basins in Korea, by environmental management class (EMC). Flow duration curves by EMC at Sutong and Gongju sites were derived on the basis of natural flow in the Geum River basin. As a result, they were found to be consistent with the results of previous studies. Time series of mean monthly flow data by EMC were plotted together with those of simulated flow data by reservoir operation scenario; Sutong and Gongju points both showed flow behaviors corresponding almost to "A" in EMC. In addition, the characteristics of habitats by species of fish were identified through monitoring fish habitat at the Sutong site, so that optimal ecological flow rate was estimated. For this purpose, relations between flow discharge and weighted usable area for *Coreoleuciscus splendidus* and *Pseudopungtungia nigra* were projected using physical habitat simulation system, and EMCs consistent with flow duration curves (estimated taking in-stream flow) were assessed. The results or findings reported in this study are expected to serve as basic data for making a plan to efficiently monitor and manage aquatic ecosystems in the Geum River basin.

Keywords Ecological flow rate · Flow duration · EMC · PHABSIM

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Introduction

Recently in integrated basin management, the concept of environmental flow has attracted the hydraulic and hydrological sector's attention, along with the conservation of aquatic ecosystems (The Nature Conservancy 2006). This term is commonly used to refer to flow regime designed to continuously maintain a river under specific ecological conditions (Smakhtin and Anputhas 2006). Generally, all elements composing a flow regime have their own roles and functions. For example, high-stage regime affects, mainly, channel maintenance, wetland flooding, etc., while low-stage regime dominates algal growth, fish spawning, etc. Accordingly, the best way to keep a river healthy is to maintain all elements of abiogenetic flow regime as they are. But it is almost impossible to do so without any change, since the development of various water resources to respond to sharply increasing water demands is indispensable to man's livelihood. This is why there has been a change in the ecological environment of a river. For the improvement of its self-purification and, consequently, the restoration of its own normal functions, it is required to further habitats for aquatic organisms, prevent pollutants and secure environmental in-stream flow for maintaining a river (Gore et al. 1989).

Environmental flow is very complex and difficult to estimate (Hughes 2001). Especially, a method to estimate flow rate considering fish habitats necessary for the restoration of aquatic ecosystems, including fish, remains still in an early stage. This results from the absence of a theoretical background to quantitatively analyze effects a change in flow regime has on riparian ecosystems, or of related data. Ko et al. (2009) mentioned in their study that the eco-hydrological healthiness of a river should be assessed using an extensive variety of hydraulic, hydrological and ecological data and analysis models. The USA had experienced a decrease in the population of Salmonidae since the 1960s. To respond to this challenge, a study on ecological flow rate in a river to conserve fish habitats was first introduced. Based on the study, flow rate for fish habits was estimated through flow–weighted usable area (WUA) relations provided by the Physical Habitat Simulation System (PHABSIM) (2001). In 1970s, the Fish and Wildlife Service (FWS) estimated the flow rate by species of fish, stage of their growth and condition of their habitats using in-stream flow incremental methodology (IFIM) to determine in-stream flow for maintaining a river (Stalnaker et al. 1995). Also, the United States Environmental Protection Agency (USEPA) and United States Geological Survey (USGS) have continuously and systematically monitored various organisms (including fish) by determining the so-called "Monitoring Protocol". These monitoring data have been used for not only multidisciplinary joint surveys and habitat analyses, but also riparian restoration and other projects.

In measuring environmental flow, one of the hydrological characteristics that ecological experts pay attention to is "flow variability". (Bunn and Arthington 2002). Flow variability is known as an important factor dominating the structural or functional diversity of rivers and their surrounding wetland or the diversity of aquatic species. Recently, the International Water Management Institute (IWMI) proposed a method to roughly estimate environmental flow in a target basin, based on the behavior characteristics of its flow duration curve (Smakhtin and Eriyagama 2008). Flow duration curve refers to a curve that visually relates flow values measured at given time intervals to the percentage of time those values are likely to be met or exceeded (Park 2003); it is a hydrological tool enabling the intuitive assessment of flow variability in a target point. Accordingly, the behavior characteristics of a flow duration curve under a specific condition contain important information that would make it possible to roughly assess the ecological conditions of a target basin.

This study reviewed the applicability of the above method proposed by the IWMI to the Geum River basin, one of the four major river basins in Korea. To do so, time series of flow data for the target basin were produced and analyzed using a water-balance assessment model in conjunction with multi-purpose dam developments at the same basin. Also, for the reasonable assessment of basin-wide environmental flow, ecological monitoring was carried out to identify the characteristics of habitats by species of fish and estimate optimal ecological flow rate.

Methodology

Flow duration curve (FDC)

Flow duration curve, one of the universal tools commonly used in hydrology, is a means of illustratively representing the relations of flow values to annual flow duration (or percentage of time) (Maidment 1992). Generally, flow duration analysis is divided into two: in mean annual flow duration analysis, flow values individually estimated for 365 days is ranked from the 1st to the 365th in descending order, and mean flow corresponding to the specific days of flow duration is estimated in proportion to the data period, while, in flow duration analysis over the entire data period, flow values collected for the same period are ranked from the first to the last in descending order, and then their non-exceedance probability is represented in terms of percentage (Park 2003). In Korea, flow duration is assessed, mainly, on the basis of the days of flow duration. On the other hand, the US and EU assess flow duration using the concept of probability.

A flow duration curve can be considered as part of a spectrum consisting of all elements that represent flow regime in a stream point. The curve provides very important information in assessing flow variability. Especially, Smakhtin and Eriyagama (2008) developed a method to roughly estimate environmental flow with a focus on the duration of natural flow. In here, natural flow means flow regime in a river that is not regulated by hydraulic structures (e.g., dam, etc.). The IWMI has provided time series of monthly natural flow data from simulations carried out based on meteorological water balance all over the world, with the coverage period ranging from 1901 to 2000. But a micro approach to a specific point requires proper follow-ups, such as down-scaling, since these data are based on a square grid with about 50 km in scale. Therefore, this study composed basin-scale scenarios in accordance with the construction of multi-purpose dams, which, in turn, were used to derive a water-balance analysis model. Then, time series of flow data were directly simulated using this model to estimate a flow duration curve.

Environmental management classes (EMCs)

The estimation of environmental flow aims, among others, to maintain or improve aquatic ecosystems under prescribed conditions. However, this requires the prior definition of proper environmental management classes (EMCs). EMCs refer to a basic scenario for changes in aquatic ecosystems that may occur according to the level of environmental protection (or management) and the flow regime of a river corresponding to the same level. This suggests that the higher the EMCs are, the more water has to be reserved for environmental flow, and the more extensively the variability of flow regime has to be allowed. Table 1 shows the EMCs proposed by the IWMI. They are, on the whole, similar to the corresponding ones suggested in the White Paper on a National Water Policy for South Africa [released by the Department of Water Affairs and Forestry (DWAF 1997)] (Smakhtin and Eriyagama 2008). As seen in the table, they consist of six classes in total, and contain the brief descriptions of ecological conditions and management perspectives for each class. Rivers around which densely populated areas are situated or which experience an ecological change due to basin developments fall under classes C–F. Especially, classes E and F represent a serious status in which no further development plan can be allowed. Actually, these classes have to be categorized considering complex aspects, such as empirical relations between riparian flow regime and ecological conditions, the development level of a country, etc. In Korea, however, there have been no studies that can meet these requirements. In this study, EMCs proposed in Table 1 were applied with no consideration of circumstances unique to Korea. If the results of future studies on environmental flow carried out in Korea, based on the foregoing holistic method, are reported, it is expected that there will be more reasonable improvements.

Estimation of FDC

This study used a method proposed by Smakhtin and Anputhas (2006) to estimate environmental flow. For such estimation, a reference flow duration curve (FDC) for natural flow in a target river was first drawn out. It is a curve defined by 17 sites on a horizontal axis (percentage of time) (including 0.01, 0.1, 1, 5, 10, 20, 30, 40, 50, 60, 70, 80, 90, 95, 99, 99.9 and 99.99 %). The curve was shifted point by point to the left, as shown in Fig. 1, to determine flow duration curves for each EMC in Table 1. Unknown flow (at the tail of the flow duration curve) that occurred, whenever it was shifted point by point to the left, was estimated using linear extrapolation. This process represents the simulation of the effects of a decrease in flow due to basin developments on aquatic ecosystems, as flow variability unique to a river (i.e., behavior characteristics of a natural flow duration curve) is maintained. In this regard, the method used in this study can be said to be very efficient.

Table 1 Environmental management classes (EMCs) (Smakhtin and Eriyagama 2008)

EMC	Most likely ecological conditions	Management perspectives
A	Natural rivers with minor modification of in-stream and riparian habitats	Protected rivers and basins. Reserves and national parks. No new water projects (dam, diversions) allowed
B	Slightly modified and/or ecologically important rivers with largely intact bio-diversity and habitats despite water resources development and/or basin modifications	Water supply schemes or irrigation development present and/or allowed.
C	The habitats and dynamics of the biota have been disturbed, but basic ecosystem functions are still intact. Some sensitive species are lost and/or reduced in extent. Alien species present	Multiple disturbances associated with the need for socioeconomic development, e.g., dams, diversions, habitats modification and reduced water quality
D	Large changes in natural habitats, biota and basic ecosystem functions have occurred. A clearly lower than expected species richness. Much lowered presence of intolerant species. Alien species prevail	Significant and clearly visible disturbances associated with basin and water resources development, including dams, diversions, transfers, habitats modification and water quality degradation
E	Habitats diversity and availability have declined. A strikingly lower than expected species richness. Only tolerant species remain. Indigenous species can no longer breed. Alien species have invaded the ecosystem	High human population density and extensive water resources exploitation. Generally, this status should not be acceptable as a management goal. Management interventions are necessary to restore flow pattern and to 'move' a river to a higher management category
F	Modifications have reached a critical level and ecosystem has been completely modified with almost total loss of natural habitats and biota. In the worst case, the basic ecosystem functions have been destroyed and the changes are irreversible	This status is not acceptable from the management perspective. Management interventions are necessary to restore flow pattern and river habitats (if still possible/feasible) to 'move' a river to a higher management category

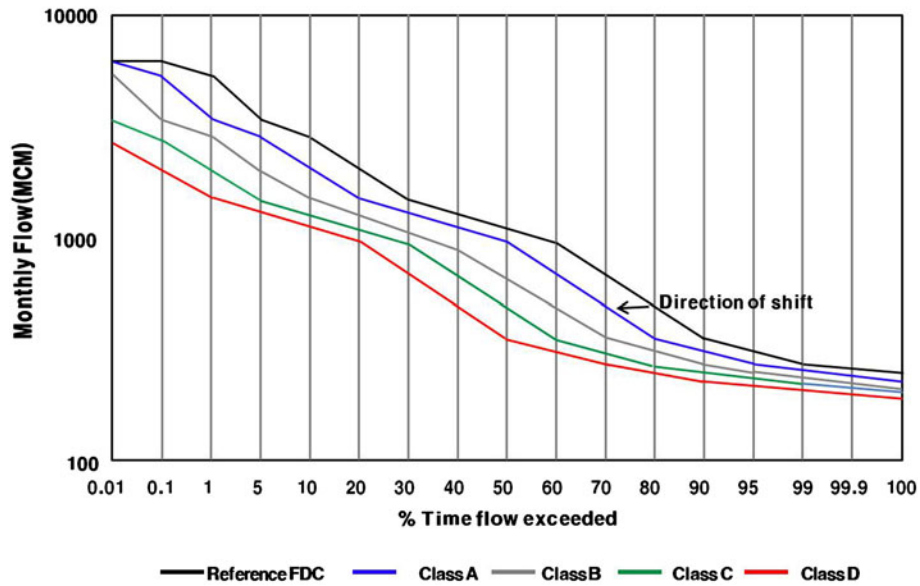


Fig. 1 Estimation of environmental FDCs for each EMC (Smakhtin and Eriyagama 2008)

Simulated time series of environmental flow

Flow duration curves for each EMC, determined as shown in Fig. 1, provide just general information about the flow regime of allowable environmental flow. Hughes and Smakhtin (1996) proposed a method to produce time series of flow data at a target point using time series of flow data and a flow duration curve at a reference point.

Their findings made it possible to systematically derive from time series of natural flow data at a target point flow duration curves for each EMC (as shown in Table 1) and the corresponding time series of flow data. Smakhtin and Eriyagama (2008) suggested that these data would provide important information for experts engaging in other sectors who carried out researches on environmental flow (e.g., ecology).

Study sites and field methods for fish assemblage sampling

As seen in Fig. 2, the study site for the estimation of ecological flow rate is located about 50 km downstream of Yongdam Dam, so that it is directly affected by outflow discharge from the dam. Water depth at the site ranges from 1.0 to 30.0 m. Velocity varies depending on flow regime, and bed materials consist of coarse gravels, cobbles, boulders, etc. Riffle, run, pool, etc., are found in a survey river reach, and perennial plants and trees, including Salix species, inhabit the right and left bank of the river. Also, it is reported that *Pseudopungtungia nigra*, categorized as one of endangered species, inhabits the river (Hur and Kim 2009).

Based on the Guideline to Fish Habitat Monitoring (Kim and Kim 2009), fish-habit monitoring at the study site was carried out. Monitoring processes subsequently followed a preliminary survey, a field survey and then the compilation and assessment of survey results. In the field survey, four cross sections were measured using a total station to identify the characteristics of those cross sections at each point. Velocity was measured using an electromagnetic flow meter (Model 801, Valeport, UK), and water depth was measured at intervals of 1 m using a bathymeter. Based on substrate-size classes as proposed by Woo (2001), bed materials were subdivided into silts (1, 0.1 mm or smaller), sand (2, 0.1–1.0 mm), fine gravels (3, 1.0–50.0 mm), coarse gravels (4, 50.0–100.0 mm), cobbles (5, 100.0–300.0 mm) and boulders (6, 300.0 mm or larger). The cross sections of the river were classified in accordance with Rosgen's method (Rosgen 1994). Fish samples were collected 200 m upstream and downstream of the survey river reach for 1 h and 1 h, respectively.

Estimation of habitat suitability index (HIS)

Coreoleuciscus splendidus and *Pseudopungtungia nigra* were selected as species of fish samples for the estimation of HSI at the study site; they appeared as dominant species at the time of fish sampling, and *C. splendidus* was sensitive to flow rate. Also, *P. nigra* is designated as one of the endangered species by the Ministry of Environment, and appears, especially, in the Geum River and not in other river systems.

The Instream Flow Study Guidelines recommended by the Washington Department of Fish and Wildlife was referred to for the estimation of HSI (Stalnaker et al. 1995).

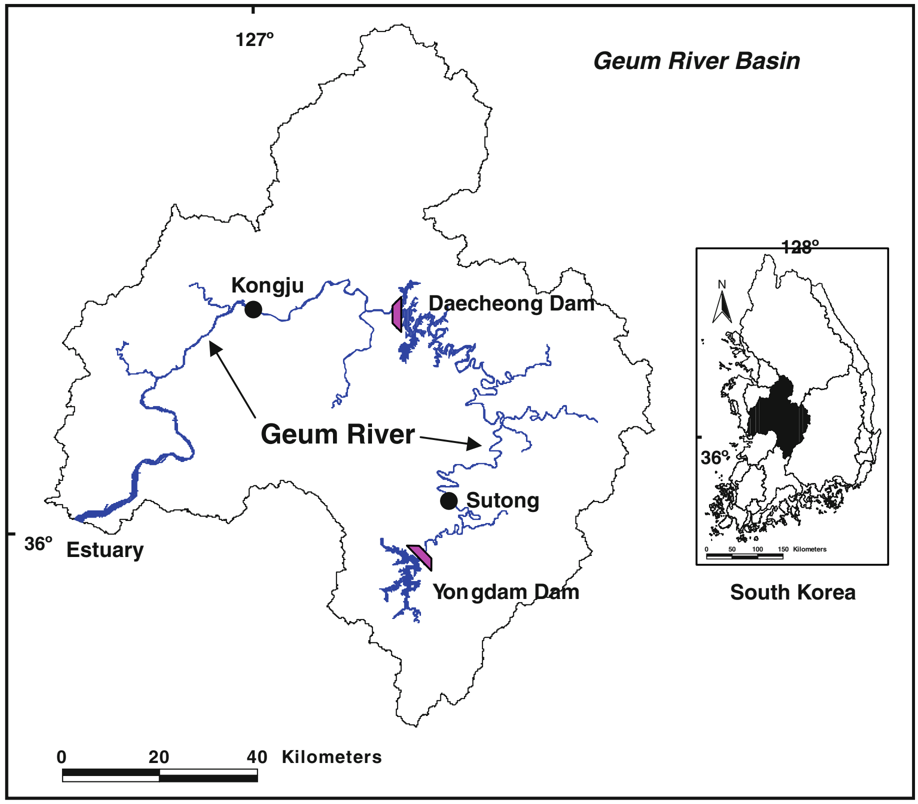


Fig. 2 Geum River basin

HSI was determined on the basis of the number of fish population appearing at the target point. Comprehensively considering the distribution of riparian cross sections and the number of fish population appearing during the survey period, the maximum value of HSI was set at 1.0, and the rest of the HSI values were determined in terms of relative ratio to the maximum value. Prior to fish sampling, information about river characteristics and cross sections at the target point was collected. HSI for bed materials was estimated using dichotomy, and HSI for water depth and flow velocity was estimated using a univariate curve. The determination of sites and methods for estimating HSI was based on the study undertaken by Hur and Kim (2009) as follows. First, sites for estimating HSI were so selected that there might be no structures obstructing stream flow at their cross sections, and that riffles, pools, runs, etc., might be embedded. Second, river cross section and width were measured using a total station, and flow rate was estimated using water depth and flow velocity that were identified during the measuring. Third, river information was input into a computer system to estimate the ratio of the area corresponding to the range of specific water depth, flow velocity and bed materials to total area in terms of percentage. Fourth, fish samples were collected at sites to measure river cross sections in conformity with the Commercial Law, and then identified, measured and counted on the spot. Fifth, the expected value of each measured cross section was calculated. Finally, HSI was estimated.

Estimation of ecological flow rate

A change in physical habitats for species of fish samples in a channel reach that results from flow characteristics (e.g., flow rate, velocity, depth, etc.) was projected using PHABSIM. Then, optimal ecological flow rate was estimated through their flow–WUA relations (Petts and Maddock 1998). That is, the estimation of ecological flow rate for a specific species of fish was made using a flow–WUA relation curve for the same species. This curve, in turn, was estimated using the results of field survey (e.g., stage, flow discharge, river cross section, etc.), HSI and PHABSIM.

The optimum flow regime suitable for fish habitat can be determined by performing hydraulic modeling. In this case, the WUA can be estimated by the multiplication of cell size of the reach and a combined HSI using Eq. (1):

$$\mathrm{WUA} = \sum_{i=1}^{n} A_i \times C_i \qquad (1)$$

where, A_i is an area of cell i and C_i = combined HSI of cell i.

Gordon et al. (1993) estimated the combined HSI, Ci by the combination of the suitability criteria of depth, velocity and substrate size, and determined by the standard computation, geometric mean method and minimum value method. In this study, the standard computation shown in Eq. (2) was employed (Palmer and Snyder 1985).

$$C_i = f(v_i) \times f(d_i) \times f(c_i) \qquad (2)$$

where, v_i is HSI of cell i regarding velocity, d_i is HSI of cell i regarding depth of flow and c_i is HSI of cell i regarding substrate size.

Results and discussion

Composition of scenario for flow duration analysis

This study chose as a target basin the Geum River basin where the two multi-purpose dams (Daecheong Dam and Yongdam Dam) had been operated (Fig. 2). The Geum River basin is the third largest basin in Korea, with about 9,835 km^2 and 395.9 km in catchment area and river length, respectively. Daecheong Dam, one of the two multi-purpose dams, is located in the center of the basin, and Yong-dam Dam, the other multi-purpose dam, is located most upstream of the river. It can be assumed that the earlier stage of the Geum River basin is a natural stage when both dams had not been constructed. Since then, the construction of Daecheong Dam might have caused a change in the physical and hydrological characteristics of the basin, and the subsequent construction of Yongdam Dam might have resulted in another change. To analyze a change in flow regime due to such dams, scenarios conditional on unregulated and regulated flow at Sutong point 15 km downstream of Yongdam Dam and Gongju point 35 km downstream of Daecheong Dam were composed on the basis of the time when the two dams were, respectively, constructed: two scenarios for the Sutong point (one for the presence of Yongdam Dam, and the other for the absence of Yongdam Dam) and three scenarios for the Gongju point (one for the absence of the two dams, another for the presence of Daecheong Dam alone, and the last for the presence of both the dams) (Ko et al. 2009).

Simulation of flow time series by scenario

This study simulated flow time series for each scenario using KModSim, a water-balance analysis model developed by Korea Water Resources Corporation ("K-Water") in collaboration with the US Colorado State University. The model enables the easy construction of networks for complex basin systems by simulating basin-wide water distribution and reservoir operation scenarios considering various water demands in a river basin. In this study, a change in flow duration due to the construction of the two dams was simulated using KModSim that had been composed for the Geum River basin and gone through precision validations and adjustments over lots of years (Jung et al. 2007). In a scenario prior to the dam construction for the estimation of unregulated flow, flow data at the Sutong point and Gongju point were produced using KModSim, with 1984–2005 (22 years in total) as the coverage period. This scenario assumes that there had not been the two dams (Daecheong Dam and Yongdam Dam located in the Geum River). In a scenario after the dam construction for the estimation of regulated flow, flow data at the same point were produced using the same model. This scenario assumes that the two dams had been operated for the period ranging from 1984 to 2005. Figure 3 shows the schematic map for networks to carry out simulations using KModSim.

Estimation of flow duration curves by EMC

Flow duration curves by EMC at the Sutong and Gongju point were estimated using time series of mean monthly flow data that were simulated under a scenario conditional on unregulated flow (or natural flow). Ordinates for each flow duration curve were computed using global environmental flow calculator (GEFC). GEFC is a program (provided by the IWMI) to roughly estimate environmental flow. Figures 4 and 5 show the plotting of the results on semi logarithm paper. In the figures, it can be seen that a tendency toward decreasing flow due to basin developments is systematically simulated, while the flow regime of natural flow (or the shape of flow duration curves) is maintained.

Table 2 shows the quantitative summary of the above results; in the table, the ratio of mean annual runoff (MAR) by EMC to natural MAR is presented. Jones (2002) held that, if mean annual runoff in an arbitrary river decreased to 2/3 of natural MAR or lower, the probability that the river might be kept healthy could decrease from "high" to "moderate". In addition, Tennant (1976) reported that the lower limit of mean annual runoff necessary for maintaining aquatic ecosystems was some 10 % of the natural flow. Figures as shown in Table 2 (especially, figures corresponding to EMCs A–D that are among allowable EMCs) are relatively consistent with the results of the foregoing previous studies. In this regard, Figs. 5 and 6 (that are flow duration curves by EMC estimated in this study) will serve as basic data to make a plan to efficiently monitor and manage aquatic ecosystems in the Geum River basin:

EMC of the Geum River Basin under dam construction scenario

Time series of mean monthly flow data by EMC (with 1984–2005 in coverage period) were produced using flow

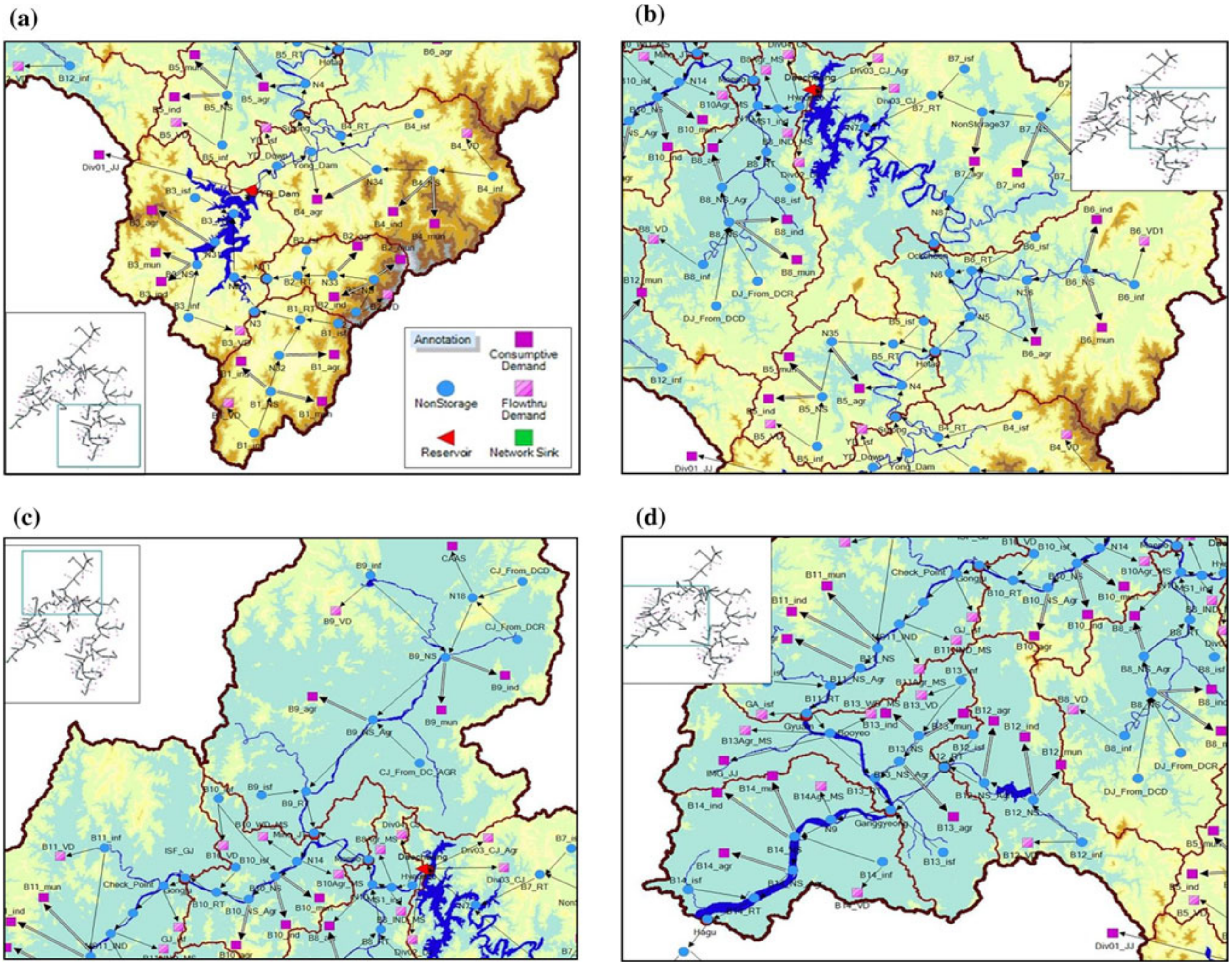


Fig. 3 KModSim GUI features and flow network in the Geum River basin. **a** Up-stream (Yongdam dam). **b** Mid-stream (Daecheong dam). **c** Tributary (Miho river). **d** Downstream (Geum river estuary)

duration curves by EMC for the Geum River basin. Figures 6 and 7 show the plotting of the corresponding data with 2001–2005 as the coverage period, along with time series of simulated flow data by dam operation scenario (as mentioned above). In the figures, it can be seen that both Sutong point and Gongju point showed behaviors close to Class A. According to Smakhtin and Eriyagama (2008), the probability that lots of rivers all over the world may fall under Class C is high. But this is somewhat conflicting with the results of this study. Accordingly, the two hypotheses about environmental flow in the Geum River basin can be established as follows: the first one is that a change in flow duration due to the dam construction did not quantitatively have significant impacts on aquatic ecosystems in terms of flow regime in the basin abounding with lots of water. Especially, flow duration at LWL (that is expected to have significantly improved, compared with that of natural flow in accordance with dam operation protocols) surpassed Class A over most of the period. This suggests that there are fewer difficulties with basin management in terms of various water uses (e.g., river occupation permission, etc.). The second one is that flow duration characteristics in the basin are more sensitive than in the river basins of other countries. It is known that the coefficient of river regime for the major river in Korea is very large, since about 2/3 of annual rainfall occurs in the summer and, consequently, seasonal variations in flow duration are substantial (Lee et al. 1993). To take into account these characteristics in estimating environmental flow duration curves (proposed in this study), it is judged that there is a need to subdivide the process of deriving flow duration curves based on 17 sites on a horizontal axis (percentage of time). In fact, Smakhtin and Eriyagama (2008) who developed this method also suggested similar opinions.

The extension and application of such a method to other basins or the emergence of any other reliable studies

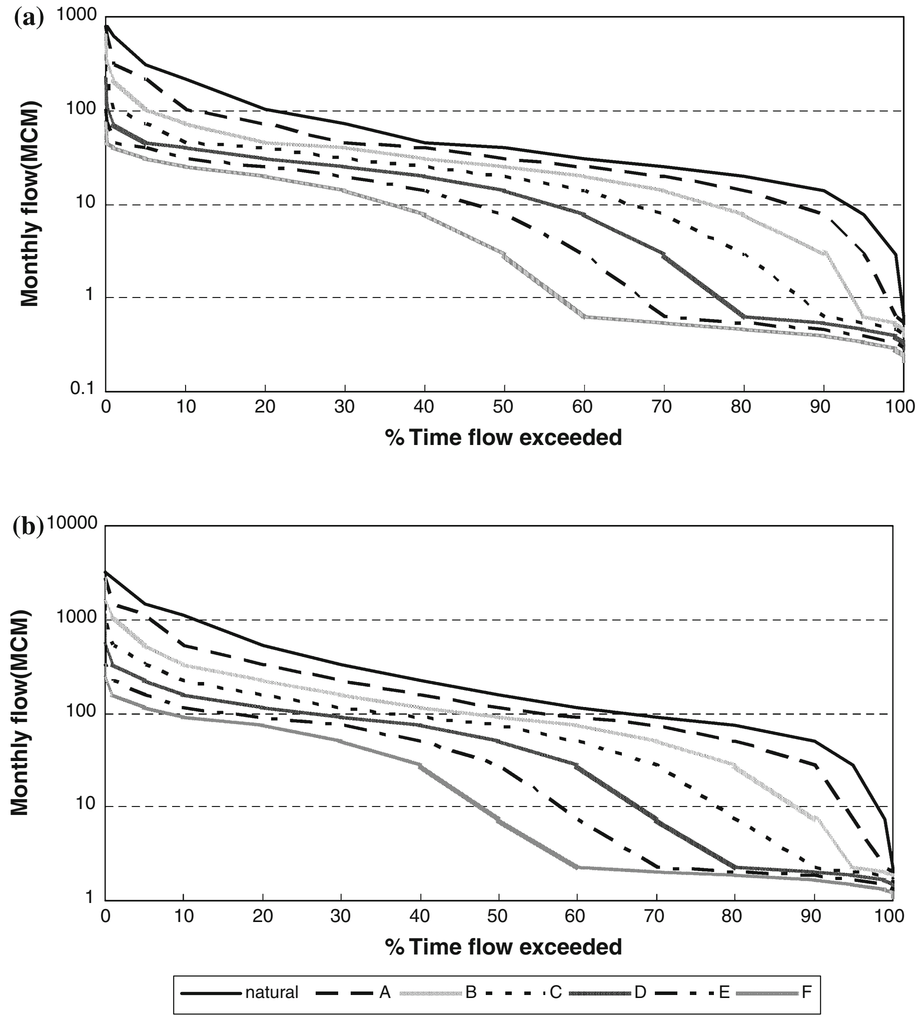


Fig. 4 Flow duration curves for each EMC at Sutong (**a**) and Gongjoo (**b**)

(containing the effects of a change in riparian flow duration on aquatic ecosystems in the Geum River basin) would enable the validation of the above hypotheses. It is expected that methods and findings proposed or reported in this study will be used as basic information for joint studies to estimate environmental flow that have been multidisciplinarily undertaken. Accordingly, this study identified the characteristics of habitats by species of fish through monitoring fish habitats at the Sutong point and estimated environmental flow necessary for ecosystems.

Evaluation of habitat suitability index (HSI)

Table 3 shows seasonal variations in HSI for physical habitats (e.g., flow velocity, water depth, substrate size, etc.) for *C. splendidus* and *P. nigra*. HSI for flow velocity was found to be most extensively distributed in June (Summer) with flow rate at its maximum; it ranged from 0.2 to 0.6 m/s for *C. splendidus* and 0.2 to 0.7 m/s for *P. nigra* in the same month. HSI for water depth was found to be more extensively distributed in June and September (0.3–0.6 m for *P. nigra*) than in in April (0.2–0.4 m for *P. nigra*). This is because, in Korea, the rainy season begin in June. HSI for substrate size was found to range from 3.0 (fine gravels) to 4.0 (coarse gravels) for *C. splendidus,* and 2.0 (sand) to 3.0 (coarse gravels) for *P. nigra*. This indicates that seasonal variations in substrate size were not significantly shown.

The previous analysis of in-stream flow in the Geum River revealed that flow velocity and water depth required for *C. splendidus* were 0.3–0.8 m/s and 0.2–0.5 m, respectively, and that flow velocity and water depth required for *P. nigra* were 0.1–0.3 m/s and 0.5–0.8 m, respectively (Ministry of Construction and Transportation 1999). When the results of this study were compared with those of the previous study, there were not significant differences in flow velocity required between them. But water depth required was found to be shallower in this study than in the previous study. It is judged that these differences result from the fact that the previous study adopted total average over the whole Geum River.

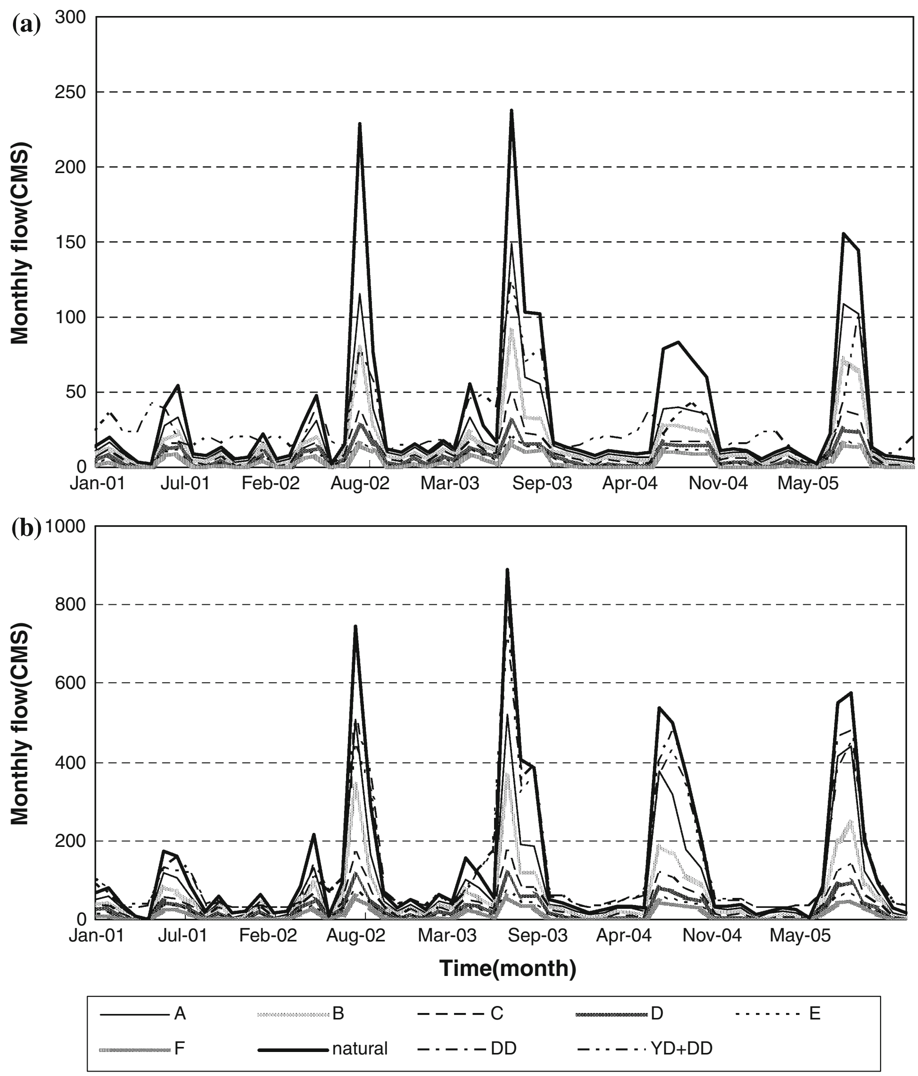


Fig. 5 Time series of monthly flow data at Sutong (**a**) and Gongjoo (**b**) from 2001 to 2005

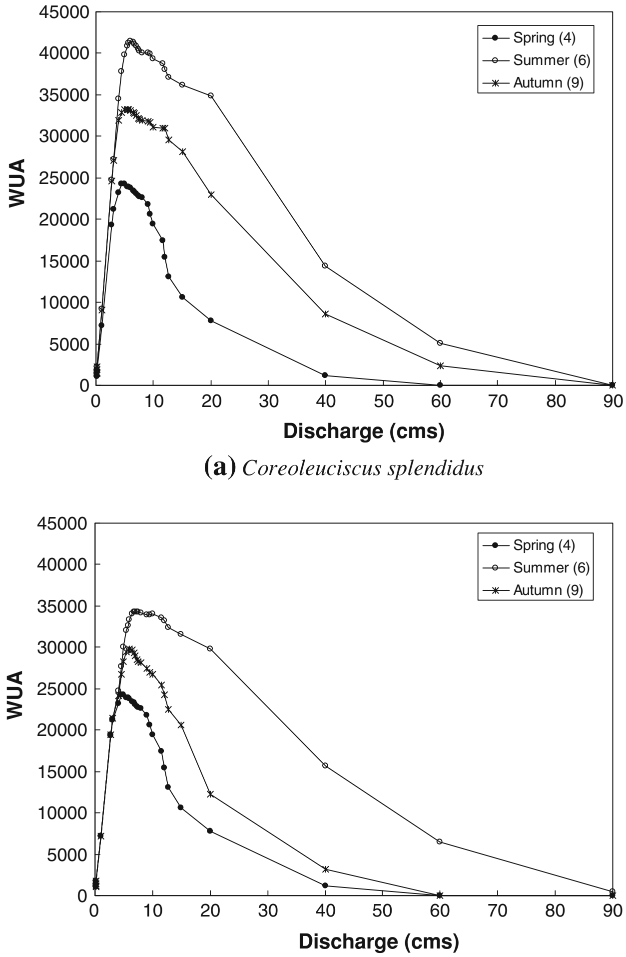
Table 2 Estimation of long-term EF for each EMC

Sites	Long-term EF (% natural MAR)					
	A	B	C	D	E	F
Sutong	69.4	45.8	31.4	22.5	16.3	11.7
Gongju	67.8	43.5	28.4	19.3	13.5	9.4

Estimation of ecological flow rate using PHABSIM

Figure 6 shows flow discharge-WUA relations for *C. splendidus* and *P. nigra* that are estimated using PHABSIM. Optimal WUA was identified using seasonal variations in flow rate. Table 4 shows seasonal variations in flow rate for optimal WUA and EMC values that are required for *C. splendidus* and *P. nigra*. As seen in Fig. 4a and b, optimal ecological flow rate required for *C. splendidus* and *P. nigra* in Summer (June) was 6.0 and 7.0 m^3/s, respectively. The figures indicate that lots of flow rate is required since June. These results are consistent with the fact that most of fishes in Korea spawn in May–June. Flow rate decreases during the drought season (April), and then increases during the rainy season (summer).

The in-stream flow at Sutong point has been announced as 3 m^3/s (2007). The analysis of ecological flow rate by EMC based on this value (estimated using normal drought streamflow) showed that ecological flow rate corresponding to EMC A was estimated almost at 2.676 m^3/s that referred to in-stream flow announced for EMC A, and that ecological flow rate corresponding to EMC B–F was subsequently estimated at 0.987 to 0.150 m^3/s. As seen in Fig. 7, there were no differences between the announced in-stream flow and ecological flow rate required for EMC A and, consequently, WUAs for each cell were found to be similar. When compared with optimal flow discharge (6.0 m^3/s) in summer, WUM decreased by 34.2 %, on the whole; WUA for each cell was found to decrease at the center, and right and left bank of the river. This suggests



(a) *Coreoleuciscus splendidus*

(b) *Pseudopungtungia nigra*

Fig. 6 Variations in flow (discharge)–WUA relations for *C. splendidus* (**a**) and *P. nigra* (**b**) estimated using PHABSIM

Table 3 Seasonal variations in HSI for flow velocity, water depth and substrate size

Species	Season (month)	Flow velocity (m/s)	Water depth (m)	Substrate size (mm)[a]
Coreoleuciscus splendidus	Spring (4)	0.1–0.3	0.2–0.4	3.0–4.0
	Summer (6)	0.2–0.6	0.2–0.6	3.0–4.0
	Autumn (9)	0.2–0.5	0.2–0.5	3.0–4.0
Pseudopungtungia nigra	Spring (4)	0.1–0.3	0.2–0.4	2.0–3.0
	Summer (6)	0.2–0.7	0.3–0.6	2.0–3.0
	Autumn (9)	0.1–0.4	0.3–0.6	2.0–3.0

[a] 1.0 (silts) <0.1 mm; 2.0(sand) 0.1–1.0 mm; 3.0 (fine gravels) 1.0–50.0 mm; 4.0 (coarse gravels) 50.0–100.0 mm; 5.0 (cobbles) 100.0–300.0 mm; and 6.0 (boulders) >300.0 mm

that a decrease in EMC accompanied a decrease in flow discharge and, consequently, a decrease in the range of water depth and flow velocity required for fish habitats. At the Sutong point, the in-stream flow was simulated similarly to ecological flow rate corresponding to EMC A, although it was found to be lower than the optimal ecological flow rate.

C. splendidus and *P. nigra* spawn in May and June; actually, Kim and Park (2002) reported that *C. splendidus* spawned in April–May (April–June in this study), and *P. nigra* in May (May–June in this study). In Korea, this is a typical spawning season for them. This study confirmed that this was the case, although there were slight differences. It is judged that these differences have some correlations with, for example, regional factors or temperature. There were cases where they delayed or gave up spawning due to their micro habitat disturbance. Causes for these degradations include flow rate, water temperature and other environmental factors. Since most of the fishes appearing at this point spawn several times, it is required that a proper level of flow rate and habitat environment be secured during the spawning season.

June is a month when these two species of fish finish spawning and their spawns hatch out, so that juvenile fish coexist with adult fish. At this time, the extension of their habitats to the vicinity of the river would help juvenile fish survive various ecosystems, including other predatory or carnivorous species of fish (Hur and Kim 2009). Given that, in September 2009, *C. splendidus* of 5 cm or smaller in size were caught as samples; they inhabited, mainly, the left and right bank of the river and channel wetland.

Conclusion

This study attempted to apply an environmental flow estimation method (developed by the IWMI) to the Geum River basin, identify the characteristics of habitats by species of fish through monitoring fish habits and estimate optimal ecological flow rate. To do so, flow duration at Sutong and Gongju point in the basin was analyzed and assessed according to EMCs. Scenarios were composed based on the absence or presence of Daecheong Dam and Yongdam Dam (that are among the major multi-purpose dams in the basin). Flow data with 1984–2005 (22 years in total) as the coverage period at the two sites were simulated using KModSim, a water-balance network analysis model. As a result, the ratio of MAR by EMC (A–F) to MAR under natural flow at the Sutong and Gongju points ranged from 69.4 to 11.7 % and 67.8 to 9.4 %, respectively. This was found to be consistent with the results of previous studies. Time series of mean monthly flow data by EMC (with 1984–2005 as the coverage period) were produced, and then plotted together with those of simulated flow data by reservoir operation scenario (with 2001–2005 as the coverage period). As a result, the two sites showed flow

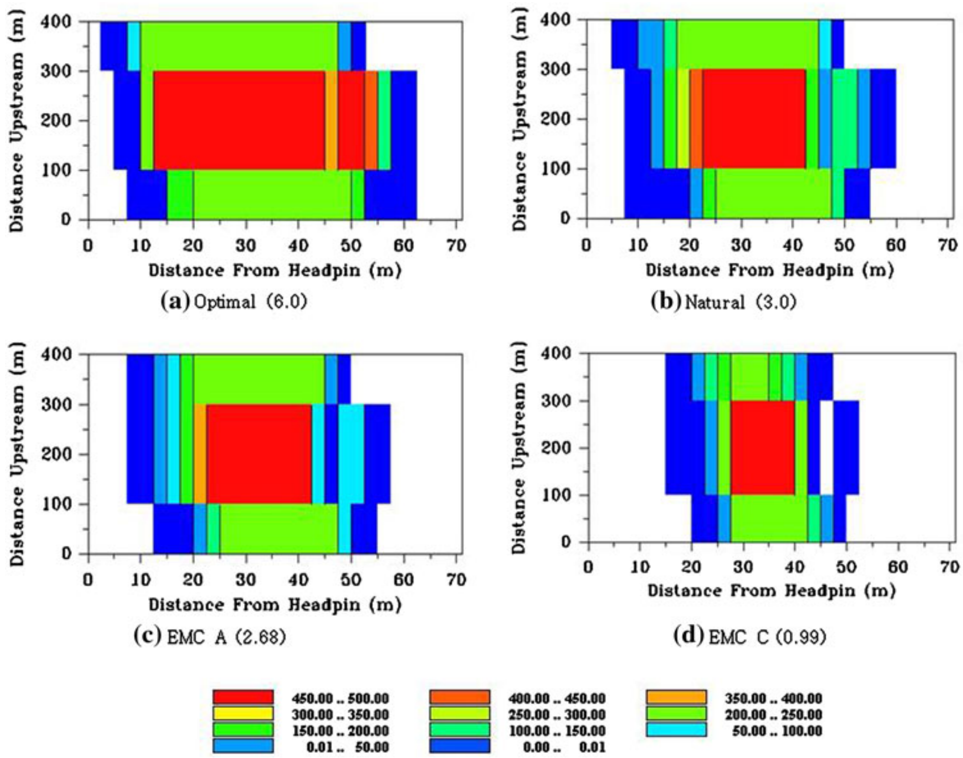


Fig. 7 Variations in WUA (m²/1,000 m) for *Coreoleuciscus splendidus* (June)

Table 4 Seasonal variations in flow rates for optimal WUA and EMC values

EMC (flow discharge, m^3/s)	*Coreoleuciscus splendidus*			*Pseudopungtungia nigra*		
	WUA (m^2/1,000 m)			WUA (m^2/1,000 m)		
	Spring (D)	Summer (D)	Autumn (D)	Spring (D)	Summer (D)	Autumn (D)
Optimal	24283.9 (4.5)	41429.4 (6.0)	33231.1 (5.7)	24283.9 (4.5)	34322.2 (7.0)	29786.6 (6.0)
In-stream flow (3.0)	21200.1	27247.4	27113.0	21200.1	21345.3	21422.0
A (2.676)	19272.8	24770.4	24648.1	19272.8	19101.8	19474.5
B (0.987)	7138.1	9174.2	9128.9	7138.1	7187.0	7212.8
C (0.237)	1741.0	2237.6	2226.6	1741.0	1752.9	1759.2
D (0.203)	1450.8	1864.7	1855.5	1450.8	1460.8	1466.0
E (0.174)	1209.0	1553.9	1546.2	1209.0	1217.3	1221.7
F (0.150)	1099.1	1412.6	1405.7	1099.1	1106.6	1110.6

EMC Environmental management classes, *D* flow discharge

behaviors corresponding almost to “A” in EMC. These results indicate that a change in flow duration due to the dam construction did not quantitatively have significant impacts on aquatic ecosystems in terms of flow regime in the basin abounding with lots of water, and that dams have been operated and managed considering their surrounding natural conditions.

For the assessment of environmental flow for maintaining environmental ecosystems, along with hydrological flow duration analysis, the characteristics of habitat environment by species of fish through monitoring fish habits at the Sutong point were identified, and optimal ecological flow rate was estimated. For this study, relations between flow discharge and WUA (Weighted Usable Area) for *Coreoleuciscus splendidus* and *Pseudopungtungia nigra* were projected using PHABSIM (physical habitat simulation system), and EMCs consistent with flow duration curves estimated taking into consideration in-stream flow were assessed. In-stream flow at Sutong point has been announced as 3 m^3/s. The analysis of ecological flow rate by EMC based on this value (estimated using normal drought streamflow) showed that ecological flow rate corresponding to EMC A was estimated almost at 2.676 m^3/s, which corresponded to in-stream flow announced for EMC

A, and that ecological flow rate corresponding to EMC B–F was subsequently estimated at 0.987–0.150 m^3/s. There were no differences between the announced in-stream flow and ecological flow rate required for EMC A and, consequently, WUAs for each cell were found to be similar. When compared with optimal flow discharge (6.0 m^3/s) in summer, WUM decreased by 34.2 % on the whole; WUA for each cell was found to decrease at the center, and right and left bank of the river. This suggests that a decrease in EMC accompanied a decrease in flow discharge and, consequently, a decrease in the range of water depth and flow velocity required for fish habitats. It is judged that these optimal ecological flow rate data will be used as basic data for analyzing and assessing flow duration. Further, the continuance of reliable studies on the effects of a change in flow duration on aquatic ecosystems would enable making a plan to efficiently monitor and manage aquatic ecosystems.

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