Ecological evaluation of reach scale channel configuration based on habitat structures for river management

Mikyoung Choi, Yasuhiro Takemon, Wansik Yu and Kwansue Jung

ABSTRACT

Ecological evaluation of riverbed geomorphology is essential for environmental assessment of river works as well as for establishment of target images in river management planning. In this paper, we analyzed inter-relationships between the reach-scale channel configuration (RSCC) and habitat structure on the riverbed based on the historical changes of riverbed geomorphology on the Kizu River in Japan. The analyses used nine sets of aerial photographs taken from 1948 to 2012, which resulted in a total of eight RSCC types classified as Single Sinuous, Semi-Wandering-Straight, S-W-Sinuous, Wandering-Straight, W-Sinuous, Bifurcated-Straight, B-Sinuous, and Braided Sinuous. Aquatic habitats were classified into four lotic habitats (Main Slow, Secondary Slow, Gently Bending Riffle, and Sharply Bending Riffle) and four lentic habitats (Bar-Head Wando, Bar-Tail Wando, Active Pond, and Terrace Pond), and their richness and diversity indices were analyzed in relation to RSCC types. The results showed that Braided Sinuous channels had the maximum number of habitats, and Wandering-Straight and Bifurcated-Sinuous channels showed higher habitat diversity than the others. These results indicated that the target image of the Kizu River management will be Braided-Sinuous channels in terms of habitat abundance, whereas they will be Wandering-Straight and Bifurcated-Sinuous channels from the aspect of habitat diversity.

Key words | aerial photograph, habitat structure, reach scale channel configuration, river evaluation, river management

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INTRODUCTION

River systems have a hierarchical structure composed of basin, segment, reach, and habitat scale geomorphology; these are different in spatial scales but are inter-related to each other (Frissell *et al.* 1986; Brierley & Fryirs 2005). For example, the geomorphological characteristics of the pool-riffle sequence reflect reach scale conditions, and these conditions are controlled by the higher hierarchy of the segment and/or basin scale boundary conditions of the flow and sediment regimes. Despite the hierarchical river system, previous works of river management or restoration were apt to focus on a specific scale of the phenomena they investigated. For example, most dam construction and operations had been conducted for flood control and/or water resources development in a basin scale management (Goodwin & Hardy 1999; Sumi & Kantoush 2010), whereas many river restoration projects had been carried out by quantitative and qualitative improvement of habitat conditions at small or local scales. In order to reduce natural disasters and restore desirable natural conditions in rivers at the same time, integrated river management is required to link the large- and local-scale management activities. To understand the integration, we have to know how the river habitats will respond to the large-scale boundary conditions such as flow regime manipulations and land-use changes (Loucks 2000; Frothingham *et al.* 2002). As methods for predicting habitat changes under changing flow regimes, several habitat

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evaluation procedures (HEP) have been proposed, and PHAMSIM (Physical Habitat Simulation System, an IFIM model) has been widely used in river management throughout the world. It was developed to improve logic, and there is a different version for each county. PHAMSIM uses physical habitat parameters that are composed of hydraulic parameters such as depth, velocity, and substrate for target species, and it calculates the required discharge volume for maintaining suitable habitat conditions (Goodwin *et al.* 2006; Li *et al.* 2011). However, because these HEP methods treat the hydraulic or physical parameters as independent of each other, the habitat suitability is always judged as a result of calculation under given boundary conditions, and it is difficult to use these independent parameters as a target image of river management.

Therefore, Takemon (2010) proposed 'Habitatology,' which is defined as the science of analyzing habitat structure and elucidating mechanisms of habitat creation and maintenance. In the study, he presented target conditions using a geomorphic channel configuration that could offer an appropriate framework for integrated spatial and temporal phenomena and elucidate the links between geomorphic, hydraulic, and ecosystem. Reach-scale channel configuration (RSCC) such as braided, meandering, wandering, or anastomozing and straight channels could be especially helpful for understanding relations between hydraulic conditions and aquatic ecosystems and could be used as parameters of a target image of river management. Since RSCC could be classified and experimented upon by hydraulic-geomorphic parameters such as discharge and slope (Leopold & Wolman 1957), sediment load and lateral stability (Schumm 1985), and slope and bed materials (Rosgen 1994), we could predict changes in RSCC patterns from both empirical and computational data on hydraulic and geomorphic conditions including flow regimes, sediment supply, and direct human impacts.

According to the hierarchical river system, RSCC may influence geomorphological characteristics such as composition and arrangement of habitat structures. Although studies on relationships between RSCC and the habitat structures are required, empirical and theoretical studies on relations between RSCC and habitat structures have been limited and have not been well documented. Only a few studies have noted that braided channels provide favorable shelter and nursing conditions for fish (Payne & Lapointe 1997; Sukhodolov *et al.* 2009). The studies on relations between RSCC and ecosystems could contribute to hieratical linkage among habitat structures, geomorphic channel configuration, and hydraulic conditions. The linkage could be supportive in understanding complex river systems and predict habitat changes under changing environmental conditions in the basin scale.

This study classified habitat structures and RSCC and detected their relations using historical aerial photographs. Habitat structures were used as ecological parameters due to easy detection in aerial photos. Various habitat structures are located on a floodplain, and their habitat diversities are closely related to biodiversity and animal communities. This is because most stream animals need a set of different habitats in different stages of their life cycles, such as deep-slow for feeding, backwater for resting, and gravel bars for spawning of some fish (Holomuzki & Messier 1993) and invertebrates (Yuma & Hori 1990). In particular, this is because the Kizu River has been known to have abundant lotic habitats such as riffle and pools, providing spawning sites for Ayu fish and invertebrates (Kobayashi & Takemon 2013) and abundant lentic habitats such as pools or wando for the living spaces of bitterlings and unionid mussels on floodplains. Thus, existence and nonexistence or abundant and scarce habitat structures are important for species diversity in the Kizu River.

This study aims to understand the relations between RSCC and habitat structure in the Kizu River, which is located in central Japan. The Kizu River experienced riverbed degradation and vegetation expansion after dam construction and sand excavation over a 65-year period. We illustrate historical changes of RSCC and habitat structures along with their relationships, and we discuss how the appropriate target image of RSCC and methods of RSCC are applied to river management.

METHODS

Study area

The study area was established in the lower reaches (0–26 km) of the Kizu River, a tributary of the Yodo

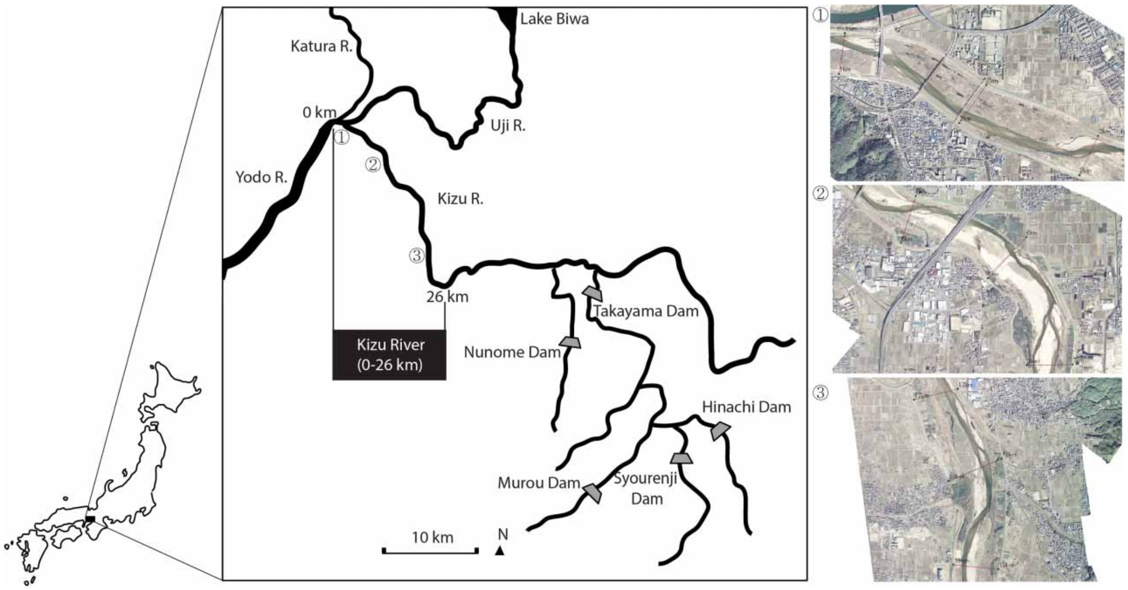


Figure 1 | Study site of the Kizu River in the Kizu River basin.

River in central Japan (Figure 1). The Kizu River is a typical sandy river with weathered granite mountains in the upper stream and a basin with an area of 1,596 km^2. A total of five dams, Takayama Dam (constructed in 1969), Syourenji Dam (1970), Murou Dam (1974), Nunome Dam (1992), and Hinachi Dam (1999), are located in the basin. The peak discharge of the river is caused by seasonal typhoons in summer and autumn. Figure 2 shows hourly peak discharge during a 60-year period. Some discharge data in the 2000s is omitted because of measurement error. The largest flood event occurred in 1959 and reached almost 6,000 m^3/s, whereas intensity of peak discharge decreased by about 3,000 m^3/s after the dam construction. The annual mean discharge is about 25 m^3/s, and high discharge is about 43 m^3/s. The annual mean bed-load transported to the lower reach was estimated to be about 183,000 m^3/y in the 1960s but about 23,000 m^3/y in the 2000s (Kobayashi & Takemon 2013). Due to reduction of sediment supply and peak discharge resulting from the

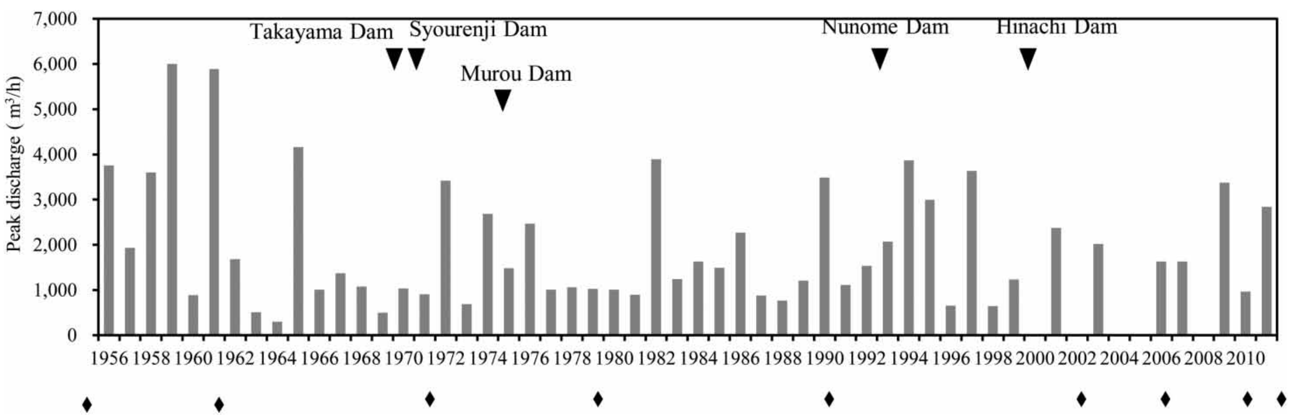


Figure 2 | Historical changes of discharge from 1956 to 2011 at Inooka station (16 km from conjunction) in the Kizu River. ◆ denotes data taken from aerial photographs.

dam construction, the riverbed was degraded, and vegetation expanded.

Materials

Geomorphological channel parameters and habitat structures were measured using aerial photos taken by the Yodogawa River Bureau between 1948 and 2012 in the Kizu River. The orthorectified and georeferenced photos taken in 1948, 1961, 1971, 1979, 1990, 2002, 2006, 2010, and 2012 were compiled and overlaid sequentially using ArcView (Version 10, ESRI). All aerial photos were taken during low water depth periods except the photo from 1990, which was taken during the typhoon season (about 0.1 m higher than the normal water level). We divided the study area into 2 km units according to the mean wavelength of the Kizu River (Choi *et al.* 2016). There are 13 channel reaches per year, because the study site is 26 km long. Only 1961 has 12 channel reaches, owing to a missing aerial photo.

Reach-scale geomorphological parameters

In order to define the type of RSCC, parameters of the number of channels (CN) and sinuosity (S) were used. We divided channel types into eight categories to show more detailed conditions in the Kizu River (Table 1). CN was defined as the average number of flow channels by ten transects with 200 m intervals in 2 km unit. CN was classified into single, wandering (CN up to 3), and braided (CN > 3) by Howard *et al.* (1970). The wandering channel (CN up to 3) was divided into three groups (semi-wandering, wandering, and bifurcated) in detail, because almost 90% of reaches in the Kizu River were included in these channel types. S was calculated by the ratio of channel length to downstream valley length, and it was classified into straight ($S < 1.05$), sinuous ($1.05 \leq S < 1.3$), and meandering ($S \geq 1.3$) according to Schumm (1985). A total of 116 reaches were divided into eight channel types during 1948–2002: Single Sinuous (SSi), Semi-Wandering-Straight (SWSt), S-W-Sinuous (SWSi), Wandering-Straight (WSt), W-Sinuous (WSi), Bifurcated-Straight (BfSt), B-Sinuous (BfSi), and Braided Sinuous (BrSi).

Table 1 | Image of RSCC

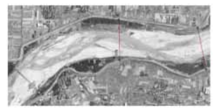
		Wandering						
Channel type	**Single sinuous**	**Semi-wandering straight**	**Semi-wandering sinuous**	**Wandering straight**	**Wandering sinuous**	**Bifurcated straight**	**Bifurcated sinuous**	**Braided sinuous channel**
Image								
Abbr.	SSi	SWSt	SWSi	WSt	WSi	BfSt	BfSi	BrSi

Image of Single Sinuous channel, Semi-Wandering-Straight channel, Semi-Wandering-Sinuous channel, Wandering-Straight channel, Wandering Sinuous channel, Bifurcated-Straight channel, Bifurcated-Sinuous channel, and Braided Sinuous channel.

Characteristics of aquatic habitat structure

Habitat types were classified into four lotic habitats (Main Slow, Secondary Slow, Gently Bending Riffle, and Sharply Bending Riffle) and four lentic habitats (Bar-Head Wando, Bar-Tail Wando, Active Pond, and Terrace Pond) using aerial photos referring to Takemon (2010; Figure 3). Main Slow was defined as slow flow with smooth water surface located between riffles in the main channel, and Secondary Slow was slow flow with smooth water surface located between riffles in the secondary channel. The riffles were also divided into two types, Gently Bending Riffle and Sharply Bending Riffle, on the basis of Kobayashi & Takemon (2013). They reported that the angle of riffle flow direction to channel direction and shapes influenced the biomass and community compositions. They detected that traverse or converge types of riffles had higher biomass and taxonomic richness of invertebrates than did diverge types of riffles in a recent field survey. In this study, Gently Bending Riffle (similar to diverge type of riffle) was defined as shallow flow with rough water surface overflowing a lateral bar with a bending angle smaller than 30°, and Sharply Bending Riffle (similar to traverse and converge types of riffle) has a bending angle larger than 30°. The wando was defined as lentic water located at the bar opening to the channel; Bar-Head Wando was located at the bar head, and Bar-Tail Wando was located at the bar tail. The pond was defined as isolated lentic water; Active Pond was located on the low floodplain, and Terrace Pond was located on the terrace. All aquatic habitats having water-surface in channels and bars were measured. We measured the number of each habitat type and diversity indices, e.g., habitat richness and diversity index was calculated for each 2-km unit. The habitat richness was defined as the total number of aquatic habitat types. The habitat diversity index was calculated using the Shannon–Wiener index (H'):

$$H' = -\sum_{i=1}^{R} p_i \log p_i$$

where p_i is the proportional abundance of the *ith* type, and R is the richness of habitat types.

The relations of habitat structures to channel types were compared using one-way ANOVA with a post-hoc test by Turkey-HSD. An α value of 0.05 was used to indicate statistical significance for all tests. Statistical analyses were performed using SPSS software (release 19, SPSS Inc.).

Analysis

The relations of the average number of eight habitat types to eight channel types, the relations of the number of each habitat type to eight channel types, and the relations of

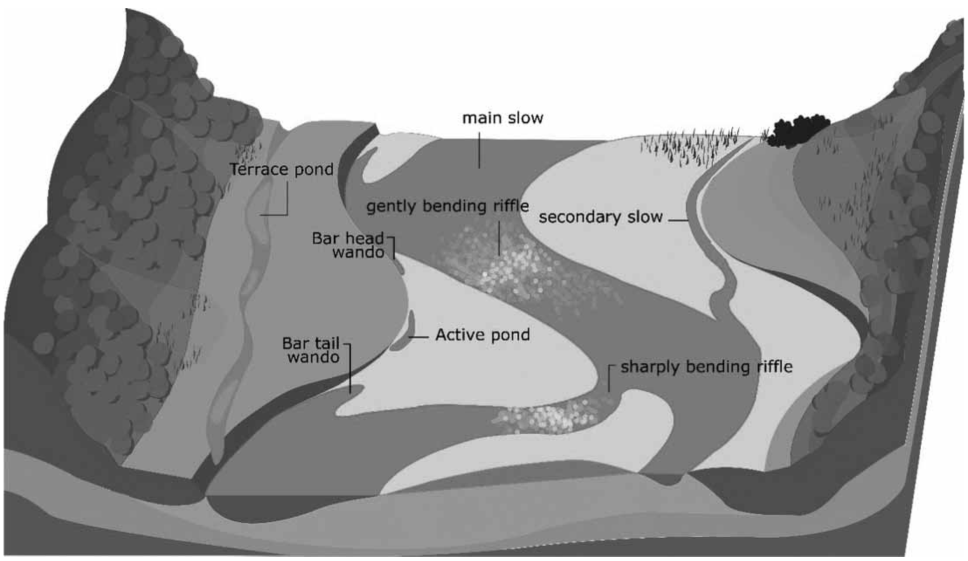


Figure 3 | Image of habitat classification. Revised by Takemon (2010).

habitat indices to eight channel types were analyzed using one-way ANOVA in order to understand the relations of habitat structures to channel types. An α value of 0.05 was used to indicate statistical significance for all tests. Statistical analyses were performed using SPSS software (release 19, SPSS Inc.).

RESULTS

The historical changes in RSCC and average number of habitat structures were compared by year (Figures 4 and 5). According to the classification of RSCC, channel configuration was divided into eight channel types (Figure 4). Channel type composition of the Kizu River showed distinctive changes historically. BrSi channels showed only in 1948 and 1961, and BfSt and BfSi channels showed before 2006. Wsi channels significantly decreased in 2006 and 2010; by contrast, SWsi channels sharply increased during the same period.

The range of fluctuation in the average number of lotic habitats was not wide over the years; only gently bending slow significantly decreased after 1948 (Figure 5(a)). Otherwise, Active Pond tended to decrease with time, whereas Terrace Pond tended to increase (Figure 5(b)).

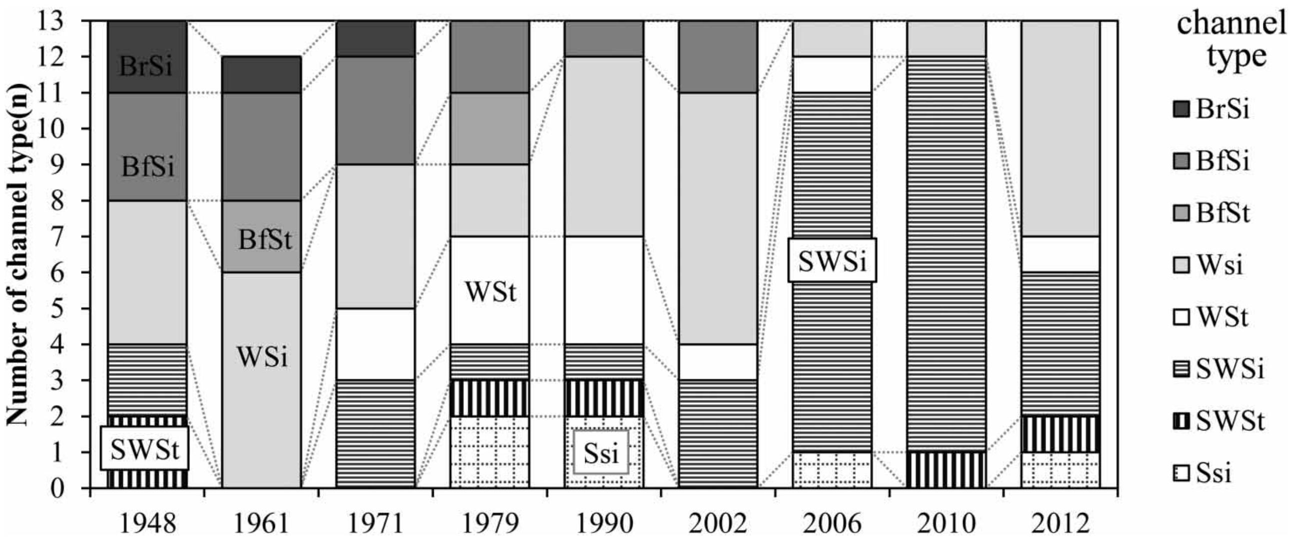


Figure 4 | Composition of channel types from 1948 to 2012. One unit of number of channel type represents a channel type of 2 km. A year has 13 units, because the study site is 26 km long.

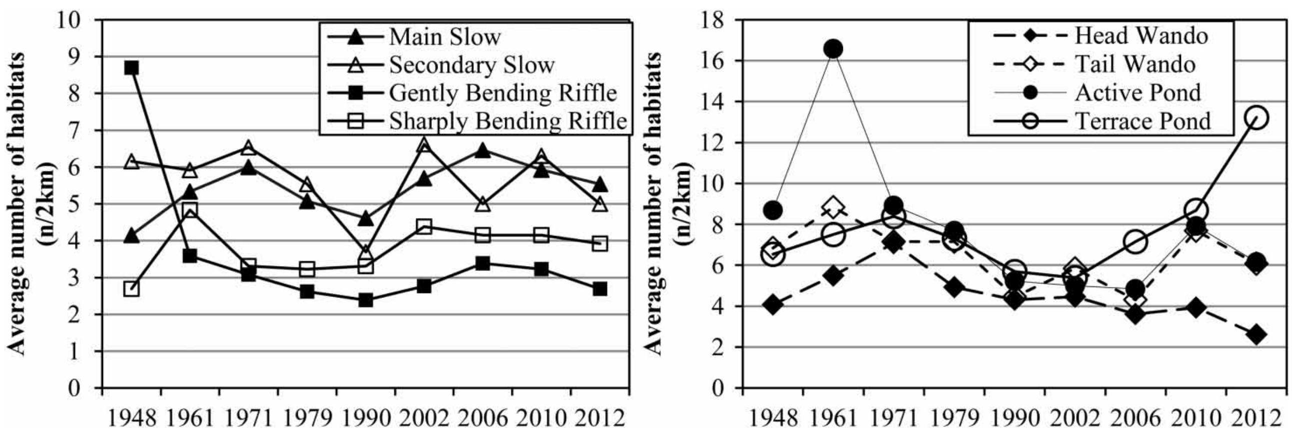


Figure 5 | Composition of the average number of (a) lotic habitat types and (b) lentic habitat types from 1948 to 2012.

The total number of habitats for eight habitat types were significantly different among channel types (Figure 6), and among these the number of habitats for each habitat type was different (Figure 7). The total number of habitats tended to increase with channel types from Ssi to BrSi channel types; thus, the total number of habitats were greater in BrSi than in the Ssi, SWst, and Wst channel types. Figure 7 shows that lotic habitats (Secondary Slow, Gentle Bending Riffle, and Sharply Bending Riffle) except for Main Slow showed maximum values in BrSi channel types. These habitats tended to increase gradually from Ssi to BrSi channel types. The number of all lotic habitats tended to have more values in sinuous channels than in straight channels, although there was no significant difference. The number of Secondary Slow was greater in SWsi than in SWst. The number of lentic habitats showed maximum or minimum values in specific channel types. The number of Bar Head-Wando showed the greatest number of BfSi channel types (Figure 7), and Bar Tail-Wando showed the greatest number of BrSi channel types. Terrace Pond was the greatest in SWst channel types and was the least in BrSi channel types.

Variations in habitat richness index and diversity index were analyzed in relation to eight channel types (Figure 8). Habitat richness showed lower values in BrSi channel types than in the other channel types. There was greater habitat diversity in WSt and BfSi channel types than in SWst.

DISCUSSION

This study showed that the channel types of the Kizu River historically changed from braided or bifurcated channels to semi-wandering channels. Reduction of sediment supply and stabilized flow resulting from dam construction may cause lateral stability with terrestrialization. The lateral stability may result in a decreasing number of Gently Bending Riffle and Active Pond and increasing Terrace Pond. Choi (2014) found that the Kizu River experienced decreasing channel width with degraded riverbed and increasing terrace area with vegetation expansion. The braided channels, as has been shown in the past, were characterized by many numbers of channels and mid channel bars (Table 1), and thus, lotic habitats such as riffles and slows are frequently located in wide active channels. Since riffles are zones of temporary sediment accumulation, and clusters of gravel are organized into ribs (Brierley & Fryirs 2005), the high pore space in gravel provides a spawning site for fish and invertebrates. Thus, the braided channels may be suitable for fish and invertebrates owing to abundant riffles and slows. In terms of hydraulic habitat conditions, braided channels are also known to be suitable channels for fish diversity. Sukhodolov *et al.* (2009) indicated that braided channels were shown to provide more favorable shelters and nursing conditions for fish larvae and juveniles, and Payne & Lapointe (1997) examined a braid-like reach dominated by a wide, dissected midstream bar, which offered

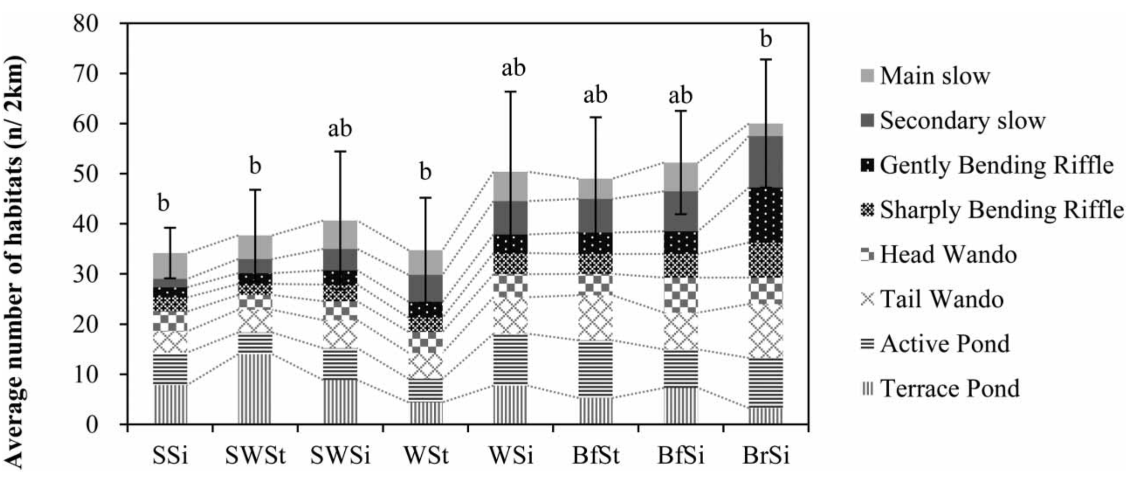


Figure 6 | Comparison of the number of eight habitat types among eight channel types in the Kizu River based on all the data during 1948–2012.

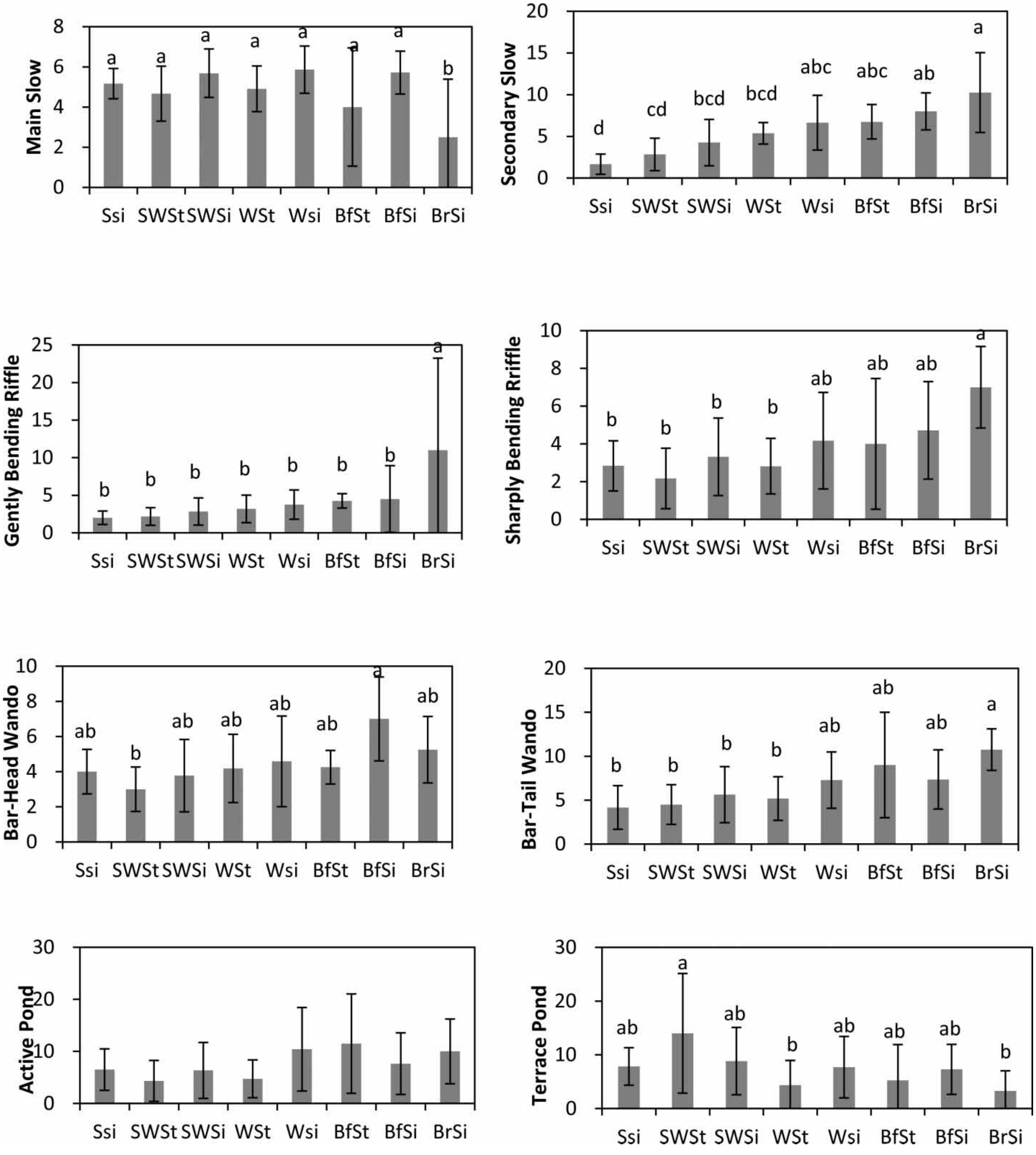


Figure 7 | Relations of the number of each habitat (n/2 km) to channel types (mean values and SD). Single Sinuous ($n = 7$), Slightly Wandering Straight ($n = 6$), Slightly Wandering Sinuous ($n = 34$), Quite Wandering Straight ($n = 11$), Quite Wandering Sinuous ($n = 36$), Bifurcated Wandering Straight ($n = 4$), Bifurcated Wandering Sinuous ($n = 14$), and Braided Sinuous ($n = 4$).

three to five times more potential habitat for juveniles by suitable depth and velocity. On the contrary, quantitative riffle evaluation in terms of biomass and richness of invertebrates showed that previous channel conditions before the 1970s tended to have lower potential than recent channel conditions in the Kizu River (Kobayashi &

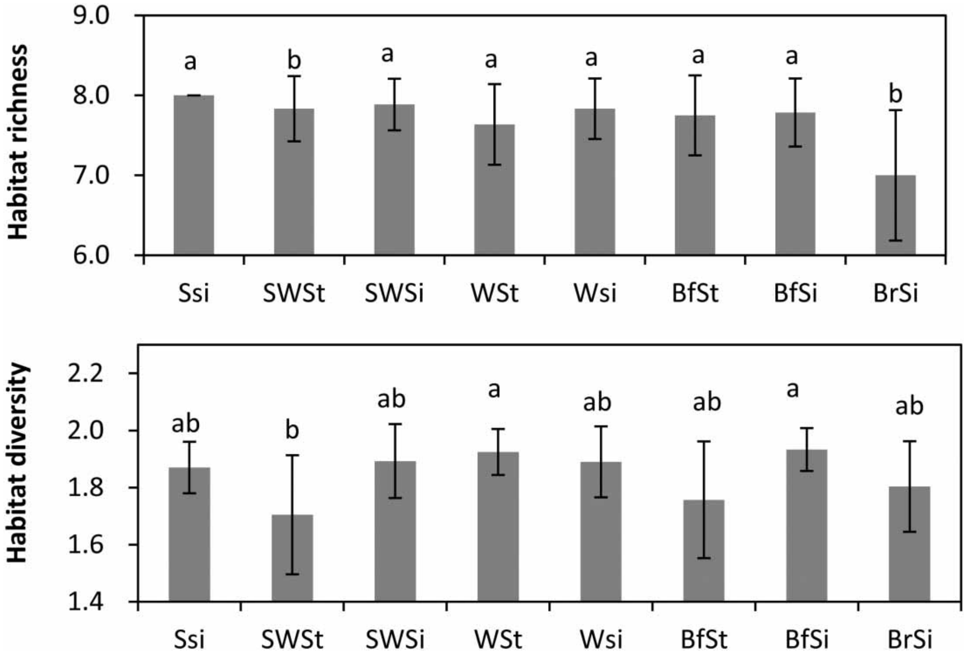


Figure 8 | Relations of habitat richness index and habitat diversity index to channel types (mean values and SD). Single Sinuous ($n = 7$), Slightly Wandering Straight ($n = 6$), Slightly Wandering Sinuous ($n = 34$), Quite Wandering Straight ($n = 11$), Quite Wandering Sinuous ($n = 36$), Bifurcated Wandering Straight ($n = 4$), Bifurcated Wandering Sinuous ($n = 14$), and Braided Sinuous ($n = 4$).

Takemon 2013). They detected that traverse or converge types of riffle (similar to Sharply Bending Riffle in this study) had higher biomass and taxonomic richness of invertebrates than did diverge types of riffles (similar to Gently Bending Riffle) in the recent field survey. Although an extreme number of Gently Bending Riffles were detected in braided channels, this habitat type may have a low quality of invertebrates. That is, braided channels can be considered as a suitable image of the Kizu River with abundant habitat structures and a high potential for fish spawning. However, a qualitative and quantitative assessment of geomorphological conditions should be conducted based on various points of view.

The single or semi-wandering channel can be considered to be a suitable condition in the Kizu River in terms of the potential of lentic habitats. Because single channels or slightly wandering channels are characterized by narrow active channels and vegetated terrace (Table 1), lentic habitats (especially Terrace Pond) can be easily found on vegetated floodplains. The Yodogawa River Bureau has said that many lentic ponds or wando provide habitats for protected bitterlings *Acheilognathus longipinnis* and unionid mussels are distributed on floodplains in the Kizu River. In particular, the ponds are surrounded by vegetation such as Terrace Pond, which could be useful for them, because these ponds provide suitable substrate and shelter from disturbance. According to Choi (2014), Terrace Pond has a flooding frequency between 8 and 16 day/year and tends to have a high abundance of bitterlings and mussels. These pond habitats are widely located on single or semi-wandering channels. In particular, bitterlings and mussels do not live in lotic habitats in the Kizu River, and thus the Yodogawa River Bureau has tried to start making artificial ponds.

When the sediment supply and flow volume are lower than they are now, which may be caused by climate change or artificial controls, the stability of the river geomorphology will accelerate, and the gap between the riverbed of the active channel and the terrace will increase. Even though channel configuration maintains single or semi-wandering channels in the Kizu River, lentic habitats on the active channel and terrace may experience significant quantitative degradation. In order to maintain or restore channel configuration for habitat diversity, an increase of disturbance in the basin scale is required. In order to increase disturbance of the downstream of the dam and the water capacity in the dam, comprehensive sediment management at basin scale has been developed in Japan and worldwide, e.g., 'sediment replenishment,' 'sediment bypassing tunnel,' and 'flood mitigation dam' without impoundment and dam removal (Sumi & Kantoush 2010). The Kizu River basin has been tested on the sediment replenishment activities in the Nunome River below Nunome Dam (since 2004), in the Uda River below Murou Dam (2006), on Hinachi Dam (2008), and Shorenji Dam (2009). The monitoring of geomorphic changes after sediment replenishment continues and various methods of replenishment have been studied. Although many systematic developments, such as determining quantity, selecting effective techniques, and predicting flushing flows are required (Ock *et al.* 2013), the importance of watershed management such as sediment management will gradually increase with the degradation of river quality. In order to effect this river management, ecological river conditions using RSCC can contribute as a determining direction. In the case of Kizu River, alteration from stable floodplain to unstable floodplain could be considered for the purpose of habitat diversity with biodiversity, or the maintenance of recent channel conditions could be considered for protected species.

CONCLUSION

Ecological riverbed geomorphology information is essential for the environmental assessment of river works. However, environmental ecosystem surveys, especially those covering wide areas, take a lot of time and labor. This study's authors classified and used habitat structures as ecological parameters and evaluated river conditions by using historical aerial photos. Although relations between RSCC and species diversity are not clear, we tried to present the possibility of analyzing ecological river conditions by using historical data.

We tried to introduce a method of river management based on relations between RSCC and habitat structures using historical aerial photos. The Kizu River changed from unstable channel conditions such as braided or bifurcated wandering channels to stable channel conditions such as single or semi-wandering channels by dam constructions during a 65-year period. Braided channels have abundant lotic and lentic habitats; on the other hand, single or semi-wandering channels show abundant Terrace Ponds, which provide habitats to protected bitterlings and mussels. The intermediate channels, such as wandering channels or bifurcated wandering channels, have a high habitat diversity with a balance of lotic and lentic habitats. Since river management such as sediment replenishment or sediment bypassing tunnels requires visible ecological target images, ecological analysis of RSCC could contribute to the ongoing discussion on river management.

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