Eco-Geomorphological Evaluation of the Riverbed Changes of the Katsura River in Relation to Low-head Dam Removal

XIAO ENBANG

2021

Acknowledgement

This thesis is the result of more than three years work during the Human Security Engineering Program in Kyoto University, Japan, which would not been possible without the valuable contribution from many people involved. It is my pleasure to have the opportunity to express my grateful mind to all of them.

I would like to express my sincere gratitude to Prof. Tetsuya Sumi for his kindly support throughout my entire Ph. D study. His immense knowledge, kind heart, passion to the research, and enlightening comments are continuously guiding me to the right direction not only in the research field, but also in my career life.

I would like to thank Prof. Yasuhiro Takemon, who is my direct supervisor and the most special person I have ever met in my life. His has the sharp sense of science and nature, his enormous knowledge seems like directly from the nature itself, his creative and extremely experienced mind are directing this study and thesis from the very beginning till the end. I want to live a unique life and be an energetic person like him, and at last but not the least, he has the best coffee in the world in my opinion.

I appreciate the many helps and paper revise from Pro. Sohei Kobayashi, who is currently doing ecological research in Wenzhou University, China. His patient and friendly talk always make me relax and calm, his comments and advises for the field work helped me a lot. I also want to express my gratitude to Prof. Sameh A. Kantoush for his always kind attitude and supportive words. My sincere gratitude also goes to Dr. Daisuke Nohara, for his kind help in technical support and valuable career advice.

A big thanks to Dr. Takahiro Koshiba, who contribute a lot to this thesis especially for the numerical modeling and statistical analysis. His endless curiosity and logical mind impressed me so much, I enjoyed talking with him and learning from him, I hope our friendship will last forever. I want to thank karim I. Abdrabo for his excellent review ability and time management skills, his encouragement gave me the strength I needed in the darkest time, I will remember the countless nights we were talking and encouraging each other at the lab till the early morning.

I want to thank Chen-Peng An from Taiwan, for his technical support for the data cleaning process in this study, I benefit a lot from his optimistic attitude in life and created mind in programming, I enjoyed our friendship very much. I want to thank Wang Jue for

her great help in image analysis and field work. Many thanks also go to Dr. Dina ELLEITHY, Dr. Doan Van Binh for scientific discussion and stimulating comments.

I want to thank lab secretaries: Ms. Hisae Obara, Ms. Junko Ibaraki and Research Assistant Ms. Chikako Morimoto. Without your kind support my life will be much more difficult, thank you!

I thank all my lab mates and for the valuable discussions, for the kind supports, and I enjoyed so much with you during my PhD study.

Last but not the least, I would like to express my greatest gratitude to my family, my wife, and my parents, without your endless love and support there is no chance for me to finish this study. I want to thank Shiomi Kaoru, and Shiomi Hiroshi, and all Shiomi family members, for you give me and my wife a home feeling even we are 1500km from China, our hearts are always warmed by you, we are a family. Pidou, Doumei, and Xiaojindou, thank you for always comforting my heart no matter how late I come home, exhausted, to have you in my arm makes me instantly feel better and relax. I am so lucky to have you and I love you all.

Abstract

Nowadays, almost all river systems have been heavily regulated by man-made hydraulic structures. Large dams are well known for their capability of altering flow regime and trapping sediment from upstream, and their influence on the river channel have been intensively studied. Low head dams (LHDs) however, though have overwhelmed number comparing to the big ones, are much less studied for their geomorphic and environmental influences. In the recent three decades the river ecological restoration became a hot topic and has absorbed much attention to the widely distributed LHDs. Even though many studies have recorded the short-term channel morphological changes and the biological response to the LHDs removal, few mentioned how to link these two parts and how to countermeasure the degradation of the ecological functions by weirs and their removal. Since Takemon (2011) proposed a new disciplinary called "Habitatology" as a powerful tool to link the river geo-physical characteristics and aquatic ecological functions from the management point of view. This study followed the idea of Habitatology to investigate the empirical relationships between river geomorphic parameters and riffle habitat structures by studying the channel historical changes in a gravel bed river with multiple LHDs.

Another issue regarding the management scheme of low-head dams is that as many more LHDs are being removed, however, some researchers are proposing to build more similar ones for restoring the river ecological functions in terms of hyporheic flow. After literature review and field observation we hypothesized the fine sediment dynamism behind a LHD determines the efficiency of the hyporheic flow which would have been induced by a LHD. The fine sediment deposition at the top of the riverbed would greatly compromise the desired hyporheic flow by the newly built LHDs. Thus, this study is also dedicated to figure out the LHDs' effect on the hyporheic flow by field study and numerical modeling. The results are agreed with our hypothesis. However, the underlying theory of fine sediment dynamism behind a LHD – like structures are urgently needed to be thoroughly studied.

Finally, we tried to develop an integrated environmental management scheme for the regulated gravel bed rivers especially under the impact of cascade built LHDs. We also argued that the mechanism of fine sediment deposition behind a LHD could be a crucial issue that needed to be understand thoroughly, for developing the suitable management strategy to restore the river hyporheic exchange in the near future.

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Chapter 1 General Introduction

1.1 Long history of river regulations

Fear and respects were once the major impressions that the human race have when it comes to rivers and the water they contained, which result in not only life births, but also perishes. The desire that the fierce water could be "controlled" or "manageable" are marked in our DNA before the dawn of the human civilization. The first dam that could be traced back was built around 3000 B.C in Jordan, since then hundreds of millions of its successors appeared to almost all major river systems in the entire planet. Historically, river channel diversion and canalization are frequently happened due to the urban development, however, it is until the 1960s after World War II, that the human industrial power started to have much more severe impacts on the rivers systems and at a much faster pace than the previous era. Since then, rivers have been subjected to severe human-induced changes, "altered" or "regulated" by man-made works (Petts, 1990), in spite that the river corridors constitute one of the most valuable natural resources and contain a disproportionately abundant of the total biodiversity of a given region (Naiman et al., 1993; J. V. Ward et al., 1999).

1.2 The invisible majority --- low head dams

Large impoundment dams have profound influence on the flow regime and sediment movement, and have been intensively studied, however, the number of low-head dams, also known as weirs or "run-of-river dams" is much more than large dams globally, and much less attention was drawn by the low-head dams due to their smaller size and the insignificant effect on flow regulation previously (Born et al., 1998; Juracek, 1999; Shafroth et al., 2002). In the last three decades, river restoration became a hot topic and dam removal is treated as a potential powerful tool for improving river ecosystems conditions and biodiversity, most of the removed dams are lower than 4m in height. The reason of removal can be summarized as 1) safety issue, 2) economical consideration and 3) environmental concerns. Most low-head dam – related studies are following dam removal cases (Carpenter-Bundhoo et al., 2020; Cook & Sullivan, 2018; Cumming, 2004; Kanehl et al., n.d.; Kishi & Maekawa, 2009; Maloney et al., 2008; Orr et al., 2006; Rumschlag & Peck, 2007; Santucci et al., 2005; Shafroth et al., 2002; Stanley et al., 2002), very few studies investigated the river channel geomorphic and ecological response to the existing low-head dam (S. Csiki & Rhoads, 2010; Poff & Hart, 2002), especially at different spatial and temporal scale. River restoration projects absorbed huge amount of the fund from all aspect of the society, some of them includes dam removal(Cook & Sullivan, 2018; Ding et al., 2019; Kanehl et al., n.d.; Orr et al., 2006; Peters et al., 2017; Stanley et al., 2002; Wang & Kuo, 2016), however, some includes construction of new dams for promoting the hyporheic exchange (Berlinghieri, 2013; Hester et al., 2018; Hester & Doyle, 2008; Liu & Chui, 2020; A. S. Ward et al., 2011). Without a thorough understanding the effect of the low-head dams and their removal on both riverbed surface and subsurface domains and the underlying mechanism, the systematic management of the countless cannot be realized. The low-head dams-related river restoration projects are more like a “act first, and report afterwards” movement.

Geomorphologist usually studied the short-term changes of the riverbed geomorphology after dam removal, while ecologist studied the effects of the dam removal based on the species and community changes before and after removal. However, very few of them are interested in explaining how the geomorphological changes induce the changes of the aquatic animals’ assemblages. In other words, the linkage between riverbed geo-physical characteristics and the living conditions of the aquatic animals has not been well developed yet.

1.3 Habitatology --- linking river geomorphology and ecology

Takemon (2010) proposed a new disciplinary called “Habitatology”, which can be used as a linkage between river engineering part and ecological part. According to Habitatology, the target river ecological conditions could be evaluated and determined by reach scale channel geomorphic configurations, explicit hydrogeomorphic features should be used as independent variables for hydraulic calculation in order to understand the processes and mechanisms of creating and maintenance of any habitats. Fig.1-1 shows the framework of the riverbed management scheme according to Habitatology.

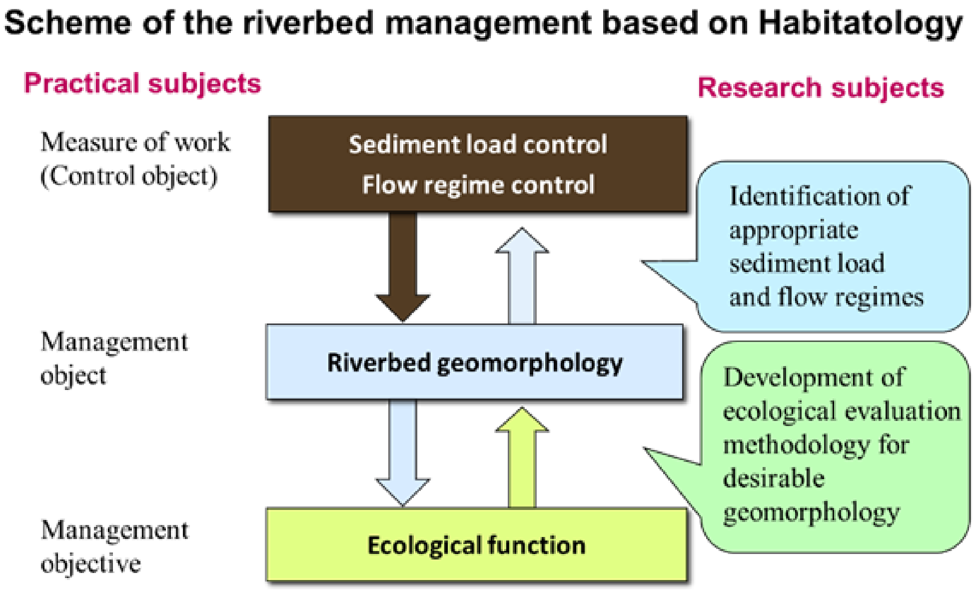


Fig. 1-1 Framework of the integrated management scheme by Takemon.

1.4 Motivation and objectives

When I was doing Masters’ study in the northern area of China, I was shocked by the countless of small check dams in the river channel during a field survey. After confirming the reason of constructing of those structures from the local authorities, the answer is to store water and create a large water surface area and create beautiful landscapes, in other words, for aesthetic purposes. However, the eutrophication and bad water quality seems ironic considering the original purposes. After literature review and information collection, I found that the management strategy of low-head dams is a big issue not only in China, but all over the world. Therefore, my motivation is to understand the mechanism of the influence of low-head dams on the river geomorphological characteristics and ecological functions and thus give recommendation for the management schemes.

In order to fill the knowledge gaps and to contribute to better environmental management strategy especially for gravel bed rivers with multiple low-head dams, in this study, by analyzing the historical riverbed changes, I want to discover the empirical relationships between channel geomorphic characteristics and the riffle habitat structures in a river segment with multiple low-head dams, emphasizing the impacts of low-head dams' removal. The results will be used for recognizing what kind of river geomorphological changes will result in the suitable riffle habitats. I also tried to figure out the effect of a low-head dam/ and a low-head dam's removal on the riverbed hyporheic exchange by two study cases. Then combined the results of the two assessments, I proposed the management recommendations.

1.5 Chapter outline

This thesis consists of seven chapters, as is showed in the Fig. 1-2, the main contents of each chapter is listed up as follows:

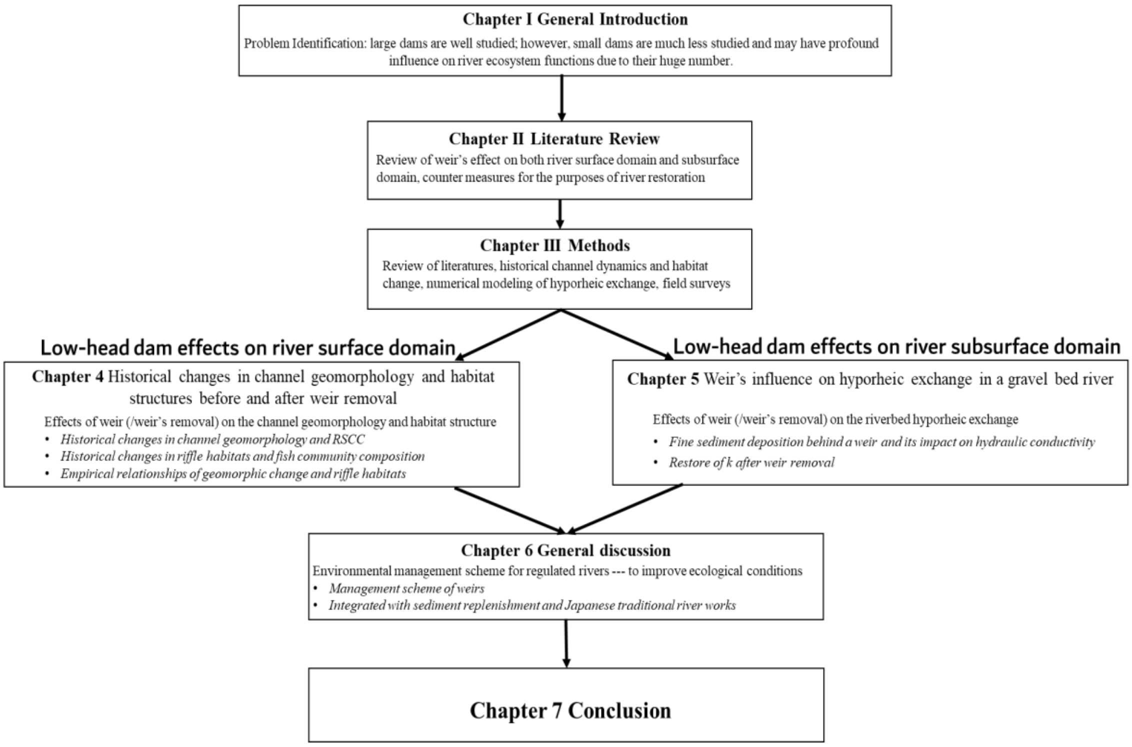


Fig. 1-2 Schematic view of thesis structures.

Chapter 1 presents an introduction to the study framework, describing the major concerns and motivations to conduct the study, showing the general methodologies and objectives.

Chapter 2 includes a thorough review of the related literatures and highlighting the insufficient understanding of the low-head dam's effect on the river ecological functions, especially the logistical relationships among low-head dams, channel morphology, and ecological functions. The influence of low-head dams on the ambient HE is another important issue which we will focus on, due to the existing contradictory opinions and suggestions among different previous studies. And we will propose our own hypothesis.

Chapter 3 introduces the study sites, data collection, theory, equations, equipment that we used for this study.

Chapter 4 focuses on the geomorphology and habitat structure evolution in a gravel bed river with multiple low-head dams. We selected five representative years to study the channel change: 2005, 2013 (before historical peak discharge), 2015 (after historical peak discharge and before No.6 weir removal), 2017 (after No.6 weir removal and before No.4 weir removal) and 2019 (after No.4 weir removal). Geomorphology and habitat structure will be detected visually from the associated images, channel longitudinal and cross-sectional profile will be used for revealing the underlying theory for the channel evolution. Two low-head dam removal cases will be focused and their effect on the channel geomorphology and habitat structure will be summarized. The geomorphological data will be used as input to our hyporheic model and empirical model in the next chapter.

Chapter 5 compares the riverbed hyporheic flow conditions before and after low-head dam removal by providing two case studies. The case of No.1 weir in Katsura river was used to represent the influence of an existing low-head dam on the hyporheic exchange. The case of No.4 weir removal in the upstream of Katsura river was used to represent the influence of low-head dam removal on the hyporheic exchange. We first estimate the hyporheic change induced by NO.1 weir, field survey provides sediment characteristics especially the top layer hydraulic conductivity upstream of the No.1 weir, which is used as input to our hyporheic mode to estimate the hyporheic exchange rate. Since hydraulic conductivity is the controlling factor of HE, in the other case we conducted *in-situ* estimation of hydraulic conductivity 8 months after the complete removal of the NO.4 weir. Field surveys were conducted twice, to investigate the spatial distribution and temporal change of hydraulic conductivity with 1 month time-interval, to evaluate the HE potential of the riverbed after low-head removal.

Chapter 6 presents the general discussion and proposal for developing the new environmental river management strategy especially for the rivers under the impact of multiple low-head dams. Two major objectives of the proposal are: 1) To improve the high-quality habitats in terms of riffle structures and 2) to improve the riverbed hyporheic exchange are integrated in the same river management schemes.

Chapter 7 covers the conclusions obtained from this study and provides the recommendations for future development of the current study.

Chapter 2 Literature review

2.1 Dams and river regulation

Dams are among the most common river training structures and have profound impacts on the river morphology and thus the habitat conditions of aquatic organisms (Kibler et al., 2011; Orr et al., 2006; Petts, 1984). Large impound dams are well known and have been intensively studied however, small dams are much less focused due to their relatively small size and impact on the flow and sediment alteration (S. J. Csiki & Rhoads, 2014; S. Csiki & Rhoads, 2010). According to the ICOD (international commission on large dams), there are about 45000 large dams globally (WCD 2000). In the United States, the Army Corps of Engineering is responsible for maintaining inventories of dams and more than 76500 large structures are included (USACE 2000). While an estimated more than 2,000,000 small dams exists in the United States which are not included in the national inventory (Graf, 1993).

Globally, the small hydraulic structures (impoundment area < $0.1km^2$) are estimated to make up 99.5% of the 16.7million artificial barriers that fragment river ecosystems (Lehner et al., 2011). In order to understand how these small dams modify river ecosystems, at the first step the ecological classification should be done, instead of classifying dams by single parameters like dam height or impoundment area. (Poff & Hart, 2002). However, until now, there is still no widely accepted classification system for these small weirs, which is due to the incomplete documentation of how small dams have influenced the river morphology and sediment dynamism for the many years existence, both individually and cumulatively, and the resultant river ecosystem responses. Another reason is that the morphological and ecological research that document the pre-removal conditions, especially long-term river channel evolution is rarely seen, for most of the studies are following dam removal projects (S. Csiki & Rhoads, 2010).

2.2 Definition and classification of small dams

Naming and classification have always become a problem to any studies that related to the small dams, the lack of a unified standard to classify is the prior obstacle to form a systematic theory and understanding of their existence and effect. According to ICOLD, a large dam is defined as a structure with a height of 15 meters or greater from lowest foundation to crest, or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters (ICOLD). According to (Fencl et al., 2015) who searched 54 peer-viewed publications from Web of Science (WOS), run-of-river dam, low head dam, and weir are found frequently used in scientific researches (see S1, Supporting information). Many studies use the term “run-of river dams” to describe structures that do not fit the large dam concept of ICOLD. Table 2. Summarized the definition that used by some researchers and organizations (S. Csiki & Rhoads, 2010). “Low-head dams” are also often used by researchers and media to describe a structure similar to run-of-river dams (Casserly et al., 2021; Cook & Sullivan, 2018; Cumming, 2004, 2004; Fencl et al., 2015; Maloney et al., 2008; Santucci et al., 2005; Stanley et al., 2002). Others use “weirs” to describe the hydraulic structures in their research (Abdollahpour et al., 2017; Bonjour et al., 2018; Carpenter-Bundhoo et al., 2020; Fahmy, 2015; Im et al., 2011; Jia et al., 2005; Sindelar et al., 2017; Williams, 1995). Through literatures, we found some similarities of these three similar concepts. Here the comments and different features are summarized in table 2. Based on the authors understanding. Table 2-1 is referred to Csiki and Rhoads (2010), shows the definition of run-of-river dams used by various of researchers and organization.

Table 2-1 Definition of run-of-river dams, from Csiki and Rhoads (2010).

Source	Definition
Stanley and Doyle (2002)	Run-of-river structures are dams that create reservoirs with small storage capacity and do not alter the river's flow regime
Pennsylvania Fish and Boat Commission (no date, http://www.fish.state.pa.us/rrdam.htm)	Run-of-the-river dam is a man-made structure which: 1) is built across a river or stream for the purposes of impounding water where the impoundment at normal flow levels is completely within the banks and all flow passes directly over the entire dam structure within the banks, excluding abutments, to a natural channel downstream. 2) has hydraulic characteristics such that at certain flows persons entering the area immediately below the dam may be caught in the backwash.
CET/AECOM(2007)	Run-of-river dams span the entire width of a river channel, are less than 25 ft (7.6 m) high, and water flows continuously over the crest of the dam. The drop at the dam crest, and the often-dangerous currents downstream, contribute to hazardous conditions for river users and pedestrians.
Doyon (NHDES, email message to author, 2009)	Generally, a dam is considered to be run-of-river when: the spillway is approximately the width of the channel it

	blocks, and there is little to no detention or storage of inflows to the impoundment created by the dam.

Table 2-2 Common and distinguished features about run-of-river dam/low head dam/weir.

Terms used in scientific research	Common points	Distinguished features
Run-of-river dam	1) All of the structures are less than 15m in height, in most of the studies dams are less than 5 meters. 2) Impoundment at normal flow levels is completely within the banks and all flow passes directly over the entire dam structure within the banks 3) Water retention time is short (seconds to minutes)	Some run-of-river dams are used for hydraulic electricity generating, often with turbine and power facilities besides.
Low head dam		Cross sectional shape is similar to a large dam (Trapezoidal), well height is usually less than 5m, widely used by researchers and normal people and media.
Weir		Various in shape, e.g., Triangular, Trapezoidal, sharp crest, broad crest and ogee shaped weir, sometimes movable, can be operated.

According to literatures, the common characters and distinguished points of the run-of-river dams, low-head dams and weirs are summarized in Table 2-2. We found that the term Low-head dam are more generally used and can be easily recognized by both the academic society and the public sectors. Weir can be seen as one type of the low-head dams featured by versatile functions and cross-sectional shapes(Abdollahpour et al., 2017; Fahmy, 2015; Gebhardt et al., 2019; Jia et al., 2005; Sindelar et al., 2017). In this sense in the rest of this study, the term low-head dam is mainly used for describing the general situations, discussions, and proposals. While, according to the original name in Japanese for the low-head dams in Katsura river, we used the directly translated names for calling them, for instance: the No.1 weir, No.4 weir, and Kuga weir.

2.3 A global trend of dam removal

Recently small dams are drawing more attention because they are increasingly being considered for removal, while the motivation of the removal varies from place to place. Generally, there are three main reasons: 1) safety issue, due to the hydraulic recirculation formed just below a low-head dam, sometimes low-head dams are called drowning machines, especially in the United States (Fritz & Hager, 1998; Leutheusser & Fan, 2001). 2) flood risk mitigation 3) economic considerations, for many of the low-head dams are well beyond their serving time, the maintenance fee is costly and usually removal is the best option for river managers. And 4), for the environmental reason, improving the ecological conditions and restore the river longitudinal continuity (Poff & Hart, 2002).

In the U.S., 467 dams have been removed in the last century (Poff & Hart, 2002), and most of the dams removed are less than 6m in height. 326 dams have been removed in Japan and including only 1 large dam (Arase dam, Kyushu). There are 18113 dams have been built until 2003 in Korea, 97% of them are less than 2m Kim et al., 2015. More dams are expected to be removed especially the small dams (e.g. low-head dams) due to their life span is usually around 50 years (Garcia de Leaniz, 2008). Thus, it is critical to document the effect of both existing weirs and their removal on the river morphology and ecology, to better guide the dam removal projects in the near future.

2.4 Effects of low-head dam on the channel surface domain

2.4.1 Large impoundment dams as a reference

Large impoundment dams are well known for its ability to greatly alter the flow regime and as a “blackhole” for the incoming sediment. Upstream of the dam, the decreased flow velocity can result in deposition at the inlet of the reservoir (Marston et al., 2005). Generally, the trapping efficiency of the bedload is 100% (Toniolo et al., 2007). Downstream of the large impoundment dams, the sediment-hunger water can result in the armoring of the riverbed, incision and narrowing (Kondolf, 1995; Magilligan et al., 2016; Petts, 1984).

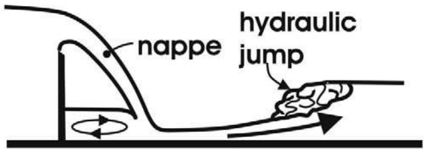
2.4.2 Hydraulic effects of low-head dams

A very detailed and thorough review of the hydraulic effects of low-head dams have been reviewed by Csiki and Rhoads (2010), I made a short version of the review mainly based on their work, detailed information can be found in the original paper.

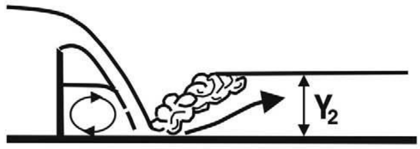
Low-head dams represent barriers to flow that extend across the entire width of a river channel, and disconnects the river channel geomorphology and ecological functions (Graf, 1993; Orr et al., 2006; Petts, 1984; Santucci et al., 2005). Even though the general effects of the low-head dams are well known (e.g., to form a impoundment area just upstream of the dam), surprisingly few researchers have studied the mechanism of the hydraulic, geomorphic and ecological effects in detail, by field investigation, physical experiments and numerical modeling methods (S. Csiki & Rhoads, 2010).

The main hydraulic effect of the low-head dams upstream is to produce a pool of low-velocity water upstream of the dam (S. Csiki & Rhoads, 2010; Pearson & Pizzuto, 2015b; Vanoni, 2006). The low-head dams provide sufficient hydraulic head to power water wheels or turbines or for the water intaking by locally increasing the water surface elevation, particularly during low flow periods. The effect of the low-head dams on the water surface profile extends upstream in a backwater curve. The shape of the profile caused by a dam has the form of an M1 backwater curve (Chow, 1959). The elevation initially changes slowly over distance (i.e., relatively flat) and then increases more rapidly upstream. The spatial extent of the backwater effect for a given flow stage depends on the ratio of the dam height (P) to the gradient of the river. The higher the low-head dams and the flatter the river profile, the farther upstream the backwater effect will extend (S. Csiki & Rhoads, 2010).

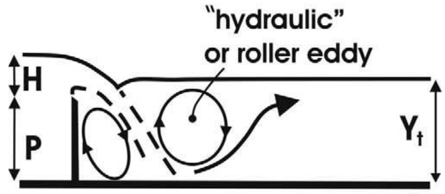
Downstream of the low-head dams, the hydraulic conditions can be changeable as the increasing of discharge (S. Csiki & Rhoads, 2010; Leutheusser & Fan, 2001). The status can be generalized by Fig. 2-1. The hydraulic jump will be submerged with the increasing discharge, there will be a strong circulation current formed just downstream of the dam body, which is the reason why low-head dams are sometimes called “drowning machines” (Fencl et al., 2015; Poff & Hart, 2002, 2002).



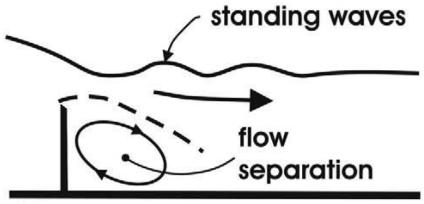
a) Swept-out jump



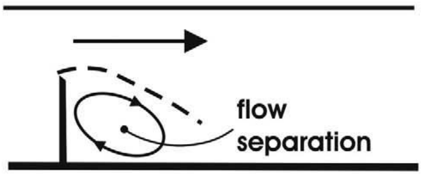
b) Optimal jump



c) Submerged jump



d) Surface nappe $Y_o/Y_t \approx 1.15$



e) Surface nappe $Y_o/Y_t = 1.0$

Fig. 2-1 Changing hydraulic conditions downstream of a low-head dam with increasing submergence of the dam. Ciksi and Rhoads, 2010. *Source:* Leutheusser and Birk (1991) and Leutheusser and fan (2001)

Though many studies have investigated the hydraulic conditions upstream of a low-head dams (Leutheusser & Fan, 2001; Stüer et al., 1999), few studies have reported the sediment characteristics upstream of a low-head dam, especially the processes of deposition and erosion of both bedload and fine sediment (Pearson & Pizzuto, 2015b).

Unlike large impoundment dams which normally trap all sediment upstream in its reservoir, the trapping efficiency of a low-head dam can be highly uncertain (S. J. Csiki & Rhoads, 2014).

2.4.3 Geomorphological effects of low-head dams

As the number of removals of low-head dam increases, it is crucial to understand the effects of these structures on river geomorphology and sedimentology (Kim et al., 2015; Pizzuto, 2002; Stanley et al., 2002). This understanding needs to include both situations (While in place and after removal). It is also necessary to know how rivers respond to removals so that possible future removals can be anticipated and predicted. Few studies have examined sediment storage upstream of low-head dams, and considerable uncertainty exists about the capacity of such dams to trap sediment (Brune, 1953). The trap efficiency, or fraction of the total incoming sediment load retained by a reservoir, is a function of the settling velocity of sediment particles and the retention time of water containing suspended sediment within the reservoir (Verstraeten & Poesen, 2000). At low stages, the low-head dams backwater effect should produce a pool within the upstream channel analogous to an impoundment behind a large dam (Stanley & Doyle, 2002). The backwater effect will reduce flow velocities and sediment-transport capacity that promotes deposition of sediment beginning at the upstream end of the backwater reach and extending downstream (Vanoni, 2006). As the flow stage increases, the inflexion point in the water surface profile will migrate toward the wire. Thus, the upstream spatial extent of the zone of backwater will progressively diminish. As a result, high velocities and bed shear stresses will propagate toward the dam and material deposited at lower stages may be gradually mobilized. When the low-head dam is fully submerged, only portions of the flow immediately upstream and downstream of the dam will be affected by the structure, which acts as a local submerged obstacle on the channel bed. Under these conditions, transport of fine suspended sediment should be unimpeded with this material moving over the crest of the dam (Casserly et al., 2021).

Based on field observation, Hosoda (2012) studied the downstream effect of the back-step structures by both numerical and physical modeling, which has explained the frequently observed mid-channel bar structure just downstream of a low-head dam-like structure. He found that the Non-equilibrium model can be more appropriately reproduce the bed deformation of experiment than the equilibrium one. The bar formation is due to the flow structure generated by the sudden channel expansion because of the dam construction (Hosoda & Shirai, 2012).

In the case of low-head dams' removal, Most removals have occurred only over the past 20 to 25 years. Accordingly, scientific information on river response to removals is sparse. The magnitude and extent of river response to dam removal depend on prevailing conditions before removal. If the dam has trapped minimal amounts of sediment, upstream and downstream effects on river morphology should be minimal, and the response following removal should also be minimal. The magnitude of incoming bed-material load will depend on the extent to which hydraulic conditions behind the dam can move coarse material up into the flow and over the dam. Another hand, if a low-head dams has trapped substantial amounts of sediment, then upstream and downstream responses may be pronounced, and responses should be similar to those associated with the removal of impoundment dams (Poff & Hart, 2002).

In such cases, the potential for large amounts of sediment to be flushed downstream represents a primary concern. Overall, the prediction of river response to dam removal is still an inexact science(Pizzuto, 2002). Removal of a dam will locally increase the water-surface gradient, flow velocity and bed shear stress upstream of the former structure, resulting in the entrainment of any stored sediment (Burroughs et al., 2009). This material will be flushed downstream and, depending on hydraulic conditions in the downstream channel, possibly deposited, resulting in aggradation (Burroughs et al., 2009; Pizzuto, 2002). Given the focus on low-head dam removals and possible downstream flushing of accumulated material, more attention has been focused on upstream than downstream effects.

Specifically, the geomorphic literature predicts three significant changes around low-head dams related to dam-induced alterations to flow and sediment regimes. First, the backwater effect of low-head dams creates ponding in the upstream reservoir, producing wetted stream widths and depths greater than downstream of the dam, with the spatial extent of these impacts entirely dependent upon local system channel geometry, channel slope, and height of the dam (S. J. Csiki & Rhoads, 2014). The combination of backwater ponding effects and partial sediment excavation during high flows in the impoundment is thought to maintain these greater depths and prevent complete sediment infilling of the backwater zone (Pearson & Pizzuto, 2015a). Second, the combination of some sediment trapping in the impoundment during low flows and the high energy acceleration as flow drops over low-head dams produces scour of the bed and banks, in some cases creating a deep plunge pool and mid-channel bar comprised of coarse ground material immediately downstream of the low-head dam. Third, the enhanced flow energy and partial clear water effect immediately downstream of the dam during low and moderate flows induce mobilization of fine fractions of the substrate, producing a coarsening of the substrate below low-head dams, leaving only coarse material (cobble, boulder, bedrock) behind

(Pearson & Pizzuto, 2015b).

2.4.4 Biological & ecological effect of low-head dams

Low-head dams alter biodiversity in aquatic ecosystems by modifying geomorphic, hydrological, and ecological connectivity (Dudgeon et al., 2006; Marren et al., 2014). However, for small, low-head dams, the potential impacts on geomorphic and ecological effects are infrequently examined and poorly understood. Although the impact of low-head dams likely extends beyond the dam structure's immediate vicinity, the spatial extent of low-head dam impacts has not been previously measured in the ecological literature, only estimated (Yan et al., 2013). Many literature documents how large dams alter aquatic ecosystems (Graf, 2006), but data on low-head dams are limited (Poff & Hart, 2002).

A quantitative measure of dam footprint facilitates testing how dams' interface with a wide range of ecological concepts (e.g., thresholds, disturbance, and edge-effects). For example, dams or their footprints may create habitat edges producing behavioral responses that may help explain the observed phenomenon in species distributions (Fortin et al., 2013). Differences in width and depth between upstream and downstream could function as breakpoints (Tiemann et al., 2005) where dams separate habitats (lentic upstream vs lotic downstream) which are important determinants of macroinvertebrate distributions (Tullos et al., 2014). However, comparative breakpoint research that relates geomorphic (e.g., habitat structure) and ecological (e.g., organismal) patterns of low-head dam impacts have not been undertaken in geomorphology (S. Csiki & Rhoads, 2010) and rarely in stream ecology.

2.5 Low-head dam's influence on the subsurface domain

2.5.1 The ecological significance of hyporheic zone (HZ) and hyporheic exchange (HE)

The hyporheic zone (HZ) of streams, which is the region of sediment and porous space beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water. The HZ is an interfacial zone important to many key stream processes and organisms, due to its large surface area of sediment grains within the streambed and the high activity of microbes living in it. HZ plays a key role as a reactive zone, transforming pollutants and natural solutes, as well as providing a habitat for benthic communities (Boano et al., 2014), including macro-invertebrates, microorganisms, and some fish species that dwell in the hyporheic zone for parts of their lives (Marzadri et al., 2014). As an active ecotone, the HZ is sensitive to external disturbances. Many human activities affect the hyporheic zone, either through disruption of the hydrological exchange pathways or via direct contamination (Hancock, 2002; Kasahara et al., 2009; Meŝtrov & Lattinger-Penko, 1981).

Within the hyporheic zone, the most important process is the interactions between stream surface water and groundwater, the hyporheic exchange has been a major focus by many researchers in the past two decades (Jones and Mulholland, 2000). Normally, the hyporheic downwelling flow supplies benthic animals with dissolved oxygen and the hyporheic upwelling water provides nutrients to the stream organisms (Datry et al., 2015).

Due to the temperature difference between groundwater and stream water, hyporheic exchange also controls the temperature pattern in the hyporheic zone, which provides a "refugee zone" for the benthic organisms during the extreme weather conditions (Dole-

Olivier & Marmonier, 1992; Orghidan, 2010, 2010).

2.5.2 Mechanisms and factors that control HE

Pressure undulations along the sediment water interface (SWI) drive hyporheic exchange in a river reach. Hydrostatic and hydrodynamic pressure variations are generated by channel geomorphic features such as dunes, ripples, bars, man-made in-stream structures and channel curvatures, which will cause nested hyporheic paths in the shallow aquifer domain. (Gomez-Velez & Harvey, 2014). In flow environment, the pressure that the stream water imposed on the SWI is often termed as the total head, which consists of hydrostatic and nonhydrostatic (e.g., hydrodynamic) components (Lee et al., 2021). In open channel flow conditions, for a given point at the SWI (Fig. 2-1), the total head is described by eq.1.

$$H = Z + \frac{P}{\rho g} + \frac{V_{av}^2}{2g} \qquad \text{eq.1}$$

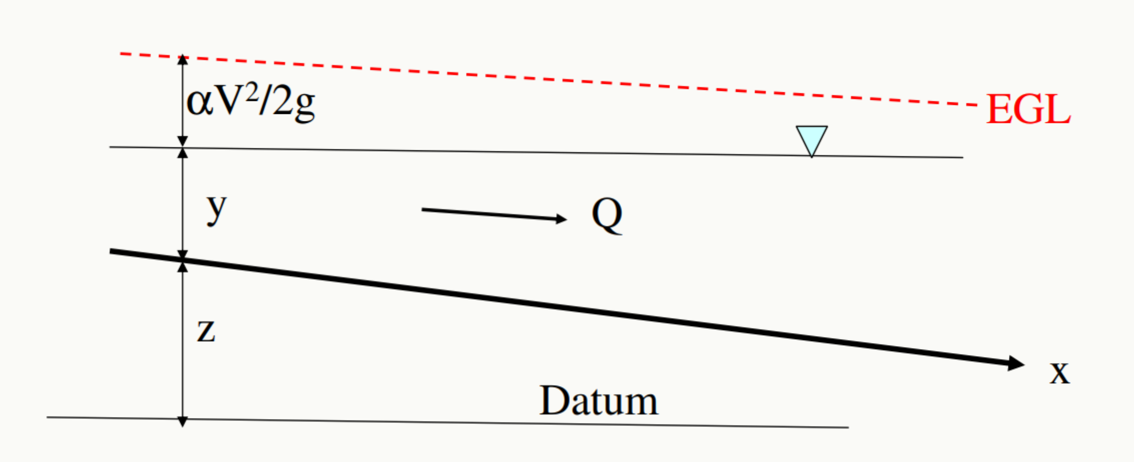


Fig. 2-2 Hydraulic head at a point in the riverbed

Where H is the total head, Z is the elevation head, which is defined as the channel bottom relative to a datum, $\frac{P}{\rho g}$ is the pressure head, in which p is the internal pressure (Pa), ρ is the density of water, g is the gravitational acceleration, the pressure head is usually represented by the vertical depth of the flow, V_{av} is the mean flow velocity. The sum of elevation head and hydrostatic pressure head is also called piezometer head, which can be the dominant driver of hyporheic exchange, especially in case of subcritical flow with lower Froud number, the hydrodynamic pressure is often neglected. (Gooseff et al., 2006; Harvey & Bencala, 1993; Kasahara & Wondzell, 2003; Lautz & Siegel, 2006). The hydrodynamic pressure becomes prominent when there is higher velocity and Froud number, for instance in shallow sandy bed river with ripple and dunes as the dominant riverbed geomorphic features, the hydrodynamic pressure oscillations could no longer be neglected and has to be carefully solved as the research work done by Elliott and Brooks (1997a), who use an idealized sinusoidal curve to approximate the actual dynamic pressure applied on the riverbed. Once the pressure distribution on the SWI is known, the head distribution within the hyporheic domain can be determined by solving the Laplace equation as a boundary condition and then the resulting advective flow can be calculated by Darcy's law. The water flow in a homogeneous and isotropic porous medium is governed by the Laplace equation, which in the three dimensions Cartesian coordinate system is written as (Bear, 1972) :

$$\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} + \frac{\partial^2 h^2}{\partial z^2} = 0 \qquad (1)$$

Where h is the hydraulic head (total head), and x, y and z are coordinates. The Darcy's law is given by:

$$q = -K\nabla h \tag{2}$$

Where q is the Darcy flux, K is the hydraulic conductivity. Notice that this theory has strict applicability constrains: 1) the hyporheic flow though the riverbed is laminar, the flow is continuous and steady, the riverbed is saturated, isotropic, and homogeneous. According to Menichino (2014), the Darian flow prevailed and solid at $K \leqslant 10^{-4}$m/s, and at $K = 10^{-2}$m/s, the entire flow domain became non-Darcian. In order to implement the theory, the Reynold's number should be lower than 1. The combination of Laplace equation and Darcy's law has been applied for many computational fluid dynamic models such as Modeflow, and most researchers used this theory at larger spatial scales such as bar scale (Tonina & Buffington, 2011), reach scale (Gariglio et al., 2013) and even basin scale (Gomez-Velez & Harvey, 2014).

Hyporheic exchange rate can be highly variational spatially and temporally due to the different boundary conditions of hydrology, geomorphology, physical characteristics of riverbed such as aquifer hydraulic conductivity (k) and porosity (n), and man-made hydraulic structures (Baxter & Hauer, 2000; Bayani Cardenas et al., 2008; Boano et al., 2013; Boano, Revelli, et al., 2007; Chen, 2004; Chen et al., 2018; Crispell & Endreny, 2009; Gariglio et al., 2013; Marzadri et al., 2014). Hyporheic exchange is enhanced by channel bedforms that generate greater subsurface head gradients (Harvey & Bencala, 1993), and coarse sediment with large hydraulic conductivities (Packman & Salehin, 2003). On the other hand, hyporheic exchange has a negative relation with the stream water depth (H) (Ren et al., 2019) and the introduction of fine sediment into an otherwise coarster bed can act to decrease hydraulic conductivity and hyporheic flow rates by as much as an order of magnitude (Koltermann & Gorelick, 1995; Packman & MacKay, 2003; Wu, 2000)

2.5.3 Heterogeneous of hydraulic conductivity of the riverbed

Though the hyporheic exchange is largely controlled by the hydraulic conductivity of riverbed and surrounding aquifer (Kollet and Zlotnik 2003; Nowinski et al., 2011), however, traditionally, the riverbed was treated as a homogeneous layer for simplification in many previous hydrological studies (Boulton et al., 1998). The natural heterogeneity of riverbed hydraulic conductivity has been increasingly recognized in the recent years by both hydrologists and ecologists (Sophocleous, 2002). The hyporheic exchange is directly affected by the spatial and temporal variation of riverbed hydraulic conductivity (Packman and Salehin, 2003). Researchers implemented various methods in the field to acquire 3-D structure of riverbed hydraulic conductivity. Cardenas and Zlotnik (2003) used Constant Head Injection Test method to invest k in a gravel stream, and k showed great spatial variability ranged from 0.15-74.5m/day. Yamada et al (2003) used Parker test for the high permeable area and Falling Head Method for the low permeable area of a gravel bar in the Kamo river (2003). Nowinski (2011) studied the k changing with time in a point bar of an artificial channel, and he concluded that the decrease of k was due to fine material movement and accumulation. One of the widely acknowledged model for describing k evolution in the riverbed is the clogging-flushing theory. In this theory the k would be continually decreased due to fine sediment accumulation in the top layer of the riverbed until the next flood event flushing out the fine materials and a new layer with the maximum initial K0 would be formed (Schälchli, 1992; Cheng Cheng et al., 2011; Simpson1 and Meixner, 2012;). However, such model simplified many hydrological and hydraulic factors such as the variation of sediment load, the local geomorphic settings, and biological activities on hydraulic conductivities (Springer et al., 1999; Schubert, 2002; Packman and MacKay, 2003; Blaschke et al., 2003; Genereux et al., 2008).

2.5.4 Modeling of hyporheic exchange

Due to greatly variation of spatial and temporal scales of the hyporheic flow, hyporheic modeling efforts also greatly differed in spatial scales. Basically, there are two distinguished categories of models that have been widely recognized and used by researchers, the physically based and phenomenological models (Boano et al., 2014).

A large body of literatures can be found using phenomenological models to describe stream-aquifer system, with the best known is the transient storage model(Boano, Packman, et al., 2007; Haggerty et al., 2000; Harvey & Bencala, 1993). The greatest advantage of transient storage model is the simplicity compared to the much more complicated physically based model; however, the simplicity also caused many problems as the model could not describe the key hyporheic process in the medium.

Physically based models rely on the mass and momentum conservation principles to investigate the interstitial flow rate and pattern in the sediment medium domain. Elliott and Brooks (Elliott & Brooks, 1997a, 1997b) developed a “”pumping and turnover” theory to investigate the transportation of the nonsporting solutes between a permeable streambed and the overlying water of a stream at the ripple and dune scale, this is a 2-dimensional model which discusses the vertical hyporheic exchange process with steady flow and isotropic and homogeneous riverbed conditions. Cardenas et al., (2004) presented a three-dimensional model of hyporheic exchange in a channel bend, what makes this study special is that unlike many pure modeling studies which do not consider the real situations and oversimplified the model settings, Cardenas collected the field data of hydraulic conductivity which is the dominating factors that controls the actual hyporheic exchange rate, he argued that the natural conditions of the riverbed in terms of the heterogenous of the hydraulic conductivity should be considered in the hyporheic studies. His study is at the river reach scale. Boano et al (2007) investigated the hyporheic exchange under unsteady flows conditions, to understand how hyporheic exchange would response to the water level and velocity alteration. As to larger than the reach scale, at river segment scale and river system scale, Geomez and Harvey (2014) proposed the NEXSS model aiming at estimation of the magnitude of hyporheic exchange at the river basin scale. One weak point of the physically based model is that it requires high amount of data which sometimes difficult to get especially from the field (Boano et al., 2014). Accordingly, Cardenas (2009a) developed a “hyporheic meter” to estimate the lateral hyporheic exchange magnitude for the single thread rivers which requires only the channel sinuosity and valley slope that can be easily acquired by remote sensing methods. This tool is especially useful for empirically connecting channel geomorphology and ecological functions in terms of hyporheic exchange magnitude. The limitation is that this model only considered the lateral components of the hyporheic exchange, while the author pointed out similar empirical relationships can also be found for the vertical components, which will make the model 3-dimentional and thus making this tool even more valuable for practically making the hyporheic exchange an important indicator of the stream ecological functions in the river restoration projects.

2.5.5 Removing old ones while constructing new ones? ---- Contradictory opinions

In spite of many efforts has been made to investigate the HE theory, drivers, and controlling factors by models, few studied the man made in-stream structures and their influence on the HE, especially for the large number small dams and weirs which would alter the geomorphic setting of the reach scale hyporheic regime completely and potentially making the theoretical modelling efforts unreal. In fact, few mentioned to restore the impaired HE by considering the possible negative effect of low head dams and weirs (Kasahara et al., 2009), since most researchers think they can be used as facilitators for the HE and propose to install more in stream obstacles such as wood introduction and small dams to create the water head and thus enhance HE (Bakke et al., 2020; Berlinghieri, 2013; Crispell & Endreny, 2009, 2009; Daniluk et al., 2013; Hester et al., 2018; Hester & Doyle, 2008; Kasahara et al., 2009; Liu & Chui, 2020; Menichino & Hester, 2014; Rana et al., 2017).

Very few but I found one literature which is against the mainstream idea of in-stream structures will promote hyporheic exchange. Berlinghieri (2013) questioned the effects of in-stream restoration structures on the hyporheic exchange in her Master thesis. After collecting data from three restoration structure sites (newly constructed weirs) using piezometers and temperature loggers, she found that the hyporheic flow paths may not have fully developed in the first 16 months following the weirs construction, which is against the many researchers' idea mentioned before. She then used a heat transport model trying to quantify the hyporheic flow network in each site. However, she did not examine the hydraulic conditions of the water and subsurface based on hydro-dynamic knowledges. In other words, her study is not physical process-based, but rather an empirical study, thus it’s difficult to test the phenomenon-based hypothesis in her study. In her conclusion, she pointed out that the heterogeneities of the hyporheic flow pattern and the characteristics of the subsurface material properties should be studied more in futures work (Berlinghieri, 2013).

2.6 Subjects remained to be studied

Throughout the literatures, we found the following knowledge gaps:

1) The lack of linkage between geomorphic change and habitat structures in relation to low-head dam removal.
2) There are different opinions about the effect of low-head dams on the riverbed hyporheic exchange, there is an urgent need for studying this topic.
3) Integrated riverbed management schemes are required to tackle the environmental problems in gravel bed rivers with multiple low-head dams.

Most studies related to low-head dams and their impacts are following dam removal cases, and usually only short – term channel responses were recorded. To thoroughly understand the weir and its influence on the river ecological functions, the mechanism of how geomorphological alteration will affect the habitat structures is critical and fundamental theory needed to be well developed in advance. However, studies that provided the channel evolution with multiple weirs and at longer time scales are rarely seen through our literature review, which is important to understand the interrelationships between channel geomorphic features and habitat structures, under the influence of weirs and their removal.

Many modeling studies concluded that the construction of “in-stream geomorphic structures (IGS)”, which, can be generally seen as weir-like structures will facilitate hyporheic flow, however, these studies are either only based on pure modeling results or with preliminary field experiments (Hester et al., 2018; Hester & Doyle, 2008; Liu & Chui, 2020). The lack of empirical data for the existing weir or similar structures to the "IGSs" may misguide big river restoration efforts and fund to construction of new weirs, while at the same time, more and more old ones are being removed.

Hypothesis:

The appropriate river management strategy can be highly variable according to each river's current conditions, including upstream boundary conditions(e.g., discharge and sediment supply) and downstream geomorphic confines (e.g., levees and low-head dams). In this study, our target river belongs to the gravel bed river category and was influenced by multiple low-head dams. In other words, the downstream confines are mainly levee and low-head dams, thus based on the different situations of upstream boundary conditions, our hypothesizes about the influence of the multiple low-head dams are:

Based on the subjects that remained to be studied mentioned above, the objectives of this thesis are:

1) To present the historical channel geomorphic and riffle habitats change in a gravel bed river with multiple weirs and further to discover the empirical relationships between them by statistical analysis tools.
2) To compare the hyporheic flow conditions at a reach with weir and a reach after weir removal by field investigation and numerical modeling.
3) To propose the integrated river environmental management schemes for improving the aquatic habitat structures and hyporheic flow conditions.

Chapter 3 Methods

3.1 Study area

Katsura river is one of the three main tributaries of the Yodo River located in the Kansai Area of Central Japan. Katsura river drains a 1159-km^2 basin in the Kyoto prefecture (Fig. 3-1), it flows ~107km from the headwaters to its confluence with the Yodo river. Before running into the Kameoka city, the river is mainly flowing at the mountainous area, where the channel is confined by the valley bedrock. There is a major multi-purposes dam which located at the northern area of Kameoka City, the Hiyoshi dam was started building in 1992 and finished in 1996, which creates a narrow and long reservoir with an area of 2.74km^2 and mainly for the flood control, to countermeasure the frequently flooded Katsura River and also for the sake of downstream flow maintenance and water supply. Kameoka basin and the Kyoto Basin are connected by Hozo valley, which is narrow and extremely circuitous, therefore, sediment can hardly be transported to the downstream Kyoto basin through the valley which will deposited in the Kameoka City instead, before entering the Hozo valley, and resulted in high frequency of flooding in the Kameoka City and lack of sediment supply for the downstream segment for the Kyoto City.

From the outlet of the Hozu valley to the confluence with the Yodo river, Katsura river runs through the entire Kyoto City from north to the south. Over 500,000 residences living in the catchment of the 0.0-18.0K segment of Katsura river. Some of the most popular tourist site such as Alashiyama, Togetsukyo are located densely in this area. The river is confined by levees which are higher than the adjacent resident area. Due to the frequently happened flooding, the Yodo River Bureau sets priorities for flood mitigation, countermeasures include riverbed excavating, deforestation at the floodplain and multiple low-head dam removal projects. From downstream of Hiyoshi dam to the entrance of Hozu river, 12 low-head dams have been built in the main channel, while in the study segment (0.0-18.0K), 8 had been built (Fig. 3-2). Originally, they were built for the same purposes which is to rise water level upstream for the irrigation water intake. However, due to the land-use change, the irrigation is no longer needed in the study segment, now the authorities are removing low-head dams for the purpose of flood mitigation.

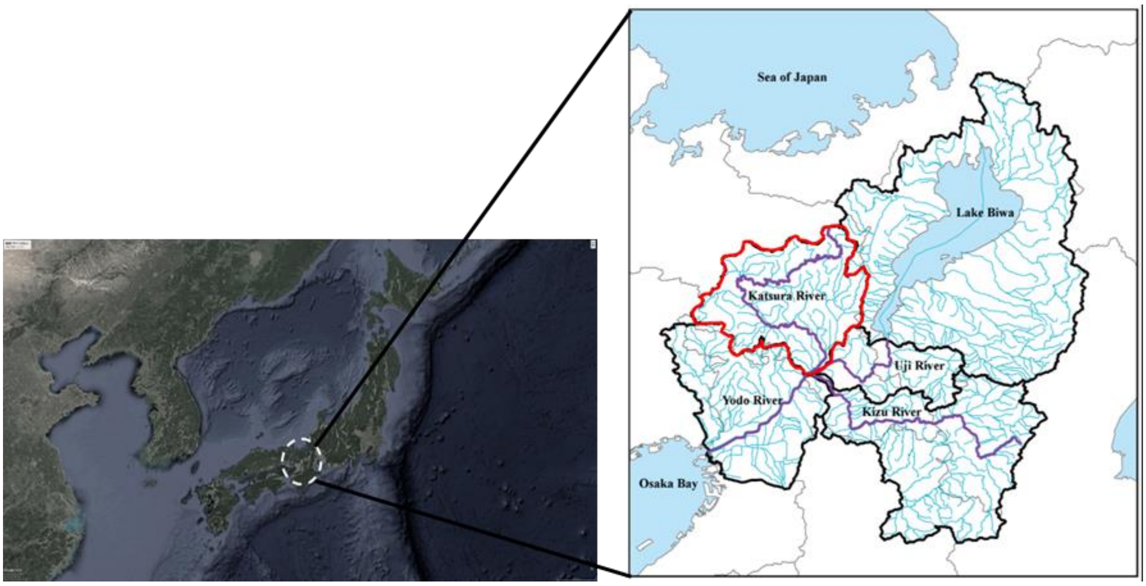


Fig. 3-1 The Yodo River basin and its sub-basins in the central area of Japan, the Katsura river basin boundary is marked with red line, yellow line indicates the study segment.

Katusra river catchment is mostly composed of granite, chalk, clay/mudstone, and sandstone (Ministry of Land, Infrastructure and Transport 2014). As to the riverbed geological information, borehole data from No.4 and no.1 weir site are available from Yodo river bureau. As Fig. 3-5 shows, the riverbed is mainly composed of gravel.

Deposited clay layer was probably existing previously while eroded and flushed out by the river flow, only existing at the bank side and deeper layer (about 15m under the riverbed surface), at the No.1 weir site.

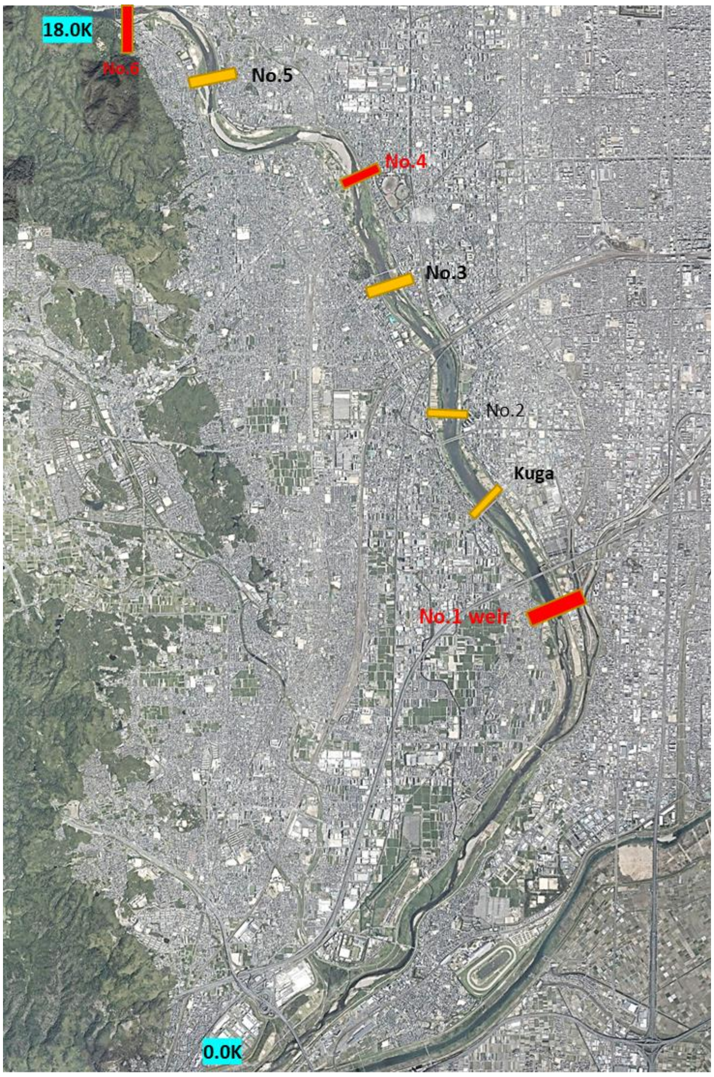


Fig. 3-2 Study segment of Katsura river, the image was taken in 2019.

Water quality and basic hydrological conditions data (Table 3-1) are referred to (Hanamoto et al., 2018), while notice that these data are mainly detected at the downstream part of the study segment (7.0K). Katsura river is maybe the most frequently flooded river in Kyoto basin, and due to the dense population living at the two sides of river, the flood risk mitigation is always the priority for the river managers, the riverbed excavating work is continuously on going since about two decades ago, river ecosystem conditions monitoring has also been doing simultaneously. Weir removal plan has been proposed mainly for the purpose of flood mitigation, while the fish way efficiency assessing was also done due to the concern of the weirs blocking the fish migration.

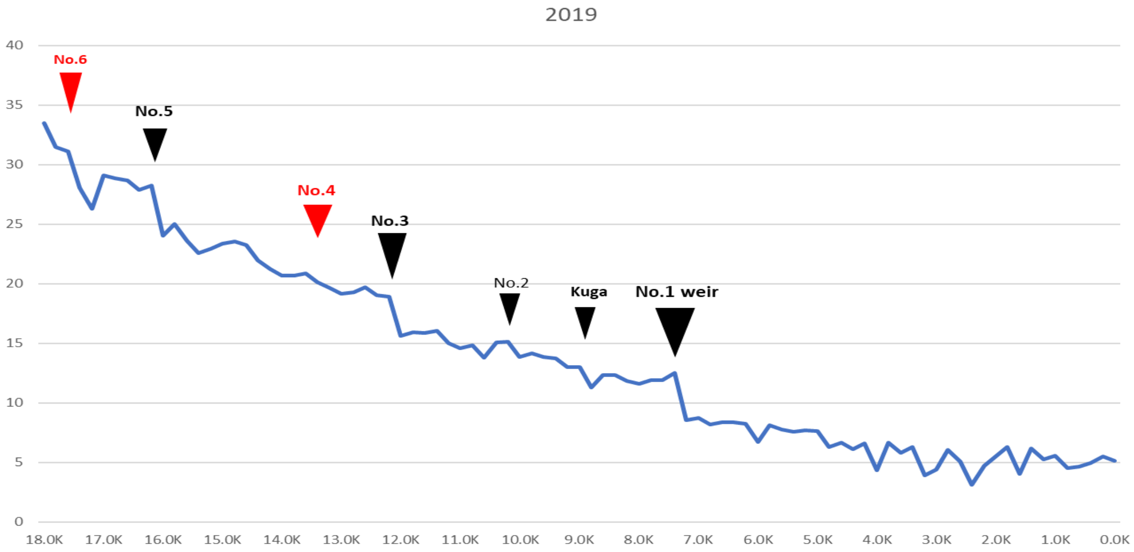


Fig. 3-3 The 2019 longitudinal profle (thalweg) of Katsura river.

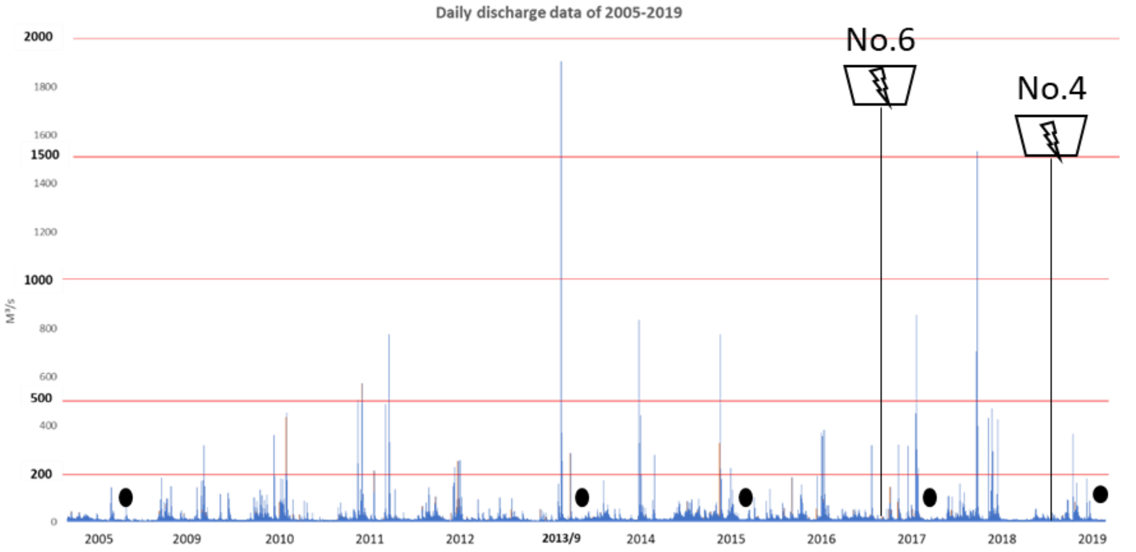


Fig. 3-4 Daily discharge data of 2005-2019, notice that data from 2006-2008 is missing, aerial photos and satellite images used in this study were taken in 2005, 2013, 2015,

2017 and 2019 during low flow seasons, as well as the cross-sectional data, as the five solid black circles indicated.

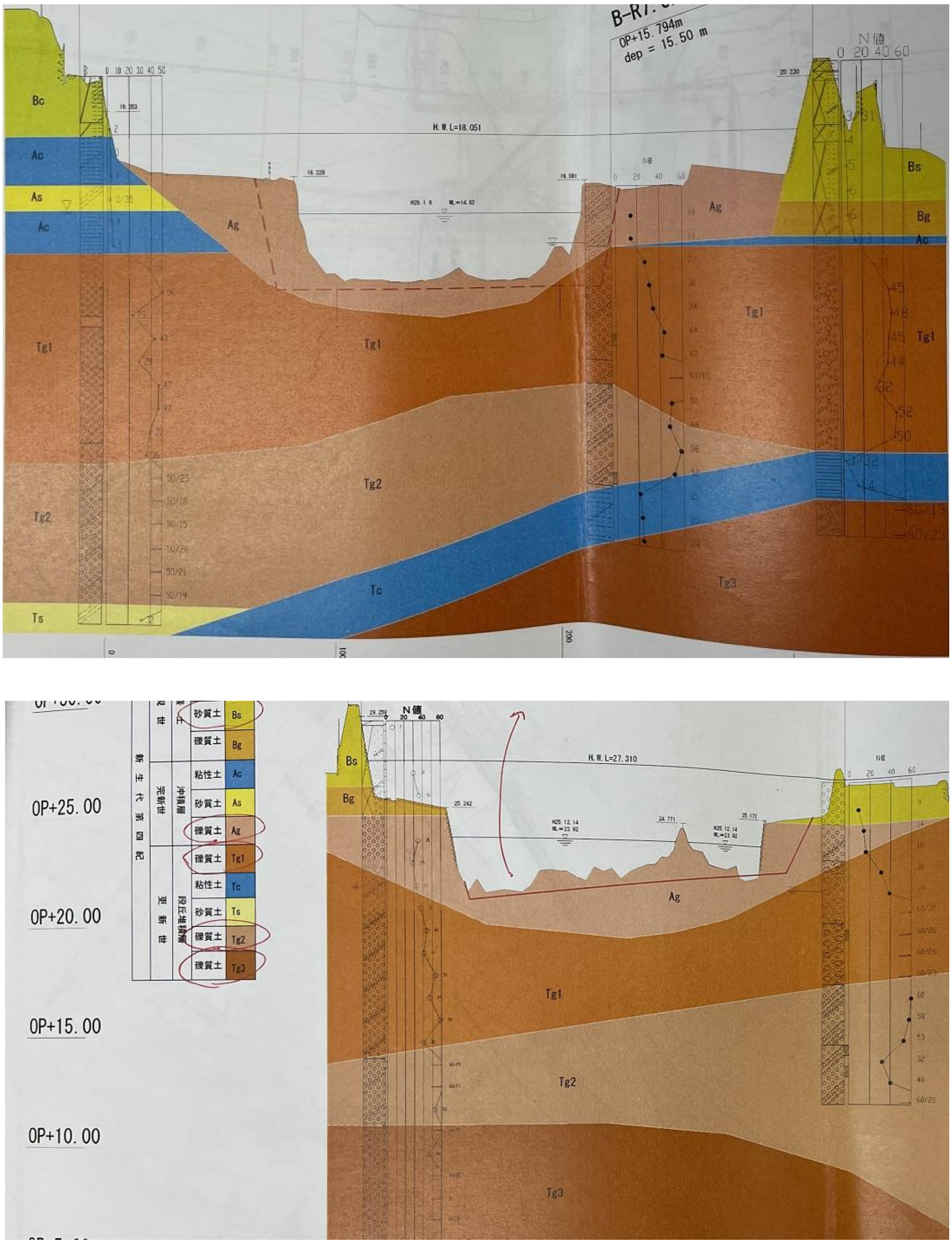


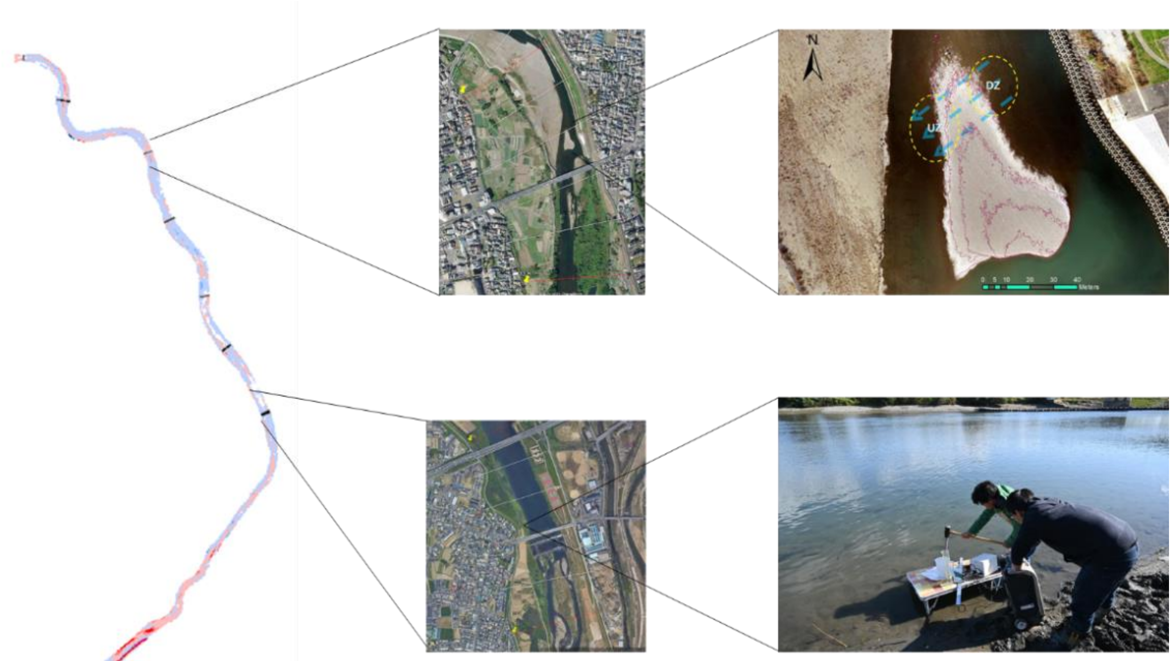
Fig. 3-5 Geological data by borehole survey at No.1 (top) and No.4 weir (down) sites, data from Yodo river bureau. Ag and Tg1 are both gravel soils based on Geological Standard of Japan.

Table 3-1 General charactersitics of Katsura river (Hanamoto et al., 2018).

Water quality parametersa	Temperature (°C)b	21.6 (9.4–27.3)
	pHb	7.4 (7.4–7.5)
	Suspended solids (mg/L)b	5.8 (3.5–19.8)
	Flow rate (m3/s)c	22.4 (18.0–36.6)
	Flow velocity (m/s)c	0.54 (0.50–0.67)
	Depth (m)c	0.48 (0.44–0.56)
Hydrological conditionsa	Hydraulic radius (m)c	0.47 (0.44–0.55)
	Friction velocity at sediment-water interface (m/s)c	0.048 (0.045–0.058)

The spatial scales of this study varies based on different purposes, in chapter 4, we firtst analysized the historical geomorphic and habitat change of the study area at the segment scale, then the two weir removal sites were focused, channel response to weir removal was studied in detail at the reach scale.

In chapter 5, the effect of weir and its removal on the hyporheic zone was investigated at the reach and local scale. First the hyporheic flow pattern was simulated in the No.1 weir reach, then field survey was conducted at upstream of No.1 weir, to estimate the *in-situ* hydraulic conductivity value of riverbed. After No.4 weir removal, field surveys were conducted twice at the local bar scale, to evaluate the riverbed hyporheic exchange potential after weir removal.



Segment scale Reach scale Bar/local scale

Fig. 3-6 Various of spatial scales of this study.

3.2 Methods of this study: a brief overview

3.2.1 Image analysis

The high-resolution satellite images (1-3m) from google earth were used to measure the geomorphic features and habitat structures, aerial photos taken by Yodo river bureau in specific years were used as supplementary data.

3.2.2 Interpolation of river bathymetry from channel cross-sectional measurements

Five sets of biennially surveyed channel cross-sectional data (collected from Yodo river bureau) were used to show detailed historical riverbed morphological changes of

Katsura river. Bluekenue and Arc-GIS software were used to interpolate the 200-meter-interval data into DEM, in the interpolation process, OKA algorithm was selected due to its lowest RSME. After having 5 sets of DEM data, the Geomorphic Change Detection Software (GCD) was used to detect the riverbed volumetric change between two time period.

3.2.3 Numerical modeling of hyporheic flow induced by a weir

To model the hyporheic exchange induced by a regular-shaped weir, the combination of Laplace model and Darcy’s law was selected for its capability of simulating hyporheic exchange with hydrostatic pressure as the dominant driving force for HE, in addition, the geological information of the riverbed at the modeling weir sites also indicates the riverbed is mainly composed of gravel soil, thus the isotropic and homogeneous conditions of sediment can be assumed.

3.2.4 Field survey

Constant Head Injection Test (CHIT) was conducted in the field for estimating riverbed hydraulic conductivity, we designed and assembled a set of equipment which is suitable for the study site of Katsura river. The equipment with two men operating is capable of measuring one point by 10-15 minutes. Other field survey methods for instance level survey using a total station, water quality by test kit, sediment sampling, drying and sieving are done according to the standard protocols.

Statistical analysis tools

Basically, due to the various of data format, Python and Excel VBA are used for data cleaning and rearranging, MATLAB and R were used for performing correlation and regression analysis.

3.2.5 The framework of the integrated methods

Fig. 3-7 shows the framework of how the methods in this study were organized and corresponding to main chapters.

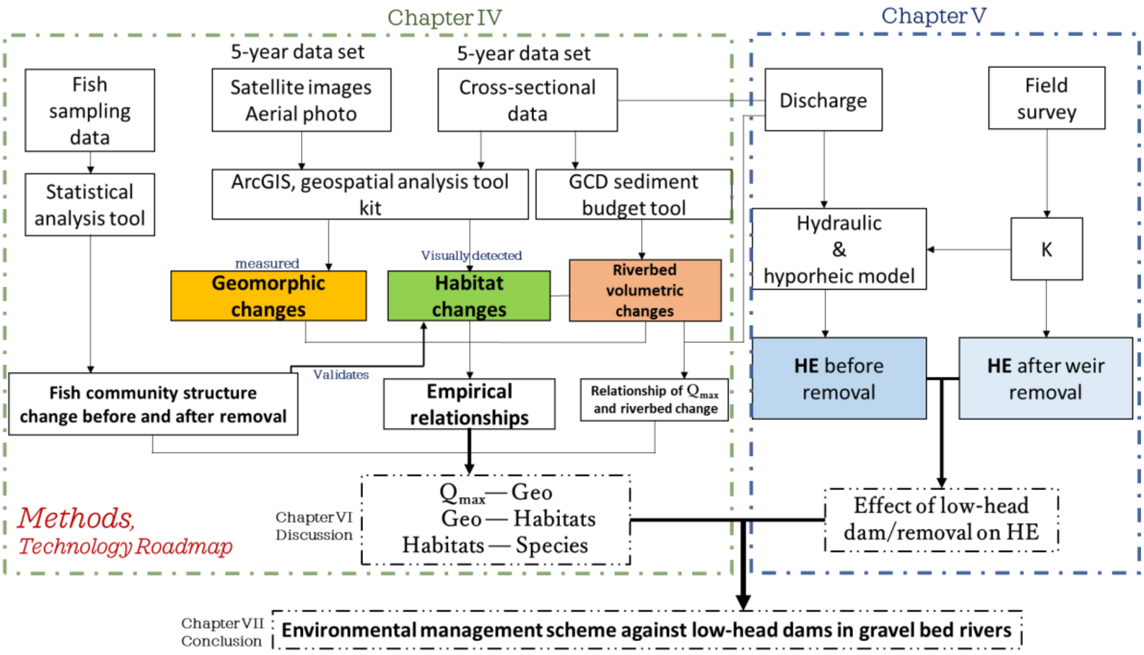


Fig. 3-7 Technology roadmap of this study

Chapter 4 Historical changes in channel geomorphology and habitat structures before and after low-head dam removal

4.1 Introduction

Katsura river is a frequently flooded river and has been a primary concern for the river managers. As the weir removal projects along with sediment excavating are ongoing, concerns of the impacts of flood mitigation works on the river environmental conditions are also rising. Therefore, in order to develop appropriate management schemes, extracting the relationships between river geomorphic changes and the resultant habitat change is required. We want to use Katsura river as a representative of the gravel bed rivers with cascade low-head dams.

The purpose of this chapter is to record the channel evolution of a gravel bed river with multiple low-head dams, in terms of river geomorphic change and habitat structures change. Empirical relationships between river geomorphological parameters and riffle habitats were examined by statistical methods. Firstly, data was collected and analyzed to understand the historical changes in terms of channel geomorphology and aquatic habitat structures at both segment scale (0-18.0k) and the local scale (weir removal sites). Then I tried to link the geomorphology part and the ecological part by investigating which RSCC channel types contains the most abundant habitat structures and the geomorphic features of this very type of RSCC. After having target geomorphic parameters, the empirical relationship between the geomorphic parameters and the habitat structures is examined. Even though river channel patterns are ultimately controlled by a unique combination of hydraulic and sedimentary controls, however, local channel adjustments are caused by the process of fluvial erosion and deposition (Hudson, 2005), which means the channel local geometric changes and the resulted habitat structures are largely controlled by the reach scale channel dynamics (RSCD), thus the empirical relationship between the riverbed morphological changes (in sediment volumetric) and the controlling geomorphic parameters, and relationships directly with the habitat structures were examined in this study.

4.2 Study area and methods

4.2.1 Study area

The study area of this chapter covers the whole segment of Katsura river (0-18.0k). In the whole study segment, the river channel is confined by levees and thus the channel morphology is closely related to the shape of the levees.

In the upstream from the outlet of the valley, channel of Katsura river is sinuous with the steep gradient, two biggest point bars were created at the channel curvatures. Multiple weirs were constructed which resulted in wide water area just upstream of the weir. Compared to the downstream large weirs (No.3 and No.1), weirs in upstream are relative smaller in size and height, moreover, the distance between No.5 and No.4 weir are the longest thus the combined situation resulted in a higher gradient area between weirs in this part. Further downstream part is dominated by weirs and straight channel form. The cascade weirs caused a step-like river longitudinal profile with still water system occupied more than 95% in this reach due to the backwater effect of the weirs. The average channel width is the wide and gradient and flow velocity is slow.

Since No.1 weir (7.4k) is the last barrier between the water flows to the Yodo river stem. River channel becomes narrow and from longitudinal profile, we can see the gradient became event less.

4.2.2 Low-head dams in Katsura River

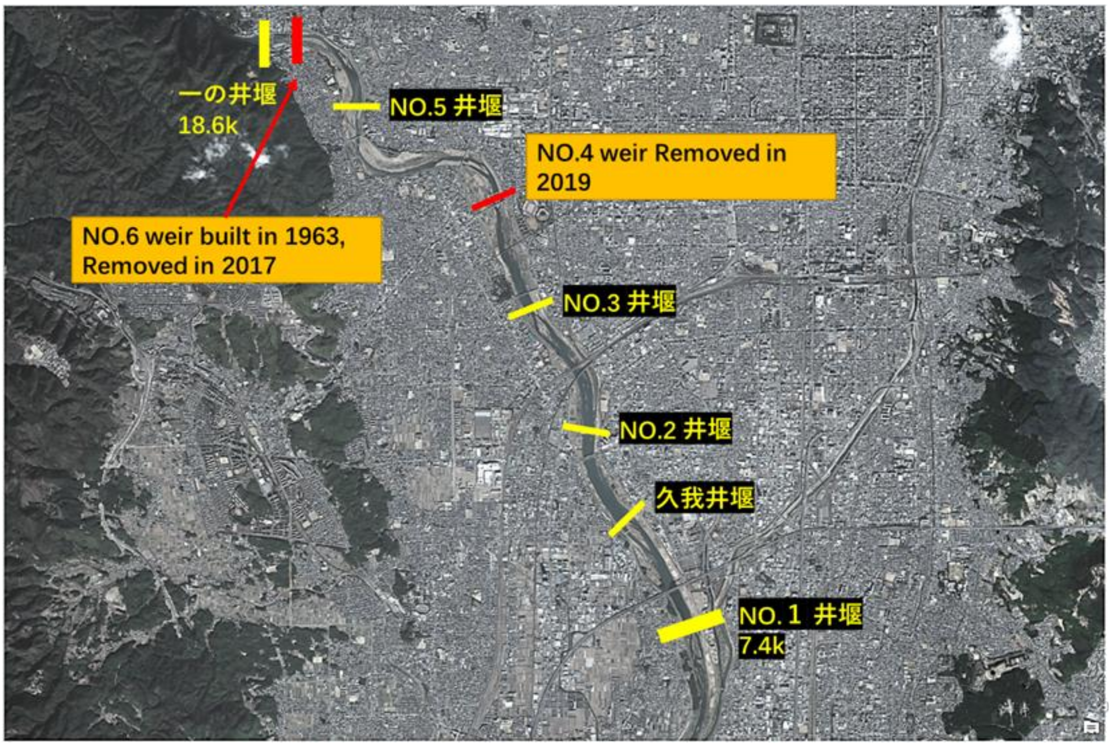


Fig. 4-1 Low-head dams in the Katsura River, two of eight have been removed in 2017 and 2019 respectively, moreover, removal works of NO.1 weir which is the largest one in the study segment are ongoing during writing of this thesis.

Table 4-1 Information of low-head dams in the study segment.

StationNo	Dam Name	Height (m)	Length(m)	Construction time period	Removal year
18.13K	Ichino	1.48	145	1951	
17.7K	**No.6**	0.86	120	1965-1975	**2016-2017**

16.12K	No.5	1.22	263	1952	
13.55K	**No.4**	2.8	150	1960	**2017-2019**
12.06K	No.3	1.99	171	1961	
10.2K	No.2	0.7	191	1948-1971	
9.1K	Kuga	1.8	222	1948-1971	
7.4K	**No.1**	4	163	1953	**2020**

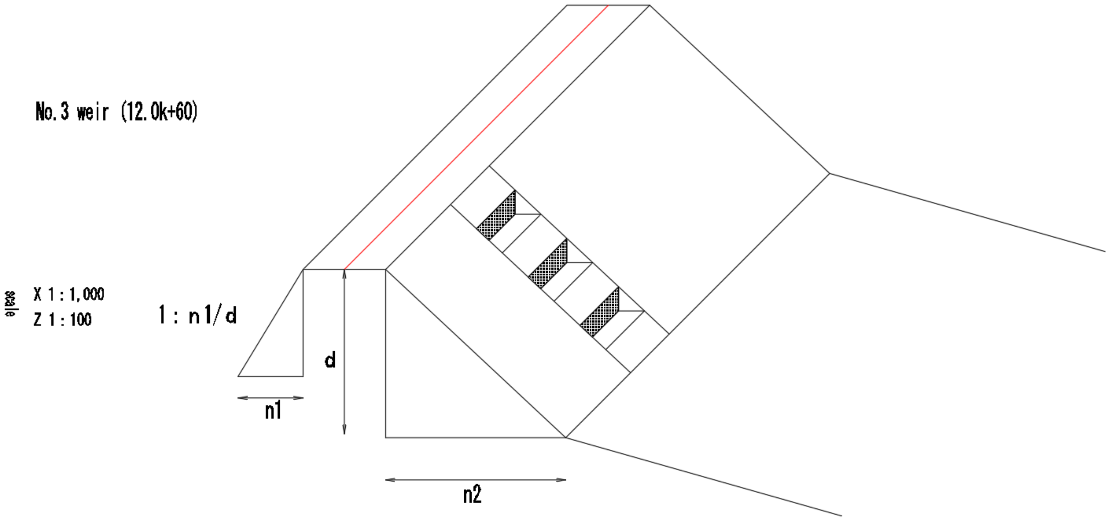


Fig. 4-2 Low-head dam shape and geometry in the study area, an example of No.3 weir, others are similar shape while various in size.

The low-head dams in Katsura river were built mainly for irrigation purposes (Fig.4-1), previously the land use pattern around Katsura river is mainly paddy field however, due to the city development and land use was changed to industrial and residential area near Katsura river, there is no need for intaking water from river and thus the low-head dams have lost their original function. Among low-head dams in Katsura river, the No.1 weir was the biggest one with 4m in height, located at the at the most downstream end and closest to the conjunctions of the three tributaries of the Yodo River. No.1 weir was built in 1953 and has already over 67 years old before removal in 2020. The riverbed survey has not been done after the weir removal, and thus the riverbed change after No.1 weir removal is not included in this chapter, however, the analysis will be done after receiving the river cross-sectional data from Yodo river bureau.

No.6 weir was built on 1960-1970s and removed during 2016-2017 during the low flow season. No.4 weir was located downstream of No.6 weir, with No.5 weir still exists in the middle part. It was removed during 2017-2019 during low flow season.

Among all low-head dams, the No.1 weir is located at the most downstream end, and it is the biggest one in the study area (Fig. 4-3).

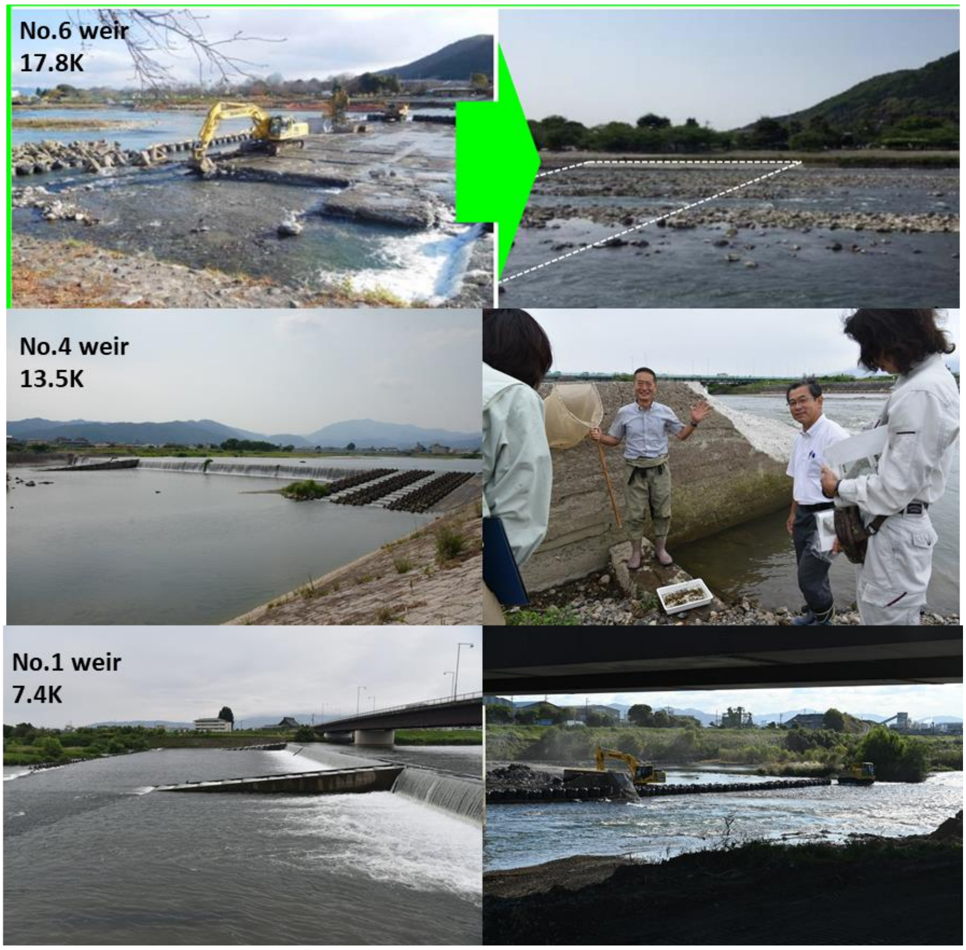


Fig. 4-3 Before and after (during) removal photos of No.6, No.4 and No.1 weir in Katsura River.

4.2.3 Materials

The Yodo River Bureau basically does biennially riverbed cross-sectional survey with a 200-meter interval after the flood season for the Katsura River (0-18K) while during some typhoon year the additional surveys would be carried out. Cross sectional data of the year 2005, 2013, 2015, 2017 and 2019 were selected in order to coincide with the arial photos acquired from the Yodo River Bureau and google earth software, which the latter is probably the most convenient and economically costless way for collecting high resolution historical geo-images. All selected aerial photos were taken during low-flow conditions, the criterion for the usable images is to check if the riffle habitats (white, wavy currents) could be clearly identified, which indicates the spatial resolution of the images are around 1m except for 2005 (3m).

Discharge and water level data was collected from the Water Information System (Ministry of Land, Infrastructure, Transport and Tourism), which contains the annual peak hourly measured discharge and the hourly measured discharge data for the mentioned years. Biennially conducted river environmental surveys and assessments report were also acquired from the Yodo River Bureau for extracting useful information such as sediment grainsize and biological data. Sediment grainsize measurements for the whole study segment was conducted once in 2011, and several times during weir removal projects latterly. According to the measurements, the mean grainsize diameter is 12mm and the average maximum grainsize diameter is 70mm, for which the estimated critical discharges are 2700m^3/s and 2900m^3/s respectively. Therefore, we measured the number of flood events and durations (hour) exceeding xx and xx. Finally, five categories of events magnitude were examined (200-500, 500-1000, 1000-1500, 1500-2000, 2000-2500m^3/s). Other supplemental data such as grainsize information for the whole study segment, and biological survey data are also collected from Yodo River Bureau.

4.2.4 Parameters of Reach Scale Channel Configuration (RSCC)

Similar to Mikyoung's study (Choi et al., 2018) in the Kizu river, a set of reach-scale geomorphological parameters were selected and definitions were showed in Table 2.5. low flow channel width (W), Sinuosity and shoreline length (Sl) were measured from high resolution aerial images (~1m), channel slope (S), and floodplain vertical shape index (FVSI) were measured using cross-sectional data with a 200-meter interval. According to knowledge, we first propose shoreline length to illustrate the geomorphic complexity of a given reach, with the higher the SL value indicates the more complicated geomorphology features that a reach has. SL is consisting of bare shoreline and vegetated shoreline, which does not only have geomorphological meanings, but also an indicator of aquatic habitat possibilities at the local scale. FVSI was calculated based on cross-sectional data with 200-meter intervals First the relative elevation of the riverbed elevation survey points relative to the normal water level was arranged in an ascending order, then the area of arranged shape B can be determined. And the triangle shape A is constrained by three points: the riverbed tangent to the water surface, bottom of the bank, and the top elevation of the bank (see Fig. 4-4). the value is positive if B-A is greater than A, and negative if it is less than A. A positive value of FVSI indicates a convex floodplain vertical shape, and a negative value indicates a concave vertical shape. FVSI shows the frequency distribution of riverbed relative to normal water level, which indicates the potential capabilities of a given reach in terms of creating suitable habitats for various biotic communities in rivers (Takemon, et at., 2013).

Table 4-2 Parameters of RSCC measured using satellite images and cross-sectional data in Katsura river.

Parameters	Definition	reference
Channel slope (S)	Ratio of fall (height) to distance along the channel	Gordon et al (2004)
Low flow channel width	The average width of active channel	Hohensinner et al (2011)
Sinuosity	Ratio of the main flow channel length to the valley length	Leopold and Wolman (1957)
Shoreline length (Sl)	Total shoreline length of each 2 km unit, which contains two categories: bare land lines and vegetated lines.	Takemon (2020)
Floodplain Vertical Shape Index (FVSI)	Difference of integral values of relative elevation of riverbed to normal water level and those of uniformly distributed elevation within a 2km unit	Takemon et al. (2013)

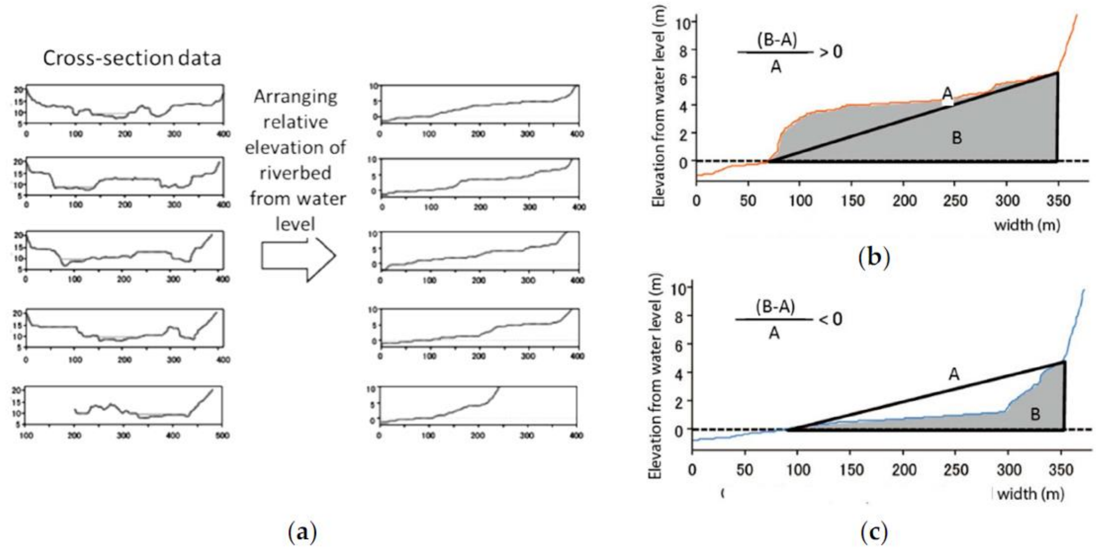


Fig. 4-4 (a) Method for calculation of FVSI using cross-sectional survey data; (b) a positive value of FVSI indicates a convex-shaped cross section profile of the floodplain; (c) a negative value indicates a concave vertical shape. Figure from Choil (2008).

Fig. 4-5 Shoreline length of three different reaches, left one is the downstream of No.5 weir, top right is the upstream of No.1 weir, and the last one is the downstream of No.1 weir.

Unlike the previous RSCC study of Kizu river which also located in Kyoto City and can be defined as a typical sandy river with much more sediment supply and thus the dominant channel form is braided channel (Choi et al., 2018) , the Katsura river has much less sediment supply and is defined as a typical gravel bed river, with a single thread channel at most parts of the study segment. Thus, parameters selected for RSCC are also simpler than that in Kizu river, we try to capture the most prominent evidence that showed \the channel form evolution and emphasize the corresponding controlling factors. In order to show the general characteristics of channel forms, we chose sinuosity and Braided index for defining channel type. As mentioned, channel sinuosity is defined as the ratio of the main flow channel length to straight-line valley length between two points. Braided index is quantified as 2 times the total bar length, divided by the reach length (Brice, 1960). Fig. 4-6 presents examples of how their variables are measured and braided index and sinuosity output values for conceptual reaches (Fuller et al., 2013).

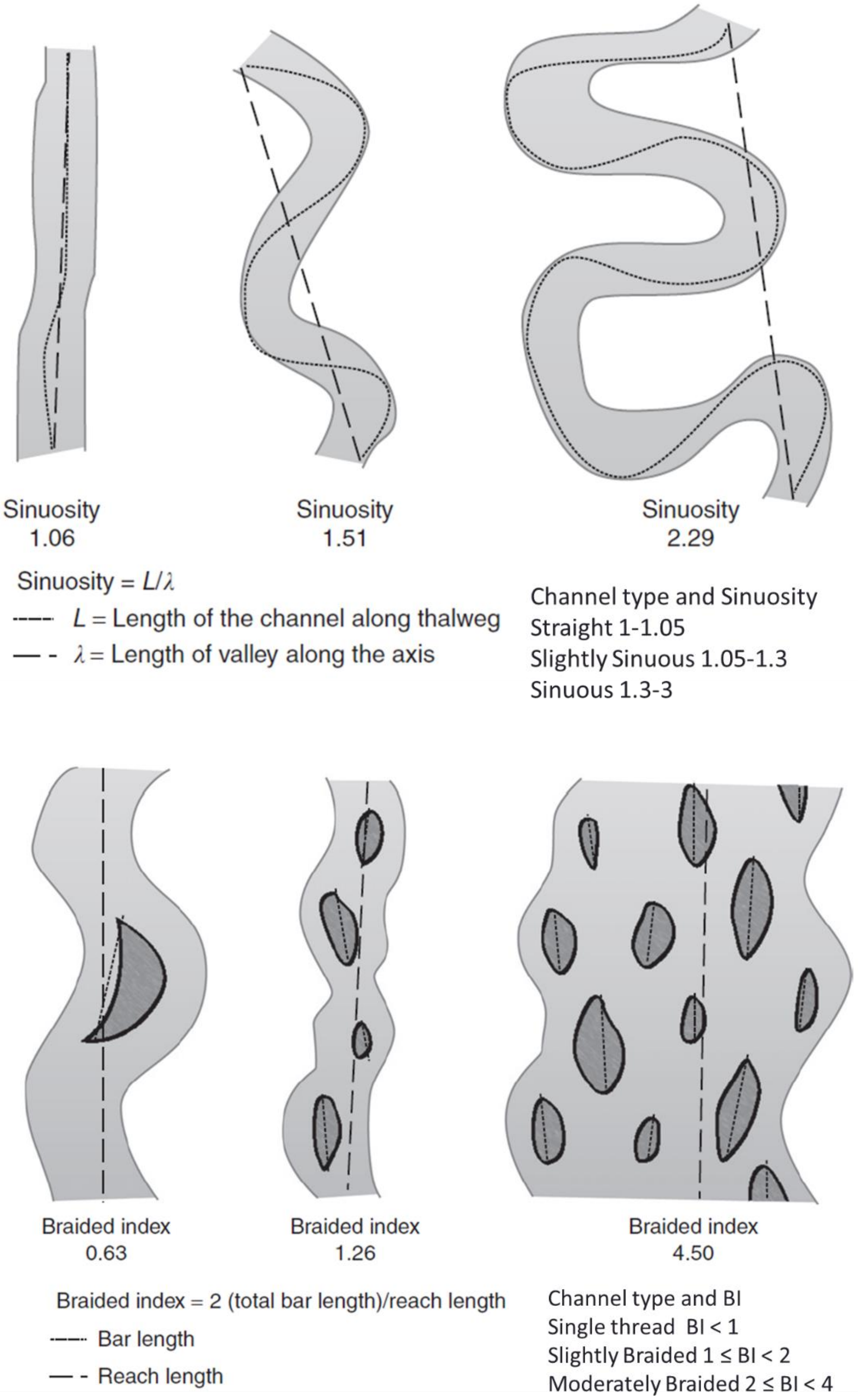


Fig. 4-6 Assessment of planform attributes sinuosity (top) and braided index (down) used to describe channel type. Figure was referred from (Fuller et al 2013) and adapted.

Based on the channel type classification criteria described before and the channel characteristics of the Katsura river, we define 9 channel types by the combination of channel sinuosity and BI, as Table 4.3 shows.

Table 4-3 Classification of channel types in the Katsura River.

Braided Index	Channel types	Abbr.
Single (BI < 1)	Single *StraighT* ($1.0 \le S < 1.05$)	S*st*
	Single *Slightly Sinuous* ($1.05 \le S < 1.3$)	S*ss*
	Single *Sinuous* ($1.3 \le S < 3$)	S*s*
Slightly Braided ($1 \le BI < 2$)	Slightly Braided *StraighT*	SB*st*
	Slightly Braided *Slightly Sinuous*	SB*ss*
	Slightly Braided *Sinuous*	SB*s*
Moderately Braided ($2 \le BI < 4$)	Moderately Braided *StraighT*	MB*st*
	Moderately Braided *Slightly Sinuous*	MB*SS*
	Moderately Braided *Sinuous*	MB*s*

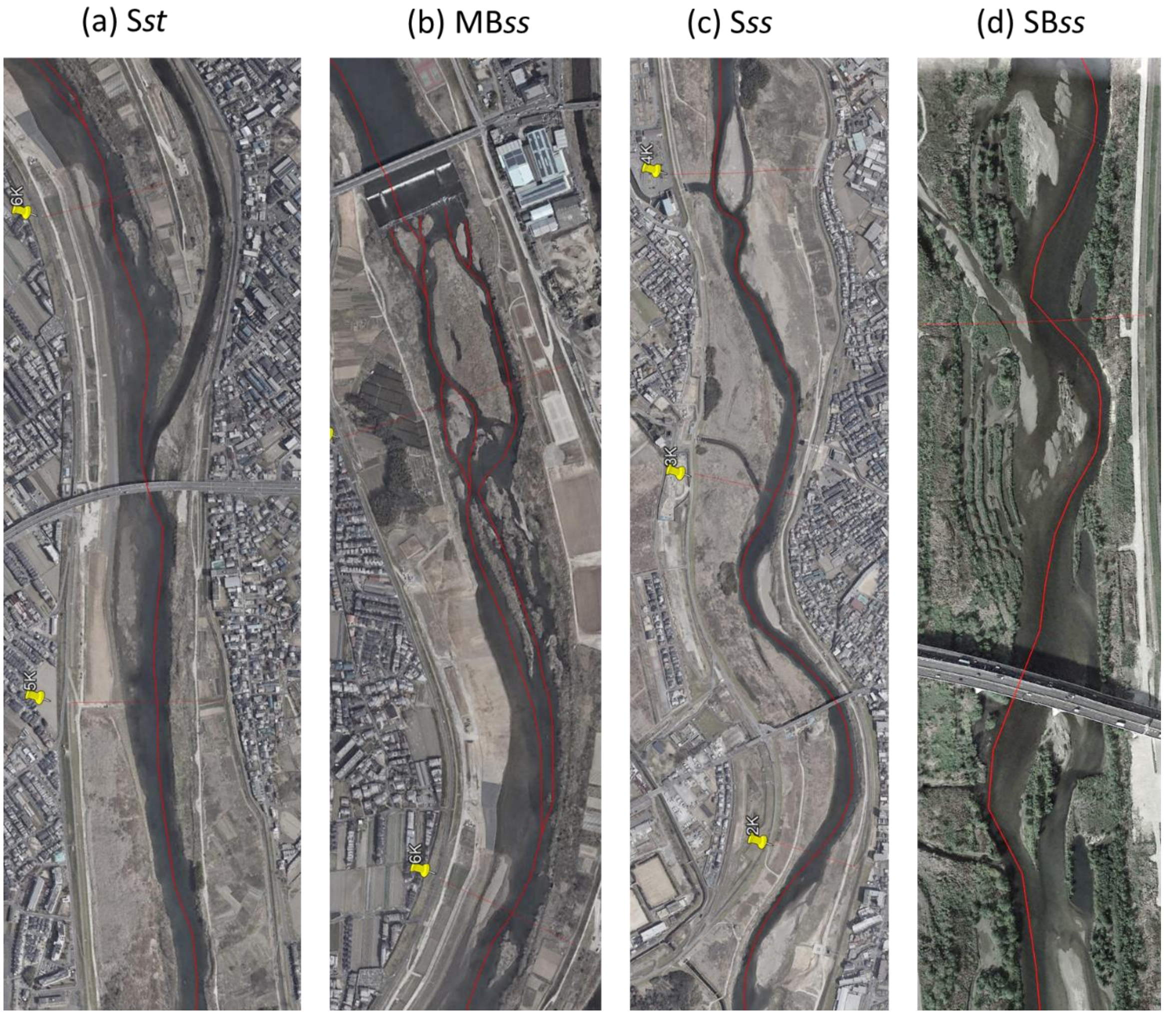

(a) S*st* (b) MB*ss* (c) S*ss* (d) SB*ss*

Fig. 4-7 Examples of the channel patterns in the Katsura river (2017), (a) indicates Single Straight (Sst), (b) shows the channel pattern downstream of a weir as Moderately Braided Slightly Sinuous, (c) presents the Single Slightly Sinuous channel type and (d) demonstrates the Slightly Braided Slightly Sinuous channel type.

4.2.5 Interpolation of the riverbed bathymetry using cross-sectional data

The Yodo River Bureau surveyed the riverbed elevation data biennially during the low flow season using the wader and boat method, with a 200-meter interval in the study area, however, due to the frequently on-going river engineering works, in some years and some specific reaches the data sets are not complete for example due to the on-going project of the NO.4 weir removal in 2017 the surrounding area was not surveyed. We first tried to use the alternative data to represent the un-surveyed area, however, the accuracy of the data from other sources could not match the ground survey data, thus, we decide to omit the area without original data and using different time period to compare the bed change.

The surveyed data uses the relative coordinate system, from 0 at the left bank mark, to the right bank mark and over. In this sense, we used the TKY2JGD Ver.1.3.80 coordinate transformation system provided by the Geospatial Information Authority of Japan to transfer the relative coordinate system into geographic coordinate system which could be imported in ArcGIS. Before processing the cross-section data in ArcGIS using geospatial interpolators, the 200-interval data was first interpolated in the mesh-generator software Blue Kenue using a linear crossline interpolator to generate more denser cross-section profiles. Then the already interpolated profile with the original profile were imported into ArcGIS and interpolated to grid by OKA methods, due to the fact the after testing IDW, UK, OK and Natural Neighbor, we found that the generated river bathymetry result by OKA showed the least RMSE value and has the smoothest surface compared to other methods. Therefore, we used the exact same algorithm to process all data sets we have. In this sense, we assume there is a global error for all the data sets when compared to the real world, however, what we care about in this study is the bed change between two data sets, thus the global errors do not influence the final results.

After interpolating five sets of DEMs, the latest version of Geomorphic Change Detection software (GCD 7.5.4) was used to visualize the riverbed change between each two sets of DEMs and calculate the volumetric storage change. The detailed method of using GCD software can be referred to Wheaton (Wheaton, 2014).

4.2.6 Habitat structures identification and classification

In total, we selected four types of habitat structure to analyze in this study, namely riffles (3 sub types), wandos, pools, and man-made habitats. Riffles were further divided into “Diverged type”, “Transverse type” and “Concentrated type” based on Kobayashi’s previous work on the Tenryu River in Japan (Kobayashi and Takemon, 2013).

For riffle-pool dominated gravel bed rivers, to accurately identify and classify riffle habitat structures, the first step is to understand the location of riffle-pool sequence undulation at larger scale from the riverbed longitudinal profile. Alternate bars and point bars are important indicators of possible riffle structures because the riffle structures were normally created at the “tail” of the upstream bars and “head” of the downstream bars. Diverge type bars usually have a “younger age”, which means they were created not so long after the last flooding event, when newly deposited sediment remains a smooth surface with well sorted sediment grains, the word “Diverge” indicates the angle of the bar edge, according to the picture of Kobayashi and Takemon (2013).

Sediment deposition in the “riffle” area would likely to cause the changing direction of the flow, which gradually will change the Diverge type habitat to the Transverse type, which is described as a thin, belt-shape area with high elevation difference, usually located at the flow direction changing place. After flooding season and during the low flow period, due to the constant water flow structures and the lack of sediment supply from upstream, finer materials from the surface of “Diverge” type habitats will be transported to the downstream, and erosional pattern will be dominant during this period. With prolonged and continues erosional pattern during low flow season, the erosion at the surface of "Transverse" type riffle will be proceeded and emphasized, gradually many small "braided gut" will be created at the T-type habitat and transform it to the Concentrate type habitat (see Fig. 4-8.). Fig. 4-9 shows the different stages of erosional pattern of the concentrated type of riffle, and up to the next flooding event will bring sediment and deposited here to form the Diverge type habitats, the cycling patterns have been detected from sets historical of satellite images.

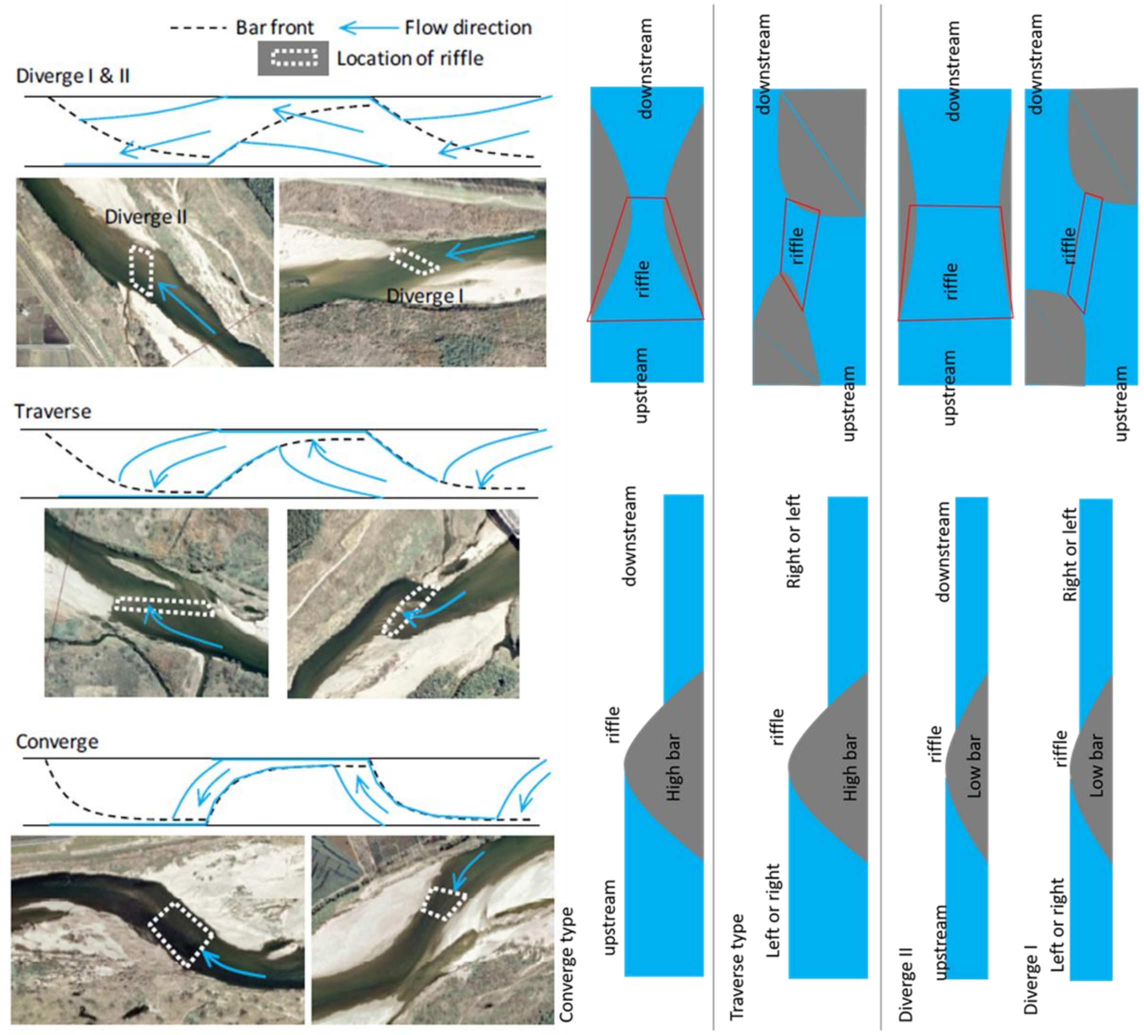


Fig. 4-8 Schematic view and aerial photos of 4 riffle types in the Kizu river from Kobayashi and Takemon, 2013.

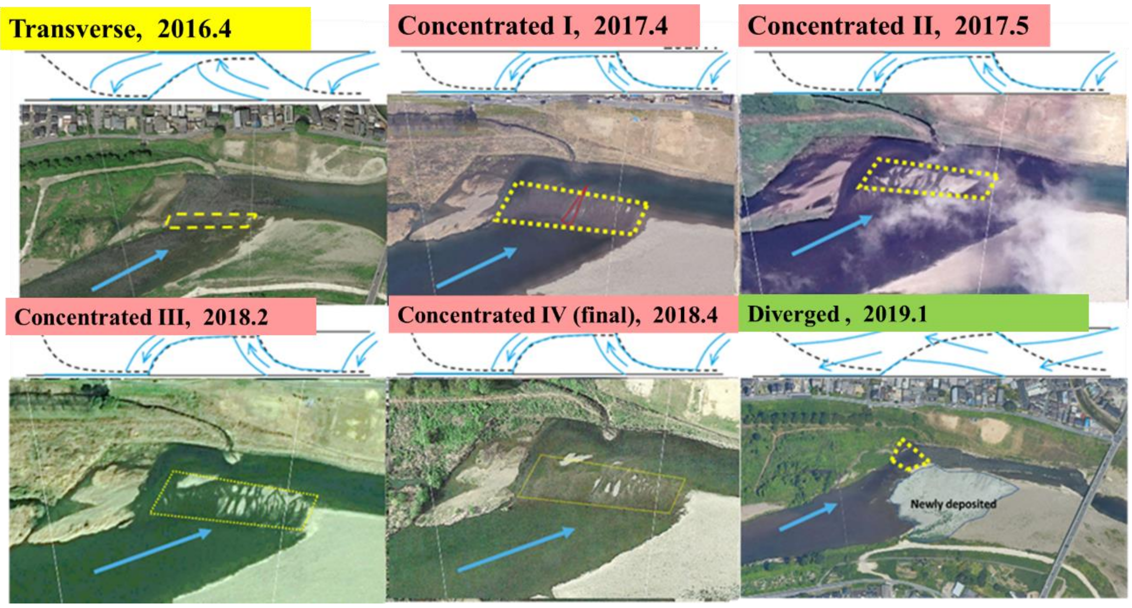


Fig. 4-9 Habitat evolutionary patterns in Katsura river, pictures showed that at 14.7K (upstream of former No.4 weir), from 2016 a Transverse type riffle gradually became multi-braided Concentrated type in 2017 and 2018, after a flood in 2019 and with new deposited sediment, it became the Diverged type riffle.

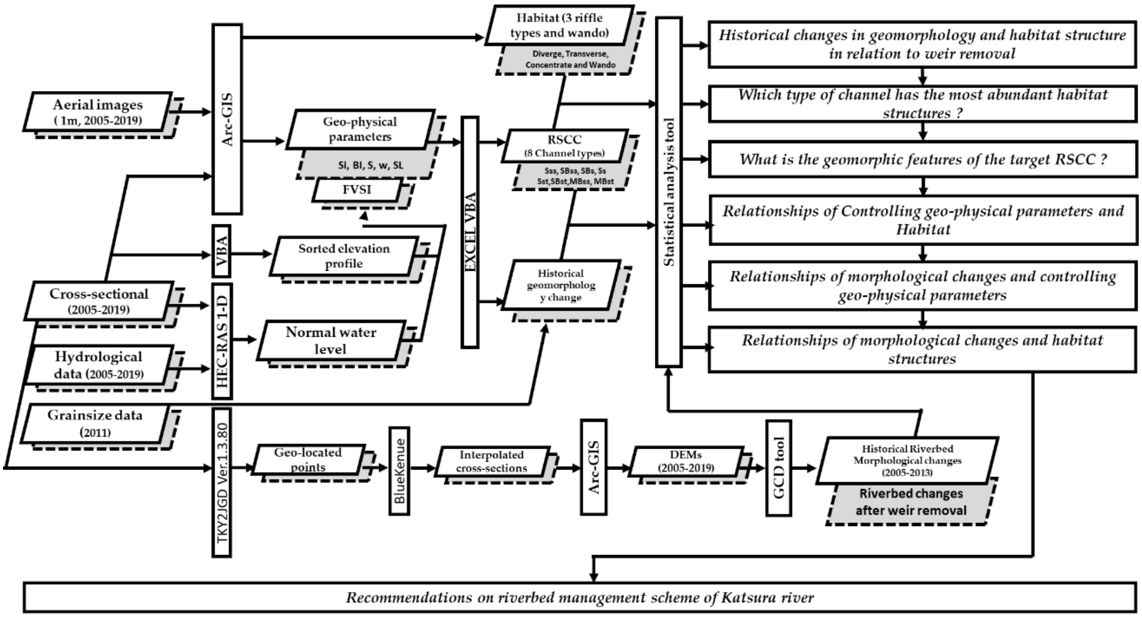


Fig. 4-10 Method flow chart of this chapter.

4.2.7 Statistical analysis

Statistical analysis focused on the empirical relationship among riverbed dynamics (volumetric changes), geomorphological parameters, and riffle habitat abundance, all variables are first listed up according to their spatial distributions (from upstream to downstream). The normality tests were done by R software. Variables that passed the normality test, and variables that are nearly normal distribution (determined by visualization of histograms) were then used for correlation analysis using Pearson correlation test method. The other data was analyzed by spearman method. While in this study, most of the data sets are not normally distributed, thus, Spearman test was used for all data sets from the beginning.

Fig. 4-11. shows the order of correlation analysis, First, analysis was done between channel geomorphic parameters and riffle structures (Geo – habitats), then the specific (stream power during low flow conditions) with riffle structures was examined (hydrogeomorphic – habitats). Secondly, we investigated the relationship between riverbed morphological dynamics and riffle habitats (morphodynamics - habitats). At last, the riverbed morphodynamics and geomorphic parameters (Morphodynamics - Geo), relationships within geomorphic parameters are examined.

The channel local geometric changes and the resulted habitat structures are controlled by the reach scale channel dynamics (RSCD), thus the empirical relationships between RSCD and geomorphic parameters, and finally RSCD with riffle structures were examined. In the second step however, in Katsura river of the cascade weirs, in reaches with weir, the riffle structures are hardly seen especially upstream of a weir due to the back water effects, downstream has chances to develop riffle structures while the location is limited to downstream-reach of the most downstream weir, because weirs differ in size and due to the close distance between each two of them, the back water effect will overlap and thus can be extended to the upstream weir. As we can see from Fig. 4-1, especially from No.3 to No.1 weir (12.0-7.4k), the two biggest one in the study area, riffle structures are very limited, only appears more since 2017 No.4 weir removal. In this sense, it is reasonable to omit this impoundment segment and check the other two segments of Katsura river, in terms of the empirical relationships among our hypothesized controlling factors and resultant riffle structures. Therefore, in the second step, we repeated the correlation analysis while eliminate the data sample of the segment between No.3 and No.1 weir. Then the regression analysis was done for the selected combination of the geo-habitat parameters. An P value of 0.05 was used to indicate the statistical significance for all tests. Statistical analysis was performed by using MATLAB R2021a (MathWorks Inc), EXCEL (Microsoft Inc) and R (Exploratory Public).

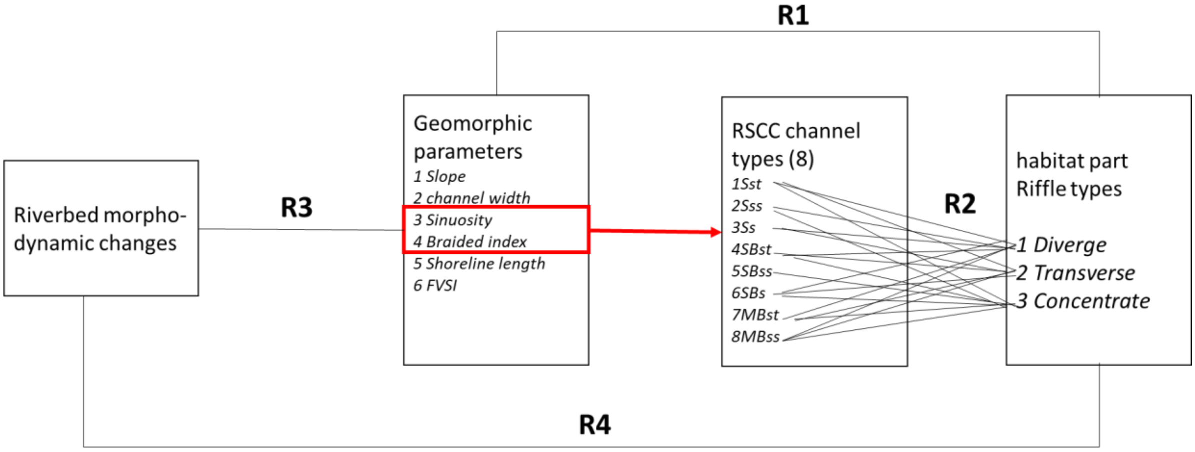


Fig. 4-11 Flow chart of statistical analysis.

4.3 Results

4.3.1 Historical changes in channel geomorphology

The riverbed longitudinal profile of Katsura river is featured by steep channel gradient from the 18.0K until the No.3 weir, gentle gradient in the segment between No.3 and No.1 weir, and flatter bed until the 0.0k. The bed slope of Katsura river is controlled by No.3 and No.1 weir, the two biggest one set up downstream boundaries for the two segments, since channel slope is a fundamental characteristic of the river. The results also showed that the upstream and downstream bed are more active comparing to the segment within No.3 and No.1 weir. Fig. 4-12 shows the historical water profile of Katsura river during low flow conditions. The surface water profile is distinctive from upper to the lower segment in Katsura river due to the weir construction, step-like segmentations are dominated from upper to the lower until No.1 weir. Only limited area that has more natural surface water profile can be found, located at downstream of No.6 weir and downstream of No.5 weir. However, the longitudinal profile was drastically changed in 2017 and 2019, due to two weirs' removal, the original step-like profile was changed to more natural profile. As to the lower segment downstream of No.1 weir, local erosional and depositional patterns were detected during the study period.

The low flow channel width profile of Katsura river is coincide with the slope profile, which the upper reach has the mixed large width just upstream of No.5 weir (16.1k) and smaller width downstream of it. While the low flow channel width is the largest within the segment between No.3 and No.1. In further downstream from No.1 weir until the river conjunction, the low flow channel width is the smallest.

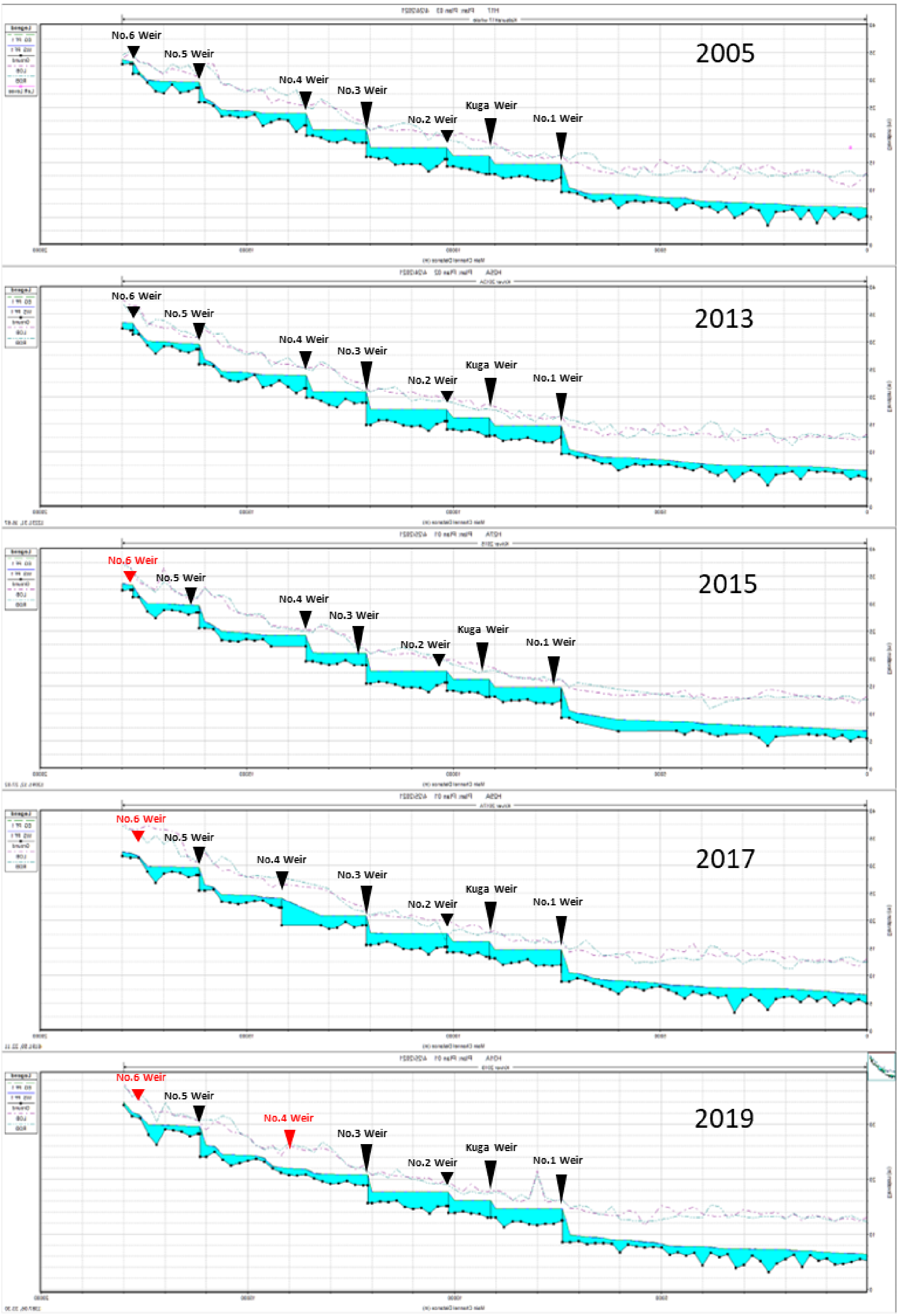


Fig. 4-12 Surface water profile during low flow conditions in the study period.

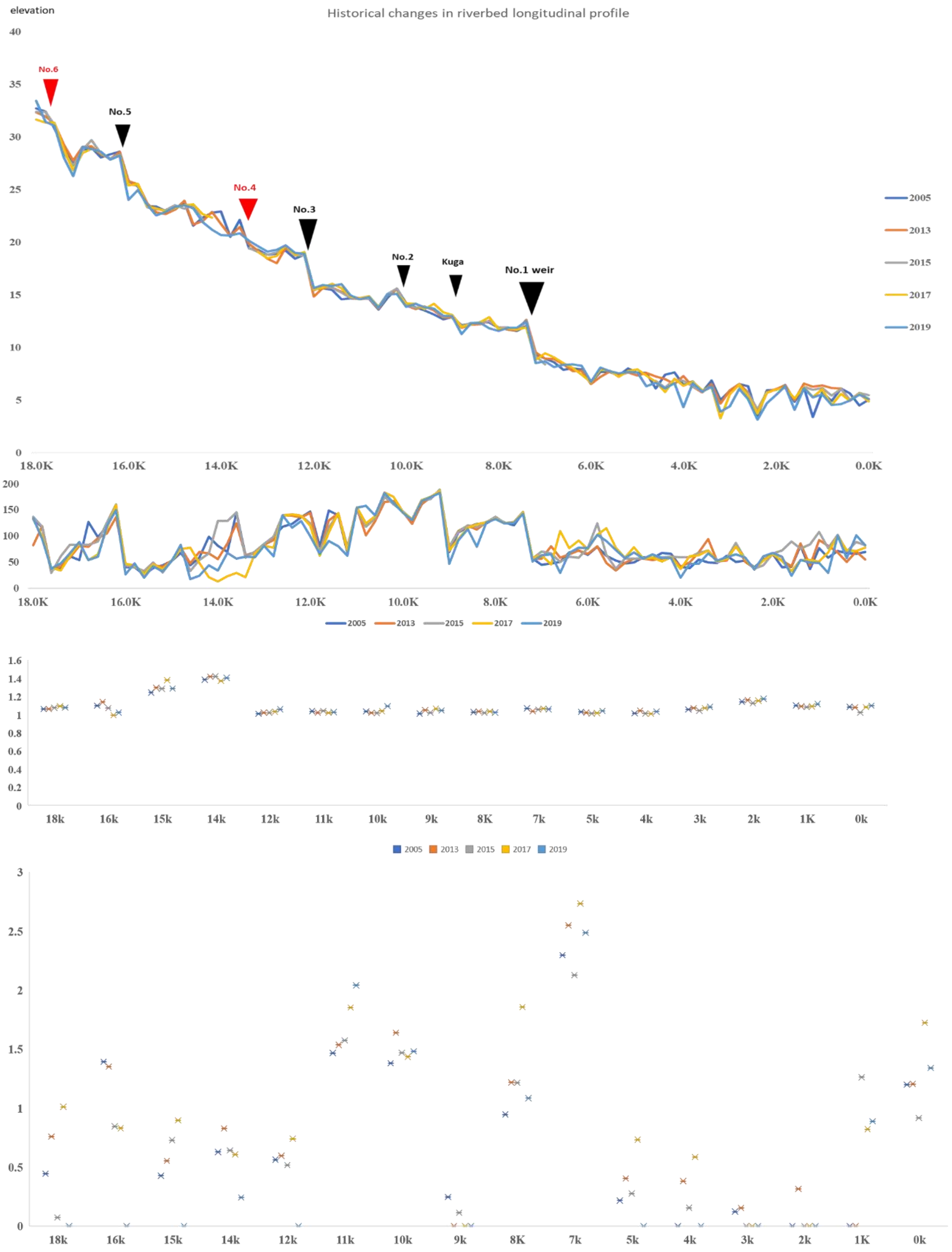


Fig. 4-13 Historical changes in channel slope, low flow channel width, sinuosity and braided index, picture order from top to downside.

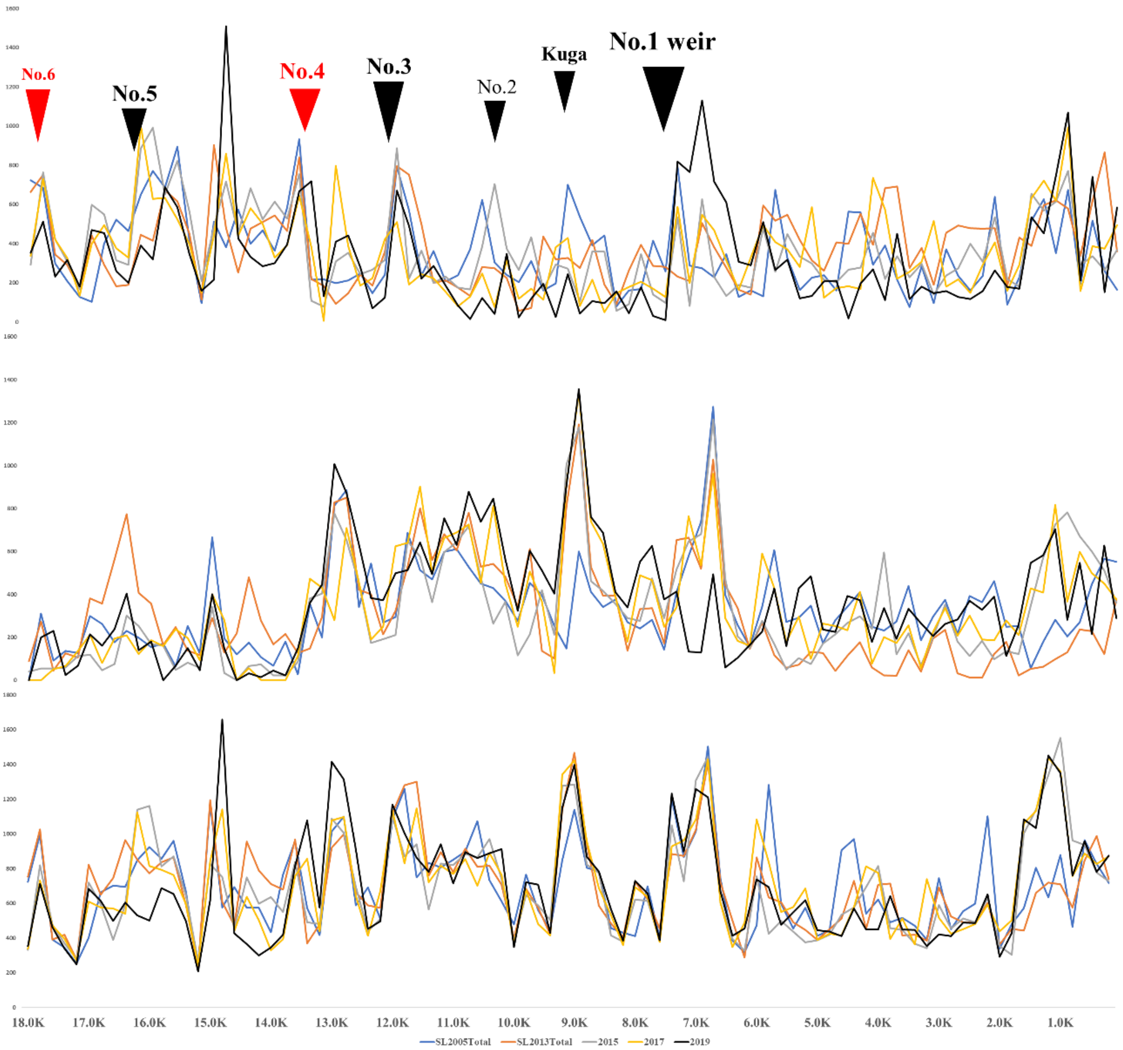


Fig. 4-14 Historical changes in shoreline length, top: changes in bare shoreline length, middle: changes in vegetated shoreline length, and down: changes in the total shoreline length.

The historical changes for the profile of low flow channel width are highly correlated to weir removal, for instance in the year after the breaching of No.4 weir, the low flow channel width decreased dramatically from more than 140m to 20m (Fig. 4-13, yellow line). As to the weir dominated segment between No.3 and No.1 weir, the channel width at downstream of No.3 weir also showed significant change in 2019, which is due to more sediment deposition at this reach. As to further downstream, low flow channel width slightly increased from 2005 to 2015, in 2017 it further increased during the 5.0-7.0k, while decreased at the lower end. In 2019, low flow channel width generally decreased by as significant value.

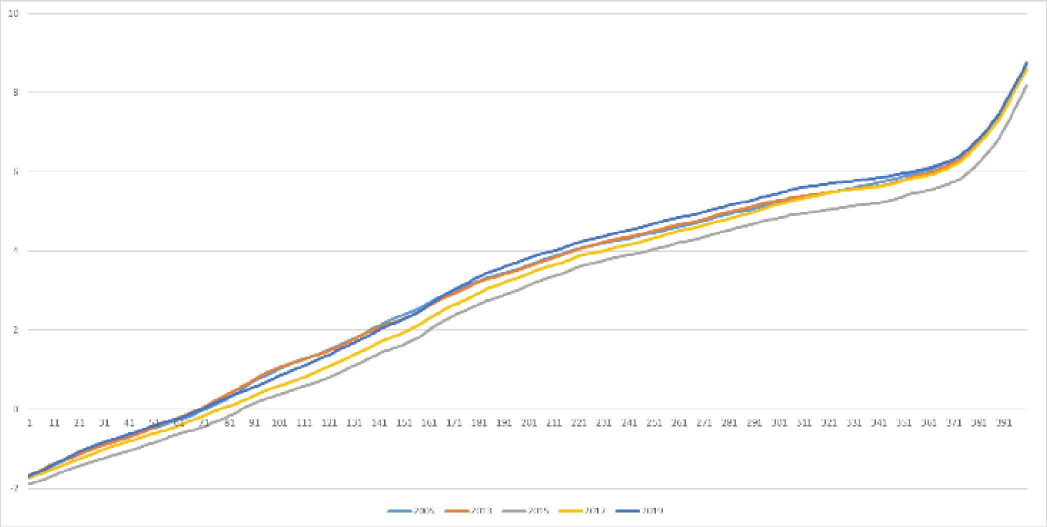


Fig. 4-15 Historical changes in FVSI for the study segment of Katsura river.

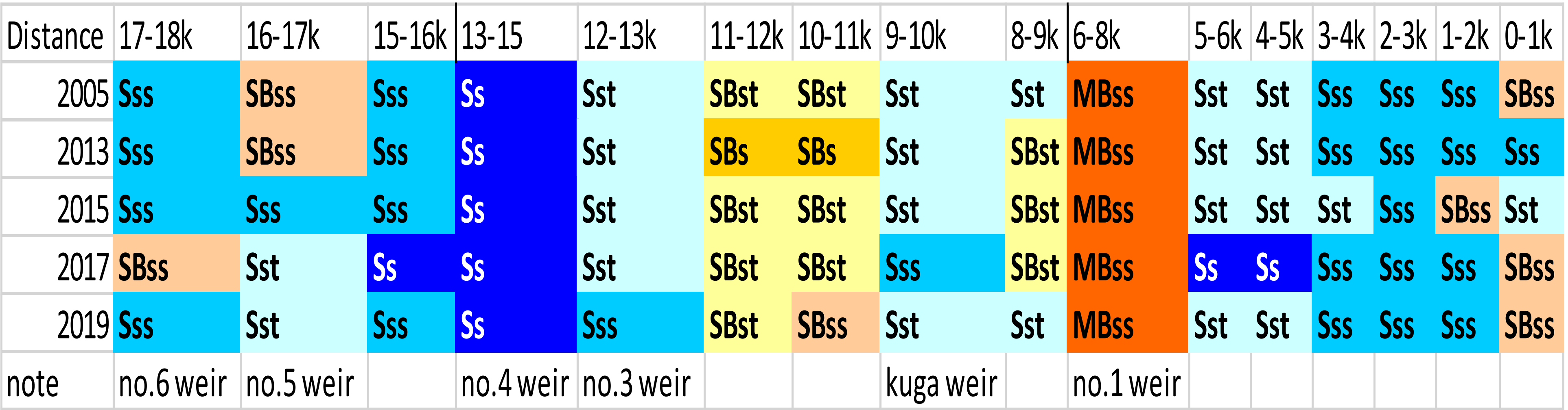
Historical changes in shoreline length are showed in Fig. 4-14, the top picture shows the historical bare shoreline change, which is longer in the upper and downstream segment, while it is the shortest between No.3 and No.1 weir. Middle picture shows the vegetated shoreline length, opposite to the upper one, the vegetated shoreline is the most abundant between the two weirs. The upper stream is the shortest in length and downstream is slightly longer especially near the conjunction. For the total length is most abundant at reaches just downstream of weir and near the conjunction. Shoreline length is generally decreased throughout the study period, while locally increased for instance in 2019 the upstream reach of former No.4 weir, showed significant increase in bare shoreline length.

4.3.2 Historical changes in Reach Scale Channel Configuration

Similar to Mikyong (2013) who used RSCC to classify the different reaches in the Kizu river, we use the similar strategy to classify the reach scale channel types in Katsura river, and later to check the habitat structures that contained in each channel type. Sinuosity and BI were used to classify the RSCC channel types, as showed in Fig. 4-16, generally from the upstream end (18.0K) until No.4 weir, the channel of Katsura river has a single and sinuous form, then the channel form become straight with multiple weirs constructed. And the braided type of channel is appeared which is mainly located downstream of each weir. Moderately Braided and Slightly Sinuous channel was found in every year downstream of No.1 weir, which is the largest one and from the historical aerial images we found this channel form (MBss) is very stable. At upstream, channel at 16-17K became less braided and more straight form historically, which indicates the gradually reduced sediment supply from upstream. However, the 17-18K and 15-16K became more braided and sinuous between 2015 and 2017, which is because the additional sediment supply from the No.6 weir removal caused local sediment relocation and thus has changed the RSCC channel type. From 2017 to 2019, due to the dominant erosion process, these two reaches had returned to the simpler form.

In the middle segment, the channel form is much less sinuous than the upstream segment, and braided channels are mainly found at downstream of the biggest (No.1) and second biggest (No.3) weir of the study segment. The historical channel form change in the middle segment also indicates the riverbed deposition and erosion patterns. From 2005 to 2013, the channel became more sinuous and braided at 10-12K and 8-9K respectively, due to the sediment deposition, which is further confirmed in the next section – the historical riverbed morphological changes. Then from 2013 – 2015, similar to what happened in the upstream segment, the channel form had returned to the original simpler form. While since the No.4 weir was removed during 2017 and 2019, the channel form again become more braided and sinuous.

As to the downstream segment, the historical channel form change is coincided with the upper segments. Sediment deposition mainly happened near the conjunction (0.0K) and formed braided channels.



Distance	17-18k	16-17k	15-16k	13-15	12-13k	11-12k	10-11k	9-10k	8-9k	6-8k	5-6k	4-5k	3-4k	2-3k	1-2k	0-1k
2005	Sss	SBss	Sss	Ss	Sst	SBst	SBst	Sst	Sst	MBss	Sst	Sst	Sss	Sss	Sss	SBss
2013	Sss	SBss	Sss	Ss	Sst	SBs	SBs	Sst	SBst	MBss	Sst	Sst	Sss	Sss	Sss	Sss
2015	Sss	Sss	Sss	Ss	Sst	SBst	SBst	Sst	SBst	MBss	Sst	Sst	Sst	Sss	SBss	Sst
2017	SBss	Sst	Ss	Ss	Sst	SBst	SBst	Sss	SBst	MBss	Ss	Ss	Sss	Sss	Sss	SBss
2019	Sss	Sst	Sss	Ss	Sss	SBst	SBss	Sst	Sst	MBss	Sst	Sst	Sss	Sss	Sss	SBss
note	no.6 weir	no.5 weir		no.4 weir	no.3 weir			kuga weir		no.1 weir						

Fig. 4-16 Historical changes in RSCC channel types of Katsura river.

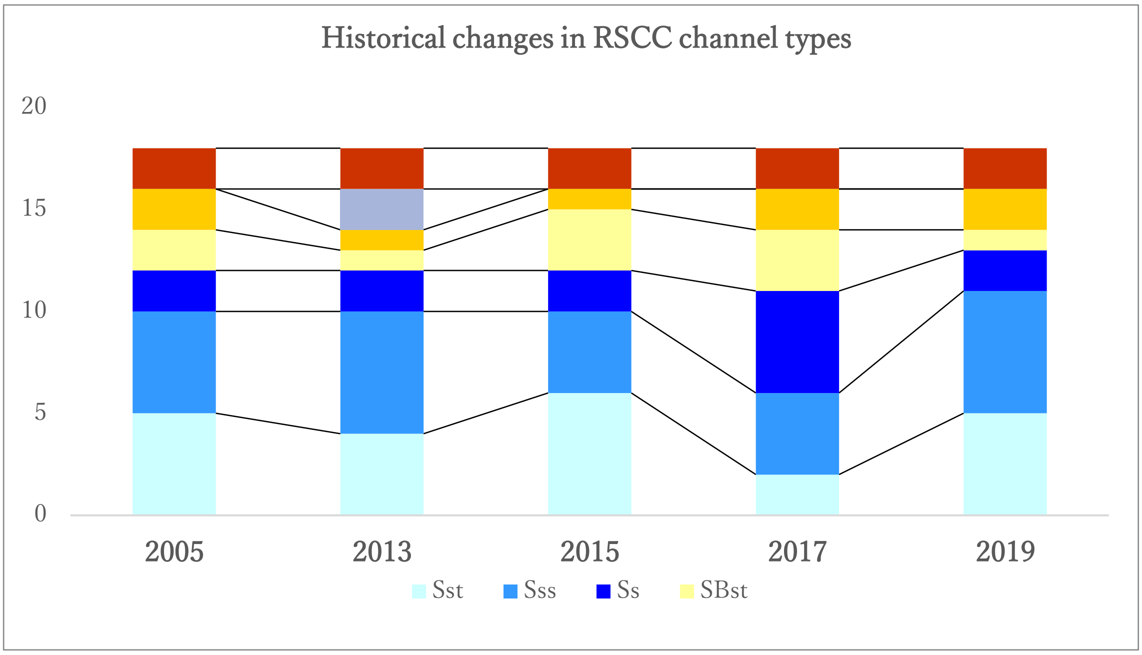
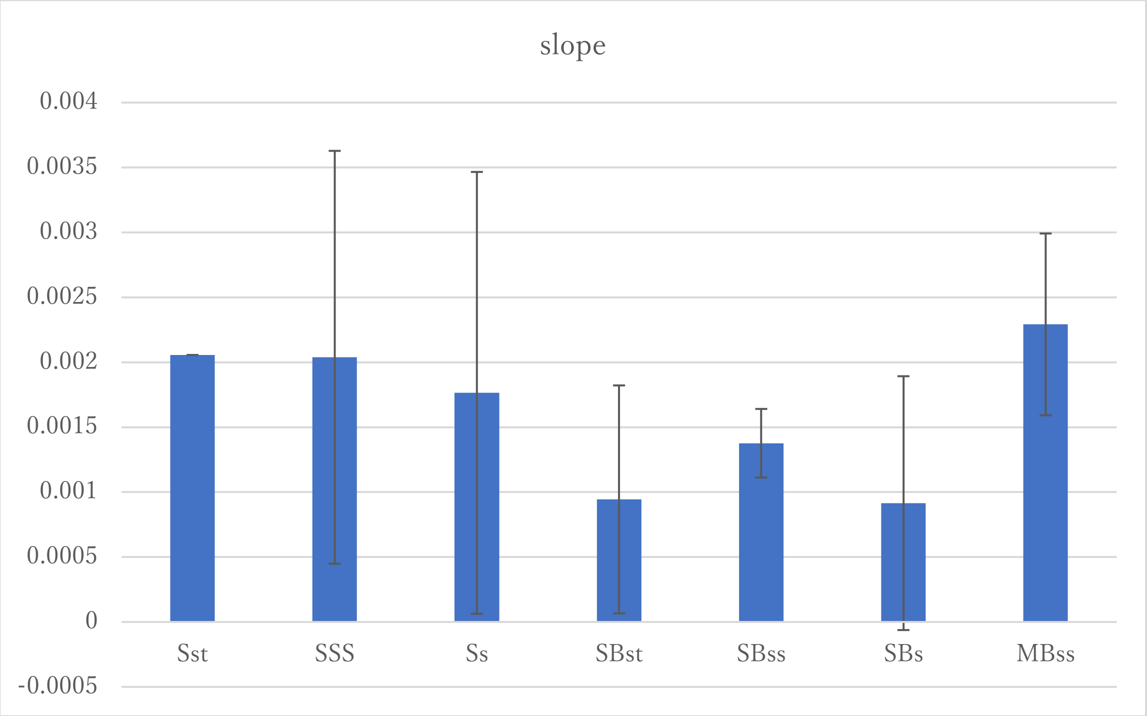
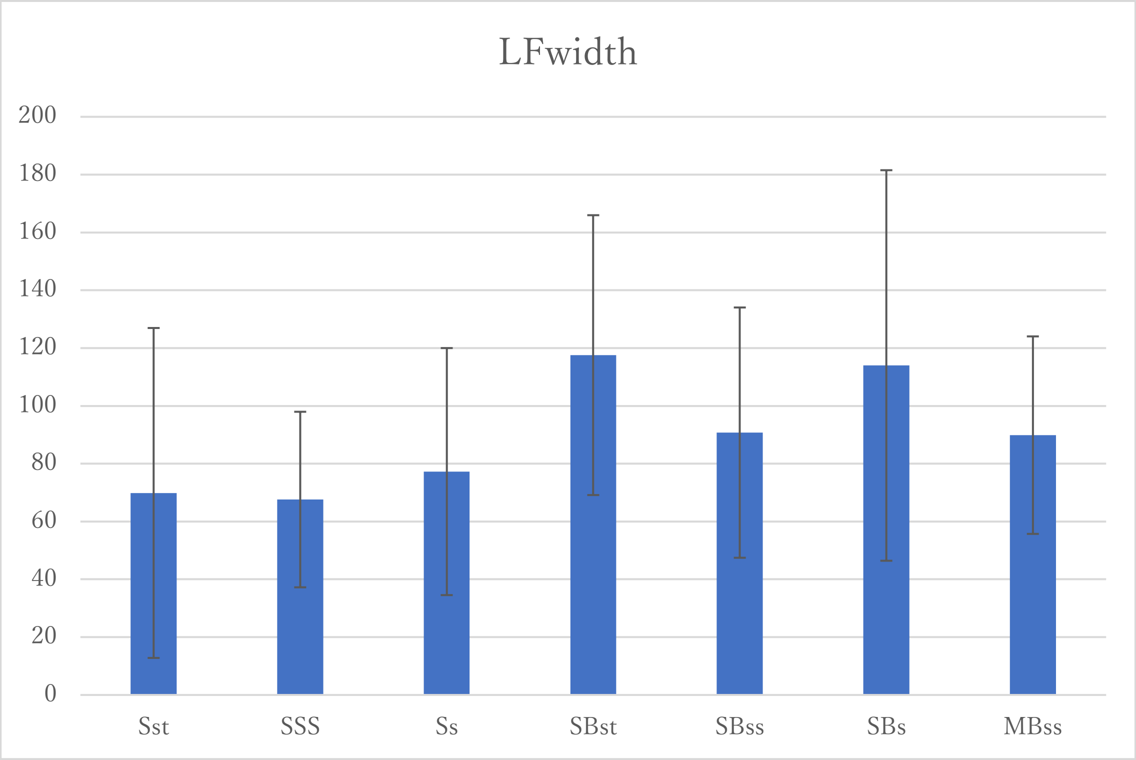
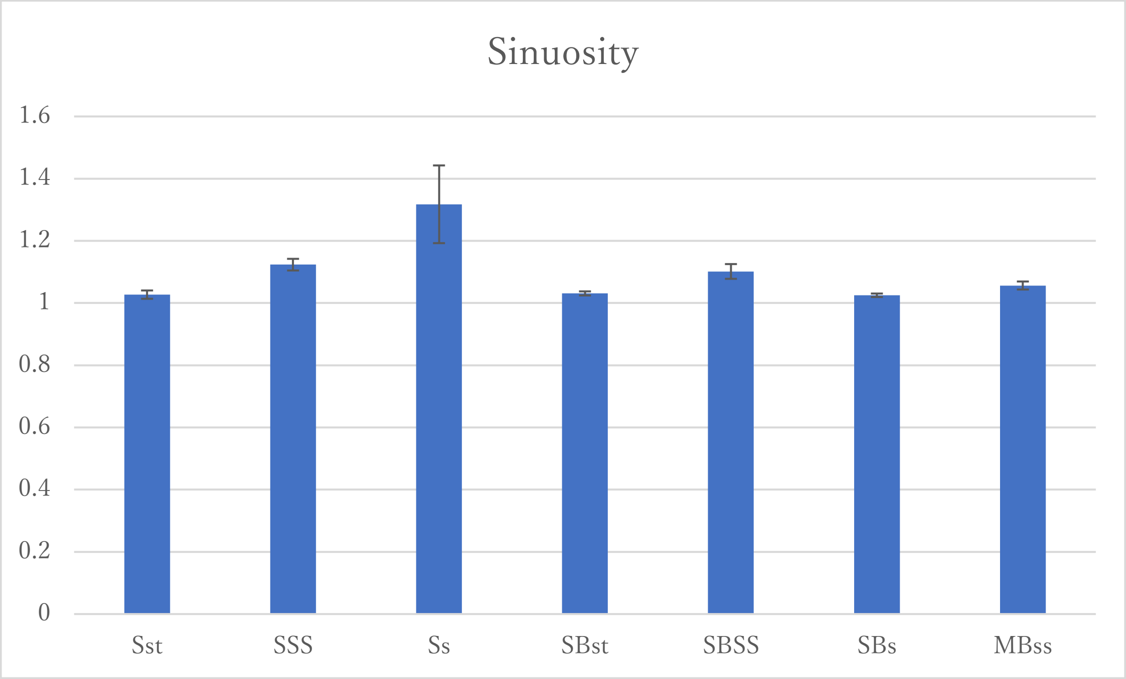


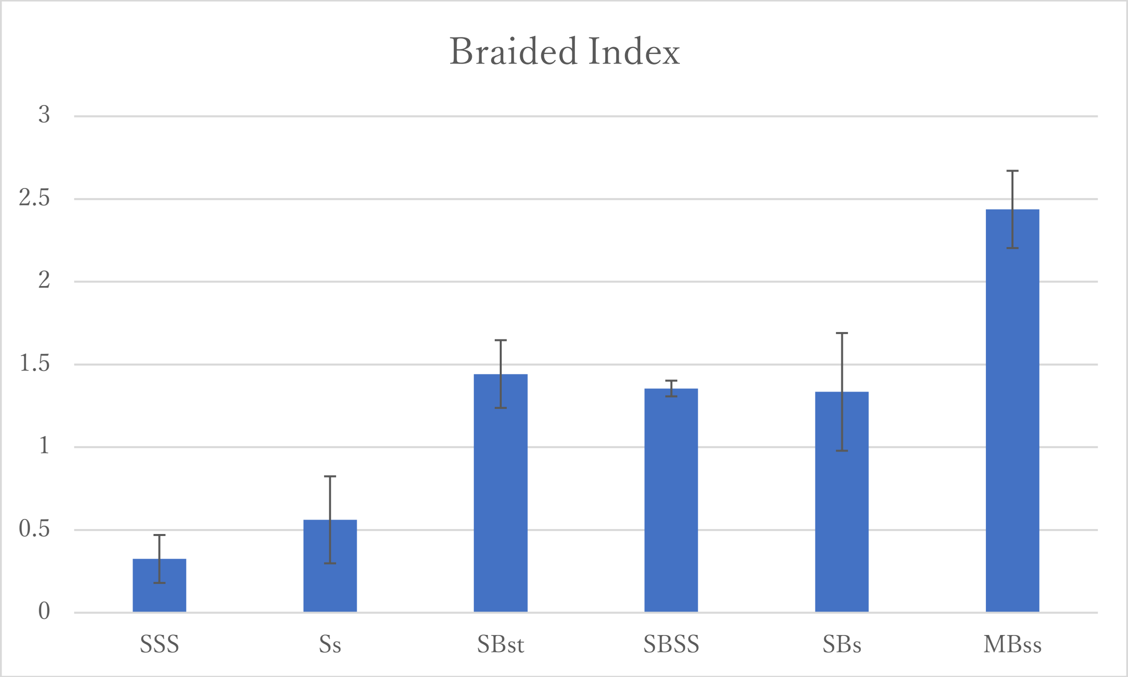
Fig. 4-17 Historical changes of channel type in Katsura river.

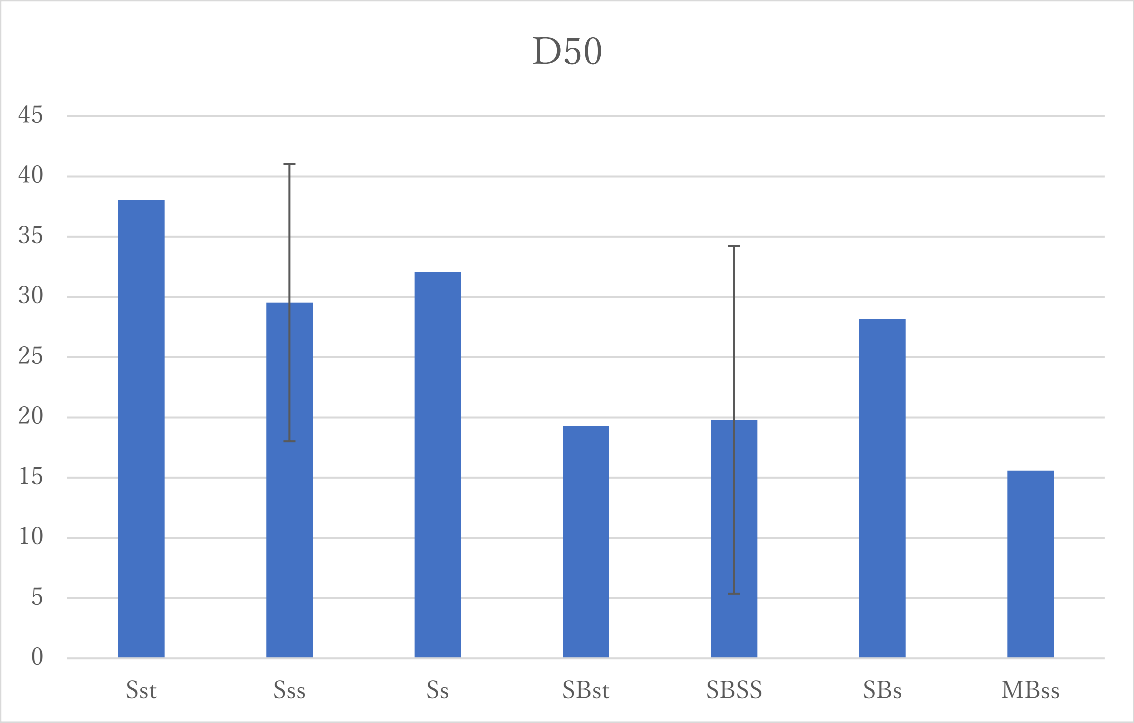
The geomorphic characteristics of each RSCC channel type are showed in the Fig. 4-18. RSCC channel types are classified based on channel sinuosity and braided index, obviously the Sinuous type of channel has the highest sinuosity and the braided channel types are high in braided index. Interestingly, the MBss channel type has the highest slope in the study segment, and MBss type of channel is located only at downstream of No.1 weir, the high slope value is contributed by the channel incision at this reach. Slightly Braided straight channels are located mainly at downstream of No.3 weir, which has the lowest slope value. Ss and Sss channels are located at both upstream where the gradient is the highest and at downstream end where the gradient is the lowest, which is the reason why the averaged slope value of these two types of channels is ranked in the middle among all RSCC types. Basically, the braided channel types have wide low flow channel width which is due to the backwater effects of the cascade weirs, and Single thread channel types has lower low flow channel width. Ss and Sss channel types has the narrowest low flow channel width in the study segment. MBst channel type has the lowest FVSI value, which indicate the channel bank shape might have better ecological functions. However, the MBst channel is only located at the downstream of No.1 weir, where the channel incision has been prevailed and thus would compromise the potential ecological functions it may provide. Generally, the single thread channel has higher FVSI value than the braided channels, this is due to the fact that the downstream sub-segment has the narrowest low flow channel width and due to the enormous sediment erosion rate, the channel become deep and thus the FVSI is higher. Located only at the downstream of No.1 weir, MBst channel has the largest D50 value (17.9mm)among all RSCC types. Ss and SBst also have large D50 (around 15.8mm).




LFwidth
200
180
160
140
120
100
80
60
40
20
0
Sst
SSS
Ss
SBst
SBss
SBs
MBss


Sinuosity
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Sst
SSS
Ss
SBst
SBSS
SBs
MBss


Braided Index
3
2.5
2
1.5
1
0.5
0
SSS
Ss
SBst
SBSS
SBs
MBss


D50
45
40
35
30
25
20
15
10
5
0
Sst
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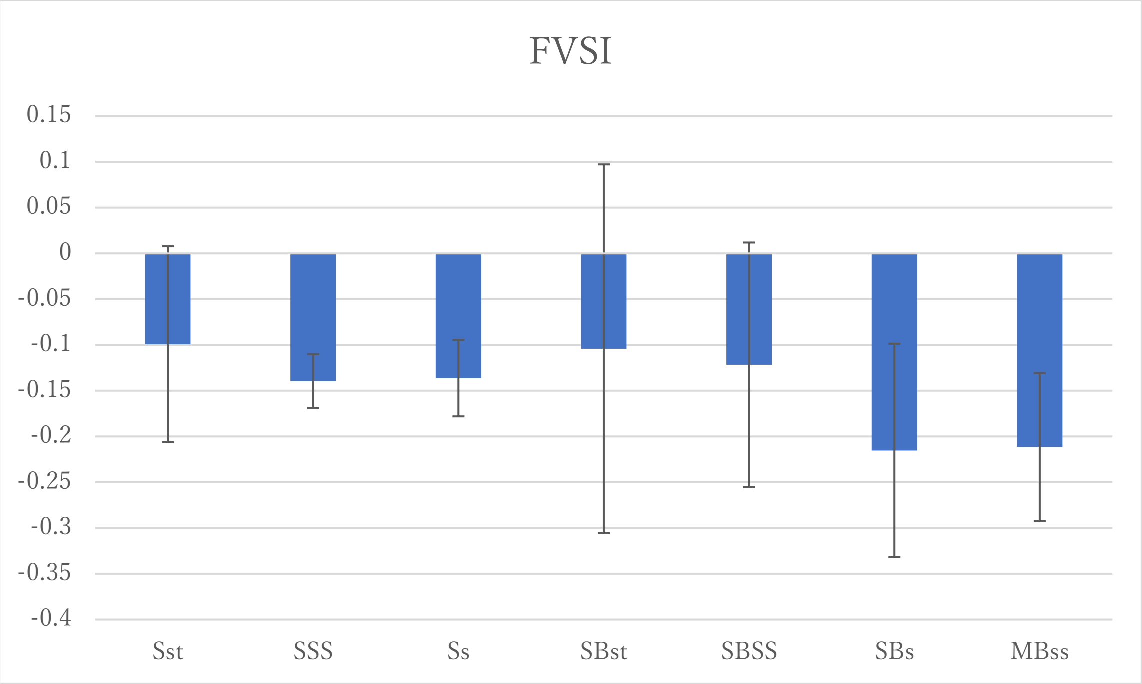


Fig. 4-18 Geomorphic features of 8 RSCC channel types. Error bars show the Standard Deviation.

4.3.3 Historical riverbed morpho-dynamics

Fig. 4-19 shows the historical riverbed morphological changes at the whole study segment scale. From 2005-2013, the US (No.6-No.3 Weir) showed a mixed pattern of deposition and erosion, for which the latter happened mainly at the outside of the channel bend. In the MS (No.3-No.1 Weir), downstream of No.3 and No.1 was deposited mainly, however, downstream of No.2 and Kuga which were located in the middle of No.3 and No.1 were changed very little, despite after the historical peak discharge of 2013. DS (No.1-0K) was aggraded at the upper part while the at downstream end near to the river confluence was mostly eroded due to the river-excavating works done in 2012 for the purposes of flood mitigation. As to 2013-2019, riverbed was significant eroded at the two weir removal sites. As a result, at both upstream and downstream of No.5 weir and No.3

weir sites, depositional pattern was detected. MS also showed depositional pattern as more sediment coming from upstream. The upstream part of DS showed the opposite changing pattern compared to 2005-2013, for which the upper part was excavated during this period, and as a result, downstream near the conjunction was deposited.

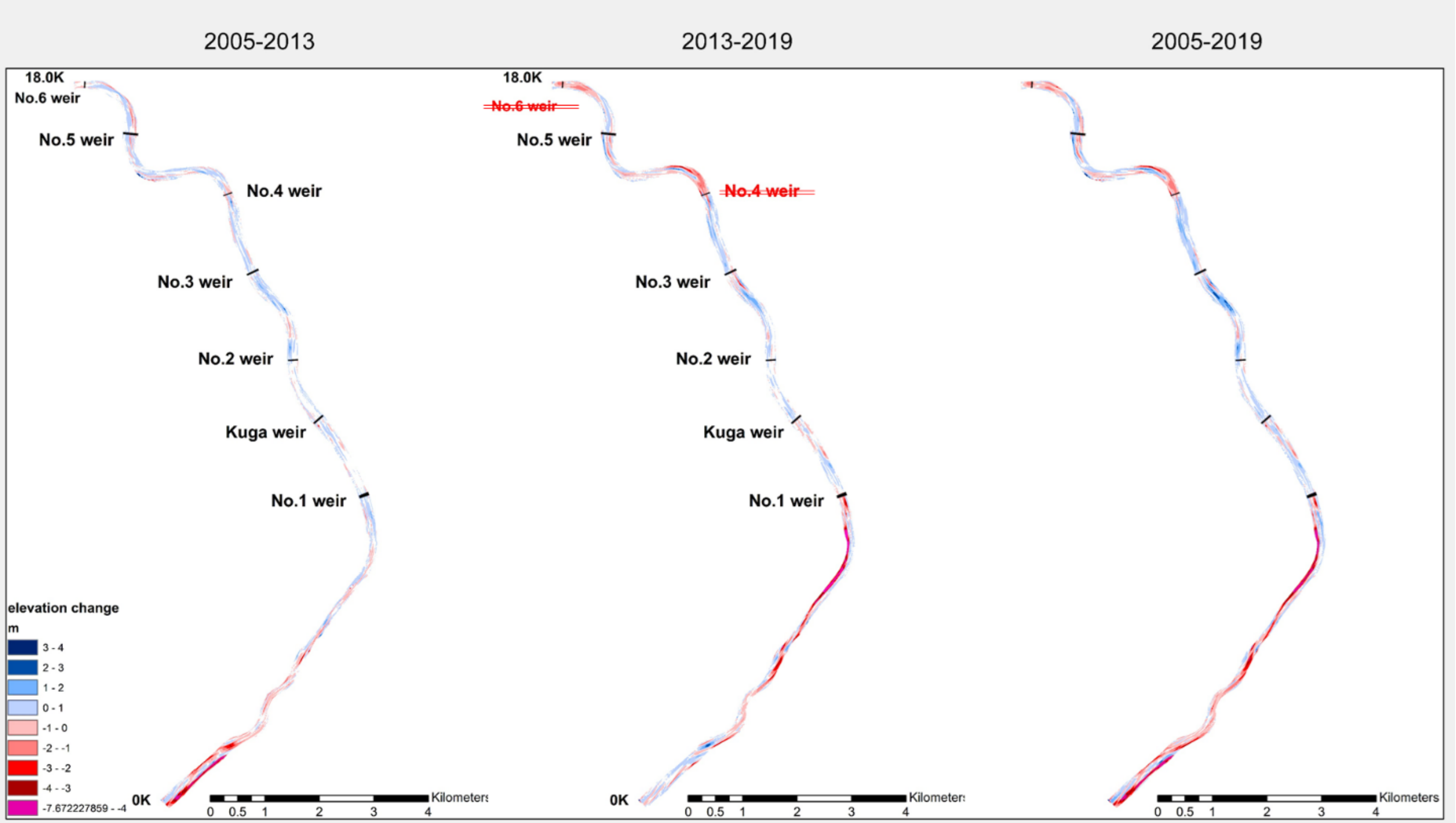


Fig. 4-19 Historical riverbed morphological changes of Katsura River between 2005-2013, 2013-2019 and 2005-2019 (whole study period), blue color indicates deposition and red color indicate riverbed erosion. Note that during no weir was removed during 2005-2013, No.6 and No.4 weir at the upstream side were removed

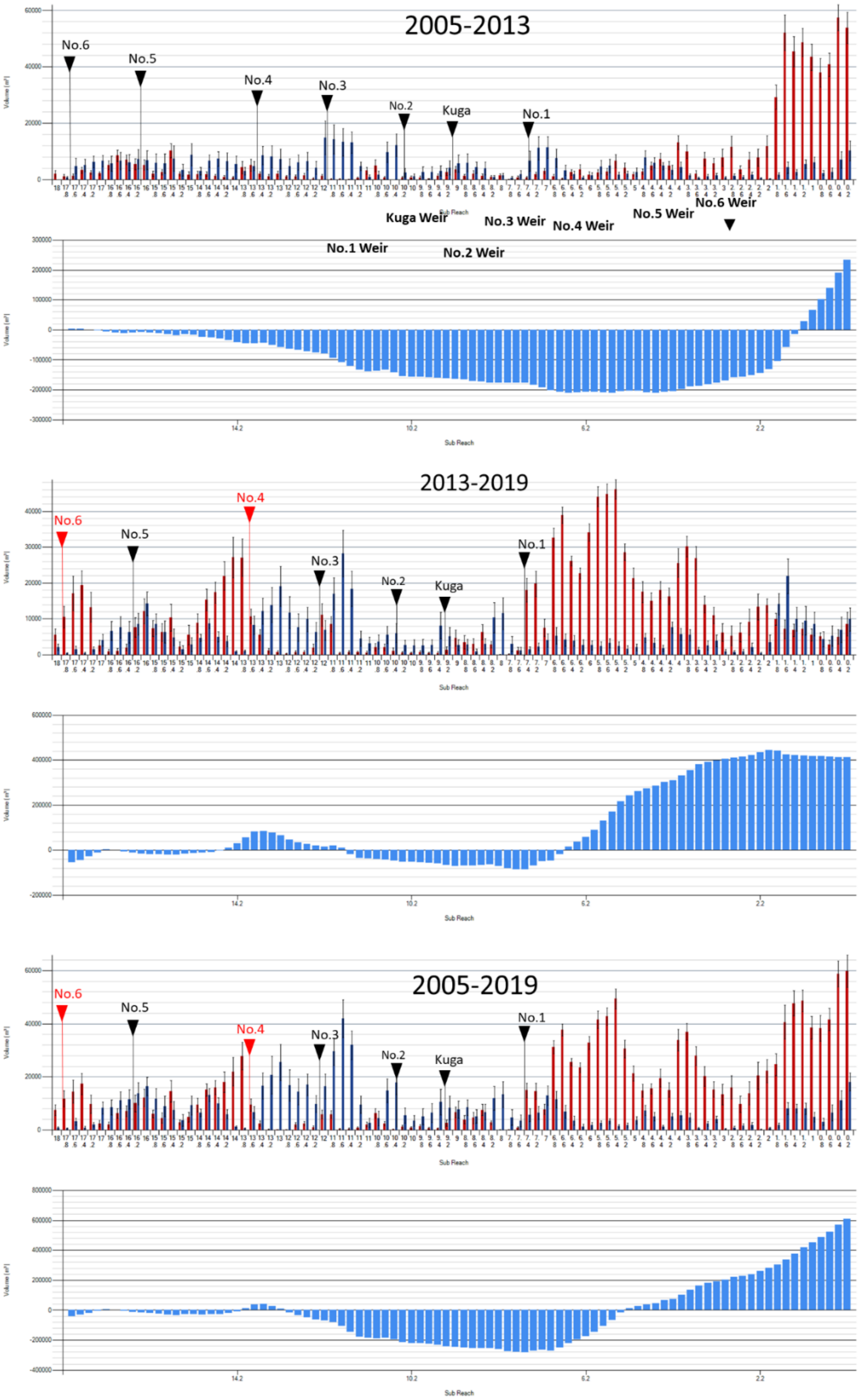


Fig. 4-20 Volumetric change of riverbed of 2005-2013, 2013-2019 and 2005-2019. Red bars indicate riverbed erosion and blue bars indicate deposition. The unit is 200 meters and back and red triangles show weirs location.

Three subsegments in Katsura river

With No.3 weir as the boundary for the upper reach (US) and middle reach (MS), No.1 weir as the boundary for the MS and Downstream Reach (DS), the three reaches showed distinguished morphological changes pattern. Before any weir removal during 2005-2013, the US showed a mixing pattern of deposition and erosion from the upstream channel end to the downstream boundary (No.3 weir) with deposition volume of , as the channel become more straight from No.4 to No.3 weir, the erosional pattern weakened, and depositional pattern prevailed.

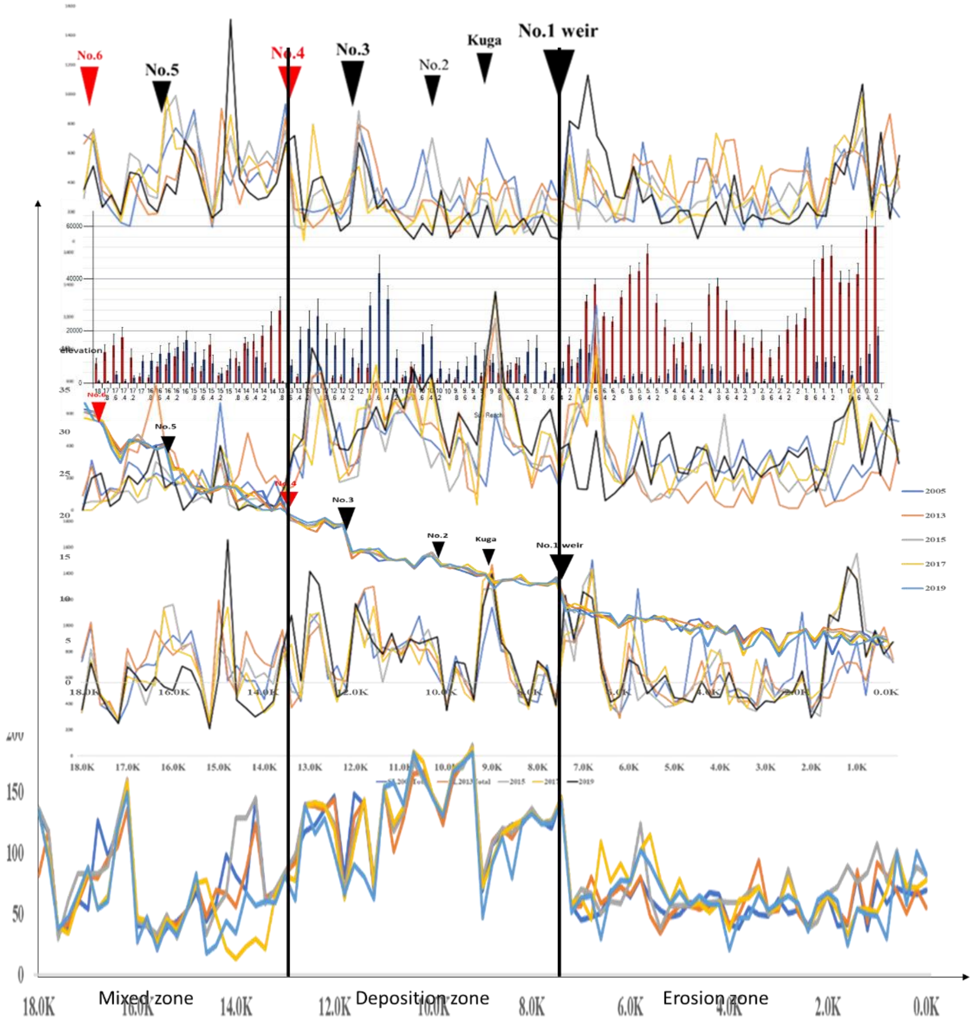


Fig. 4-21 Segmentation of Katsura river based on 1) channel deposition and erosion patterns, 2) Shoreline length, 3) channel slope and 4) low flow channel width.

4.3.4 Summary of historical changes in channel geomorphology and hydro-morphological changes

Historical changes in hydrological and geomorphological parameters in the three sub-segments (Upstream Segment, Middle Segment, and Downstream Segment) of Katsura river during 2005-2019 are showed in Table 4.1. A rough estimation from the grainsize (D_{50}) in terms of the threshold discharge is 2700m^3/s for the US, 2900m^3/s for MS, and 1300 m^3/s for DS. Daily discharge data of 2005, 2009-2019 was showed in Fig. 3-4. Due to the lack of data from 2005-2009, numbers of flood event over 500 m^3/s and duration of flood of different ranges were analyzed only for 2013-2015, 2015-2017 and 2017-2019. The last study period (07-19) has 4 flood events that over 500 m^3/s, which is the most during the two-year interval comparisons, moreover, duration of flood events that ranging from 500-2500 m^3/s are much longer than that during 2013-2015 and 2015-2017, the average riverbed volumetric change results accorded with these results.

Throughout the study period, MS showed only depositional pattern in terms of average net volumetric bed change (m^3/200m), while the US showed an undulating pattern of net change, the DS was considerably aggraded during 2005-2013 however, continually eroded from 2013-2019. Historical peak discharge happened in September 2013, thus, all three subsegments showed net depositional pattern from 2005-2013. Before and after the removal of No.6 weir (2015-2017), both US and MS were aggraded by 1926.20 m^3/200m and 1006.73 m^3/200m respectively, while DS was eroded by -1928.25 m^3/200m. The riverbed showed different changing patterns in case of No.4 weir removal (2017-2019), in which US showed the greatest erosional rate during the whole study period with an average of -2646.30 m^3/200m. MS showed similar depositional pattern compared to No.6 weir removal case, with 1006.73 m^3/200m, and DS was eroded by -553.30 m^3/200m.

Riverbed excavating was continually conducted in the study segment however, data was only available from 2013-2019. From google earth images we can clearly see the big change of riverbed from 2012-2013 in the DS, for which the left bank side floodplain was excavated to increase the discharge ability. This man-made erosional pattern can be clearly seen in the next part which is the historical riverbed morphological change.

For the RSCC (Reach scale channel configuration) parameters, average channel slope of the three reaches of Katsura river showed no big change during the study period, only US showed small changes which is further identified as the erosion upstream of No.6 weir after removal, which made the channel even flatter and later due to the man-made protection work of the Togetsukyo bridge (upstream of former No.6 weir), the elevation of the upper end of US was higher and thus the average slope became steeper. Therefore, the general channel slope cannot provide detailed information of the local change of channel gradient especially in case of weir removal. In the next part the 1-D hydraulic model HECRAS was used to show the detailed results of both riverbed gradient change and water surface profile change under low flow conditions, since gradient is one of the most important physical features of riverbed and has the fundamental controlling effect on the aquatic habitats.

Gradient and low flow channel width are directly affected by weirs and their removal, and they are also fundamentally important to aquatic animals' habitat conditions. The average low flow channel width of US was greatly decreased by 17.8m since the removal of No.4 weir in the year of 2017. The removal of No.6 weir did not have big influence on the low flow channel width due to both upstream banks are fixed levees, and riverbed is flat, thus the wetted area did not change even after weir removal. By combining channel gradient and low flow channel width, with a given discharge, the specific stream power (ω) is calculated for the different reaches and different hydrological conditions. During low flow conditions (30 m^3/s), ω is much higher is the US than in the MS and DS, which has an average of 8.37, since the weirs removal in US, ω increased to 8.55 and 9.74 in 2017 and 2019, respectively. With no surprise that the series of weir in the MS has resulted in the lowest ω around 1.5 due to its large low flow channel width and flat channel gradient.

DS has an average ω of 2.5, which did not change so much during the study period. Though the DS has the lowest low flow channel width, ω is much lower than in the US due to the very flat channel gradient (0.0005).

Table 4-4 Summary of historical changes in reach-scale hydro-geomorphic parameters.

Hydro-geomorphic parameters	**2005**	**2013**	**2015**	**2017**	**2019**
Annual Peak Discharge (m^3/s)	200.69	3194.95	1246.87	1735.83	570.43
Average Net Volumetric Sediment Change ($m^3/200m$)	/	***05-13***	***13-15***	***15-17***	***17-19***
***U**pstream* ***S**egment (18.0-13.6k)*		1956.50	-2540.77	1926.20	2646.30
***M**iddle* ***S**egment (13.4-7.4k)*		4483.20	1010.54	1006.73	1190.47
***D**ownstream* ***S**egment (7.2-0.0k)*		11579.48	-3876.17	-1928.25	-553.30
Riverbed excavating (m^3)					
US			97550	13900	112365
MS					8925
DS			323000	310900	180300
Num of events > 500m^3/s			2	1	4
duration 200-500 (h)			219	248	213
duration 500-1000 (h)			48	32	66
duration 1000-1500 (h)			13	6	16
duration 1500-2000 (h)			4	5	15

duration 2000-2500 (h)					1
duration 2500-3000 (h)					

Slope (S) thalweg/	**2005**	**2013**	**2015**	**2017**	**2019**
US	0.0025	0.0026	0.0027	0.0024	0.0030
MS	0.0012	0.0012	0.0012	0.0013	0.0013
DS	0.0006	0.0006	0.0005	0.0005	0.0005
Slope Average bed elevation (ABE)					
US	0.0024	0.0025	0.0025	0.0023	0.0028
MS	0.0012	0.0014	0.0013	-0.0022	0.0014
DS	0.0007	0.0007	0.0006	0.0006	0.0006
Low flow channel width (w)					
US	75.9	70.6	80.9	60.5	61.3
MS	125.8	124.9	126.1	119.3	117.2
DS	55.9	59.4	66.7	64.6	59.5
Sinuosity					
US	1.20	1.23	1.21	1.21	1.20
MS	1.02	1.03	1.02	1.04	1.05
DS	1.07	1.07	1.05	1.07	1.09
Braided Index					
US	0.72	0.87	0.57	0.83	0.06
MS	1.15	1.26	1.17	1.44	1.18
DS	0.26	0.41	0.43	0.64	0.37
Total/bare/vegetated shoreline Length					
US	670.12	720.79	647.09	603.88	545.74
MS	749.66	766.97	743.69	765.12	827.44
DS	670.23	620.67	670.07	717.00	669.99
Bare shoreline Length					
US	489.94	457.42	547.73	482.06	417.86
MS	331.01	278.63	287.89	244.05	217.51
DS	308.48	435.58	331.32	375.29	354.55
Vegetated shoreline Length					
US	180.18	263.37	99.36	121.82	127.88
MS	418.64	488.34	455.80	521.07	609.93
DS	361.75	185.08	338.75	341.71	315.43

FVSI					
US	0.212	0.254	0.203	0.132	0.228
MS	0.241	0.248	0.228	0.283	0.324
DS	0.098	0.05	0.081	0.132	0.173
Grainsize data*(*H23only*) D50 (mm)		**Leftbank**	**Center**	**Rightbank**	
US		2.704	14.2	7.635	
MS		9.188	26.966	6.524	
DS		7.535	31.166	10.074	
grainsize change (local, weir site) D50 (mm)			**Center**		
upstream of NO.1			9.63		
Downstream of NO.1			14.47		
Upstream of NO.4			19.33		
Downstream of NO.4			44.38		
Upstream of NO.6			22.14		
Downstream of NO.6			11.69		

4.3.5 Historical changes in riffle habitat structures

Fig. 4-22 shows the summarized the historical changes of three types of riffles from 2005 to 2019. The total area of riffle was largest in 2005 while more than 90% were C-type riffle, others were T-type riffle, no D-type riffles were found in this year. In 2013, the total area of riffle has been decreased especially the C-type riffle, reduced by more than 60% compared to 2005, T-types however, increased by over 50%. D-types riffle was also appeared in this year. The total area of riffle decreased dramatically from 2013-2015, then slightly increased in 2017 and 2019.

Spatial distribution of three types of riffles and wandos is showed in Fig. 4-22, results showed dramatically change from year to year. In 2005, both the number and area of the C-type riffle are much higher and larger than that in other years. The C-type riffles are abundant at both upstream and downstream of the study segment. No D-type riffle was detected in 2005, T-type riffles were found only at upstream downstream of No.5 weir, and at the river conjunction (0.0K). After 8 years in 2013 after the historical peak discharge, the C-type riffle decreased significantly both in number and area. D-type riffle appeared between No.6 and NO.5 weir, along with small numbers of T-type riffles, which also appeared at downstream part. In 2015, C-type riffle continuously decreased, only appeared at limited area such as downstream of No.1, No.5 and No.6 weir. D-type and T-type riffles are also becoming less abundant compared to 2013, detected only at upstream of No.4 weir. In 2017 the No.6 weir had already been removed, riffle structures did not show considerable changes at the No.6 weir site, however, more D and T-type riffles were found downstream of No.6 weir. In 2019 after No.4 weir removal, the number of D-type and T-type riffles was increased both at upstream and downstream segment.

As to the wandos, as the Fig. 4-23 shows, generally the both the total number and area are increasing from 2005 to 2019. The number of wandos was highest in 2017 (125), while in 2019 the total area of wando was the largest ($79396m^2$).

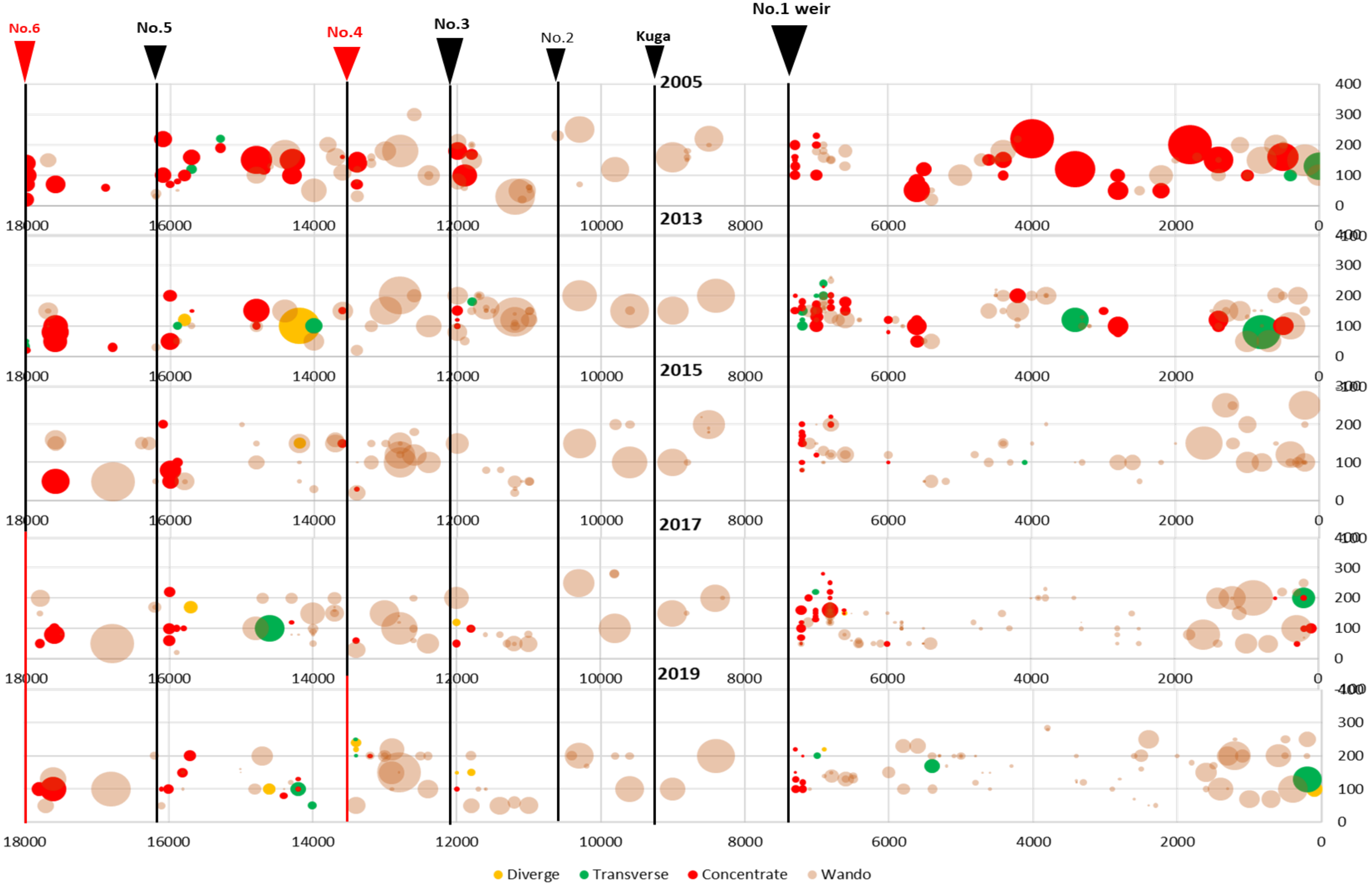

No.6
No.5
No.4
No.3
No.2
Kuga
No.1 weir
2005
2013
2015
2017
2019
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
400
300
200
100
0
● Diverge
● Transverse
● Concentrate
● Wando

Fig. 4-22 Historical changes in habitat structures in Katsura river. Green circles indicate Diverged type riffles, yellow circles indicate Transverse type riffles, red circles indicate Concentrated type riffles, and brown circles indicate Wandos.

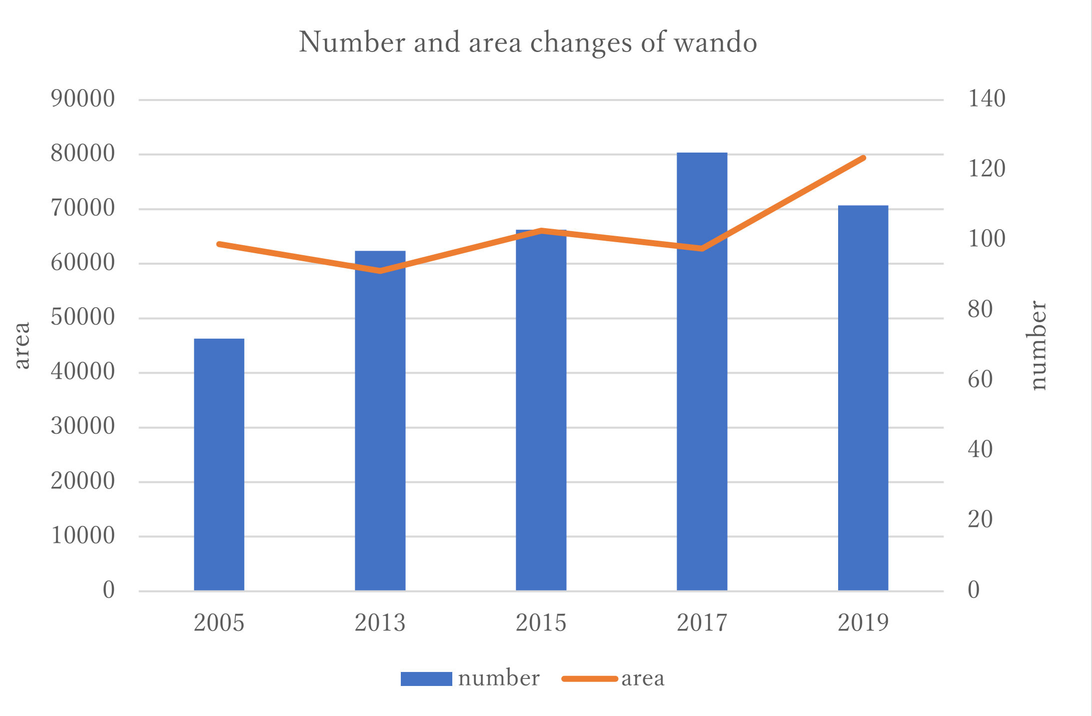


Fig. 4-23 Historcial changes in number and area of wandos in Katsura river.

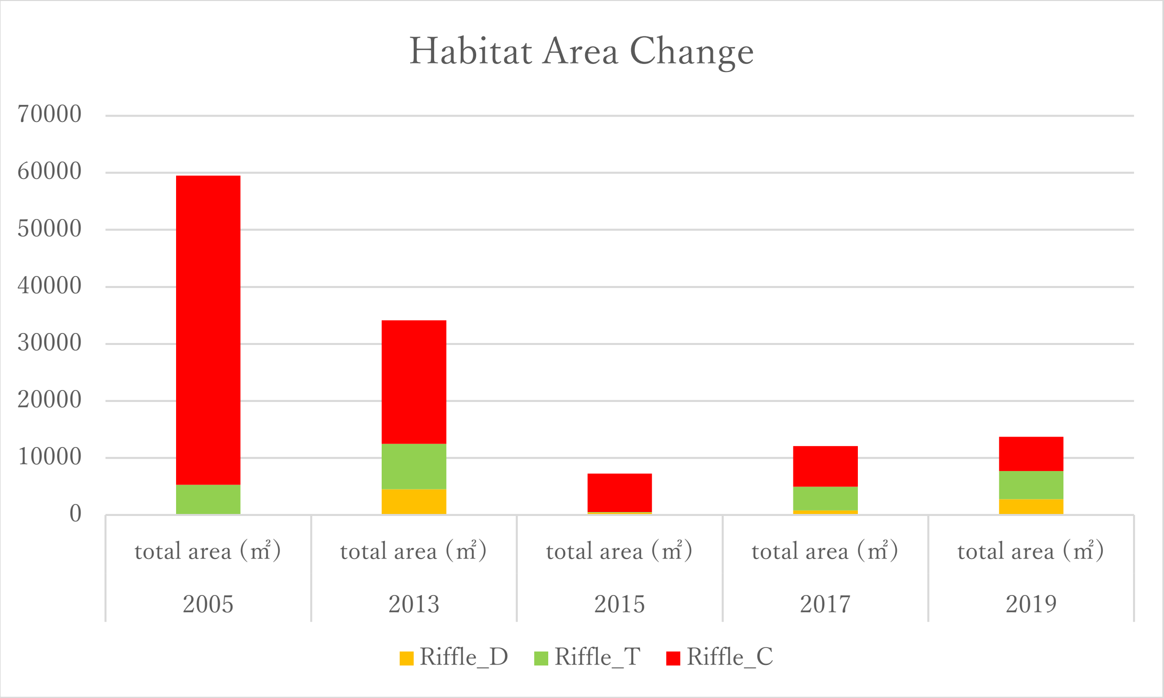


Fig. 4-24 Summary of area changes of riffle structures from 2005 to 2019 in Katsura river.

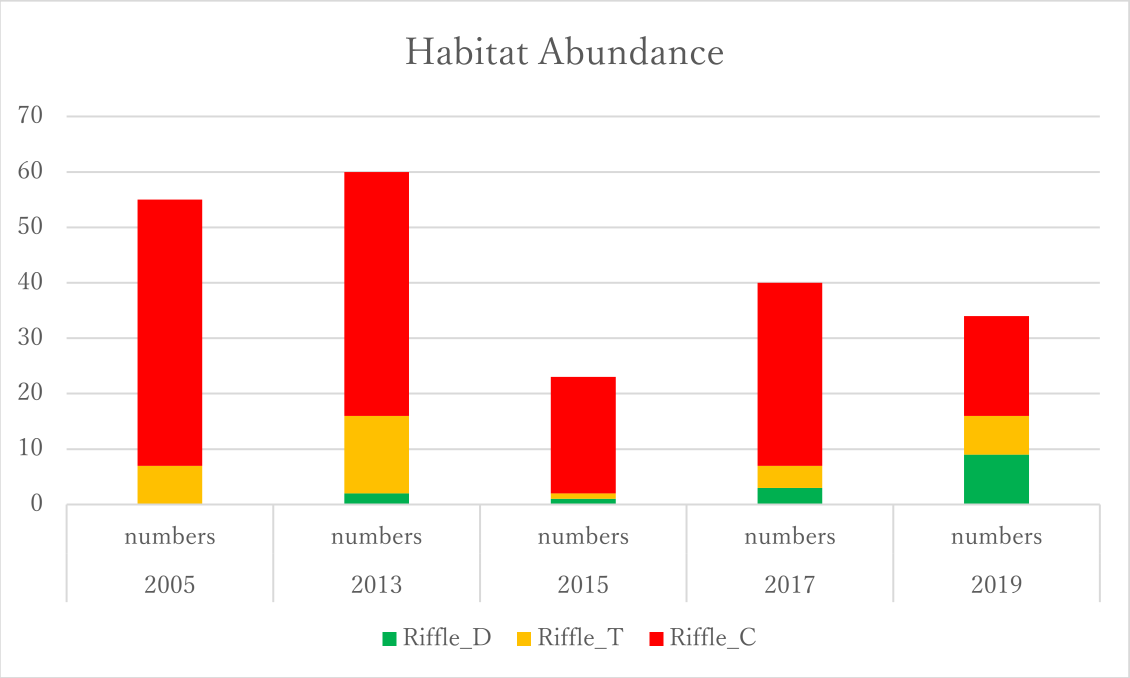


Fig. 4-25 Historical changes in habitat abundance (number of habitats) from 2005 to 2019 in Katsura river.

4.3.6 Channel geomorphology and habitat structure change in relation to low-head dam removal

The most significant effect of the weir removal on channel geomorphology is the riverbed longitudinal profile alteration. Previously (before 2017), step-like sequence dominated the UR and MR, especially in MR, four weirs have formed a cascade pool area with very small water surface slope. In UR, because of the longer distance between No.5 and No.4 weir, higher gradient existed at the limited area downstream of No.5 and upstream of No.4 weir. Similar geomorphology between No.6 and No.5 weir. Before weir removal, these two reaches are example of the very limited geo-potential area of Katsura river to form aquatic -important riffles.

As showed in Fig. 4-26, the riverbed longitudinal profile in the No.6 weir site did not change significantly from 2005 to 2015. After the removal of No.6 weir (2017), riverbed slope upstream of No.6 weir became gentle and downstream became even steeper than the previous years. In 2019, the upstream riverbed became steeper than that in 2019, which is due to the man-made riverbed protection work for the Togetsukyo bridge located at 18K.

As to the riverbed longitudinal profile of No.4 weir site, after removal (in 2019), the riverbed profile has a shorter wavelength at the vertical direction, and the riffle-pool undulation was more emphasized and smoother than the previous years.

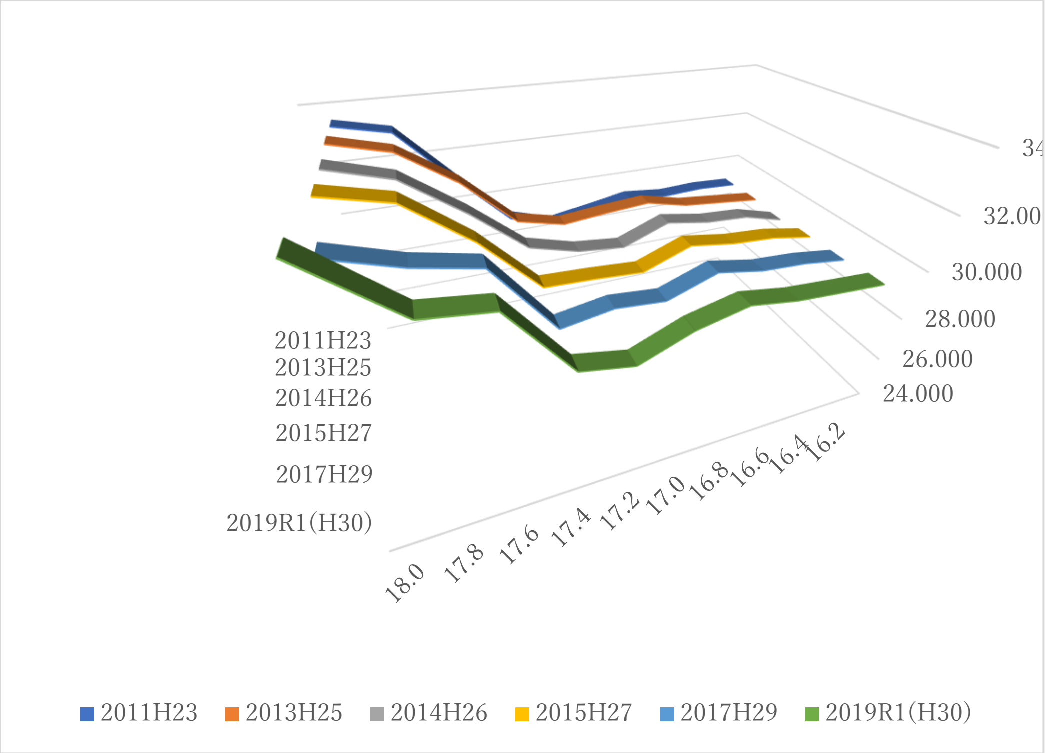


Fig. 4-26 Historical changes in bed slope of No.6 weir site, No.6 weir was located at the 17.8K.

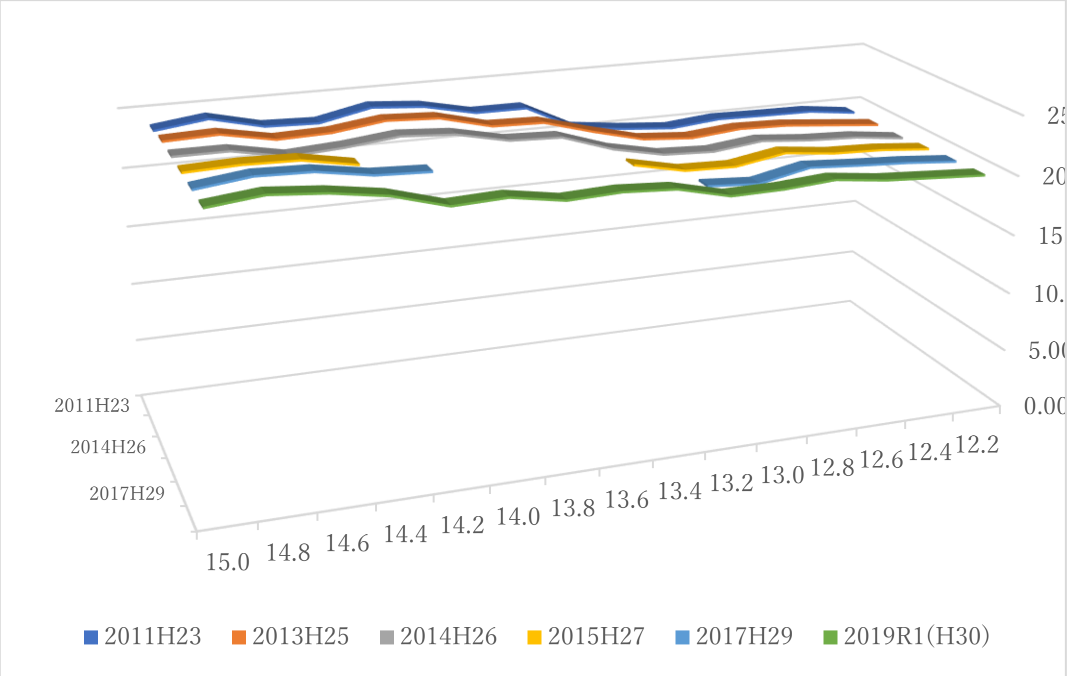


Fig. 4-27 Historical changes in bed slope at No.4 weir site (No.4 weir was located at 13.6K), in 2015 and 2017, the riverbed survey had not been done in the No.4 weir site (blank area) because of the river engineering work.

4.3.6.1 Channel morphological change before and after No.6 weir removal

Riverbed volumetric change was calculated by GCD (Geomorphic Change Detection) toolkit, embedded in Arc-GIS software. Results are showed in Fig.4-28 and Fig.4-29. During 2005 to 2013, upstream of No.6 weir showed slightly erosion (-3306.75m^3), and riverbed erosion also happened downstream of No.6 weir (-35547.94 m^3), at outside of the channel bend close to the bank. While great amount of deposition (+48308.95 m^3) was detected at the inner side of the channel bend, at the big point bar, which is a typical deposition and erosion pattern of the single sinuous river. The deposition pattern extended to the right bankside, upstream of No.5 weir, even though the center of the channel has been eroded. Downstream of No.5 weir, erosion happened mainly at the center of the channel along the thalweg line, other area of the channel was dominated by sediment deposition.

From 2013 to 2015, both upstream and downstream of No.6 weir were dominated by riverbed erosion, with -4955.27 m^3 and 31829.6m^3, respectively. The erosion pattern reached to about the middle point between No.6 and No.5 weir, and from where the deposition (20384.06 m^3) was prevailed until No.5 weir. Channel erosion was dominated for the downstream of No.5 weir, indicates the lack of sediment supply during this period.

No.6 weir has been completely removed between the end of 2016 and early spring of 2017. After the No.6 weir removal, similar to the previous studies, upstream erosion (14656.63 m^3) and downstream aggradation (17256.06 m^3) pattern were detected. Riverbed was incised by more than 1m in the channel center are of the former impoundment of No.6 weir, which is coincide with the conceptual model of low-head dam removal proposed by Doyle (2002). Downstream of No.5 weir was not affected by the removal of No.6 weir severely. Only the side channel at the right bank side was eroded just downstream of No.5 weir.

From 2017 to 2019, channel upstream of No.6 weir was aggraded (8053.21 m^3) by man-made works for protecting the base of Togetsukyo which is located just about 200m from No.6 weir. Riverbed erosion (52793.51 m^3) was prevailed at the downstream of No.6 weir. Riverbed was incised by over 1m at the center area. The channel lowering area was limited until the mid-point between No.6 and No.5 weir. Riverbed was slightly aggraded from the mid-point to the No.5 weir. At downstream of No.5 weir, the side channel at the right bank side was aggraded with big amount of sediment, while the center of the channel showed mixed pattern of both erosion and deposition.

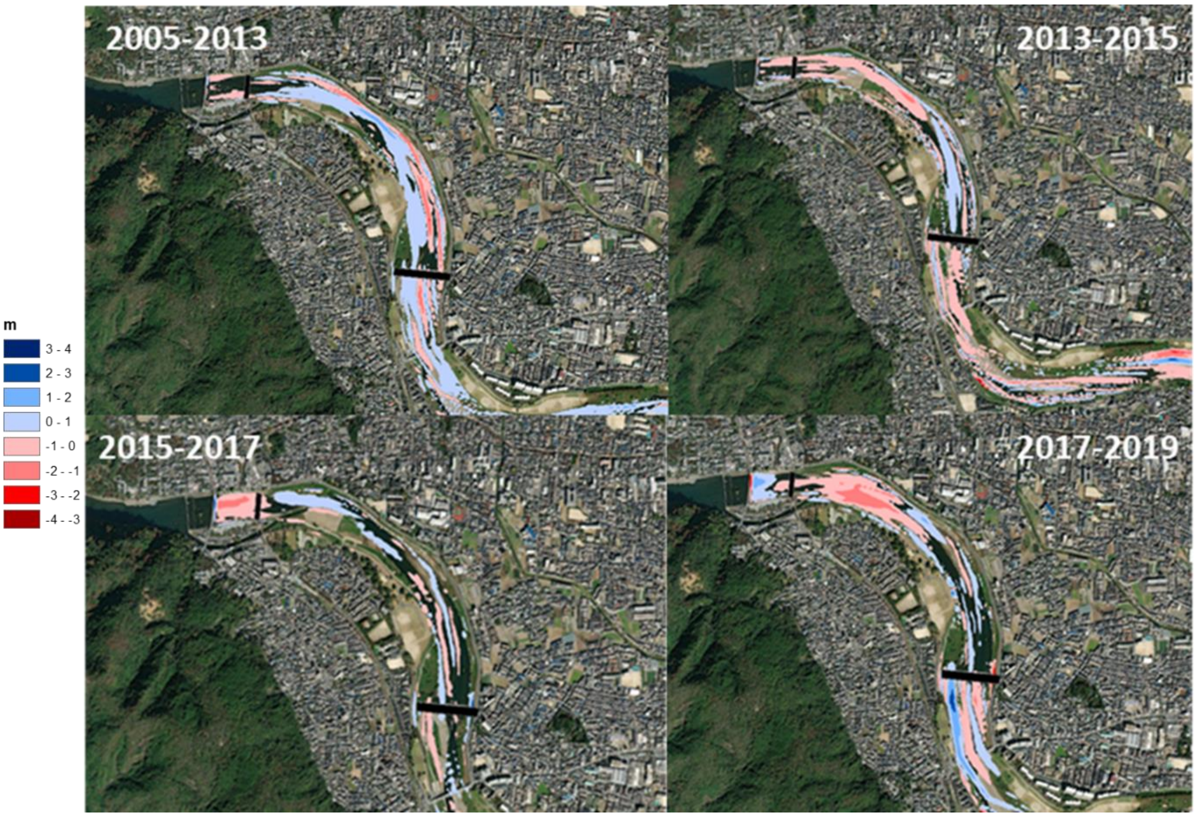


Fig. 4-28 Historical river morphological changes in No.6 weir site.

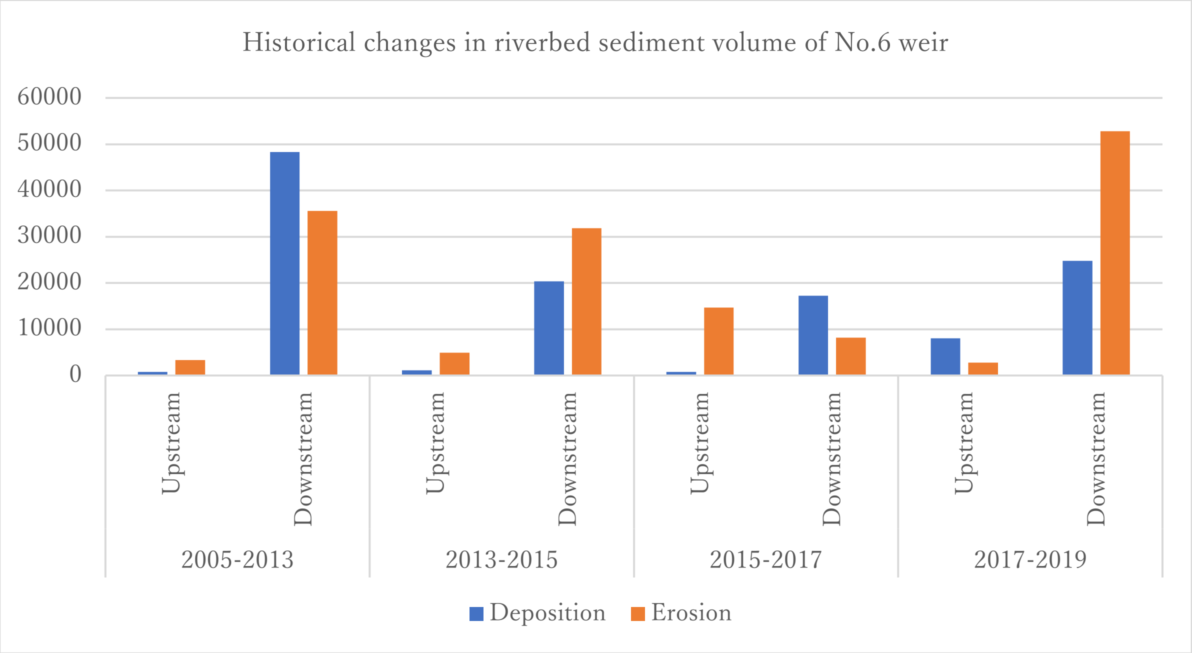


Fig. 4-29 Historical riverbed changes up and downstream of No.6 weir. Upstream is from 18.0-17.8k, downstream is from 17.6 to 16.2k just near the upstream of No.5 weir.

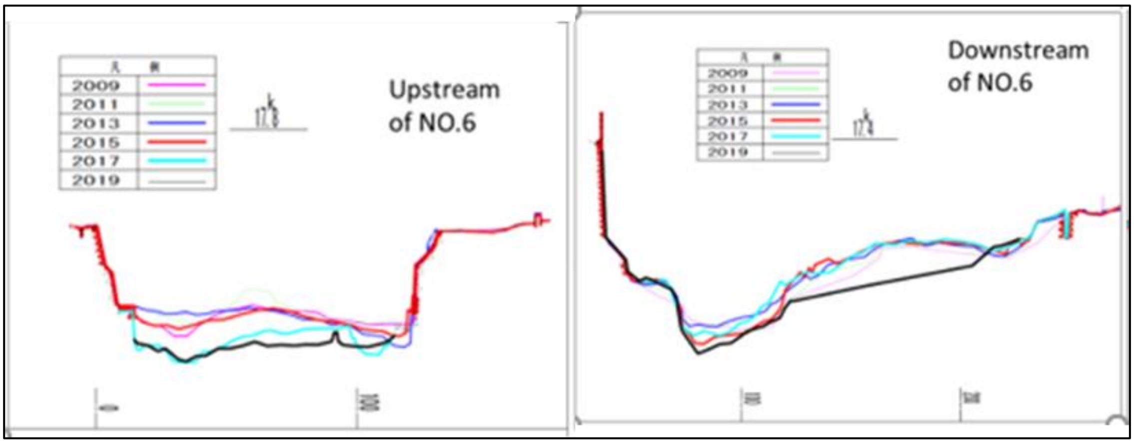


Fig. 4-30 Historical cross-sectional changes up (50m) and downstream (400m) of No.6 weir .

4.3.6.2 Channel morphological change before and after No.4 weir removal

The removal of No.4 weir in Katsura river covers a longer period compared to No.6 weir, the dam body was breached in the winter of 2016, and was completely removed in April

2019. Thus, the channel upstream and downstream flow and geomorphic changes have already been initialized since then, while unfortunately due to the engineering works, the riverbed geomorphic survey cannot be done at this reach (upstream and downstream of the weir). Fig. 4-31 shows the channel change at the No.4 weir site from 2005-2013 (before removal) and 2013-2019 (1 year after removal). Before removal, the upstream of the channel showed a mixed pattern of sediment erosion and deposition, due to the big curvature just upstream of the weir body, the inner side are mainly deposited and in the center of the channel just upstream of the weir, erosion was more prevailed. As to the downstream of the weir, clearly sediment deposition was dominated, especially the channel-center island, was aggraded more due to the trapping of sediment. Because of the backwater effect of the No.3 weir just 1.5km downstream, the sediment dynamism can be greatly affected in the entire downstream of No.4 weir.

From 2013-2019, the channel changing pattern was greatly altered due to the weir removal, the bed vertical change in Fig. 4-31 is the result of the past three flood seasons (2017, 2018 and 2019), with peak discharges are 1735m^3/S, 2005.13m^3/S and 570.43m^3 /S.

Upstream of the channel is dominantly eroded after the breaching of No.4 weir, the narrow channel at the outside of the curvature was incised about 3m, channel just upstream of the weir was also eroded more than 1m. As to the downstream of the weir, the channel-center island was excavated by man-made river excavating works for the purposes of flood mitigation, upstream change mentioned before was also a combination of man-made disturbance and natural hydro-dynamic effects.

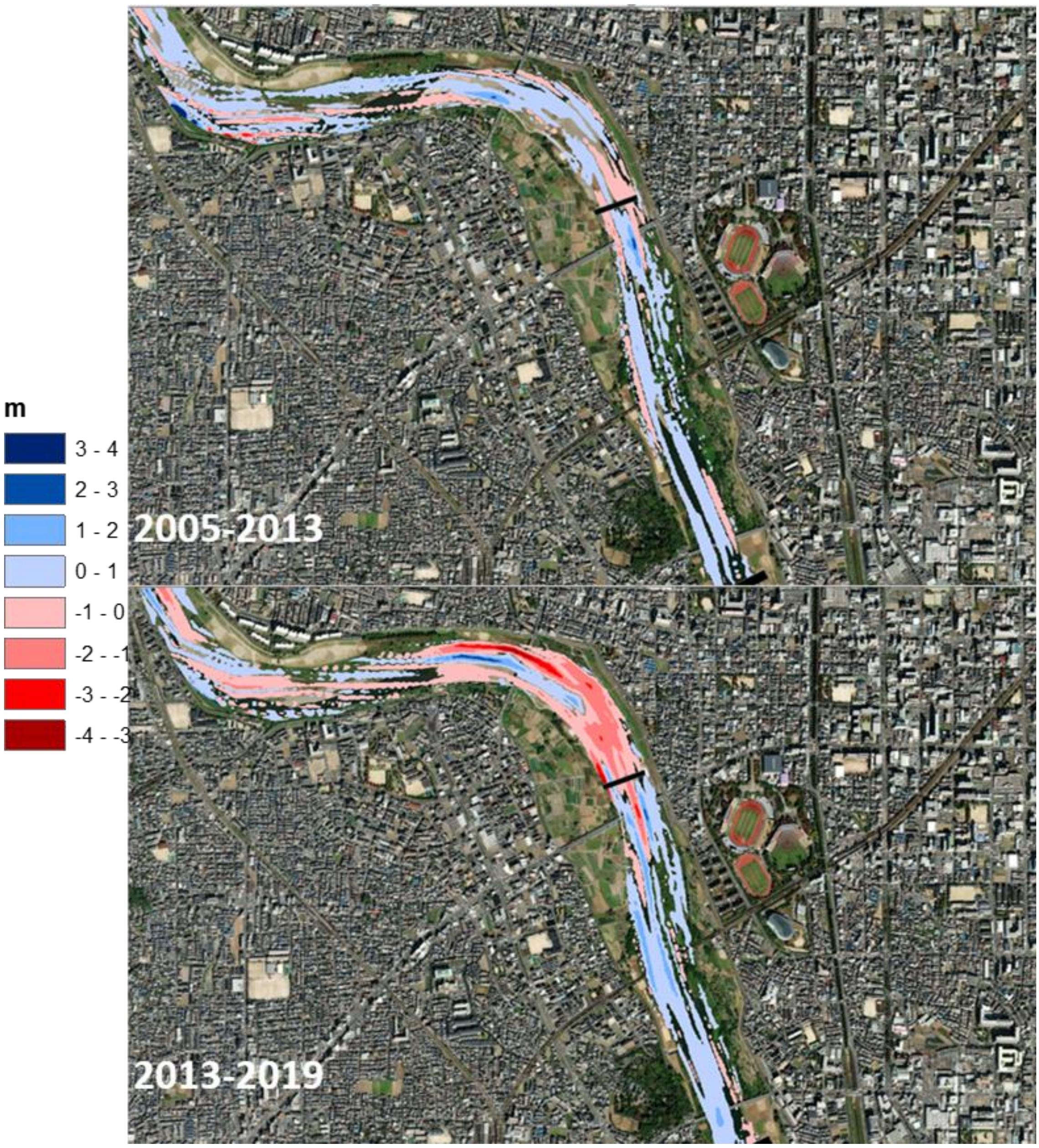


Fig. 4-31 Riverbed morphological changes before and after No.4 weir removal.

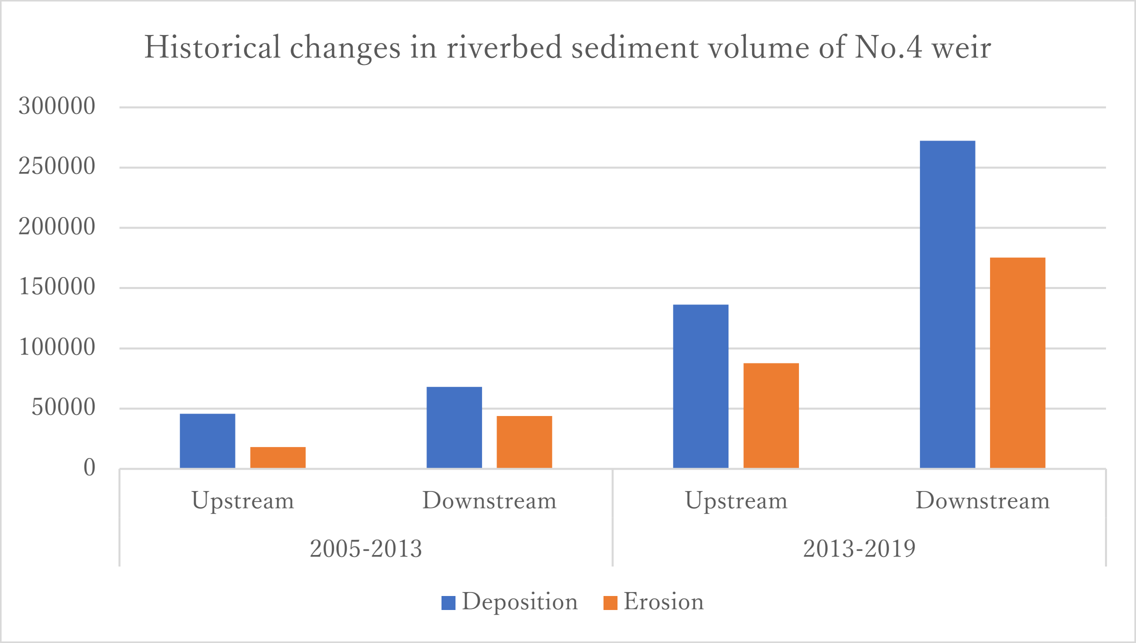


Fig. 4-32 Riverbed volumetric changes upstream and downstream of the No.4 weir during the entire study period.

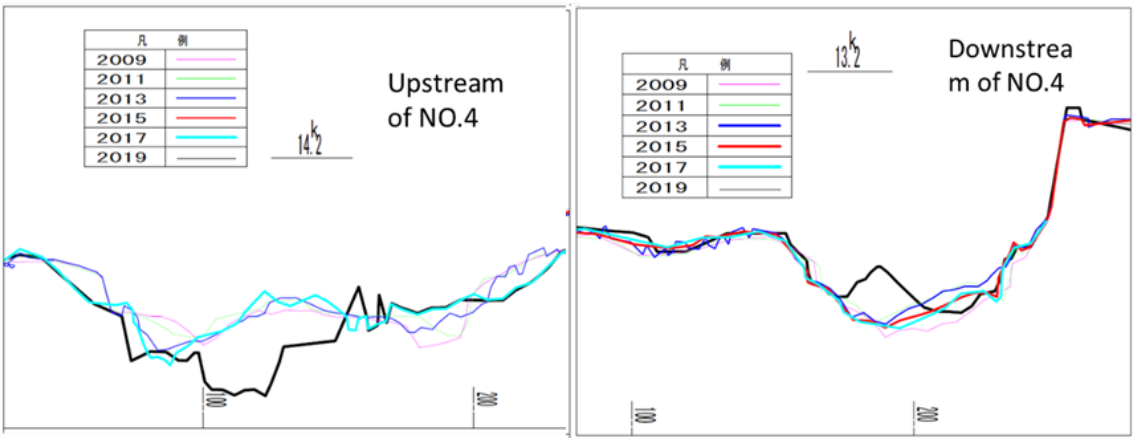


Fig. 4-33 Cross-section changes upstream and downstream NO.4 weir. After removal, the upstream channel showed significant erosion (more than 1m) and the downstream channel aggraded.

4.3.6.3 Habitat changes at No.6 weir site and No.4 site

No.4 weir was breached in the winter season of 2016, while half of the weir body was removed in the next spring. Until April 2019, No.4 weir was totally removed. In this sense, the flow structure and sediment dynamism had been already altered since the weir breaching in 2016. Therefore, the resultant change of habitat structures in 2017 is already the result of the No.4 weir removal (Fig.4-34), plus the effect of the NO.6 weir removal and also impacted by the man-made river excavating works (Fig.4-36). Fig. 4-35 showed the local area habitat change of No.6 and No.4 weir site. Result shows that after the two weirs removal, high quality riffles were developed between the two weirs, mainly upstream near the No.4 weir. However, in 2019, 2 years after the breaching of No.4 weir, the area of high-quality riffle decreased, which indicates the sediment dynamism is restrained and not sustainable. The habitat structures change is the resultant of channel geomorphic changes, which is under the combined impact of natural flow and sediment transport, weir removal, and the man-made river excavating works. The combined results showed that the even though the habitat conditions were improved after two weirs removal, the dynamism cannot be maintained if additional source of sediment are not supplied to the Katsura river.

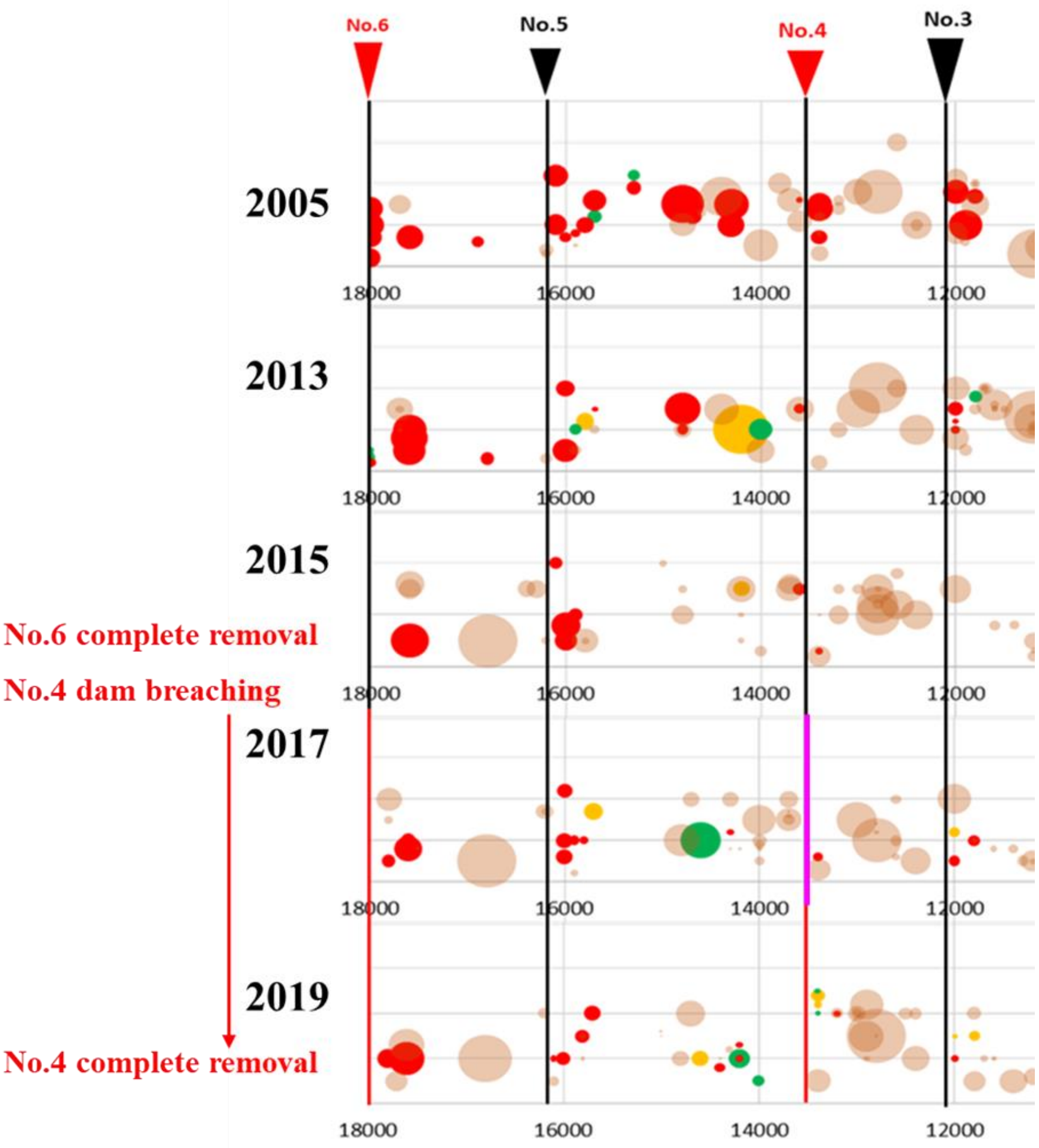


Fig. 4-34 Habitat structures change at No.6 (left) and No.4 (right). Green circles indicate Diverged riffle type, yellow ones represent the Transverse riffle type, and red ones indicate the Concentrated riffle.

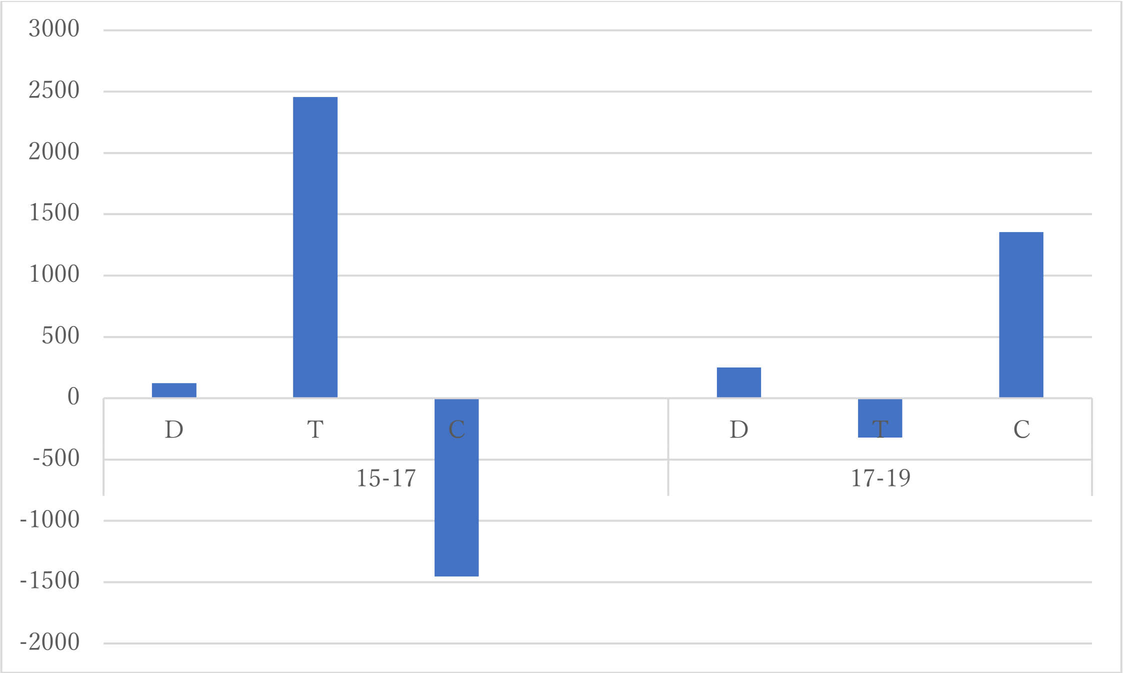


Fig. 4-35 Habitat area change in relation to the No.6 and No.4 weir removal.

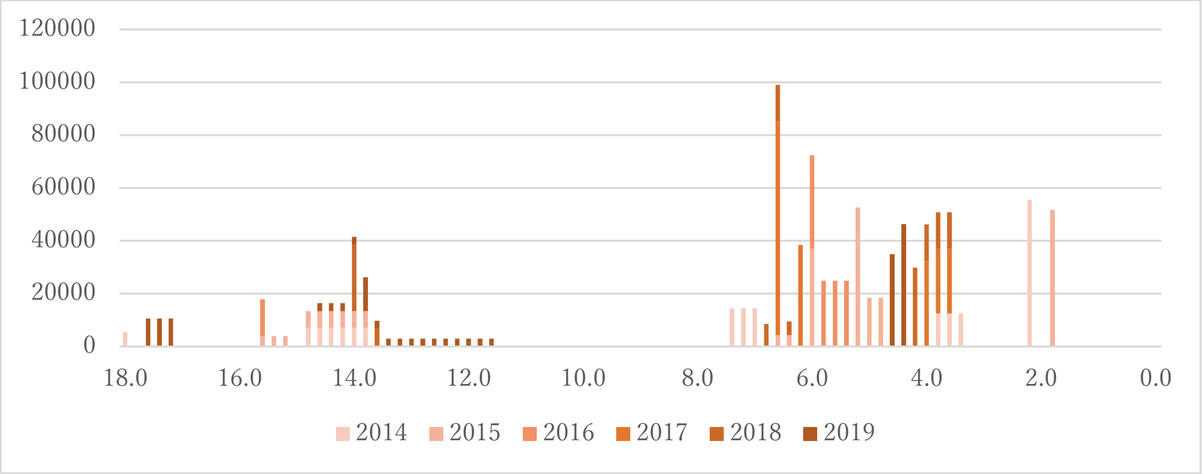


Fig. 4-36 Historical data of riverbed excavation in Katsura river.

4.3.7 Fish community composition changes after low-head dam removal

The important fish species were collected and sampled before and after No.6 and No.4 weir removal, as showed in the Table 8 and Table 9. In both table, blue color indicates the fluvial fish, yellow color indicates the fluvial-lacustrine fish, and the brown color indicates the lacustrine fish.

Historical changes in fish community structures at both up and downstream of the No.6 and NO.4 weir were showed from Fig. 4-37 to Fig. 4-40. Upstream of the No.6 weir, after removal, the total Shannon-Weiner species diversity index upstream of No.6 weir remained similar in the first year after removal, the number of individuals increased significantly in 2019 and remained about the same level in 2020. Downstream of the No.6 weir, 1 year after removal, the Shannon-Weiner index increased significantly, especially with more abundant pool dwellers, which indicate that the weir removal had restored the river longitudinal connectivity, and thus the downstream pool habitat received newly deposited sediment and therefore habitat quality was improved. While in the 2019, the Shannon-Weiner index slightly decreased downstream of No.6 weir.

Total averaged number of pool dwellers in both up and downstream of the No.4 weir before and after removal was calculated and tested by the statistical T-test (Fig. 4-41). Results showed that the average number of pool dwellers is 2.20 times more than the pre-removal conditions, indicates the quality of pool habitats were improved due to the restoration of the river longitudinal connectivity.

Generally, fish communities changing pattern at No.4 weir site was similar to No.6 weir. Featured by the more significantly increase in the downstream reach compared to the upstream reach.

The environmental monitoring surveys were conducted annually by the Yodo river bureau in Katsura river. We collected the fish species surveyed data at No.6 and No.4 weir sites and compared before and after removal, habitat types include riffle, pool and wando, the number of important species caught during each survey was listed in the Table 4., No.6 weir was removed in 2016, and fish species data before removal (2015 and 2016) , after removal (2017 and 2019) were collected and compared. For the upstream of No.6 weir, species diversity decreased and species abundance slightly increased. In the pool habitats, even though the species diversity reduced by 2, the species abundance increased significantly compared to pre-removal conditions, which is mainly contributed by *Rhynchocypris lagowskii steindachneri*. After removal, *Cottus pollux* was never found in the pools, while the *Oryzias latipes* appeared, which did not show up in the previous' survey.

Downstream of No.6 weir, species diversity did not change much in riffles, while the number of species was decreased significantly 1 year after removal, and then increased to the same level compared to the pre – removal surveys in the next year. Fish species in the pools changed greatly after weir removal, both in species diversity and abundance. Before removal, only 1 sample of *Hemibarbus longirostris* was found in 2016, however, four new species appeared in the first year after removal (*Tanakia limbate*, *Cobitis striata striata Ikeda, Rhynchocypris lagowskii steindachneri and Oryzias latipes*). In the second year after removal, species diversity decreased by 2 while the number of sampled fishes was increased by 3, which is contributed by the abundance of *Rhynchocypris lagowskii steindachneri.*

Wando habitats exists and plays and important role for providing still water habitats for the aquatic organisms in the downstream of No.6 weir. Both the species diversity and abundance increased dramatically after removal. In the first year after removal, 5 new species were found compared to the previous year (*Liobagrus reini*, *Tanakia limbate, Sarcocheilichthys variegatus variegatus, Rhynchocypris lagowskii steindachneri, Hemibarbus longirostris and Misgurnus anguillicaudatus*). In the next year, the species diversity decreased by 1, while the species abundance increased by 7.

Shannon-Weiner diversity index was calculated for each habitat in the No.6 weir site. As showed in Fig. 4-42 and Fig. 4-43 in the upstream of No.6 weir, Shannon-Weiner diversity index slightly decreased in both riffle and pool habitats after removal. In the downstream reach, the S-W index was slightly decreased in the riffle habitats, while increased significantly in the wandos and the newly created pools after weir removal.

As Figure 4. shows, in the upstream of No.4 weir, species diversity did not change a lot in the riffle habitats after removal, however, *Rhynchocypris lagowskii steindachneri was not caught during the survey and Niwaella delicata was found after removal.* S-W index was increased significantly after weir removal compared to the previous year (2017), while still lower than that in 2015 and 2016. Pool habitats are less abundance in both the species diversity and species abundance. *Cottus pollux* was newly found after removal. As to the wandos, both species diversity and abundance decreased after removal of No.4 weir.

In the downstream of No.4 weir, even though the number of species did not change so much in the riffles after removal, the species abundance increased significantly (*Cottus pollux* +16*, Rhynchocypris lagowskii steindachneri* +7 and *Liobagrus reini* +3). *Rhynchocypris lagowskii steindachneri* increased significantly in pools after removal (+11 samples). *Nipponocypris sieboldii* was newly collected after weir removal, which did not appear in the previous years. As to the wandos, both the species diversity and abundance were increased after removal, newly appeared species are *Cobitis striata striata Ikeda, Carassius cuvieri, Nipponocypris sieboldii and Rhinogobius.*

In the upstream of No.6 weir, Shannon-Weiner diversity index slightly decreased in the riffles after removal compared to the previous year, while increased significantly in pools and wandos. Downstream of No.6 weir, S-W index increased in both riffle and pools, while decreased in wandos compared to the pre-removal conditions.

Both upstream and downstream of the No.6 weir, the sampled number of *Liobagrus reini* and *Cottus pollux* showed an increasing pattern after the weir removal. Both species are fluvial-benthic fishes and primarily living in riffle habitats. The sharp increasing pattern upstream of the weir after removal indicates that riffle habitats was restored after weir removal.

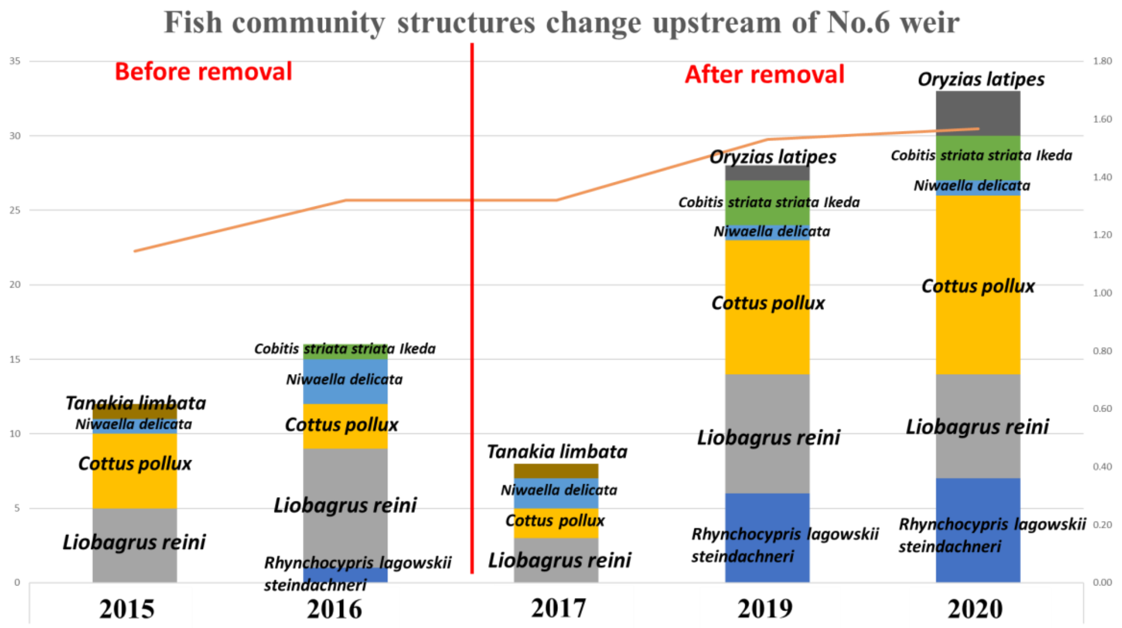


Fig. 4-37 Historical changes in fish community structures and Shannon-Weiner diversity index upstream of No.6 weir.

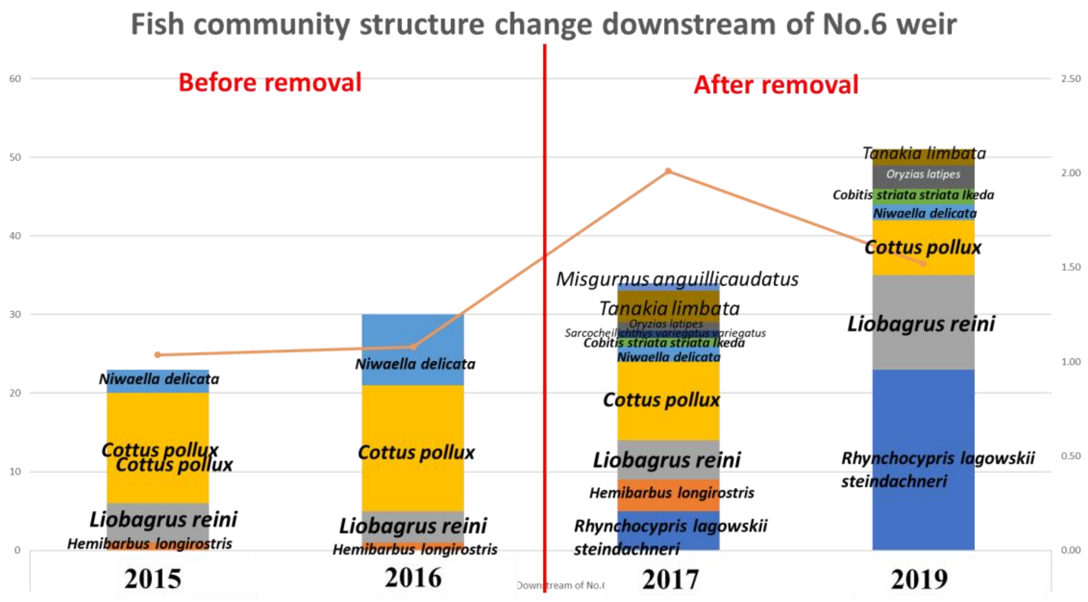


Fig. 4-38 Historical changes in fish community structures and Shannon-Weiner diversity index downstream of No.6 weir.

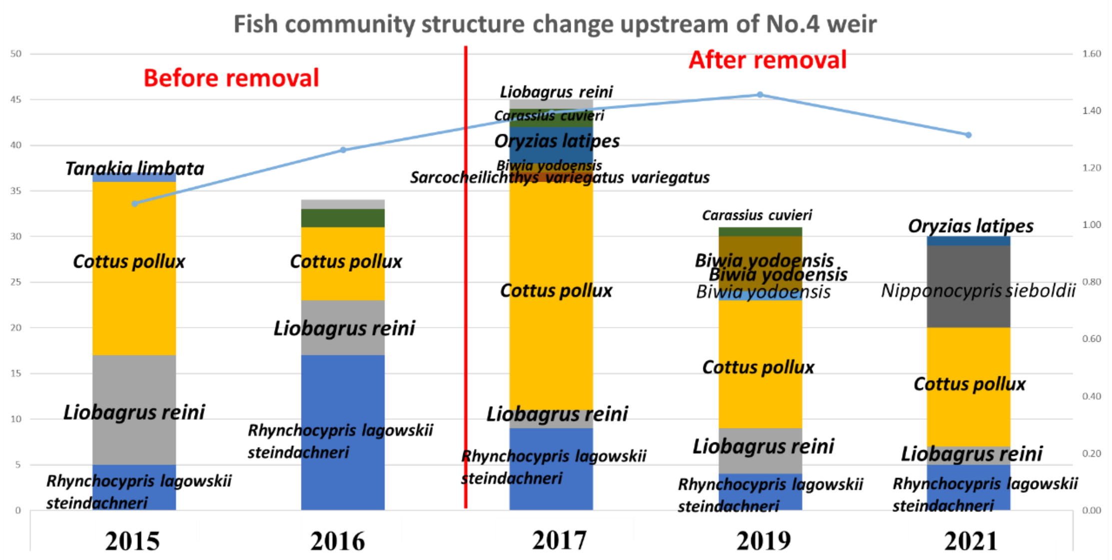


Fig. 4-39 Historical changes in fish community structures and Shannon-Weiner diversity index upstream of No.4 weir.

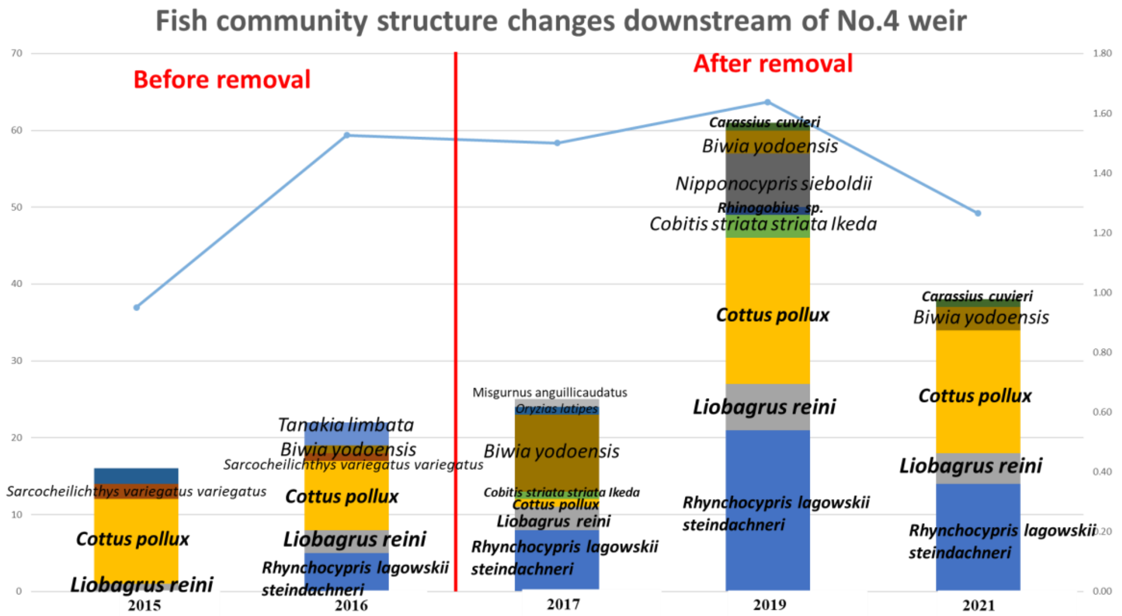
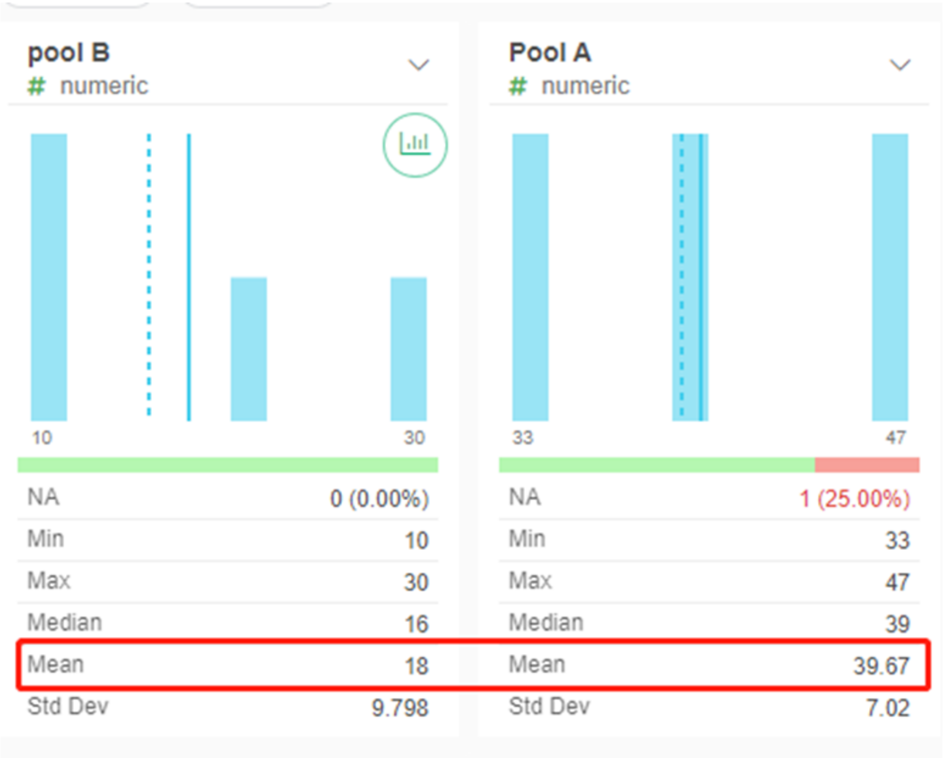


Fig. 4-40 Historical changes in fish community structures and Shannon-Weiner diversity index downstream of No.4 weir.



pool B
numeric

NA	0 (0.00%)
Min	10
Max	30
Median	16
Mean	18
Std Dev	9.798

Pool A
numeric

NA	1 (25.00%)
Min	33
Max	47
Median	39
Mean	39.67
Std Dev	7.02

Fig. 4-41 Statistical test results of the mean individual of pool dwellers in the No.4 weir site.

Table 4-5 Fish community's composition change before and after removal of No.6 weir, blue color indicates the fluvial fish

before removal/after				Upstream of NO.6								downstream of NO.6											
Taxa	Ecological Type			riffle				pool				riffle				pool				wando			
	Life Type	Swim Type	Habitat Type	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019
7 *Rhynchocypris lagowskii steindachneri*	Fluvial fish	Nektonic	Pool		1						**6**							**2**	**8**			**3**	**15**
11 *Hemibarbus longirostris*	Fluvial fish	Intermediate	Riffle														1			1		**4**	
1 *Liobagrus reini*	Fluvial fish	Benthic	Riffle	4	5	**3**	**6**	1	3		**2**	3	4	**1**	**7**					2		**4**	**5**
2 *Cottus pollux*	Fluvial fish	Benthic	Riffle	4	2	**2**	**9**	1	1			7	9	**5**	**5**					7	7	**5**	**2**
5 *Niwaella delicata*	Fluvial fish	Benthic	Riffle	1	2		**1**		1	**2**		3	1		**1**						8	**2**	**1**
6 *Cobitis striata striata Ikeda*	Fluvial fish	Benthic	Pool						1		**3**							**1**	**1**				**1**
4 *Sarcocheilichthys variegatus variegatus*	Fluvial-lacustrine fish	Nektonic	Pool																			**1**	
9 *Biwia yodoensis*	Fluvial-lacustrine fish	Benthic	Pool																				
8 *Oryzias latipes*	Lacustrine fish	Nektonic	Pool								**1**							**1**					**3**
3 *Tanakia limbata*	Lacustrine fish	Intermediate	Pool					1		**1**								**2**				**2**	**2**
10 *Tanakia lanceolata*	Lacustrine fish	Intermediate	Pool																				
12 *Carassius cuvieri*	Lacustrine fish	Nektonic	Pool																				
13 *Misgurnus anguillicaudatus*	Lacustrine fish	Benthic	Pool																			**1**	
Species diversity				3	4	2	2	3	4	2	4	3	3	2	3	0	1	4	2	3	2	8	7
Species abundance				9	9	5	16	3	6	3	6	13	14	6	13	0	0	4	1	9	15	15	14

Table 4-6 Fish community's composition change before and after removal of No.4 weir.

before removal/after				Upstream of NO.4												downstream of NO.4											
	Ecological Type			riffle				pool				wando				riffle				pool				wando			
Taxa	Life Type	Swim Type	Habitat Type	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019	2015	2016	2017	2019
Rhynchocypris lagowskii steindachneri	Fluvial fish	Nektonic	Pool		2			5	11	2	2		4	7	2			1	8		2	1	12		3	6	1
Hemibarbus longirostris	Fluvial fish	Intermediate	Riffle																								
Liobagrus reini	Fluvial fish	Benthic	Riffle	11	5	2	5	1	1							1	2	3	6		1						
Cottus pollux	Fluvial fish	Benthic	Riffle	19	8	24	13				1			1		11	7	1	17		2		2				
Niwaella delicata	Fluvial fish	Benthic	Riffle				1																				
Cobitis striata striata Ikeda	Fluvial fish	Benthic	Pool															1									3
Rhinogobius sp.	Fluvial fish	Benthic	Pool																								1
Sarcocheilichthys variegatus variegatus	Fluvial-lacustrine fish	Nektonic	Pool											1		1				1					1		
Nipponocypris sieboldii	Fluvial-lacustrine fish	Nektonic	Pool																				2				5
Biwia yodoensis	Fluvial-lacustrine fish	Benthic	Pool											1	6						1					10	3
Oryzias latipes	Lacustrine fish	Nektonic	Pool											4										2		1	
Carassius cuvieri	Lacustrine fish	Nektonic	Pool										2	2	1												1
Tanakia limbata	Lacustrine fish	Intermediate	Pool									1									2				1		
Tanakia lanceolata	Lacustrine fish	Intermediate	Pool																								
Misgurnus anguillicaudatus	Lacustrine fish	Benthic	Pool										1	1												1	
Rhinogobius sp.	Lacustrine fish	Benthic	Pool																								
Species diversity				2	3	2	3	2	2	1	2	1	3	7	3	3	2	4	3	1	5	1	3	1	3	4	6
Species abundance				30	13	26	19	1	1	0	1	1	3	10	7	13	9	5	23	1	6	0	4	2	2	12	19
H: Diversity Index																											

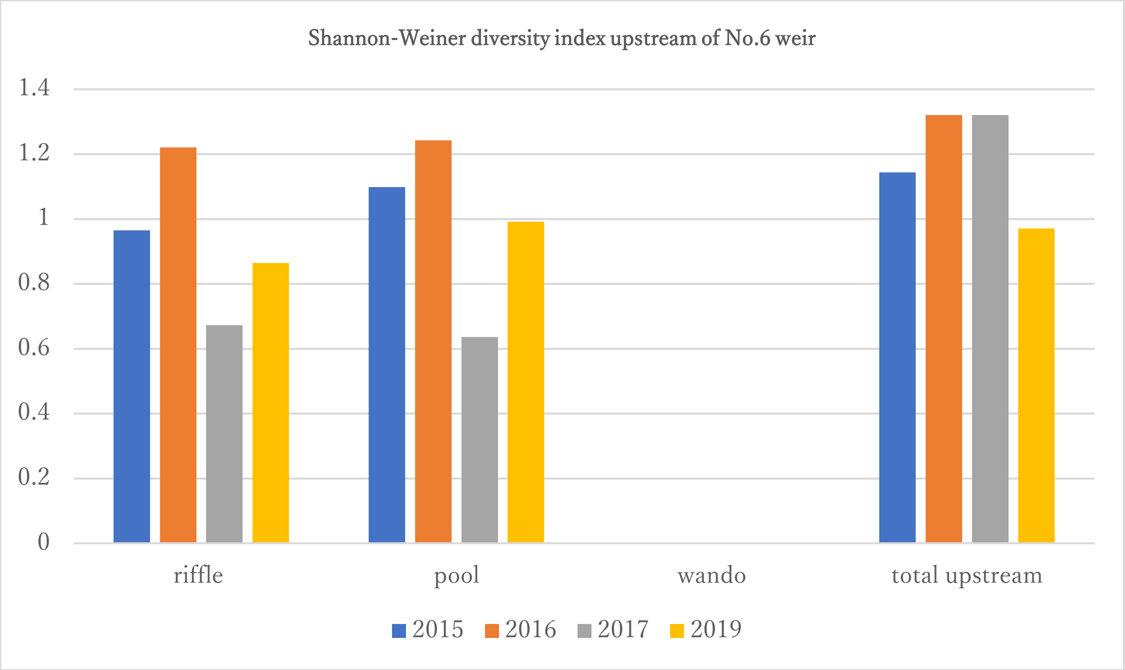


Fig. 4-42 Shannon-Weiner diversity index upstream of No.6 weir for each habitat types.

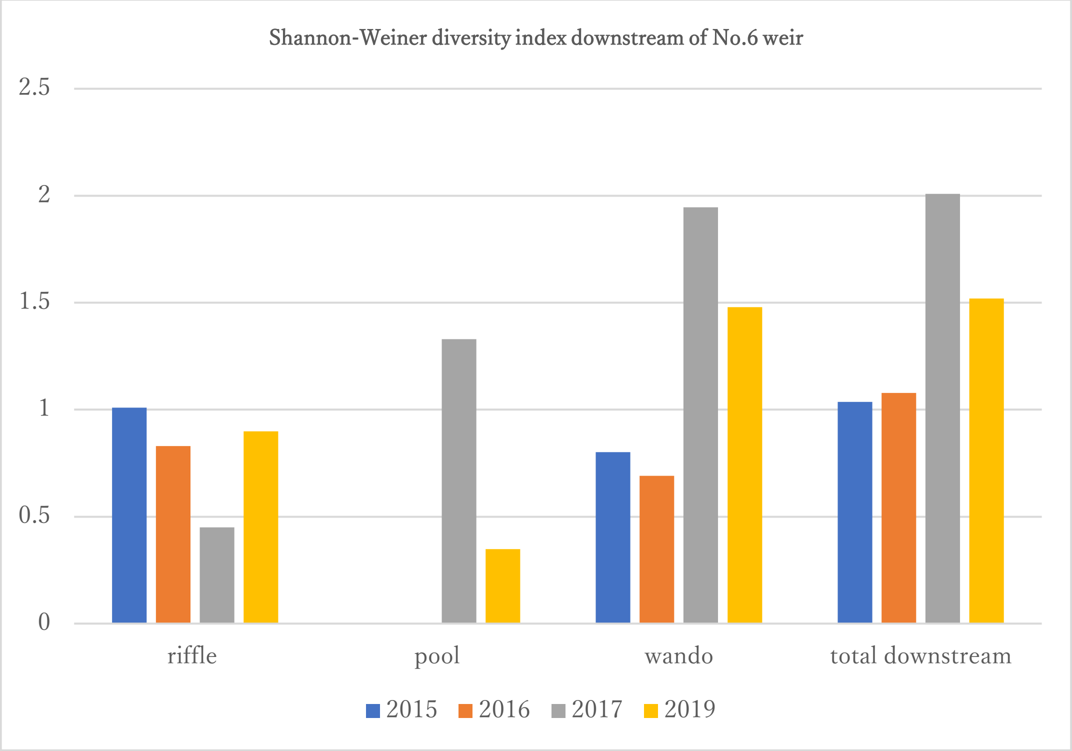


Fig. 4-43 Shannon-Weiner diversity index downstream of No.6 weir for each habitat types.

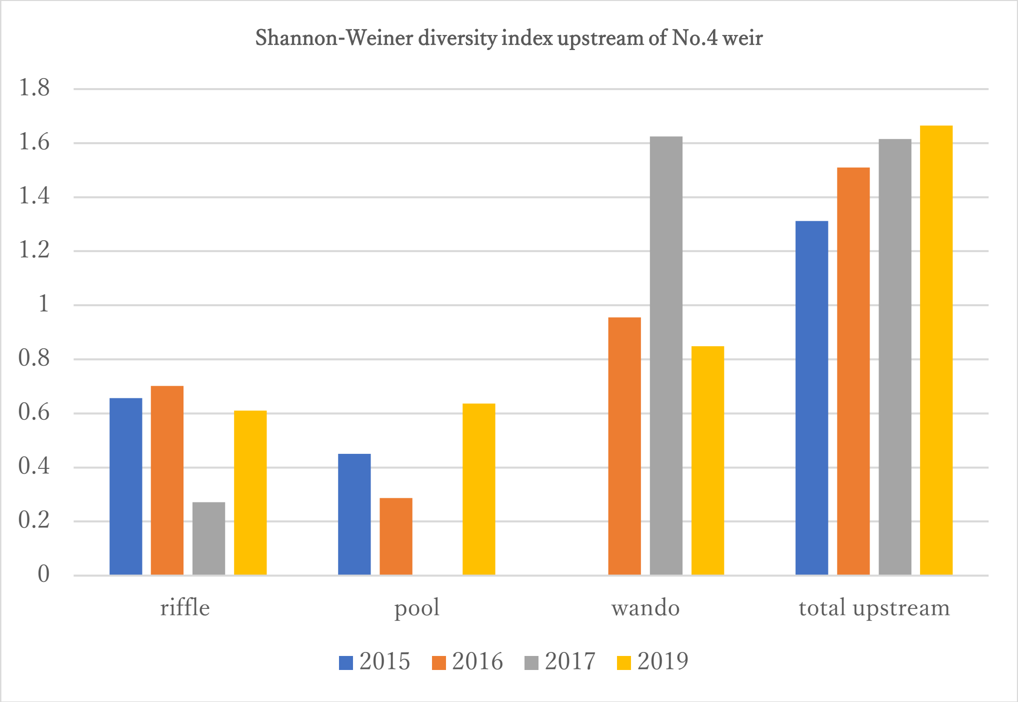


Fig. 4-44 Shannon-Weiner diversity index upstream of No.4 weir for each habitat types.

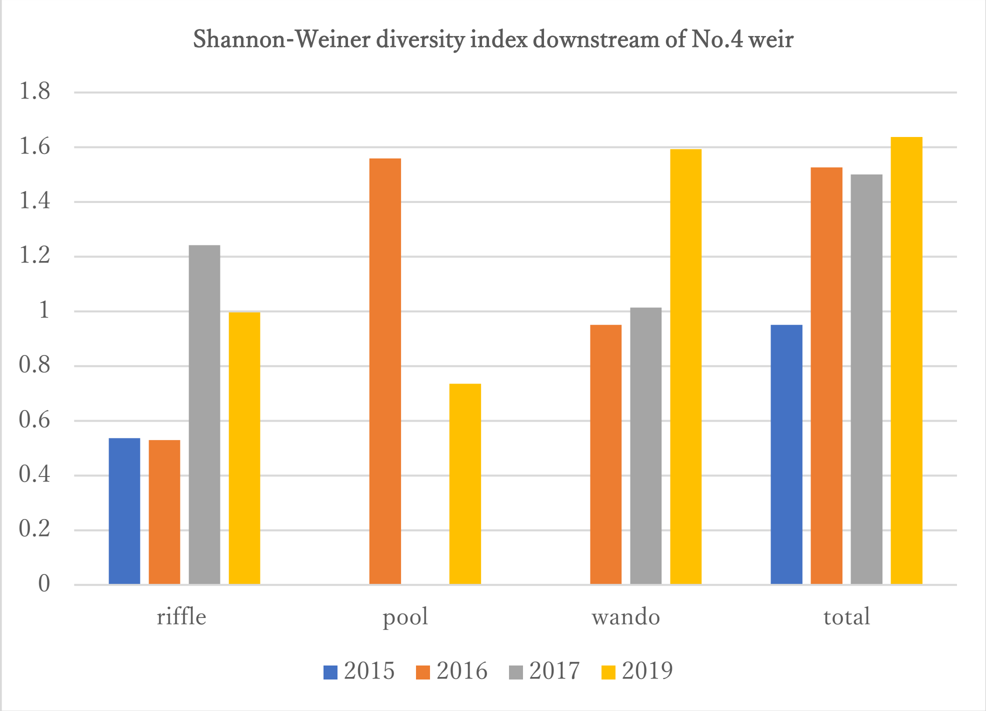


Fig. 4-45 Shannon-Weiner diversity index downstream of No.4 weir for each habitat types.

4.4 Statistical analysis

This section mainly discusses the relationship among river geomorphic parameters, RSCC channel types, riverbed morpho-dynamics and the riffle habitat structure. At first, we summarized the habitat structures contained in each type of RSCC, to find out which channel type contains the most abundant riffle habitat structures, especially we focused on Diverged and Transverse type riffles for they can provide high quality habitats for fish species and aquatic insects. Then the geomorphic characteristics of the RSCC which contains abundant riffle habitats were extracted. Correlation analysis was conducted for all parameters to investigate their relationships with riffle habitats, combinations of interested parameters were extract and further progressed for regression analysis. Recommendations and suggestions for the management schemes are given based on the above analysis.

4.4.1 Relations of RSCC and habitat structures

Single slightly sinuous (Sss) and Single sinuous (Ss) channel types were found to have the most abundant D-types and T-types riffles in terms of the number and area of the riffles. These two similar channel types contain more than 92% of the total area of Diverged type riffles and more than 68% of the total area of Transverse type riffle, they also contain more than 70% of the total number of Diverged type riffle and more than 50% of Transverse type riffle.

Based on Sss and Ss channel type, the geomorphic features of these two channel types were detected (Fig. 4-43). Sss and Ss both have relative higher channel slope of 0.002, highest sinuosity, lowest low flow channel width of less than 80m, very low braided index, and middle value of FVSI. By further identification from the RSCC map (Fig. 4-16) of the study segment, these two types of channels are mainly located in the upstream sub-segment (18.0-13.6K) and downstream sub-segment (7.4-0.0K). In the upstream sub-segment, the Sss and Ss type of channel are limited in the downstream of the weir, in the downstream sub-segment, Sss channel is mainly located from 0-4k, and Ss appeared in from 5-6k only in the year of 2017.

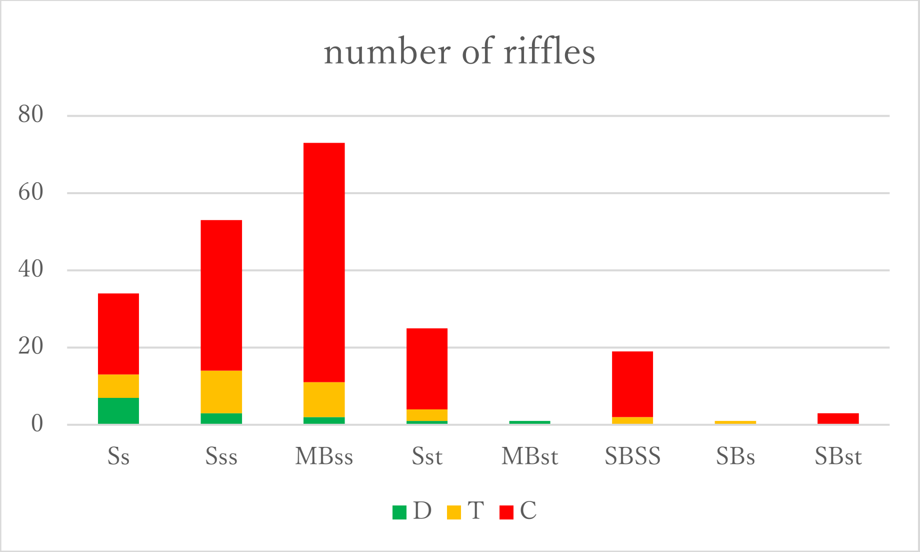


Fig. 4-46 8 types of RSCC and the number of habitat structures they contained for the whole study period.

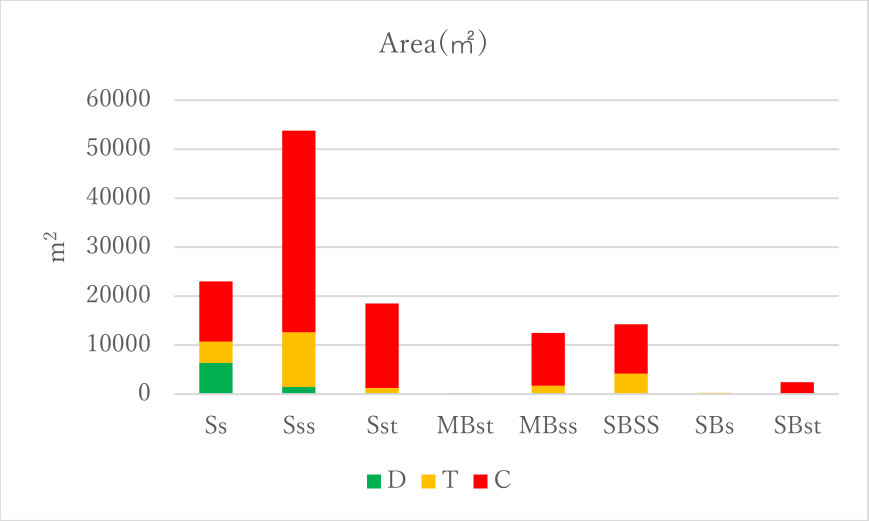


Fig. 4-47 8 types of RSCC and the area (m2) of habitat structures they contained for the whole study period.

4.4.2 Controlling parameters

Since we found that the Ss (single sinuous) and Sss (single slightly sinuous) channel contain most abundant Diverged type and Transverse type of riffle in the last section, now we try to focus on the geomorphic features of these two types of RSCC. Fig. 4-43 shows that the geomorphic features of all RSCC types, the order is ranked from the largest value to the smallest.

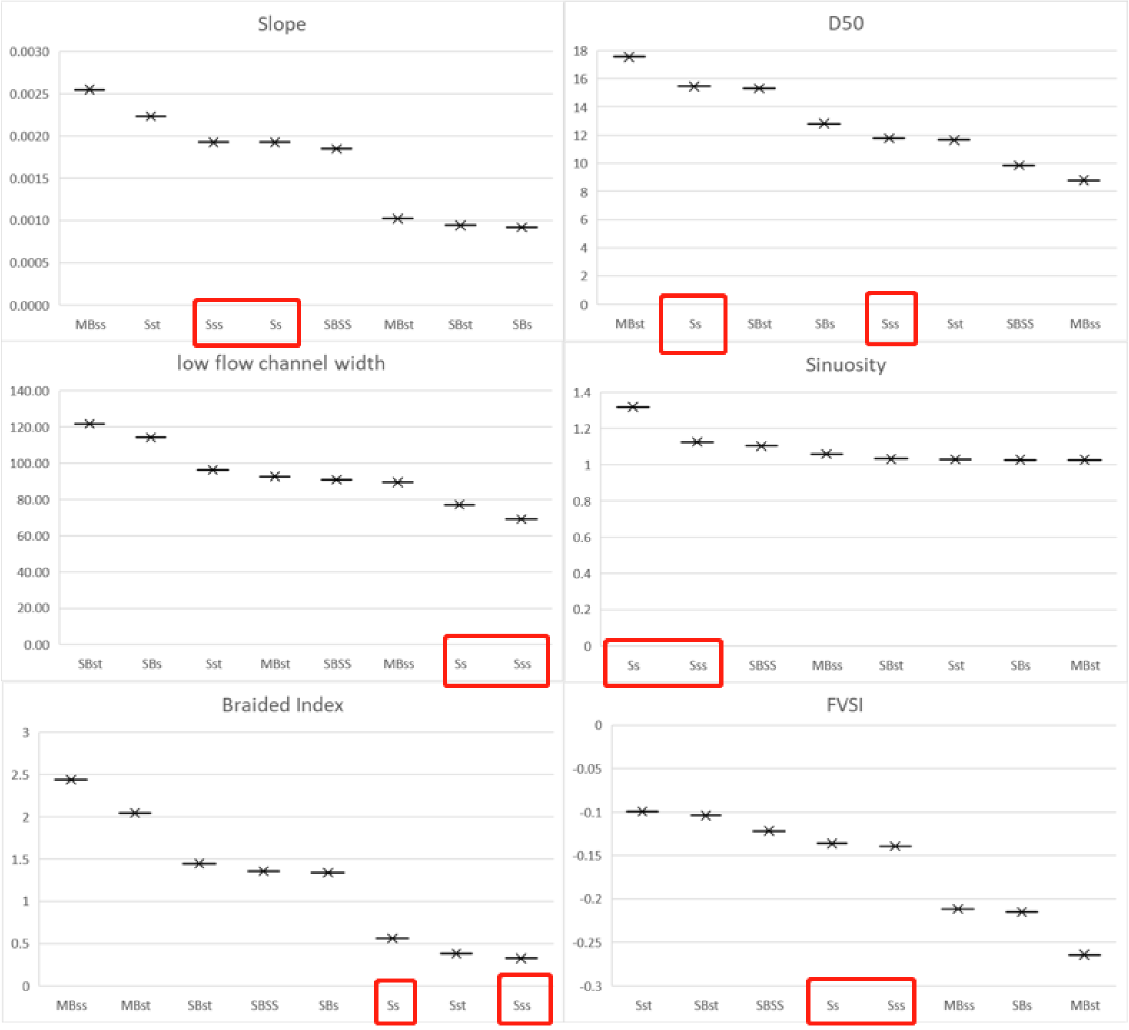


Fig. 4-48 Characteristics of the RSCC channel types that contains the most abundant D and T-type riffles in Katsura river, ordered from large values to small values.

4.4.3 Relations of riverbed morpho-dynamics and geomorphic factors with habitat structures

4.4.3.1 Correlation analysis and processes

All data was prepared and rearranged based on the spatial distribution from upstream to downstream with 200-meter interval, channel sinuosity, channel braided index was measured with 1km-interval, thus, the area of riffle structures is merged and rearranged to same 1km-interval for conducting correlation analysis. After all data sets was list up, correlation matrix was made using R. Due to the incomplete data in 2015 and 2017, only data of 2005, 2013 and 2019 were used for the correlational analysis.

The purpose of this study is to improve the river ecological conditions, by building connections between geomorphic driving factors and riffle habitat structures. Based on our purposes, we first examine the relationships at the segment scale, channel geomorphic parameters and habitat structures, then the empirical relationship between riverbed morpho-dynamics with habitat structures was analyzed, finally I tried to discover the relationships among geo-parameters and riverbed morpho-dynamics. Moreover, the same process was done for the US and DS separately.

Geomorphic parameters and habitat structures in 2005, 2013 and 2019 were analyzed, due to the data set is incomplete in some reaches of year 2015 and 2017.

4.4.3.2 Geo-habitats

No direct relationship was found between channel geomorphic parameters and riffle habitats in the three study years. However, relationships between the change of geomorphic parameters and riffle habitats were found. From 2013-2019, the $\Delta concentrated - type$ riffle and $\Delta Specific\ Streampower$ has positive relationship (+0.53) as Fig. 4-44 showed.

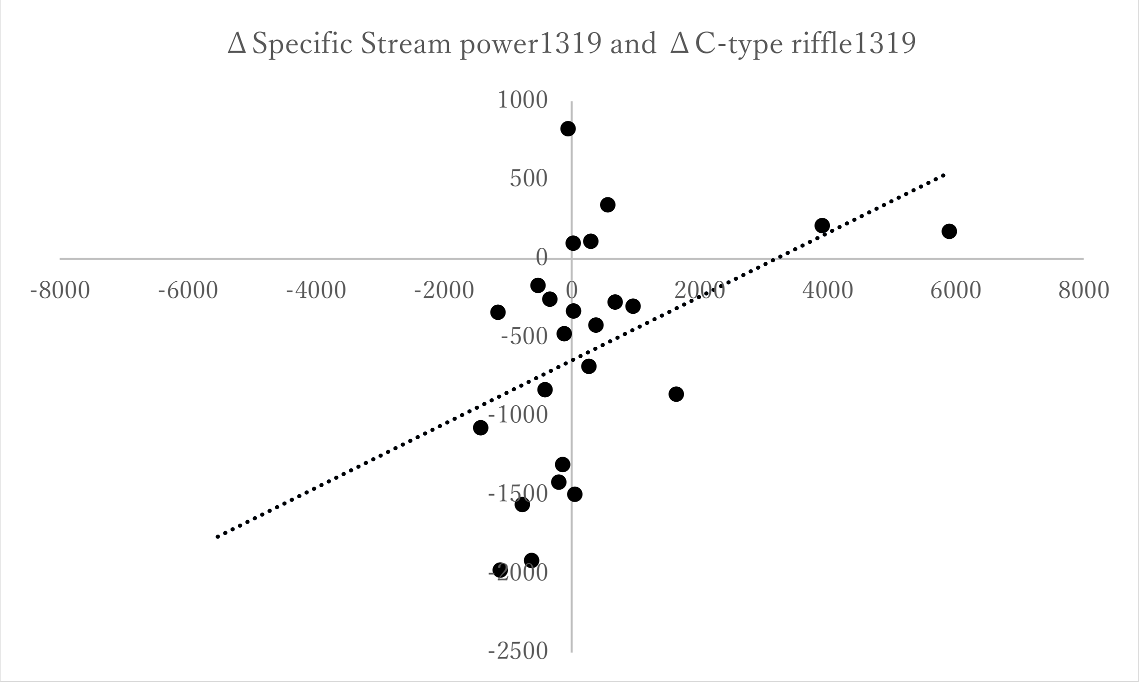


Fig. 4-49 2013-2019, ΔSpecific Stream power and ΔC-type riffle, rs = 0.53, p = 0.01.

4.4.3.3 Riverbed Morphodynamics-habitat

From 2005 to 2013, the riverbed erosion and the change of C-type riffle have negative relationship ($r_s = -0.42$), while the change of C-type riffle and riverbed net change have positive relationship ($r_s = 0.38$).

From 2013-2019, positive relationship was found between riverbed deposition and D-type riffle by the Spearman correlation test with $r_s = 0.89$ as the Fig. 4-47. showed.

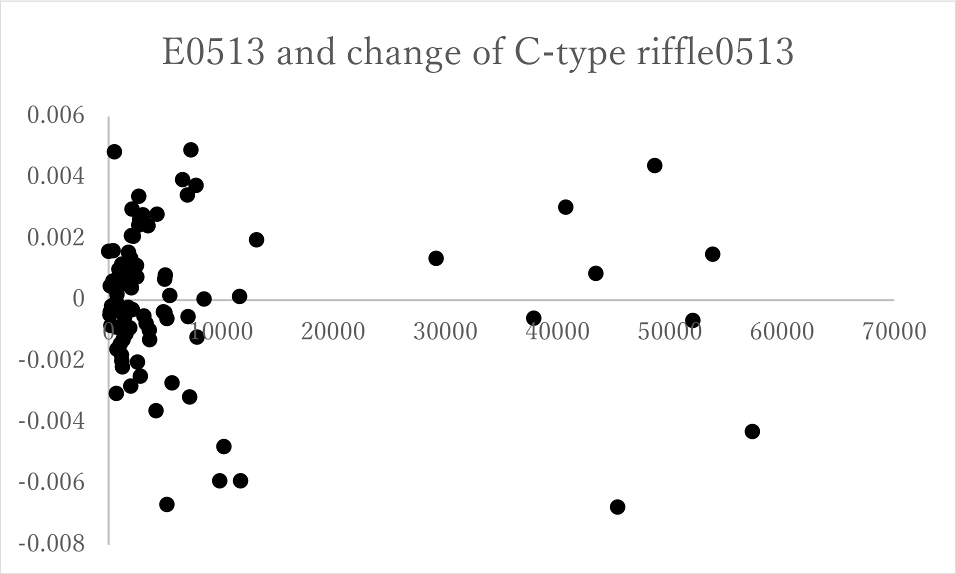


Fig. 4-50 From 2005 to 2013, relationship of Riverbed erosion and the change of Concentrated type riffle.

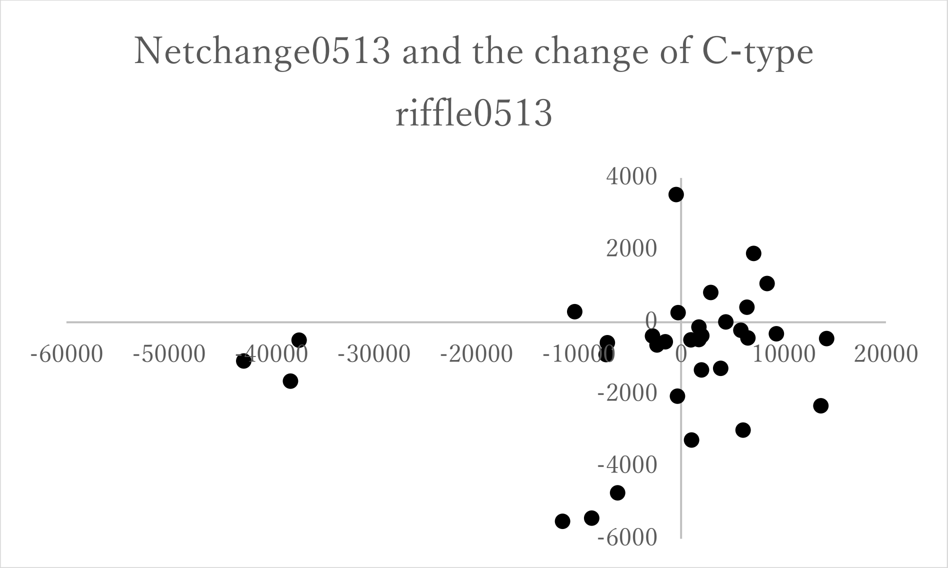


Fig. 4-51 From 2005-2013, the relationship between riverbed net change pattern and the change of Concentrated type riffle.

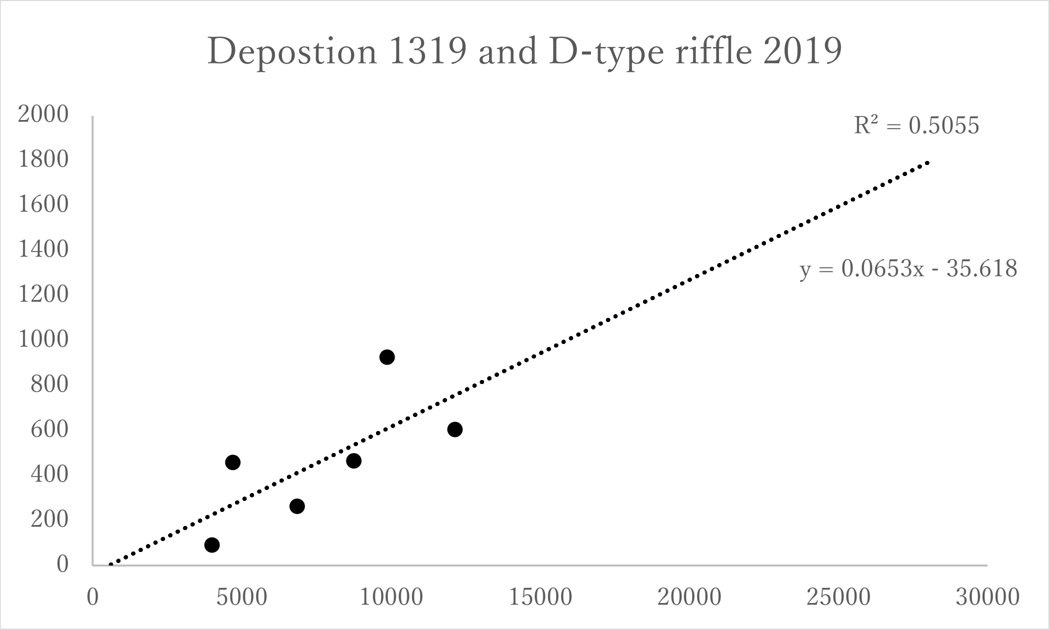


Fig. 4-52 Scattered plot of riverbed deposition of 2013-2019 and Diverged type riffle 2019.

Riverbed morphological change – Geo(change), Geo – Geo parameters.

2005-2013

In 2013, positive relationships were found between riverbed deposition and total shoreline length of 2013 (+0.45) and vegetated shoreline length of 2013 (+0.4), Fig. 4-48.

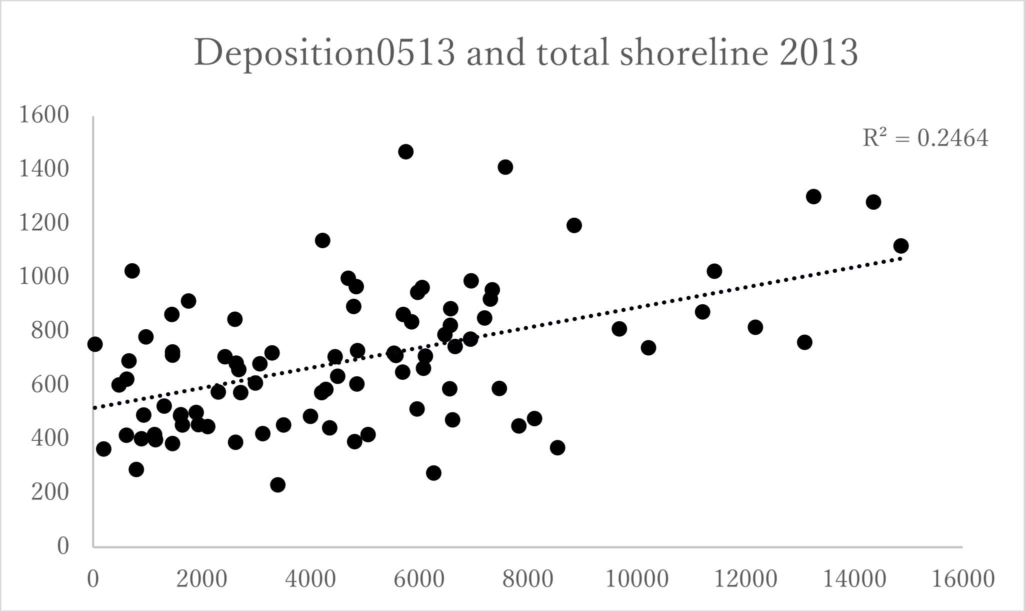


Fig. 4-53 Relationship between riverbed deposition (2005-2013) and total shoreline length of 2013.

As is showed in Fig. 4-49 Riverbed erosion is negative with Vegetated Shoreline Length of 2013 (-0.47) and Low flow channel width of 2013 (-0.46), while positive with Bare shoreline length of 2013 (+0.26). Low flow channel width is positive with Vegetated Shoreline Length of 2013 (-0.52), total Shoreline Length of 2013 (0.25) and riverbed net change (0.25), while negative with Bare Shoreline length (-0.29). Riverbed net change is positive with Shoreline length.

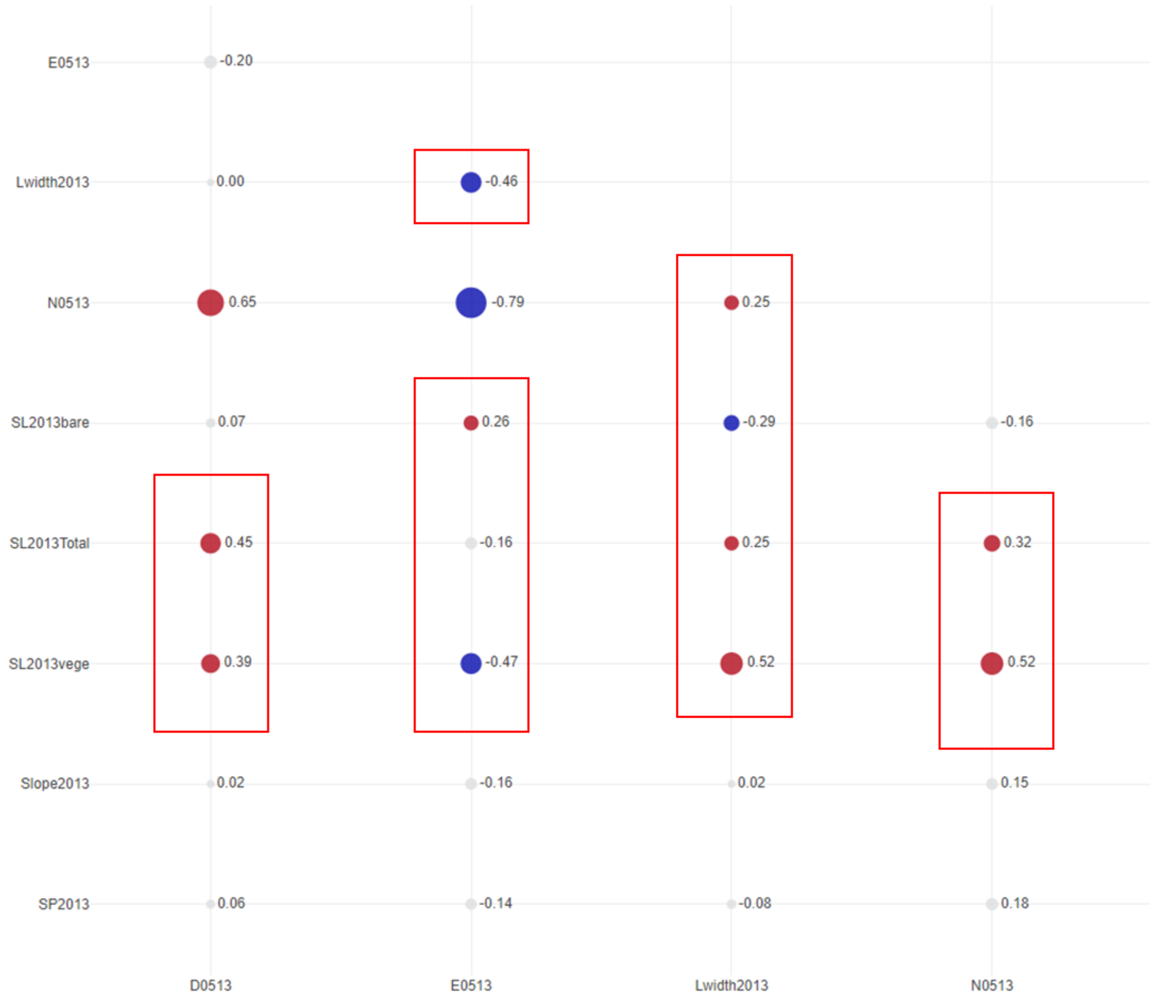


Fig. 4-54 Spearman correlational matrix of 2005-2013, red spots indicate positive relationship, blue ones indicate negative relationship. Red and blue spots appeared in this figure have all passed the significant test p = 0.05.

2013-2019

The following relationships were found by Spearman analysis as Fig. 4-50 shows: Riverbed deposition is positive with total shoreline length ($r_s = 0.37$).and SL2019 bare ($r_s = 0.27$). Riverbed erosion is negative with vegetated shoreline length ($r_s = -0.54$), total shoreline length (r_s = -0.28), and Low flow channel width (r_s = -0.47). Riverbed netchang is positive with vegetated shoreline length (r_s = 0.50) and total shoreline length (r_s = 0.38). Specific stream power is positive with bare shoreline length ((r_s = 0.22).

Low flow channel width is negative with Specific stream power (r_s = -0.27) and bare shoreline length (r_s = -0.27), while positive with vegetated shoreline length (r_s = -0.42).

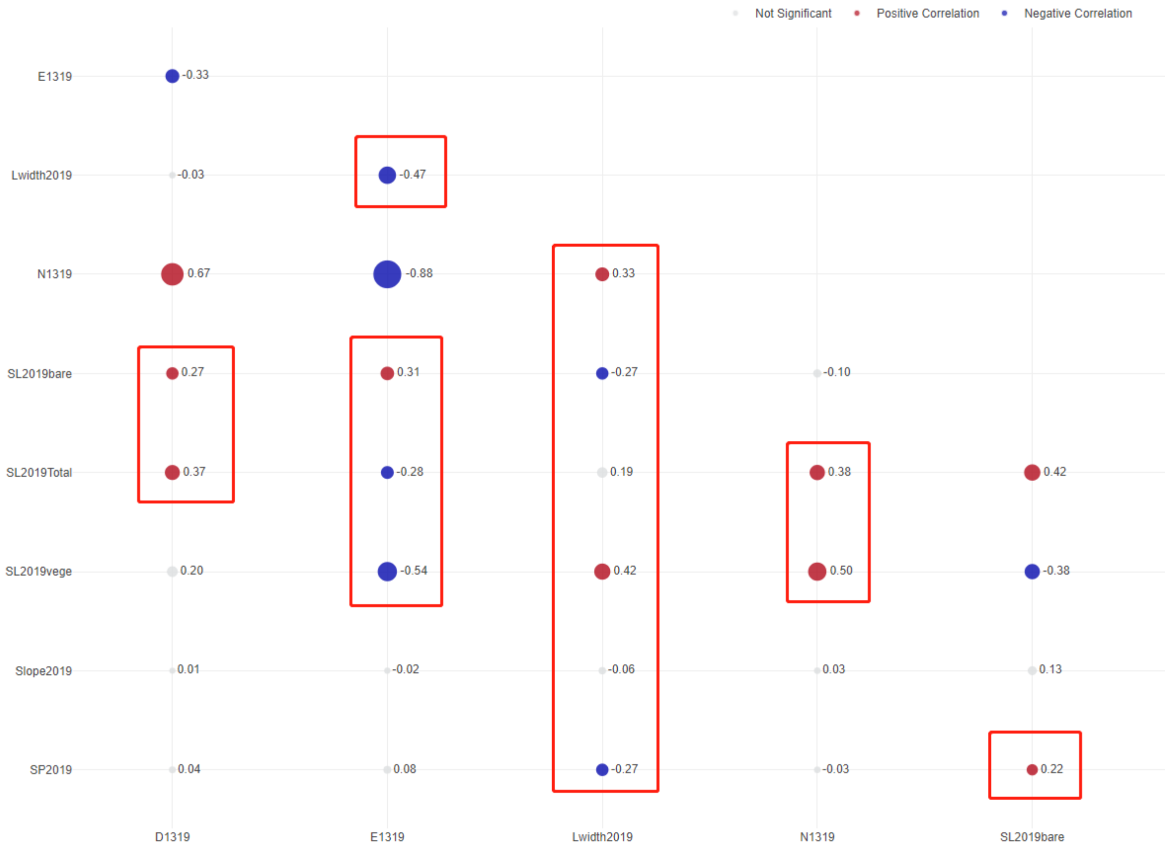


Fig. 4-55 Spearman correlational matrix of 2013-2019, red spots indicate positive relationship, blue ones indicate negative relationship. Red and blue spots appeared in this figure have all passed the significant test p = 0.05.

Summarize of the correlation analysis

Relationships among investigated parameters are summarized in Figure 4-51. The analysis shows that the riffle structures are mainly controlled by the riverbed morpho-dynamic patterns, in which the riverbed deposition has a positive relationship with the Diverged type of riffle. Linear regression analysis shows that the average deposition of 10000m^2 sediment in a 200m reach would possibly create around 617m^2 Diverged type riffle.

Riverbed erosion has a negative relationship with the Concentrated type riffle, which indicates that during the "lifespan" of a riffle structure, if it is already at the Concentrated stage, and still there's no sediment supply from upstream, the further erosional process will keep incising the riverbed and therefore, the channel become deep and riffle structure will be vanished. Oppositely, riverbed net change is positive with the Concentrated type of riffle. Whether a Concentrated riffle can be restored should be determined by how much sediment it needed and how much sediment is supplied. If the sediment supply reaches the minimum level of the requirement of a Concentrated type of riffle to be restored to the Diverged type riffle, let's say a "habitat restoration threshold" volume of sediment, then the riffle should be recovered to the Diverged type riffle. If the amount of supplied sediment cannot reach the threshold, then the Concentrated type of riffle may be maintained or even more degraded to the later stage. Until the sediment supply rate cannot compensate the rate of riverbed erosion, then the original Concentrated riffle will be disappeared.

Channel slope and specific stream power has positive relationships with Concentrated type riffle, which indicate that in a reach with still abundant sediment supply, the more specific stream power means more erosion, and therefore, more Concentrated riffle will be created.

Riverbed deposition also has positive relationship with Shoreline length (positive with both bare and vegetated shoreline). Our hypothesis is the more riverbed deposition a reach has, the more shoreline length will be formed. Shoreline length also has positive relationship with low flow channel width, however, though the vegetated shoreline length is positive with low flow channel width, the bare shoreline length is negative with low flow channel width, this is due to the fact that the widest area of channel is usually just upstream of a weir, and these areas are all heavily vegetated. Bare shoreline is often found downstream of weir, with narrower channel width and higher flow velocity.

These relationships can be used to develop a river environmental management schemes, even though each pair of the relationships are not easy to quantify with simple regression methods, because Katsura river is a representative gravel bed river which lacks of the sediment supply, under the impacts of multiple LHDs, thus the results can be used as a reference for the similar gravel bed rivers.

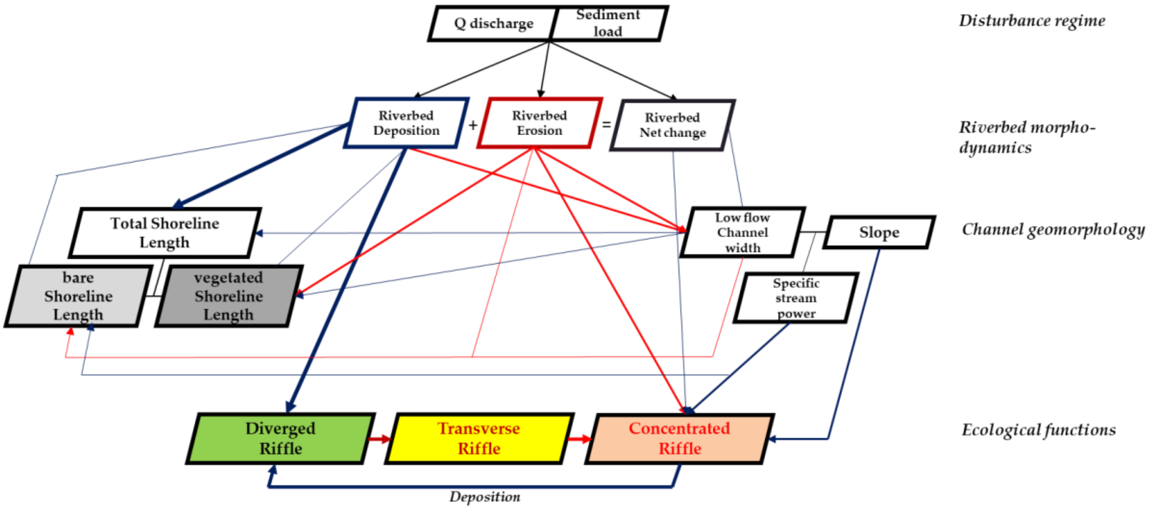


Fig. 4-56 Map of Spearman correlation analysis in Katsura river, deep blue lines and arrows indicate positive relationships and red lines and arrows indicate negative relationships.

4.5 Discussion

4.5.1 Effect of multiple weirs and their removal on the river geomorphology and habitat structure

From historical aerial images and ground survey data, channel width is the widest in the middle segment and the shoreline is dominated by vegetation. Channel slope is considerable low and thus the average flow velocity is the lowest compared to the upper and lower sub-segment. The combined cascade-weirs and straight channel from has formed a deposition zone in the middle segment of Katsura river, backwater effect covered a considerable percentage of the surface water area and has prevented riffle structures from being formed. In the upper sub-segment, mixed pattern of deposition and erosion has been detected, for the channel is sinuous and also affected by the existence of multiple weirs. With higher gradient and due to the smaller size weir and longer distance between two weirs compared to the middle sub-segment, high quality riffles are mainly developed in this area. No weir has been constructed in the lower sub – segment thus the channel width is the narrowest and flow velocity is the highest among the three sub – segments. Therefore, the lower sub-segment is dominated by the channel erosion, both contributed from the natural flooding events and man-made excavating work. Our sediment budget estimation results showed that even though the weirs are trapping sediment, but the amount cannot pair with the sediment eroded and out from the study segment. Clearly the study segment of Katsura river is losing sediment due to the lack of supply from upstream and the flood mitigation work by sediment excavation. Weir removal has provided the additional source of sediment supply and has resulted in the formation of high-quality riffles. However, the amount of sediment supply is much less than the estimated needed and the volume has already been greatly compromised by the excavating work before and after weir removal.

4.5.2 Which RSCC channel types are suitable for the high-quality riffle habitats

Based on our results, the Single Sinuous (Ss) and Single Slightly Sinuous channel type contains the most abundant Diverged type and Transverse type riffle. From the Downstream Hydraulic Geometry relations (DHG) for the single thread gravel-bed rivers (Knighton, 1998; Bridge, 2009), channel form of Katsura river should be much narrower, single thread, and riffle – pool dominated morphology because of the fundamental hydrological and sediment conditions, while due to the man-made work such as weirs and levees construction, the river channel form has been unnaturally changed to the current situation. According to Kobayashi and Mikyong’s study in Kizu river (Kobayashi and Takemon 2013; Choi, 2013), the braided channel form contains the highest diversity of habitat structures, however, there are no weirs constructed in Kizu river, and much more sediment supply makes the braided channel suitable for develop shallow riffles. In Katsura river, braided channel forms appeared only at downstream of specific weirs (mainly at No.1 and No.3 weir), much less sediment supply compared to the Kizu river and the fixed flow structure at downstream of a weir have resulted in the continuously channel incision which made the braided bars became isolated mid-channel islands, and usually heavily vegetated. Therefore, the ecological functions of the braided channel type in Katsura river are very different from the one in the normal gravel and sandy bed rivers like Kizu river.

Weir removal can reduce the channel width and thus can probably restore the channel to the Ss and Sss type, however, the increased flow velocity will possibly make the channel further eroded, because of the less sediment supply from upstream. If weir removal at the upstream and middle stream sub – segment would transfer the channel form similar like the downstream sub segment --- narrow sinuous however incised channel, the high-quality riffle habitats still cannot be developed. The critical question is how to increase the amount of Sss and Ss RSCC type while prevent the excessive channel erosion and incision under the limited sediment supply from upstream. In this sense, the management scheme against the weirs and sediment excavating should be very carefully designed and studied in advance. The possible solution might be totally or partially removal of some selected weirs, while keep or partially move the weirs that can largely controls the channel erosion for instance in Katsura river case, the No.1 and No.3 weirs are two largest ones and have prominent impact on the riverbed stabilization. To keep or partially remove these two (partially removal means remove the weir body while keep the foundation) and removal the weirs in between might be an possible river ecological restoration option.

Fig. 4-57 Braided channel form of the Kizu river.

Fig. 4-58 Braided channel form in Katsura river.

4.6 Conclusion

According to our study results for the historical changes in riverbed geomorphology, riffle habitat structures and fish community changes in the Katsura river, we summarized the important findings as follows:

1. In Katsura river, the UR showed mixed pattern of both erosion and deposition, MR is mainly deposition and DR is dominated by erosion, which is due to the combined effects of the channel form and backwater effects of the cascade low-head dams.
2. Channel responded differently to No.6 and No.4 weir removal, for which the former showed both upstream and downstream erosion. The latter only showed upstream significant erosion, this is due to the different settings of boundary conditions and man-made river engineering works, indicates the actual effects of LHDs on riverbed geomorphology are highly dependent on the boundary conditions.
3. After weir removal, channel slope became steeper, and D-type riffle slightly increased, T-type significantly increased and then slightly decreased, C-type riffle first decreased and then increased again.

4. Straight channel type became less, since sediment dynamism were increased after two weirs' removal and resulted in more deposition pattern, which further make more abundant channel types e.g., in 2019 (7 types), especially sinuous types were increased.
5. Single sinuous (Ss) and Single slightly sinuous (Sss) channel type contain most abundant Diverge-type and Transverse-type riffle. These two types of channels are featured by relatively high slope (0.002), lowest active channel width (75m), highest sinuosity (1.3), lowest braided index (0.5) intermedium FVSI (-0.13), and large D50 (15mm, and 12mm).
6. The relationship that we found among the river sediment dynamisms and geomorphic features are there is a positive relationship for channel deposition volumes with channel slope and shoreline length.
7. Empirical relationships were also examined for river sediment dynamisms and habitat structures, river erosion causes the decrease of Concentrated-type riffle. Channel deposition has a positive relationship with the Concentrated-type riffle, which is the most important founding and can be used for guiding river sediment replenishment schemes.

Chapter 5 Low-head dam’s influence on hyporheic flow in a gravel bed river

5.1 Introduction

The aim of this chapter is to evaluate the influence of weir and its removal on the reach scale hyporheic exchange (HE). The No.1 weir site was chosen to represent the weir existing situation, and No.4 weir site was studied as the representative of weir removal situation.

For the weir existing scenario, a numerical model was built up to estimate the HE induced by the No.1 weir at low flow conditions, for which the coupled Laplace model and Darcy’s model was chosen due to its suitability to model large scales in which the hydrostatic is the dominant driver for HE, this is especially useful in the weir case. And based on the borehole data conducted by the Yodo River bureau, the sediment in the No.1 weir reach is mainly consisted of gravels (Fig. 3-5) and based on which the hyporheic domain is assumed homogeneous and isotropic. The most difficult part for the weir existence is that the field data of hydraulic conductivity behind the weirs is notoriously hard to acquire, however, we were lucky to get access to the former backwater area of No.1 weir during the first day of removal and was able to get the field data of K value which was used as input to the model.

As to the weir removal case, an already removed weir with substantial morphological changes is required, and thus the No.4 weir site was chosen to represent the weir removal scenario. No.4 weir removal project was totally finished in March 2019, several months after No.4 weir removal (most likely during the flood season, August), a gravel bar was formed due to the increased sediment dynamism after removal. The controlling factor of HE, K was surveyed twice with one month interval. The objectives of this chapter are 1) to investigate the potential ecological function in terms of HE for the newly created bar after removal; and 2) to check how K will change for one month period during low flow conditions. 3) the grainsize analysis is conducted for detecting the fine sediment deposition in this bar, relationship of D10 and K was examined.

5.2 Study area and methods

No.1 weir

No.1 weir is the largest one in the study segment. It was built on 1953 and mainly for the purpose of water intake and irrigation. Due to the 4-m height, the back water effect is significant and extended to the upstream Kuga weir. Low flow channel width is the largest upstream of No.1 weir (1.6km from No.1 weir), with flat riverbed slope, the flow velocity is low. At downstream side, large mid-channel island was created and existed for a long time, from consecutive satellite images we found the island and mid channel bars are very stable, even though after historical peak discharge happened in 2013, the morphology did not change so much. And due to the fixed water flow structure, the channel is braided, narrow and incised. Vegetation is promoted due to the stable morphology of the big island.

No.1 weir was removed in October 2020, according to a flood mitigation plan for the Katsura river conducted by Yodo river bureau, including removal projects of several other weirs and riverbed excavation. The breaching of the weir body immediately lowered water level, and exposed big gravel bars at upstream end. During the first day of weir removal, we were able to visit the upstream site, where the original bed material still kept intact in the bankside, even though considerable changes had been already happened in the middle part of the channel, due to the increased flow velocity. We believe the riverbed at bank side can still represent the bed conditions of the pre-removal. In chapter 4, we did not include the No.1 weir removal, due to the riverbed cross sectional survey data are still unavailable during this study.

Fig. 5-1 Satellite images of before(2019) and after No.1 weir removal (2021), note that the upstream gravel bar exposed after removal.

Fig. 5-2 During the removal of No.1 weir, the weir has been breached, and weir body was removing, the water level has been lowered and thus we can do field survey in the former impoundment area.

No.4 weir

No.4 weir was located at the upstream (13.6K) of the study segment, which is the second removed weir in Katsura river (No.6 is the first), it was removed during 2017-2019, for the same purposes as the removal of No.1 weir. It is relatively smaller than No.1 weir, and the channel upstream of No.4 weir is curve with a big point bar, channel thalweg line is obvious in case of No.4, compared to No.1 weir. As to the downstream side, the river channel is wide due to the backwater effect of No.3 weir which is the second largest one in the study area, located only 1.4km downstream.

Fig. 5-3 Satellite images of No.4 weir, before (2016), during (2017) an after removal (2019).

5.2.1 Estimation of hyporheic exchange induced by the No.1 weir

In the present work, the dominant driving force for the hyporheic flow is hydrostatic force, therefore, the hydrodynamic force is ignored due to the very slow velocity (0.04m/s) and totally submerged conditions in the backwater area of the No.1 weir. Therefore, we used a coupled Laplace model and Darcy's law to simulate hyporheic exchange induced by a single weir.

Hydraulics model

For estimating the hyporheic exchange at no.1 weir reach, which is a hydrostatic-dominated system, the first step is to figure out the hydraulic head distribution along the SWI (sediment water interface), thus, HEC-RAS (Hydrologic Engineering Center's River Analysis System) is used to simulate steady state surface water flow under low flow condition. The model was validated by water surface elevation data from gauges. The results are then used as upper boundary conditions for the hyporheic model. We used the real channel geometry data for simulating surface water flow in HEC-RAS, Manning coefficient of the streambed is set as 0.03, suitable for the gravel bed river like Katsura. Weir geometry was set exactly same as No.1 weir, weir shape is broad crest.

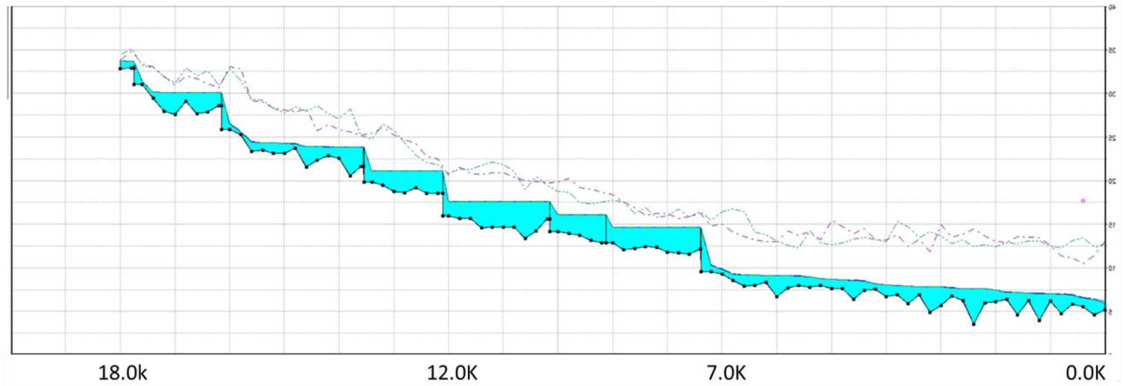


Fig. 5-4 Water surface elevation profile by 1-D hydraulic modeling software HecRAS.

Hyporheic model set up

We want to know how much hyporheic exchange rate induced by No.1 weir, under the real geometry settings, thus same with the HEC-RAS modeling, the sub-surface, hyporheic domain is using the real geometry, with a length of two kilometers. Because The system which we are considering is hydrostatic pressure dominated, the channel is straight and thus we do not consider the lateral hyporheic exchange, only vertical change will be considered in this study. And due to the rather uniform and simple riverbed morphology transversely upstream of the weir (Fig. 5-4), the hyporheic exchange induced by transversely river morphology can be ignored, thus the model is simulated in a 2-D domain. in order to simulate the hyporheic flow, some important assumptions are made before the actual modeling: 1) water is incompressible and hyporheic flow is laminar, non-turbulent. 2) riverbed is immobile, sediment is cohesionless, homogeneous and isotropic. 3) the pressure head induced by velocity distributing to the SWI is neglected, due to the fully submerged area upstream of the weir, and the low flow velocity (0.04m/s) conditions, thus the hydrostatic pressure is the dominant force to drive hyporheic flow. After having the information of water level from the HEC-RAS on the SWI, the hydraulic head distribution in the subsurface domain is governed by Laplace equation, which in 2D Cartesian coordinate system can be written as:

$$\frac{\partial^2 h^2}{\partial x^2} + \frac{\partial^2 h^2}{\partial y^2} = 0$$

Where h is the hydraulic head (total head), and x, y are coordinates. The Darcy's law is given by:

$$q = -K\nabla h$$

Where q is the Darcy flux, K is the hydraulic conductivity. Boundary conditions are summarized in Fig. 5-5.

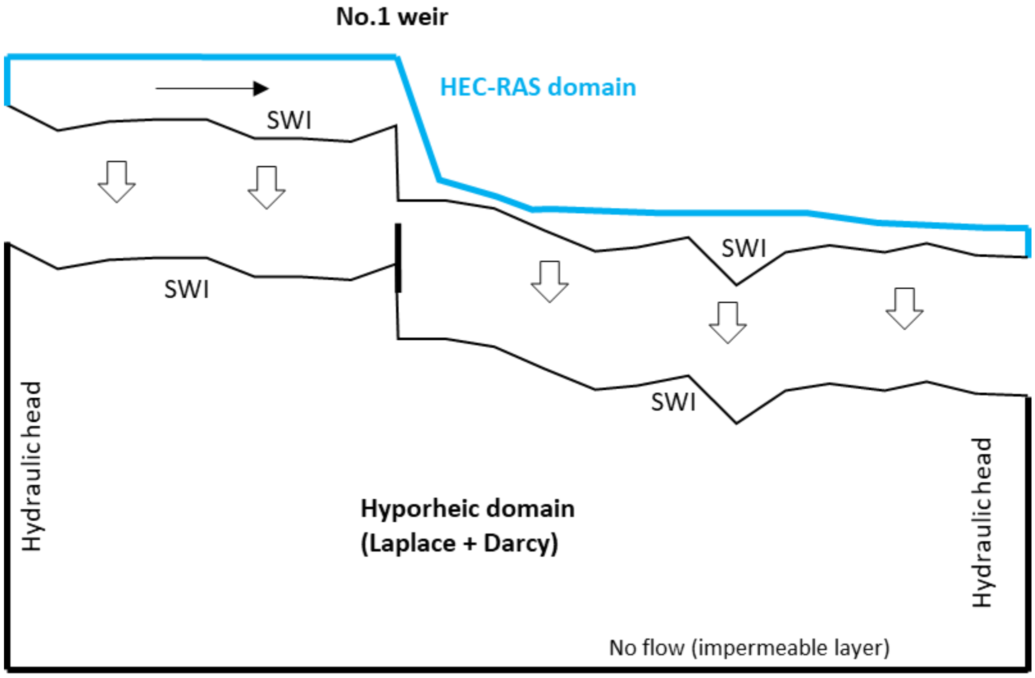


Fig. 5-5 Model settings, the HEC-RAS model for the surface water profile which is then used as upper boundary conditions for the hyporheic model. Upstream and downstream boundary conditions are assigned hydraulic heads from the upstream and downstream edges of the channel. Bottom boundary is set as no flow conditions (impermeable layer).

5.2.2 Estimation of *in-situ* riverbed hydraulic conductivity after No.4 weir removal

Field surveys were conducted at two sites which are at No.1 and No.4 weir sites. Riverbed hydraulic conductivity, geometry data, and water quality data were measured. As the table 5. shows, the former No.4 weir site, 10 months after weir removal, a middle-channel gravel bar was created, and we were able to do the on-site hydraulic conductivity estimation and measurement of geomorphic features. Survey of in-situ riverbed hydraulic conductivity was done using Constant Head Injection Test method (CHIT). Riverbed hydraulic conductivity plays an important role in the surface water and ground water exchange process which has been showed in many former studies. (Butler et al. 2001; Kollet and Zlotnik 2003). Yet it is difficult to directly measure the streambed hydraulic conductivity, due to it is usually beneath the riverbed and submerged by stream water, especially for the in-situ estimation or in relative larger spatial scale and intensity survey.

The traditional ways to investigate the riverbed hydraulic conductivity such as standard slug test, grain-size analysis and observation wells are both time- and resource-consuming procedure.

In order to quicker and use less resources to get intensive information of riverbed hydraulic conductivity in the field, we use modified Constant Head Injection Test (CHIT) method and beforehand-made spread sheet to estimate the in-situ riverbed hydraulic conductivity, and capable to get the result almost immediately. This method fits better for large scale and intensively survey of the gravel bed river especially with low accessibility.

CHIT method

The constant head injection test is standard tool used by many soil and civil engineers. While the original idea is for measuring the low K value media, e.g. silt and clay. We use the modified CHIT method developed by Cardenas and Zlotnik to measure the higher K value rivers such as gravel bed rivers. The purpose of this report is to show the instrumentation, field process, and data analysis for using the CHIT method to study the gravel bed rivers in Japan, for the development of the theory please refer the following papers. (Bouwer and Rice, 1976; Dagan, 1978; Cardenas and Zlotnik, 2003).

For sub-meter scale we assume Kh=Kv=K

$K=Q/2\pi LPy$ (Cardenas, 2003) and (Cho, 2000)

Where:

Kh is horizontal hydraulic conductivity

Kv is vertical hydraulic conductivity

K is the general hydraulic conductivity

Q is the stabilized injection rate

L: screened length

P: shape factor (dimensionless coefficient)

y: distance between stream stage and the desired water level in the permeameter

$$\boldsymbol{P} = \frac{1.1}{\ln((l+L)/r_w)} + \frac{\mathrm{A} + \mathrm{B}\ln[b-(l+L)/r_w]}{L/r_w}$$

Where: A and B are dimensionless coefficients that were originally in graphic form. These coefficients were approximated by Van Rooy (1988) (details in Butler, 1998)

Using the modified CHIT theory, we only need to measure the Q and y in the field, other values are given. By using a spreadsheet, the K value can be calculated in the field.

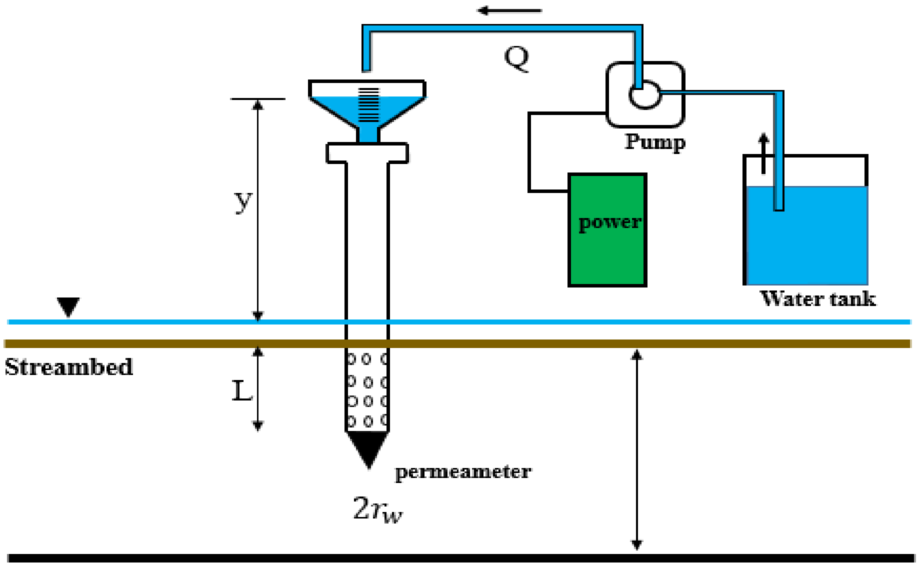


Fig. 5-6 The instrumentation of CHIIT method.

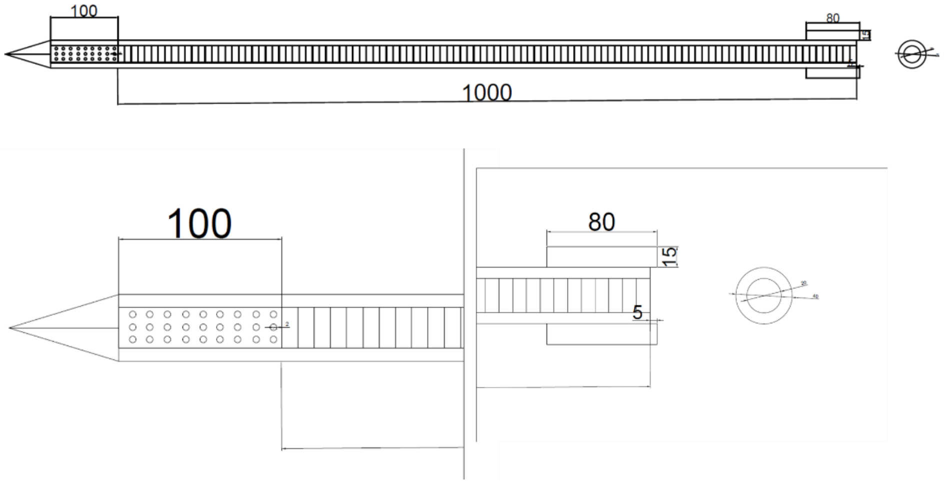


Fig. 5-7 Design of the permeameter used in this study.

The permeameter was specially designed for the higher K value riverbed materials such as gravel and sandy rivers. The total length of the pipe is 1000mm, the inner diameter of the pipe is 45 mm; the outer diameter is 50mm, the thickness of the pipe wall is 2.5mm. The tip of the instrument is a solid cone which the height is 75mm and the circumference is 50mm. The cone is made of solid steel. The bottom part of the pipe is the screened area, the length is 200mm. Diameter of all the holes is 2mm, the distance between the center of the hole to the edge of the hole area is 10mm, both the top edge and the bottom, (assume the permeameter is stand position) .

Stream water was collected in a bucket (without much suspended load, which could clog the hole area and streambed sediment), then pumped into the permeameter by the micro water pump which can adjust the discharge manually in order to keep a constant water level in the top of the permeameter. As the water level attained the designed height y and was steady (e.g., for 10s to several minutes), pull out the pipe into a volume cylinder, as the same time start the timer, thus the injection rate Q can be measured.

Known test geometry, injection rate Q and operational head y, K can be easily calculated.

Table 5-1 Summary of field surveys.

	No.4 weir site (after removal)		Upstream of NO.1 weir
Survey contents	4/12/2019	11/1/2020	10/11/2020
Drone survey	Yes		/
Geometry survey	Yes	Yes	/
Number of survey points	20	24	5
Water surface elevation	Yes	Yes	/
Ground surface elevation	Yes	Yes	/
Hydraulic conductivity	Yes	Yes	Yes
stream water temperature	Yes	Yes	/
EC	Yes	Yes	/

Field survey during No.1 weir removal

At the first day of No.1 weir removal, we went to the upstream of the weir site, *in-situ* survey of riverbed hydraulic conductivity was done at the right bank side near the weir. during measurement, we found that the fine sediment distributed not only at the shore, but also extended to the center of the channel, although after dam breaching the fine deposited at the center area of the channel has to be eroded and flushed out by some extent. From Fig. 5-8 we can see clearly that the fines are spread all over the upstream of the weir.

Fig. 5-8 Muddy layer along the right bank just upstream of No.1 weir.

Fig. 5-9 Muddy layer is thick and spread all over the channel upstream of the weir.

Field survey after NO.4 weir removal

The study site is in Katsura River which is a typical urbanized river segment in the downtown area of Kyoto City. There were eight weirs constructed in the main channel, and by the end of 2019, two of them has been removed in a government flood control and channel modification project. No.4 weir was completely removed in March 2019, and a mid-channel gravel bar was created nearby after typhoon No.10 in August. After No.4 weir removal, the riverbed excavating work has been done in the vicinity, which resulted in a flat and compacted channel.

The triangle-shaped bar has an area of 2193 square meters and located just downstream of a large point bar with a huge channel bend. The main channel was diverted into two subchannels by the gravel bar. The elevation of the left-bank side channel was significantly higher than the right side based on field observation, which, was proved by the water table mapping afterwards, indicating the hyporheic flow direction could be from left-bank side to the right side (blue lines in Fig. 5-10).

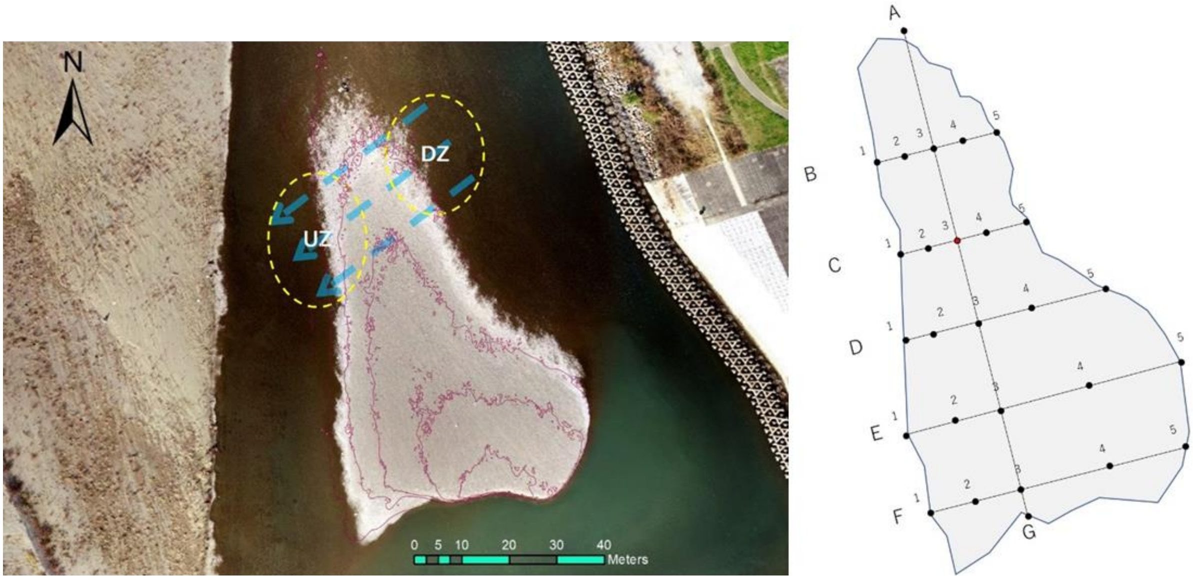


Fig. 5-10 The study site in Katsura River and the corresponding coordinate system, drone photos were taken by Takemon, 4th December 2019. The bar surface contour line interval is 10cm.

The field surveys were conducted two times during the low flow season, on 4th December and 11th January, respectively (Fig. 5-11). No heavy rainfall happened during this period, and no major anthropogenic interference was noticed. However, several small rainfalls were detected and caused water level fluctuated between the two surveys. During December, the water level fluctuated to a maximum 3cm (1.69m ± 3cm), while on January 8th, two days before the second survey, a rainfall has resulted in a 10cm water level increase(1.69m+10cm). On January 11th, the water level has returned to the same level of the first survey (1.69m).

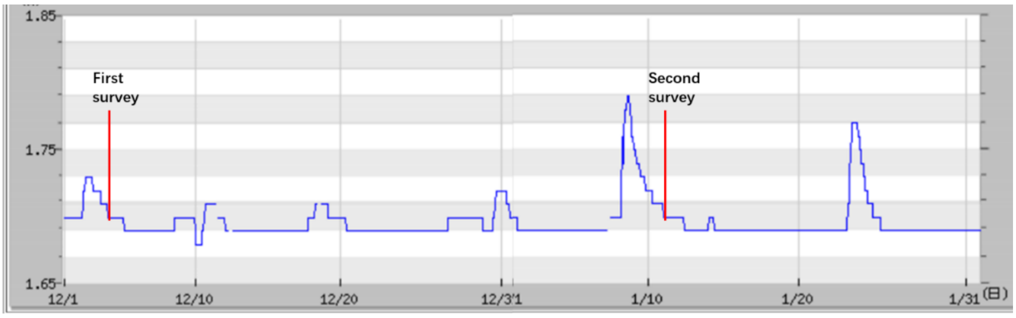


Fig. 5-11 The water level(m) fluctuation from 1st December to 31st January.

In the first survey we measured the bathymetry of the gravel bar and made a coordinate system shown in Fig. 5-10 (transects were named by A to G). longitudinally, from A to G the bar showed a significant sediment sorting, in the bar head the sediment is mainly consist of gravel and cobbles, while in the bar tail a thick layer of clean and loose sand was deposited with a higher elevation than the bar head. Cross-sectionally, the bar middle is higher than the side area. Fine materials were detected on the bar surface, however near the waterfront they were flushed and a “cleaned” bar edge area can be detected from the aerial.

Water table mapping

Water table was measured in the main channel and in the gravel bar by a level station with the accuracy of 1mm. In the gravel bar wells were dug at every survey point in Fig. 5-10 by a shovel and measured after the water table was steady.

Grain size analysis

The riverbed hydraulic conductivity (K) was estimated using Constant Head Injection Test (CHIT) following Cardenas’ method (2003). A set of equipment including a permeameter made of steel which has a length of 110cm, 2cm for the inner diameter and 2.5cm for the outer diameter, and a solid metal cone was welded on the tip for penetrating the hard gravel bed. The screened area is 10 cm long and has a 2mm diameter for the slot size. A micro water pump was used for injecting water with a manually tuned, maximum discharge ability of 6000ml/min.

While during the preliminary test for determination of precision and repeatability, our equipment was not able to estimate K for the line E, F, and point G, for the sediment is consist of a layer of clean sand on top and very loose, the hydraulic conductivity was too high for our equipment design, we also dug holes in this area and try to estimate K in the deeper layer, however the value was still over the upper limits of our equipment. thus, for this part (bar tail) we generally assume the K is high. For better understanding and interpolation, during the preliminary survey we assigned "100m/day" for the points that the K value was over the upper limit measurement ability of our apparatus, and "0" for the extremely low K situation. In the rest part of this paper, 100m/day means the K value is generally high, however, the actual value could be more than 100m/day as we estimated in the field (100-300m/day).

Thus, vertical hydraulic conductivity of saturated aquifer was estimated from A to D5. For each point measurement was made at three different depths: the top (0-30cm), middle (30-60cm) and deep (over 60cm) to detect the vertical heterogenous of K.

Aerial photos taken by DJI Phantom 4 drone were analyzed using Agisoft Metashape Pro of Agisoft LLC, to create an Orthomosaic. Grain size analysis of bed surface was done by ImageJ bundled with 64-bit Java 1.8.0_112. The historical river longitudinal profile was collected from Yodo river bureau and processed by Microsoft Excel software. All the data acquired was processed and visualized in the ESRI's ArcGIS software. The spatial distribution of K was interpolated by IDW method.

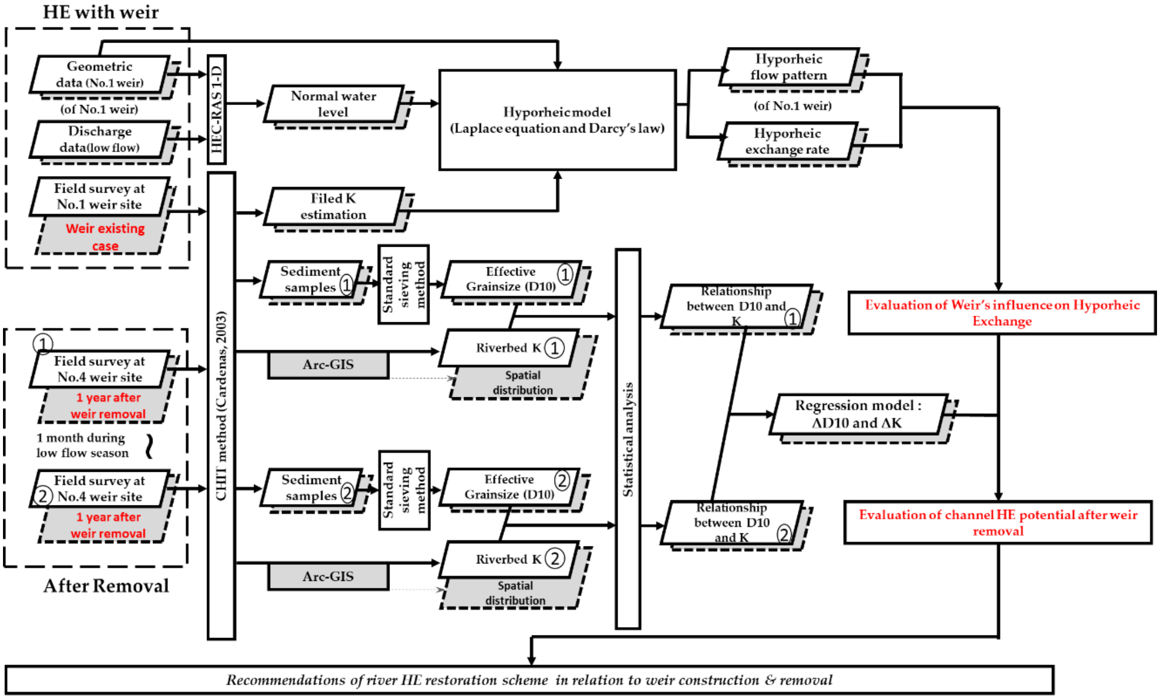


Fig. 5-12 Method flow chart for this chapter.

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5.3 Results

5.3.1 Hyporheic exchange under presents of a weir

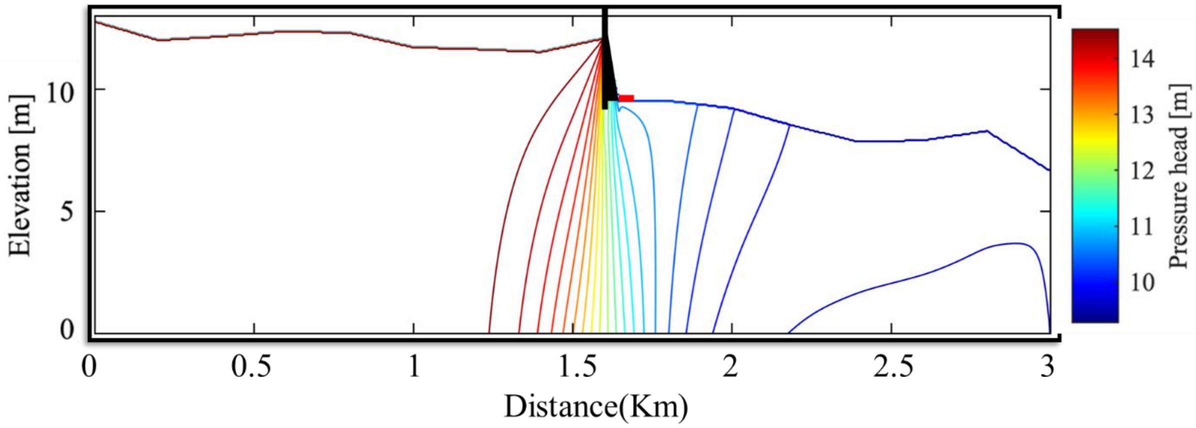


Fig. 5-13 Hyporheic model results of equipotential lines in No.1 weir.

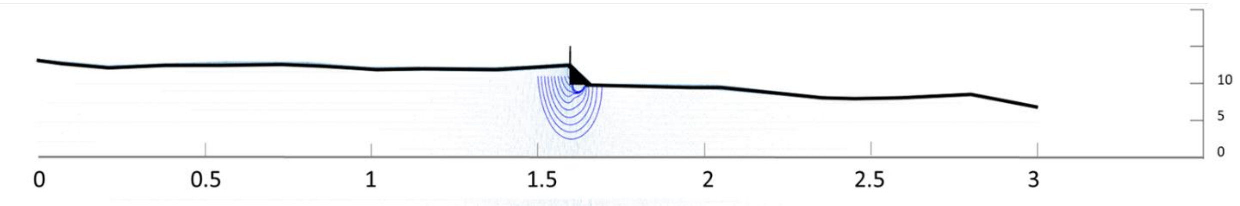


Fig. 5-14 Hyporheic upwelling flow line, indicates the size of hyporheic zone.

The model results showed that the hyporheic exchange is concentrated around the weirs only and the depth of hyporheic zone is about 10m in depth, the size of the hyporheic zone is estimated about 106176m^3, the length of downwelling zone is about 50m upstream of the weir and upwelling zone is about 50m downstream of the weir, however, the actual length of upwelling zone is limited to about 30m over the “weir skirt” protection works. If the uniform riverbed hydraulic conductivity is assumed 0.03m/day, as the normal value of the gravel sediment materials, the calculated upwelling water volume (represents the total amount of HE) is about 4.6% of the daily discharge, which is coincide with the percentage of the HE from the literatures. The K value determined the rate of HE, Fig. 5-15, shows the relationship of K value and the ratio of qHE to Q discharge.

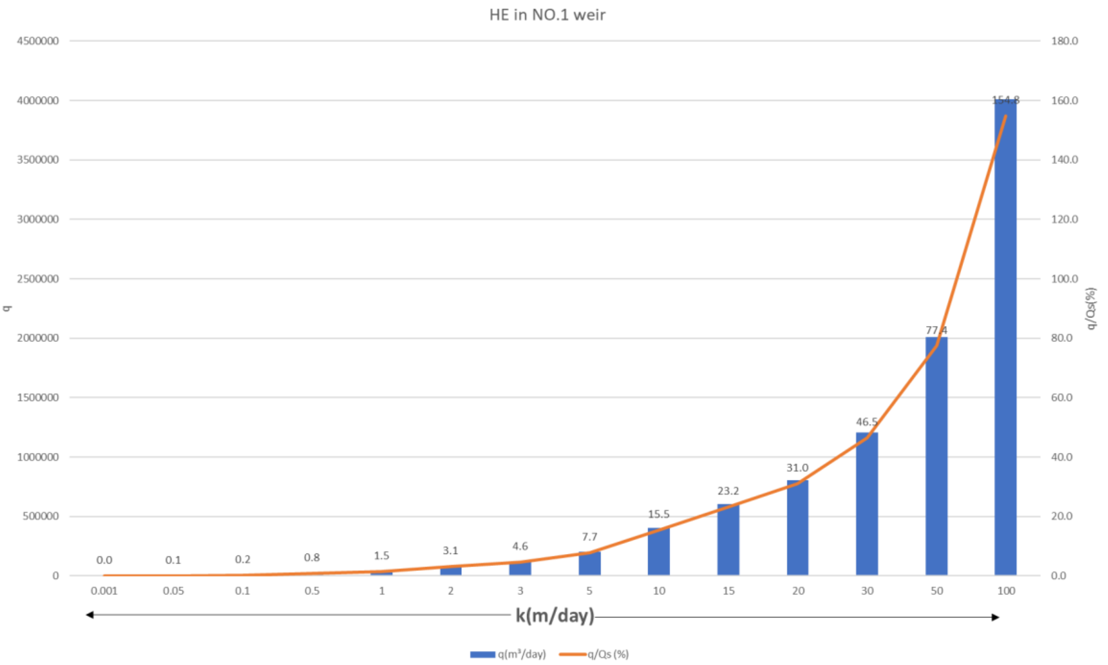


Fig. 5-15 relationship between K value and the ratio of qHE to Q discharge.

5.3.2 Riverbed hydraulic conductivity upstream of a weir

In order to estimate the HE rates induced by No.1 weir, field data of K value is a must. The riverbed sediment samples upstream of any dam or weir are notoriously difficult to collect intactly, luckily during the breaching of the weir body we were able to do the field survey at just upstream of the weir. As mentioned in the methodology part, we observed a thick layer of fined sediment deposited with sickness ranging from 10-40cm. not only in the bank shore, but also in the center of the channel. Actually the fine sediment deposition can be found in the entire area upstream of the No.1 weir, extended to 600 meters until the Kuga bridge.

The field survey of riverbed hydraulic conductivity at upstream of No.1 weir is visualized in Fig. 5-16, black color indicates the low value of K, and white color indicates the higher K. Four points along the right bank shore were estimated by CHIT methods, A is about 90 m from the weir body, and D is about 250m from the weir. the results showed that the top layers of three points are completely clogged by fine materials, water cannot infiltrate at all. The only point that showed slightly higher value of K, with 0.58m/day, at this point, the surface bed materials are mainly sand and mixed with fine sediment, interestingly, the middle (0.27m/day) and deep layer (3.54m/day) of this point showed higher K than the top layer, which is usually the opposite trend in normal riverbeds. In point A, C and D, the K of the middle layer is 0.39m/day, 0/day and 0.16m/day. Only at point A the deep layer K is 0.86m/day, C and D are 0m/day.

Based on the field survey results, we estimate that the ratio of qHE to Q discharge before removal is ranging from 0.00-0.5%, in other words, the vertical hyporheic exchange that supposed to be induced by weir is probably totally hindered by fine sediment deposition.

While it should have a higher ratio of qHE/Q (>4.6%) than the normal gravel bed rivers. Yodo river bureau conducted multiple times field survey for stream water temperatures, up and downstream of No.1 and No.4 weirs. Due to the significant temperature difference between hyporheic water and stream water in summer and winter season, the survey data can be used to roughly validate the model results.

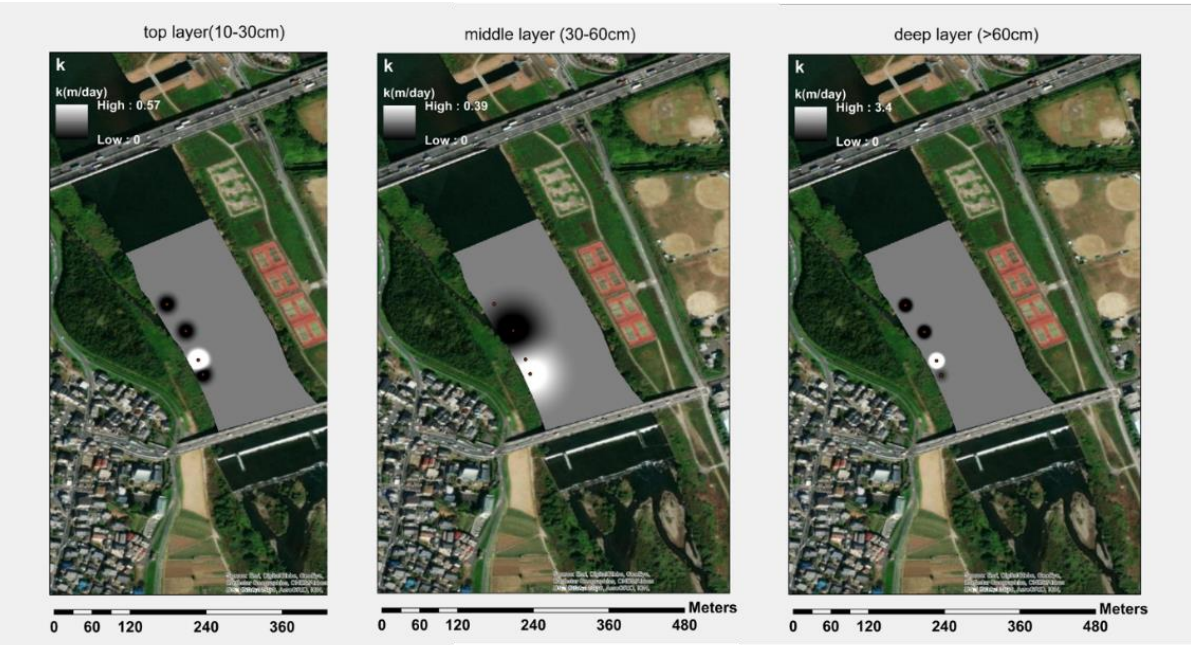
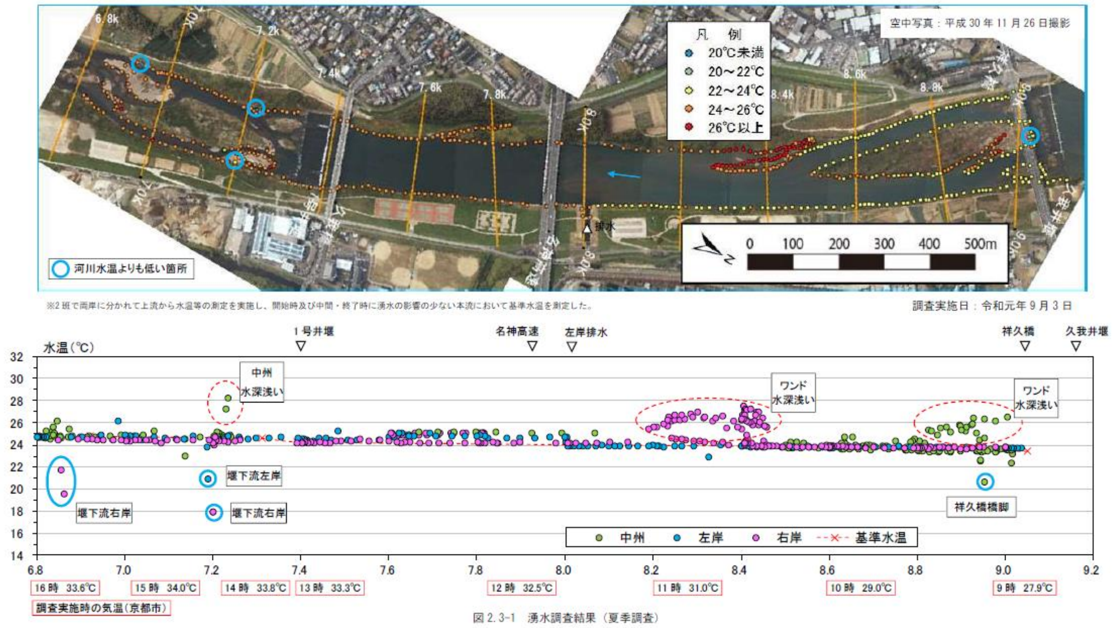


Fig. 5-16 Spatial distribution of riverbed hydraulic conductivity upstream of No.1 weir.



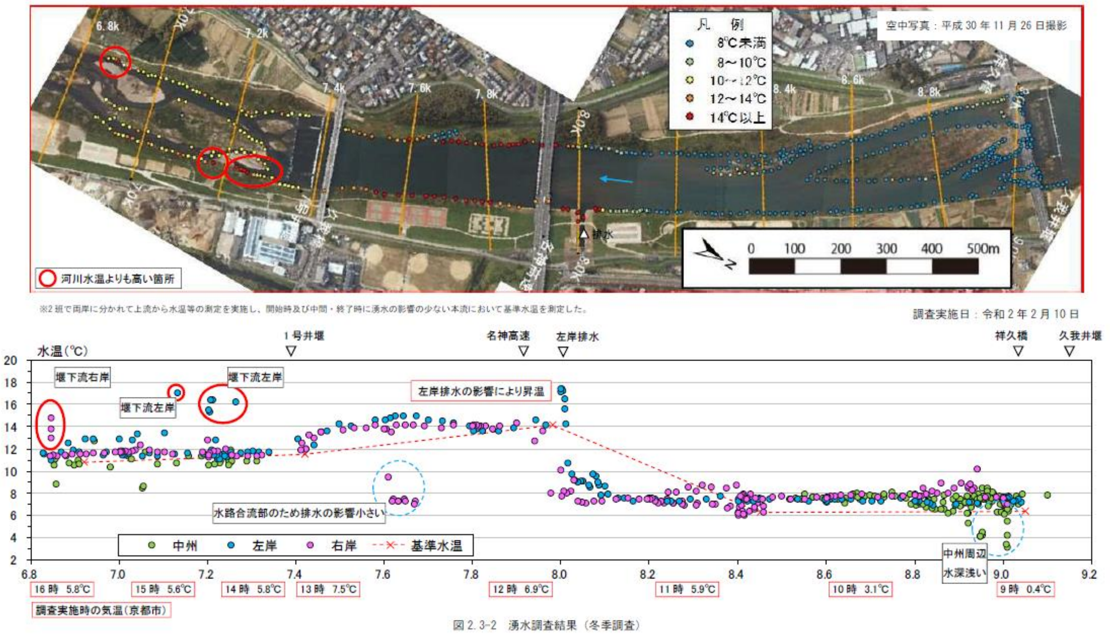


Fig. 5-17 Water temperature survey in the summer season (top) and winter season (down) by the river bureau, survey was conducted along the bank shore and edge of bar structures. For the summer survey, blue circle indicates the place that the water temperature is significantly lower than the background water temperature. For winter season, the red circles indicate places that the water temperature are significantly higher than the background water temperature.

At downstream of the No.1 weir, summer survey and winter survey showed the similar results, significant lower temperature was only detected at the bank shoreline. For summer season, three places were detected, one is at the left bank about 200m from the weir body (140m from weir protection work). Two is located at the right bank side, about 190m and 440m from the weir, respectively. As our model and field study predicted, if the K value is within the normal range of the gravel bed river, there should be more places that the hyporheic upwelling water can be detected just downstream of the weir (e.g., 60m closed to the weir), especially in the center of the channel there are no significant temperature differences were detected, normally, in the upstream of the weir, the grainsize of center area of the channel is coarser than the side areas, which means the K of channel center is higher than side areas, however, in No.1 weir case, no temperature difference were detected in the lower reach of the weir, even extended for 600m. we assume that the upstream of the weir is completely deposited with fine sediment, which had blocked the entire hyporheic flow (more than 99%), thus the hyporheic water goes from other routes such as from lateral direction and finally come out from the bankside in the downstream. one more possibility is the groundwater upwelling, however, we are not able to distinguish the water source from the surveyed data.

5.3.3 Spatial distribution and temporal change of hydraulic conductivity after weir removal

5.3.3.1 Water table of gravel bar

The water table generated in ArcGIS showed a good coincidence with the field observation (Fig. 5-18 left), which indicates that the stream water was directed from the left-bank side and penetrate inside the gravel bar to the right site due to the elevation differential. This is particularly notable at the bar head area. The possible hyporheic flow line was also drawing in the Fig. 5-10. The inundated map during the 10cm water level rise was also generated (Fig. 5-18 right), yellow line indicates the boundary of dry and wet area. Fine materials were detected along the yellow line especially at the middle part.

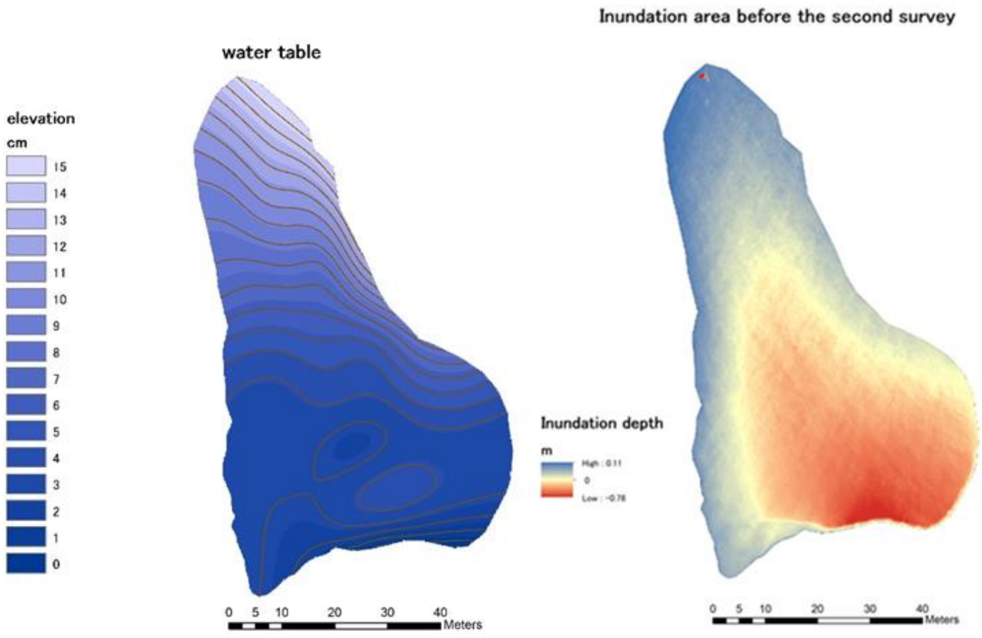


Fig. 5-18 Measured water table elevation, the contour line interval is 1cm (left). The inundated area of the gravel bar during the water level increase before the second survey, blue color indicates the inundated part (right).

5.3.3.2 Spatial distribution of K

The results of the two times survey of spatial distribution of hydraulic conductivity were showed in Fig. 5-19.

In the first survey, the K value of top layer was high (100m/day), only at point B1, B3 and C1 showed significant lower K ranged from 19.5m/day to 21.0m/day. The middle layer revealed a similar pattern but generally lower than the top layer. At B1 the K was 0.95m/day, 21 times lower than in the top layer, and K at C1 was 4.6m/day, 3 times lower that in the top layer. K in the rest part was still high. As to the deep layer, low K area covered the majority part of the bar head, only at A showed a different higher value of 18.3m/day. In the bar middle (C3, C5 and D line), K ranged from 16.6-39.1m/day, with an average value of 26.2m/day.

In the second survey, the area with a high K value increased compared to the first time. Particularly in the bar head, B1 and C1 along the water edge increased from 19.5 m/day and 21.0 m/day to "100 m/day" (estimated). Only B2 and B3 showed low K value of 8.4m/day and 1.3m/day. Fine materials were detected during the second survey at B2 and B3, the different color from the first survey indicated that they might deposited during the water level increase on 8th January. The distribution pattern of K in the middle layer is similar to the top layer of the first survey. The low K value area was still concentrated at the right-bank side of the bar head (potential upwelling zone), with an average value of 1.2m/day. For the deep layer, the edge of the bar head area showed an increase of K (at A, B5 and C5) and because in the second survey we added two additional survey points in line B and C, we were able to generate a more detailed K distribution map of the bar head. The low K area seemed "eroded" in the middle and spread to both the bar head and bar tail direction. From C5 to D5 (bar middle) the K ranged from 47.6 to 75.9 with an average of 64.6m/day. As to the bar tail (line E and F), K was still high even in the deep layer.

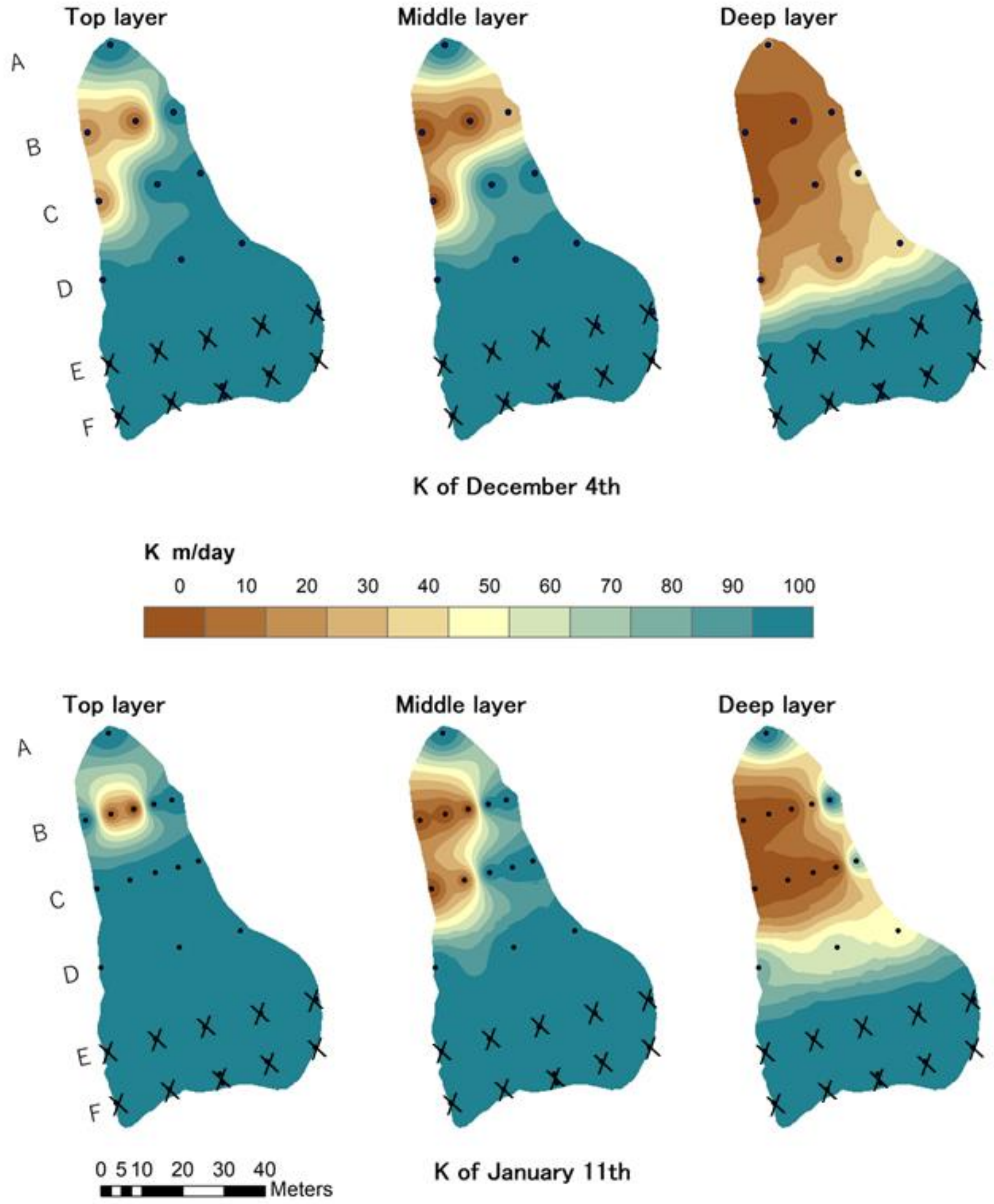


Fig. 5-19 Spatial distribution of K in December and January. Solid points indicated measured value in the field. Cross marks indicate that the k was beyond measurement ability and were assigned 100m/day during the interpolation process.

Patterns of K change

We compared the K change between the two surveys (Fig. 5-20). For the top layer, K increased significantly at up welling zone of the bar head area (B1 and C1) by 395%. While at B3, K decreased by 86.7%, the rest part remained high K value. In the middle layer k at B1 and B5 increased by 185.6% and 248.5% respectively, however at B3 K decreased by 77.5%. C1 also showed a different pattern compared to the top layer, decreased by 75.1%. Other area remained similar compared to the first survey. In the deep layer, K generally increased a t the bar head and middle. Specifically, K increased at the tip of the bar head (A), the left-bank side of the bar head (C5, D5) and at the middle of the bar. Only C3 showed a decrease of K. The rest part revealed minor change.

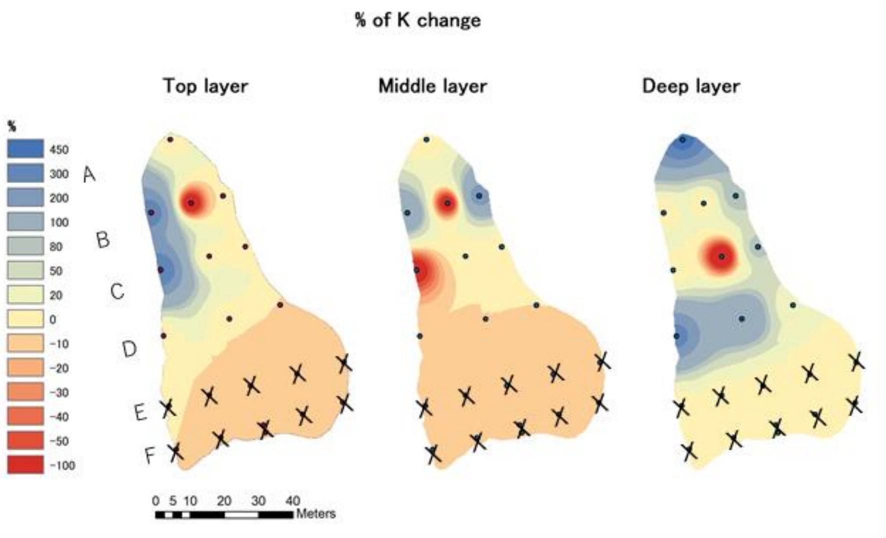


Fig. 5-20 Percentage change of hydraulic conductivity during a month-period.

5.3.4 Relationship of sediment grainsize distribution and hydraulic conductivity

5.3.4.1 Grainsize change

Results of grainsize distribution by standard seizing method are showed in Fig. 5-21 and Fig. 5-22. For the sediment grainsize of the first survey on 4th December, grainsize at the left bankside of the study site was coarser than at the right bankside. Sediment grainsize was much finer in the hypothesized upwelling zone at the right bank side of the studied gravel bar, compared to the downwelling zone at the left bank side. Due to the sediment sorting, upstream part is coarser than the downstream part. Two surveys results showed that after one month, the downwelling zone grainsize became even coarser (Point B5, B4, C5, and D5), while the grainsize of the upwelling zone became finer at point C1, and slightly coarser for point B1 and D1, which is coincide with the decrease of the hydraulic conductivity in the middle layer. The grainsize change, especially the movement of the fine grains are the fundamental mechanism of the hydraulic conductivity change. From the first survey to the second survey, the grainsize at the right bankside (hyporheic downwelling zone) became even coarser, which indicates the fine particles movement direction. This finding is coincide with the similar process observed by (Nowinski et al., 2011).

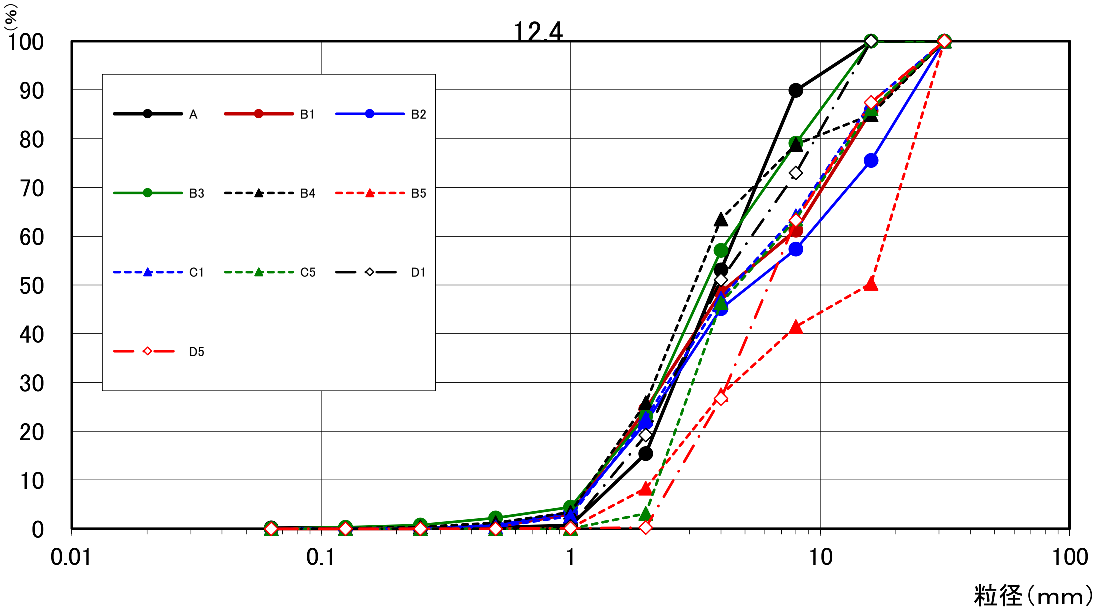


Fig. 5-21 Grainsize distribution curve of 4th December survey.

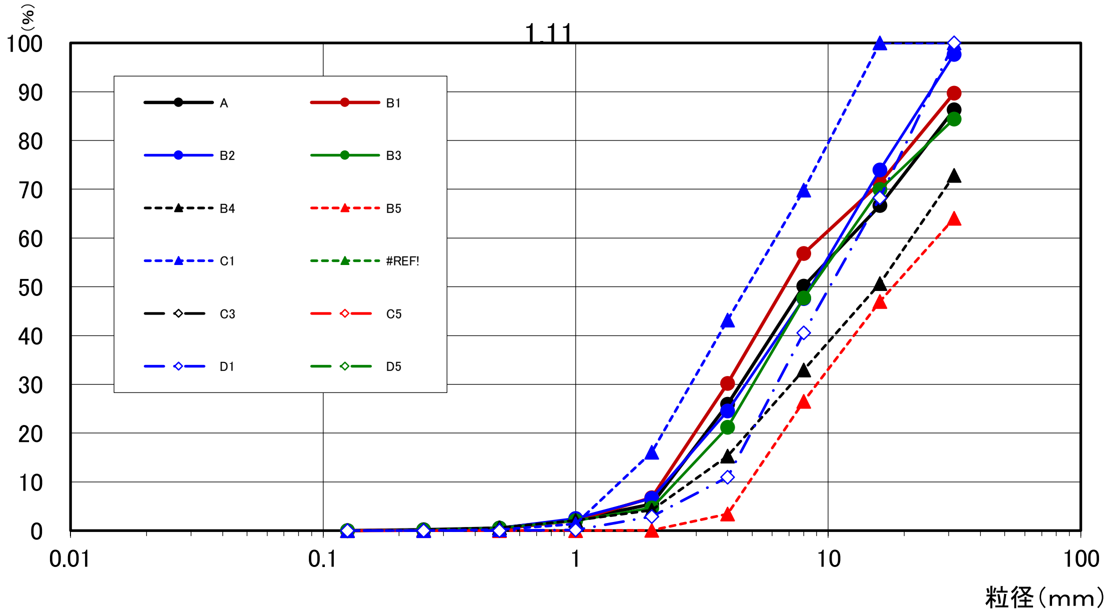


Fig. 5-22 Grainsize distribution curve of 11th January survey.

5.3.5 Relationship between D10 and K

We have examined the relationship between the effective grainsize D10 and riverbed hydraulic conductivity, as showed in Fig. 5-23 to Fig. 5-25, our results showed a clear positive relationship between the fine sediment (D10) grainsize and hydraulic conductivity in both surveys.

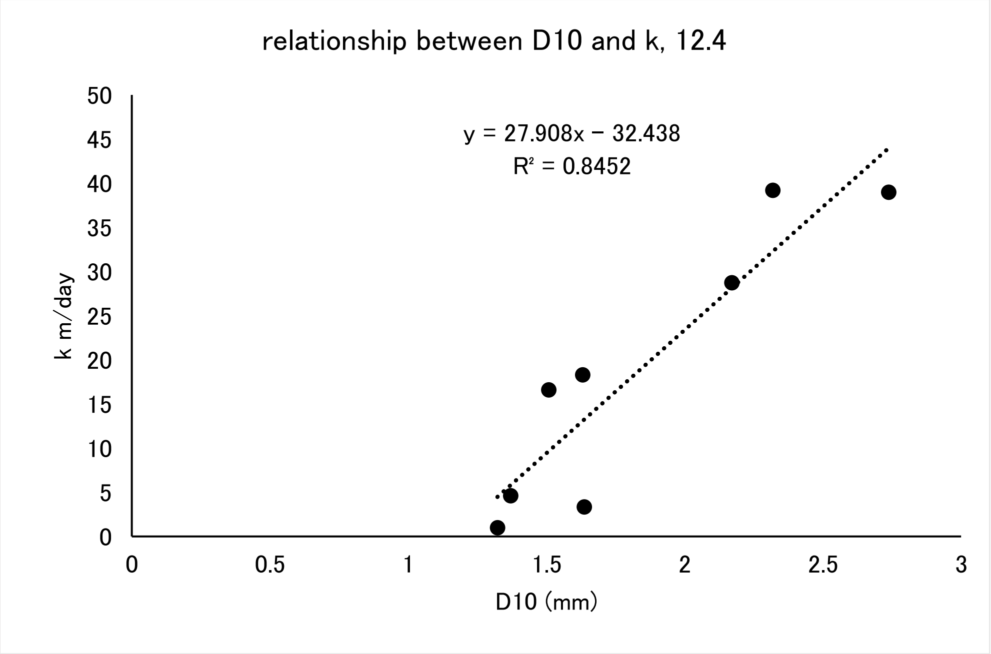


Fig. 5-23 Relationship between D10 and K from the survey of 4th December 2019.

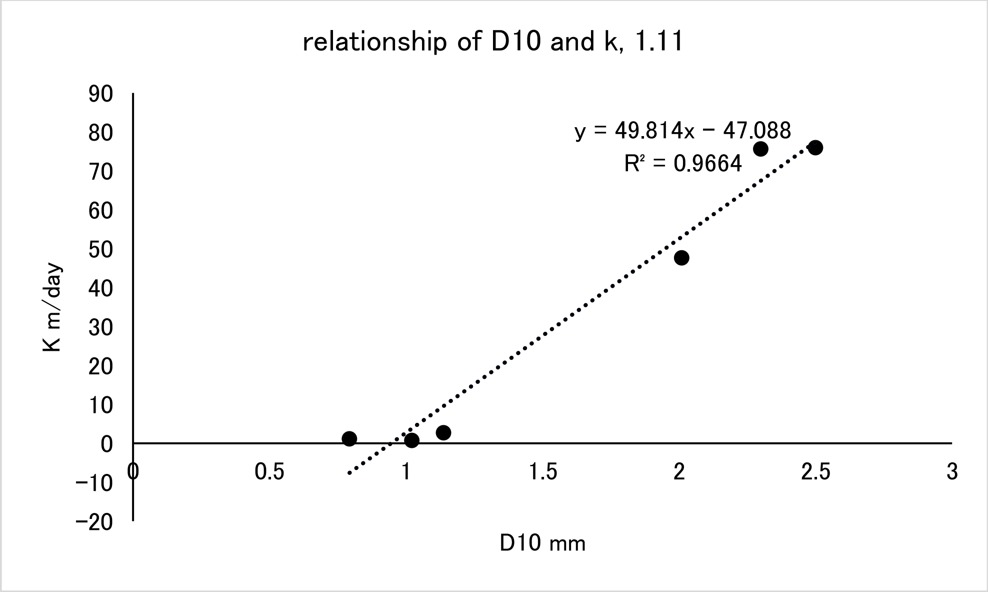


Fig. 5-24 Relationship between D10 and K from the survey of 11th January 2020.

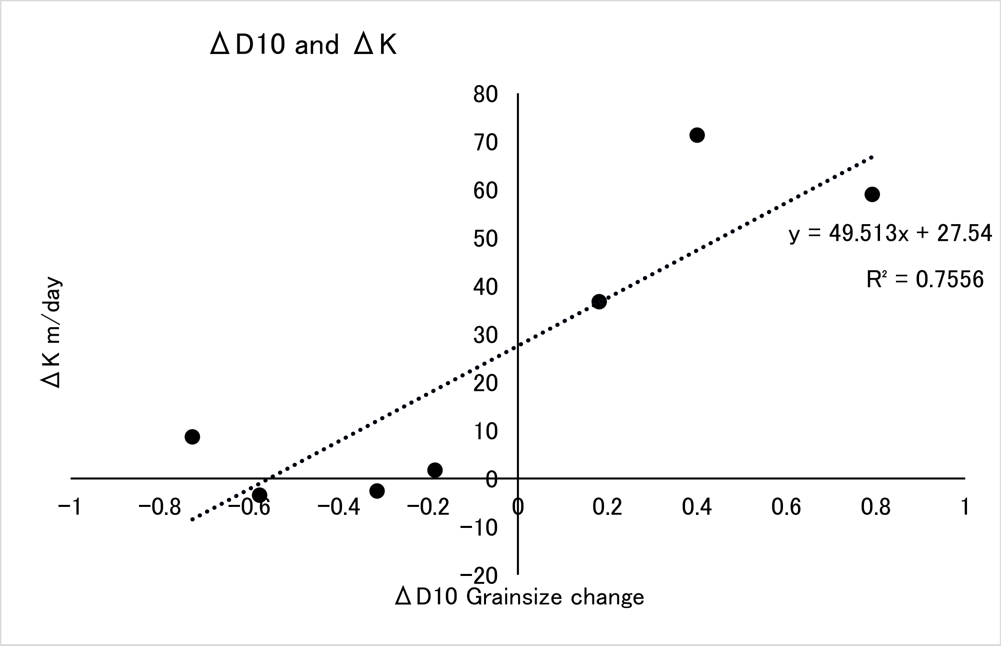


Fig. 5-25 Relationship between the change of D10 and K

5.4 Discussion

5.4.1 Low-head dam's effect on the hyporheic flow and hyporheic zone

Our numerical modeling results showed that a LHD will concentrate the hyporheic downwelling flow at upstream very close to the weir, and upwelling zone is also close to the weir at downstream side. Due to the weir's backwater effect, upstream area is usually submerged and deep, which is hydrostatic dominant, thus, prevents the potential hyporheic exchange induced by small scale riverbed morphology and hydrodynamic pressure (e.g., ripple and dunes, bar structures).

Our field survey found that a thick layer of fine sediment was deposited upstream of No.1 weir, with extremely low hydraulic conductivity especially for the top layer (10-20cm), which means the limited area of downwelling zone just upstream of the weir, are almost totally deposited by low K fine sediment, this dangerous combination can possibly block all hyporheic exchange that should have been induced by a weir, which, in many literatures, are the main purpose of proposing build new weirs. In the other two weir removal cases, as I interviewed a participant, during No.4(13.6K) weir removal, similar thick layer of fine sediment was found. However, when No.6 weir (17.8K) was removed, no fine materials were found. This is because No.6 is a small weir with only 0.8m height, and there is another weir (ichino) located just less than 300m upstream of the No.6 weir, which result in that the upstream of No.6 weir was full of bedload (mainly gravels), this makes No.6 weir almost act as a step, for which the surface flow velocity is much higher than No.1 and No.4 weir, thus, no fine sediment can deposit upstream of No.6 weir.

Unfortunately, we do not have the fine sediment deposition data for other weirs in Katsura river, not to mention the fine sediment dynamics during a long-term period. Here we propose some key questions related to the weir's long-term effect on the HE, for guiding future studies:

1. Is it a general phenomenon that fine sediment will be deposited at the backwater area of a weir? under what hydrological, hydraulics, and morphological settings would be causing deposition of fine sediment.
2. Fine sediment dynamics at both upstream and downstream of a weir, during the flood conditions, how fine sediment will be flushed to the downstream and will

this remove the fine layer temporarily? For the downstream side, is the often-found vegetation promotion related to the fine sediment trapping by the island bar just downstream of a weir?

3. How fine sediment deposition will affect the hyporheic downwelling flux rate at upstream of a weir. Is K the single dominant factor that controls the HE at upstream of a weir?
4. When a weir traps more bedload in its upstream backwater area (0-100%), as the weir gradually becomes a step-like structures, will the HE be increased?
5. Empirical relationship between fine sediment deposition and K.
6. Different from No.1 and No.4 weir, No.6 weir trapped little fine sediment upstream of its backwater area, this is due to that the upstream of No.6 another weir exists, which result in that the backwater area of No.6 weir is far more less than any other weir in Katsura River. Almost full of bedload in the backwater area of No.6 weir, therefore, its functioned as a step, and thus the flow depth is small (1.2m for No.6, 1.33m for NO.5, 2.05m for No.4, 2.20m for No.3, and 3.5m for No.1), accordingly, flow velocity is much higher than other cases, which finally results in that the fine sediment can rarely be deposited.

Based on our hypothesis of the fine sediment dynamism controlled by low-head dams, and the findings from this chapter, we propose a conceptual model to describe the process of the fine sediment movement in a river reach as Fig. 5-27 showed. Stage 0 is the natural, or near-natural conditions, the complex, different scale hyporheic flow paths were developed due to the heterogeneity of the riverbed morphology. Stage 1, immediately after the low-head dam construction, the hyporheic flow path was instantly concentrated just near the dam body, the total amount of the hyporheic exchange might be higher than the pre-dam construction status which depends on the dam height and original bed conditions. With a short period of time (days to weeks), fine sediment started to accumulate just upstream of the dam body, especially at the left and right side of the channel with slower flow velocity, clogging prevailed from the two-bank side towards the middle of channel where the velocity is usually higher. As a result, the total amount of the hyporheic exchange was greatly reduced (depends on a combination of fine sediment concentration and the dam height and other geomorphic parameters). Stage 3, with longer time (months-year scale), fine sediment keeps accumulating at the backwater area and finally blocks almost all hyporheic flow. Stage 4, as flood comes, the fine sediment layer might be flushed out and thus the general status might be return to stage 3 or stage 2, depends on the flood scale and fine sediment loads. Stage 5, as years passed after the LHD construction, the backwater area will be full of bedload, and the mixed with fine sediment layers and forma a "sandwich" structure (Fig. 5-28), and in decades time scale, the total hyporheic exchange rate induced by the LHD would be extremely limited, if not zero. Stage 6, after LHD removal, the fine sediment will be flushed out, and the hydraulic conductivity will be restored. Whether the hyporheic exchange rate would be returned to the original level depends on the upstream sediment supply and local geomorphic settlings of the very reach.

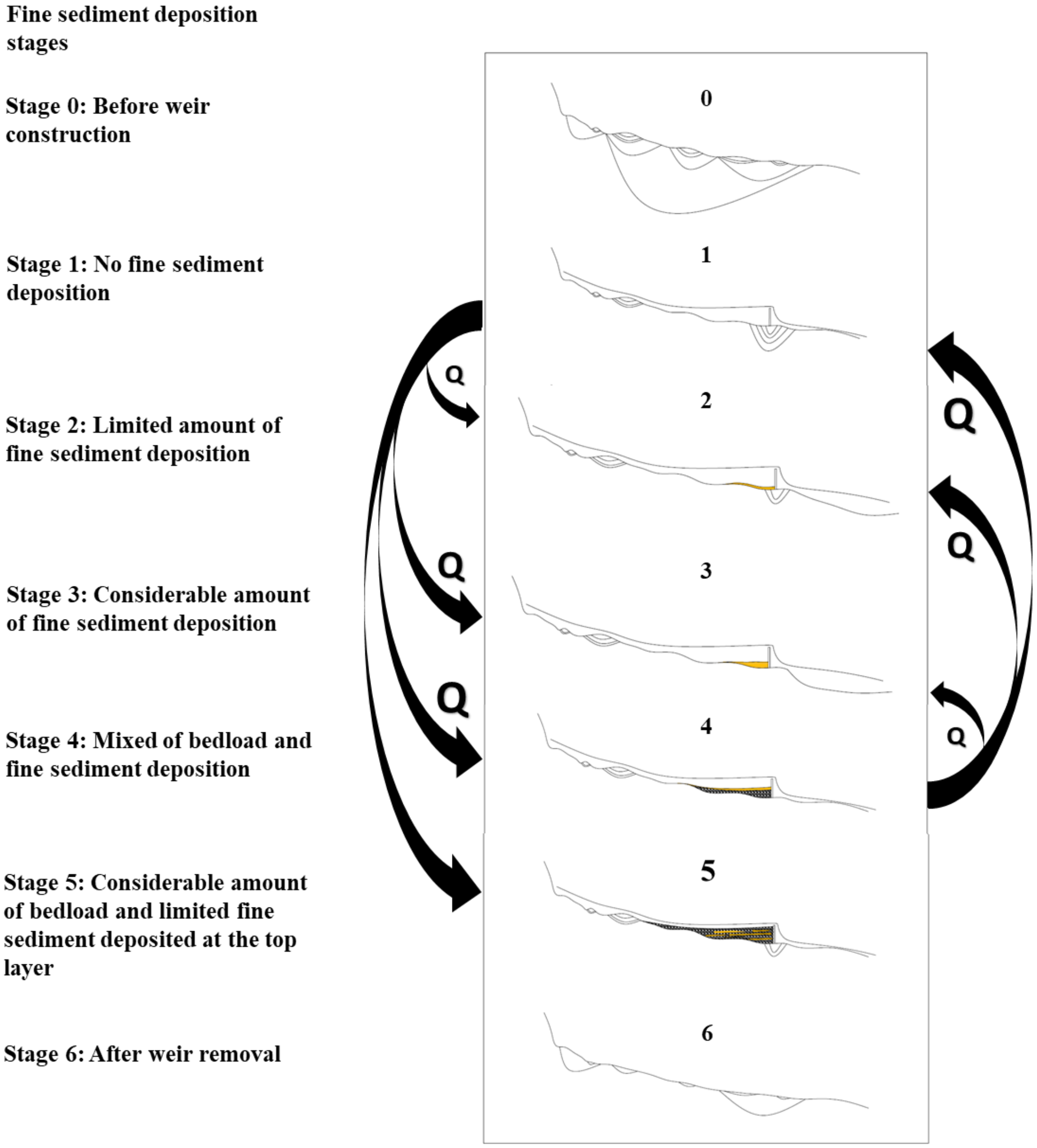


Fig. 5-26 Conceptual process of fine sediment dynamics behind a weir

Fig. 5-27 Photo of riverbed surface upstream of No.1 weir during the removal.

5.5 Conclusion

In this chapter, we tried to use two cases studies to illustrate the influence of an low-head dam on the riverbed hyporheic exchange, and the influence of the low-head dam removal on the riverbed hyporheic exchange, by investigating the riverbed hydraulic conductivity and grainsize distribution, which are the controlling factors of hyporheic flow.

Our numerical modeling results showed that as the weir becomes the main driver for the hyporheic flow, the downwelling zone and the upwelling zone will be very close to the weir body upstream and downstream respectively. The size of the hyporheic zone depends on the weir height, the higher weir height is, the greater the hydrostatic pressure will be formed. However, the hyporheic exchange is highly depended on the hydraulic conductivity of the riverbed, especially of the top layer (Boano et al., 2014; Menichino &

Hester, 2014). Our field survey at upstream downwelling zone of the No.1 weir showed that there is a thick layer (10-30cm) of fine sediment with extremely low k value (≈0-0.05m/day) on the riverbed. As we input the riverbed k value to our hyporheic model, the estimated hyporheic exchange rate could be only 0.00-0.05% of the river discharge, for which the normal value of the gravel bed river should have been around 4%. This led us to a critical knowledge gap which cannot be answered by this study: under what hydrological and geomorphological settings does a weir will trap fine sediment.

The case of No.4 represents the low-head dam removal scenario in gravel bed river. Field surveys of the riverbed hydraulic conductivity were conducted 2 times with an interval of 1month, about 8 months after the complete removal of No.4 weir. results have showed that the riverbed hydraulic conductivity is generally higher at the downwelling zone and lower at upwelling zone. The reason is hypothesized as the fine sediment movement in the hyporheic flow course as first explained by (Nowinski et al., 2011). K of top layer (0-30cm) is greater than in the middle (30-60cm) and deeper layer (over 60cm). Especially the deep layer showed the considerably lower K value, which can be explained by the man-made sediment excavating works and riverbed compaction during No.4 weir removal. K is generally higher for the newly deposited sediment, while the original bed is much harder and has much lower K. This shows the resultant riverbed conditions after man-made river engineering works.

Grainsize distribution provided us the relationship between D10 and riverbed K, which shows a good linear regression trend line. Generally speaking, after one-month period during the low flow conditions, the grainsize became coarser which resulted in higher riverbed hydraulic conductivity value compared to that in the previous survey. The recorded high-water stage (+10cm) may be the driving force of the fine sediment movement in the survey site, which may explain the reason why K has been increased. But still, we do not know the relationships of the rainfall intensity, discharge increasement, water level rise and the fine sediment movement pattern. This kind of relationships are crucial for understanding the fine sediment dynamism from the basin scale to the local habitat scale, which can provide us critical knowledge for the better river environmental management.

Chapter 6 General discussion and proposal

Clearly Katsura river is suffered from the lack of sediment supply from upstream. In addition to the shortage of sediment supply, the multiple weirs and man-made sediment excavating work greatly altered the riverbed sediment deposition and erosion pattern, the upstream segment is featured by mixed of erosion and deposition pattern due to its high sinuosity and three weirs existence. The middle segment is dominated by riverbed aggradation due to the backwater effects of multiple weirs. As to the downstream segment where no weir was constructed, the erosion pattern by both natural events and extensive man-made river excavating work are dominating in this segment.

Katsura river is a frequently flooded river, and the flood mitigation is the priority for the river authorities, which constrained the possible options for improving river ecological conditions especially in some frequently flooded local area, the sediment replenishment is usually impossible for which would increase the flooding risk for the residence. However, the weir removal projects originally for reducing the flood risk has provided us a hint to use the sediment stored in the backwater area of the weirs as potential sediment source, unfortunately, the current management method regarding the sediment stored behind a weir is just simply excavating and relocating, which do decrease the flood risk while at the same time, also greatly reduced the chance for the formation of high-quality riffle habitats at the downstream reaches. Therefore, subtle, and flexible management schemes are required to achieve the balance of flood mitigation and ecological improvements.

6.1 How to improve the riffle habitat structures in Katsura river

Combination of weir removal and sediment replenishment

First of all, obviously the riffle structures cannot be developed in the backwater area of the weirs, which means removing of the weirs and the resultant narrower low flow channel width is required, since our results have showed that the Diverged and Transverse type riffles are mainly located in the Single Sinuous and Single Slightly Sinuous channel. Sediment stored in the backwater area of a weir can be treated as potential source of sediment replenishment for improving the ecological conditions. However, the amount of sediment needed to restore the downstream riffle habitat structures should be estimated by detailed field survey and riverbed geomorphic change modeling like did in this study. If the amount of sediment stored in the backwater area of a weir is not enough to meet the requirement to restore downstream habitats, then additional sediment either from the upstream impoundment dam, or from backwater area of other weirs is required. In addition, sediment transportation modeling is also required for more accurate prediction of the effectiveness of where and how much amount of sediment will deposited. This result has to be coincided with the flood risk map in order to provide an integrated river management plan.

Relocate the replenished sediment to the required area.

Once the sediment source is guaranteed, the next problem where is this sediment should be deposited to maximum its effect of formatting high quality riffle habitats? This requires the full-scale knowledge of the targeted river or river segment, including hydrology, geology, sedimentology, biology, and geomorphology. Historical identification of riffle habitats either from field survey or satellite images are valuable information for locating the current riffle habitat structures and the potential locations where riffle could be formed. Hydrological and hydraulic modeling can be powerful tools to assist to locate such areas, for instance, using sediment grainsize, water level and flow velocity to constrain targeted restoration area. O’Neill and Abrahams provide a useful tool to objectively identify pools and riffles simply using river longitudinal profile (O’Neill & Abrahams, 1984). Notice that in his paper “riffle and pools” are indicating large scale riverbed undulations, e.g., a riffle indicates a statistically high elevation area in the riverbed, and a pool indicates a statistically low area, regardless of the water level, in this sense, this can be a useful tool to identify high elevation area where has the potential to format riffle habitat, which can be combined with field survey data and modeling results, to give more solid information for the final restoration plan.

As the amount of sediment source and the targeted area are determined, estimated discharge from the upstream site is required as the driving force to make everything happen as planned. The designed discharge can be estimated by the hydraulic modeling. In addition, in order to control the local scale (e.g.,10-100 meter), the Japanese traditional river works --- Seigyu, proposed by Takemon and currently has been implemented in the Kizu river can be a good candidate to guide the local sediment deposition and erosion at the target area.

Both weir construction and weir removal would have profound influence on the riverbed geomorphology and thus the ecological functions, and the influence can be dramatically changed due to the change of boundary conditions, thus, the management strategy has to be flexible and thoughtful for both the current and future possible scenarios. e.g., in a rive with decent supply of sediment, totally removal of all weirs and restore the river channel to its “original form” might be the best solution for river restoration purposes. However, if a large impoundment dam is constructed upstream and block almost all sediment, then, to remove some carefully selected mid-weirs (fully remove or partially remove) and keep the boundary weirs for preventing the possible over erosion of the riverbed might be a more suitable solution.

6.2 How to improve the hyporheic flow in a gravel bed river with multiple low-head dams

Our study has showed that the fine sediment deposition at the backwater area of a weir can greatly reduce the hyporheic flow generated by the hydrostatic pressure upstream in Katsura river. Though we only investigated three weirs (No.6, No.4 and No.1) but we assume weirs that has similar geomorphic settings in Katsura river would have similar fine sediment clogging issues and therefore the hyporheic flow would be greatly compromised by this process. However, this theory cannot be easily generalized to other gravel bed rivers due to the huge knowledge gap of the process of fine sediment dynamics around a step – like structure. Thus, for Katsura river, the weir should be removed to restore riverbed hyporheic flow, and not only the fine layer will be flushed out to the downstream, but also the relocating of the bedload from the impoundment of a weir would generate heterogenous river geomorphology and creates more riverbed head difference, if only the sediment will not be simply excavated and transferred outside of the channel. In addition, removal of the cascade weirs and restore the channel to the typical riffle – pool sequence dominated type will also increase the channel sinuosity, which will lead to more lateral hyporheic exchange, Cardenas has developed a simple model to estimate the lateral hyporheic exchange based only on channel sinuosity and slope (Cardenas, 2009).

6.3 The integrated environmental river management schemes proposed for Katsura river

The improvement of riffle habitats and hyporheic flow can be achieved simultaneously if an integrated environmental river management scheme could be carefully designed and implemented. The ideal processes of the Katsura river channel evolution are conceptually drew in Fig.6-1.

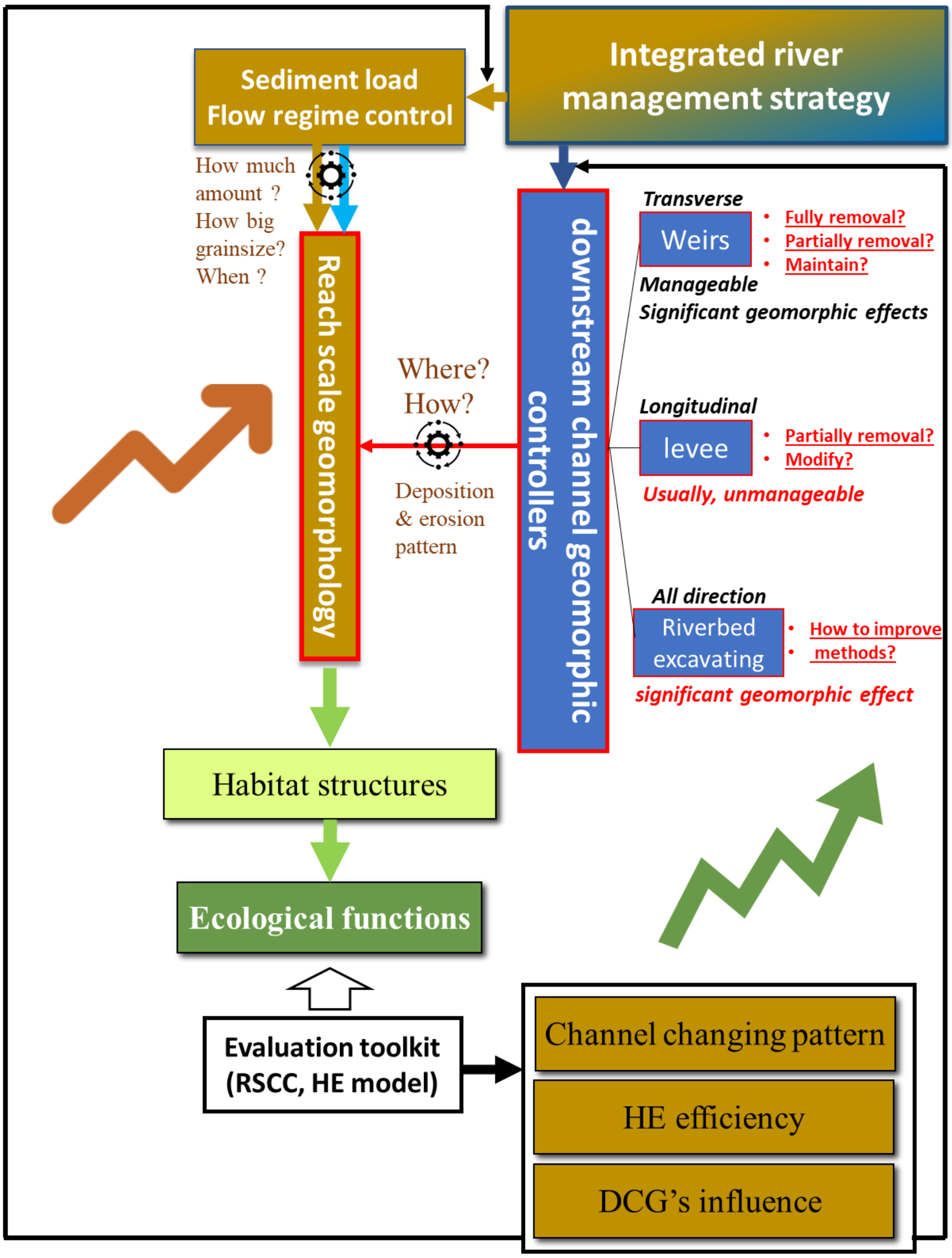


Fig. 6-1 The framework of the integrated river environmental management schemes.

Aquatic biota biodiversity and geomorphic heterogeneity. Species diversity is influenced strongly by environmental heterogeneity (J. Ward & Tockner, 2001)

For the aim of flood control, sediment excavating and making flat compacted riverbed is not the optimum idea. Even though sediment deposition can cause flood risk rise, but it is also crucial for the river ecological functions. The problem is they are just located in the "wrong place", due to the hydraulic and geomorphic influence of cascade weirs, levees and other river regulating works. Our suggestion is do not excavate all, but relocate them in the suitable places (potential riffle formation area) and capture new coming sediment e.g., by Seigyu (a type of Japanese traditional river control works) which will be deployed in the carefully selected locations (examples in Kizu river, literature could be found by Takemon)

Directions to future studies:

Sediment dynamism upstream of weir is critical to scientifically evaluate their effects and accordingly develop systematic management schemes. Trapping of both bedload and fine sediments are determined by the combination of weir geometry and local channel geomorphic settings, along with water and sediment inflow. Especially, fine sediment has profound impacts on the hyporheic exchange as is showed in this study, for which we hypothesis that the ability of trapping bedload of a weir, will affects its ability to trap fine sediments. As Csiki and Rhoads did in 2014, who used ^{137}Cs isotope method to identify whether the fine materials deposited upstream of a weir is occurring over the long term and remained stable and undisturbed or frequently eroded and redeposited. Such kind of information is extremely valuable for evaluate the effect of weir on the ambient riverbed hyporheic exchange, and we wish more this kind of data could be available in different areas with different hydrological and geomorphological settings of weirs.

Chapter 7 Conclusions

The primary impact of low-head dam on the channel geomorphology is its backwater effect which can be overlapped if multiple low-head dams are constructed in a river and with short distance between two of which. In Katsura river, the Single Sinuous (Ss) and Single Slightly Sinuous channel types contains the most abundant Diverged type and Transverse type riffle, which is limited in the reaches at the middle part of two upstream smaller weirs.

To improve the ecological functions of Katsura river in terms of riffle habitat structures especially the Diverged type of riffle, our results of river historical change analysis and statistical analysis clearly showed that the sediment deposition is needed in the Single sinuous channel (Ss) and Single Slightly Sinuous channel (Sss). Currently the backwater area is dominated in the Katsura river, thus the sediment deposition mainly happened in the weir dominant segment and thus riffle habitats can hardly be developed. In other words, the sediment replenishment is needed in the specific location where riffles could be possibly developed. Therefore, the detailed and flexible management schemes against low-head dams must be designed according to the current situations and the estimation of possible future scenarios of Katsura river.

Low-head dam has a prominent negative impact on the riverbed hyporheic exchange by decreasing the hydraulic conductivity of the top layer sediment deposited upstream, by altering the natural river gradient to a flat channel with homogenous morphology (big pound) and reduce the local hydraulic head difference by a great percentage. For the downstream of weir, fixed flow structure makes fixed and incised channel which is deep and narrow and thus “stubborn” geomorphology. This is also not good for the hyporheic exchange because the fixed channel usually has a high bed hardness due to the strong hydraulic force, the interstitial of the grainsize is squeezed and without enough fine and an armored layer usually would be created thus prevent the stream water penetrate into the hyporheic zone and participating the hyporheic exchange.

The summarized key findings from this study are as follows:

1) Low-head dams have prominent effects on stabilizing rivered and resulted in poor river geomorphic and habitats, removal of low-head dams can greatly benefit fish species by increasing sediment dynamism.

2) Promoted sediment dynamism by low-head dams’ removal is not sustainable in case of shortage of sediment supply, if so, additional sources are needed.
3) Current management strategy against low-head dams’ removal can be improved, by the results of this study, using the interrelationships of the three --- “sediment dynamism, geomorphology and habitat”
4) Low-head dams could greatly reduce the riverbed hyporheic exchange by trapping fine sediment in the backwater area and decrease the hydraulic conductivity, removal of the low-head dams can restore the high hydraulic conductivity value of the riverbed and keep a high potential for the hyporheic exchange during the low flow season.

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