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COMPREHENSIVE ASSESSMENT OF SEDIMENT REPLENISHMENT IN NAKA RIVER: HYDROLOGICAL, MORPHOLOGICAL, AND ECOLOGICAL PERSPECTIVES

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Sediment Replenishment (SR) is a common restoration measures implemented in Japanese rivers, which aims to recover the degraded river's morphology and aquatic ecosystem caused by sediment deficit. In this paper, we developed an integral assessment approach to evaluate the effectiveness of SR strategy on flow regime, river bed, and ecological changes along the downstream reaches. Several indices for riverine assessment, such as GUS (Geomorphic Units Survey), HMID (Hydro-morphological Index of Diversity), and Fish Diversity Index (H Value) have been quantified for multiple SR. Key factors as the placed sediment volume, transported rate, and flushing flow discharge of the developed approach has also been successfully applied for Naka River, based on collected data of topography, sedimentation, flow regime, morphology, and water quality. The results reveal that the efficiency of SR was fluctuant for single replenishment at Kohama and additional SR sites should be considered in the future measures of sediment management. Furthermore, the numbers of geomorphic units, such as runs, rapids, and pools were increased around 15% annually, and a tendency of equal distribution of each units can be founded as well. While habitat quality for fish spawning was promoted partly due to the alteration of the morphological and hydrological characteristics (riverbed material, riverbed level, water depth, and flow velocity) at different sites. To summarize, this comprehensive study will show the influences of SR on riverine characteristics and provide valuable recommendations for the operation of sediment replenishment works in the Naka River.

Key Words : *Sediment Replenishment, Efficiency, Hydro-Morpho-Eco Assessment, Naka River*

1. INTRODUCTION

Due to the construction of hydraulic infrastructures, such as dams, considerable sediment is trapped in the upstream reaches, which reduce reservoir storage capacity and increase the flood risks of nearby residents[1)]. Simultaneously, the problem of sediment deficit will occur at downstream reach, which will lead to a significant morphological changes, such as riverbed incision, riverbank instability, as well as armouring bed[2)]. Moreover, reduction of shallow geomorphic units, such as riffles, pools, and sandy bars, that adversely impacts on downstream fish spawning and food web system[3)]. To mitigate such negative impacts, a strategy of artificial sediment supply called sediment replenishment (or sediment augmentation) is considered. Specifically, part of upstream coarse sediment is excavated and transported to the downstream reaches below dams by tracks or conveyors. Then, the transported sediment can be alternatively stocked at bankside and flushed by flow (stockpile) or just injected to downstream reach (directly injection)[4)].

Currently, sediment replenishment works have

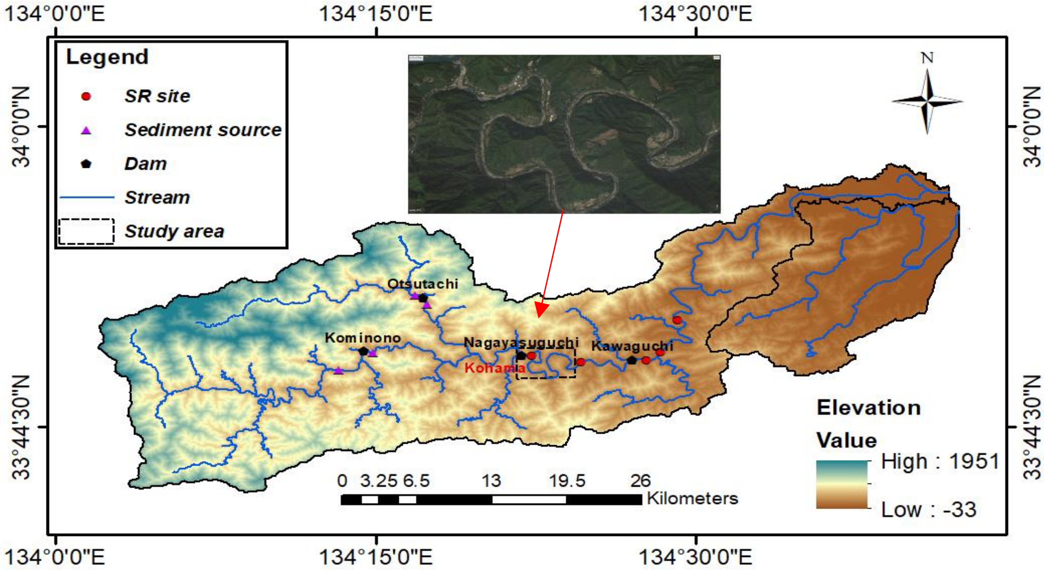

Fig.1 Location map of Naka River Basin, showing the SR site

been implemented at various river basins around the world, for instance, Uda River[5]), Nunome River[3]) and Naka River[6]) in Japan, Buëch River in France[7]), and Trinity River[3]) in USA. Some of these basins have successful and unsuccessful outcomes due to the differences in the replenishing methods, flushing flow, sediment volumes, as well as Grain Size Distributions (GSD) that utilized in each project. To be specific, in Japan, the high-flow stockpile is more common to replenish fine sand. While in Buëch River, France, a double cutting stockpile was utilized in 2016 and it is verified that this method is more efficient for finer gravels replenishing[7]). Furthermore, the high flow injection and in-channel stockpile are more preferable in Trinity River to augment coarser gravels[8]).

Though hundreds of projects have already been conducted, it can be noticed that we do not have a deep understanding between the characteristics of SR (volume, GSD, arrangement, injection method), flow conditions and its corresponding downstream impacts. Previous research mainly focused on morphological and ecological aspects during SR solely. For instance, regarding to morphology, channel width, depth, grain size distribution of bed materials ,or geomorphic unit variations are the most common factors that considered[9, 10]). While for ecology, factors of habitat quality, such as water temperature, water quality, POM, are vital for investigations[11]). Therefore, it is worthwhile to comprehensively investigate the linkages among river morphology, aquatic habitat, flow conditions and characteristics of SR. In order to recover the morphological changes and enhance the habitat quality at the downstream reaches, we would like to know the adaptable characteristics of SR, such as placed volume, GSD of placed material, flushing discharges, frequency and duration. To achieve such goal, this paper present a newly developed approach to evaluate the successful and unsuccessful hydro-morpho-ecological changes.

In this paper, we would like to summarize several indices and develop a unified methodological approach for assessment of the riverine system during SR. We will firstly introduce the study area, Naka River. Then, methodologies of assessment will be presented, and at the end, some discussions related to the assessment results and recommendations for sediment replenishment were highlighted.

2. STUDY AREA

The study area is in the Naka River Basin (Fig.1), which is located in the Tokushima Prefecture. The total area of the Naka River Basin is 874 km^2, and the total length of flow channels is around 125.0 km.

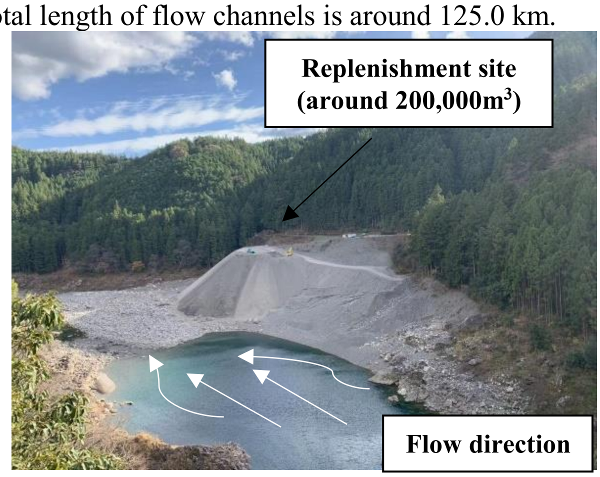

Fig.2 Photos of replenishment site at Kohama

Since 1991, SR has been started to be implemented at 6 locations downstream of Nagayasuguchi dam and Kawaguchi dam in Naka River with a total volume of 1.7 million m^3. However, since 2011, Naka river maintains only the replenishment works at Kohama, which is located at 1.0 km below the Nagayasuguchi dam (Fig.2).

The target area of this study is the 12.0 km reach downstream of the replenishment site of Kohama (**black square** in Fig.1) since we would like to exclude the impact of back water from Kawaguchi dam. Alteration in habitat structures and geomorphic units were quantified using GUS (Geomorphic Unit Survey), HMID (Hydro-morphological Index of Diversity), and H value (Fish Diversity Index). Such simple indices are efficient to investigate the morphological and ecological responses caused by SR.

3. METHODOLOGY

The flow chart of the developed comprehensive approach is depicted in Fig.3. Indicators were selected that had a direct linkage with the characteristics of the SR and monitored data that indicated the sensitivity to SR. The assessment approach commenced by analyzing basic and simple SR information about sediment quality and quantity, and flushing discharge. Then, since continuous SR has implemented from 2011 at Kohama and nearly 1 million m^3 sediment has already been replenished, we implemented hydro-morpho-ecological assessments of riverine system for last 10 years. Each evaluation methods and indicators are explained in detail in the following sections.

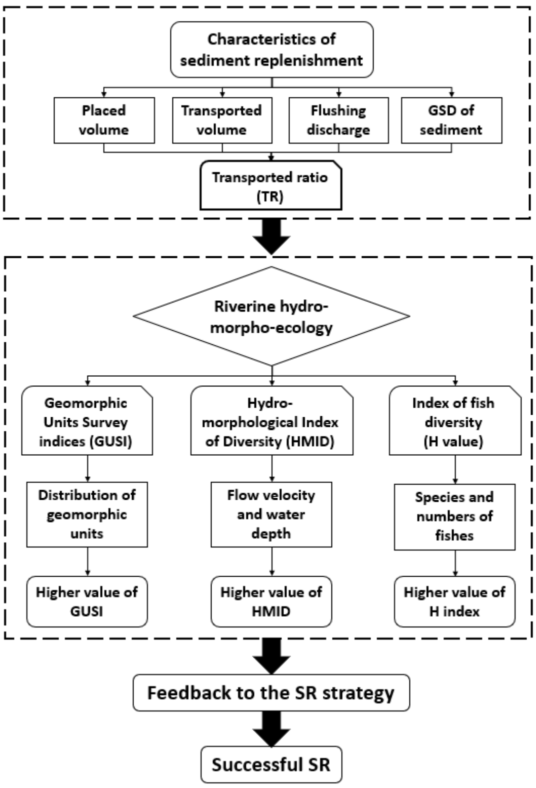

Fig.3 Flow chart of the integral assessment of sediment replenishment in Naka River

(1) Characteristics of sediment replenishment

In order to compare the results between different case studies in the world, we utilized a vital parameter called Transported Ratio (TR, in percentage), which is converted from Persistence of sediment replenishment (PD)[4]. It can be calculated as:

$$TR = \frac{Transported\ volume\ (m^3)}{Placed\ volume\ (m^3)} * 100 \qquad (1)$$

An efficient replenishment project should have a higher TR value, which means that more replenished sediment was transported to downstream reach for morphological and ecological recovery. Simultaneously, we should consider the flushing discharge and the GSD of the SR since they will significantly influence the TR value.

(2) Riverine hydro-morpho-ecology

a) GUS (The Geomorphic Units Survey)

After the assessment of replenishment works, the hydro-morpho-ecological assessment of riverine system will be implemented. Specifically, the geomorphic units, such as sand bars, riffles, pools, and puddles, are the basic linkages between riverine morphology and habitat. Hence, in the beginning, we will conduct the GUS (Geomorphic Unit Survey) in order to investigate the distribution of geomorphic units[12].

Two typical indices can be calculated simply based on the survey, which are GUS Richness index (GUSI-R) and GUS Density index (GUSI-D)[12]. They can be determined by:

$$GUSI - R = \sum NT_{GU}/n \qquad (2a)$$

$$GUSI - D = \sum N_{GU}/L \qquad (2b)$$

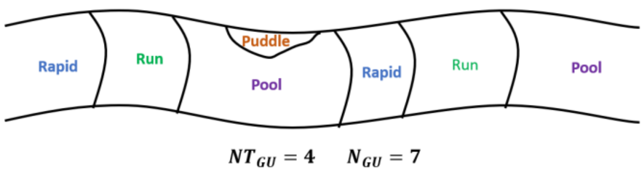

Fig.4 Example of how to calculate NT_{GU} and N_{GU} in a reach

NT_{GU} and N_{GU} are the total number of types and quantities of geomorphic units within the investigated reach respectively (Fig.4). While *n* is the number of possible types, and *L* is the length of the study reach. Through the two indices, the alteration of geomorphic units under continuous replenishment works can be easily understand.

b) HMID (Hydro-morphological index of diversity)

The HMID aims to access the heterogeneity of habitat structures according to the coefficient of variation of the hydraulic variables water depth and flow velocity[13]. It is a simple index for the assistance of habitat promotion at a reach-related scale:

$$HMID_{Site} = \left(1 + \frac{\sigma_v}{\mu_v}\right)^2 \cdot \left(1 + \frac{\sigma_d}{\mu_d}\right)^2 \qquad (3)$$

Where σ_v, σ_d and μ_v, μ_d are the standard deviation and mean value of flow velocity and water depth within the investigated reach. The value greater than 9 means that it is a morphologically pristine site and is beneficial for the diversity of aquatic habitat[13].

c) Habitat quality and species diversity

For the assessment of habitat, we would like to investigate the variation of fish species and numbers. The Shannon-Wiener index of diversity (H value) is normally used for a basic investigation of species diversity[14], which can be calculated by:

$$H = \sum_{i=1}^{n} \left(\frac{n_i}{N} log2 \left(\frac{n_i}{N} \right) \right) \quad (4)$$

Where n_i is the total number of individuals of species, N is the total number of individuals of all species. To explain the variation, morphological perspective, such as formation of geomorphic units and changes of bed level and bed material, should be mainly concerned.

4. RESULTS AND DISCUSSION

(1) Assessment of SR characteristics

Firstly, we would like to compare the TR value to other typical SR projects. As shown in the Table 1, we selected 4 projects conducting SR with different replenishment methods (stockpile or injection) and material (fine or coarse sediment). All of them have sufficient data from literatures for further research. Based on Fig.5, it is able to be noticed that both new stockpile and direct injection methods can efficiently replenish gravels (TR is 85%). While for traditional stockpile method in Japan, distribution of TR is discrete, and some low efficiency works can be observed (TR is 10%).

Table 1 Information of replenishment projects in global

Name	Water-shed area (km²)	SR method	SR location (km from dam)	D_{50} (mm)
Naka	3270	Flow stockpile	1.5	8
Tenryu	5050	Flow stockpile	2	25
Buëch	836	Double cutting stockpile	1	33
Isar	8962	Flow stockpile	5 to 20	50
Rhine	200,000	Flow injection	1 to 3.5	60

Additionally, flushing discharge was considered to analyze the potential correlations among replenishment characteristics. According to Fig.6, the correlation between TR and flushing discharge is not close as expected (R^2= 0.6). Moreover, for the placed volume around 100,000 to 250,000 m³, TR was lower than the average level since the flushing discharge restricts the erosion processes and reduces the erosion rate of the placed sediment geometry. To optimize the strategy of SR implementation, the submergence of stockpile during flood event should be enhanced[7]. It is worthwhile to separate the replenished sediment into multiple SR sites at downstream reaches. Moreover, the annual placed volume should also be reallocated reasonably. An equalization between the potential sediment deficit from downstream reaches and the annually transported volume from replenishment site is significant for restoration of downstream morphology[7].

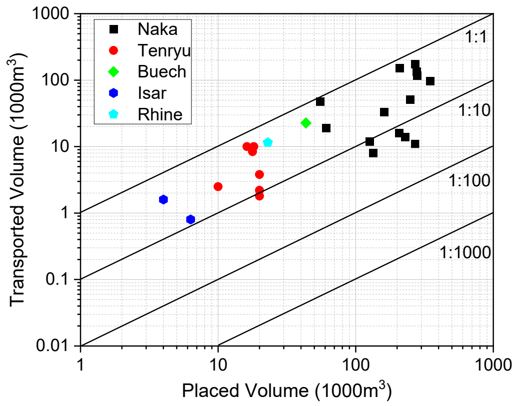

Fig.5 TR of SR projects around the world

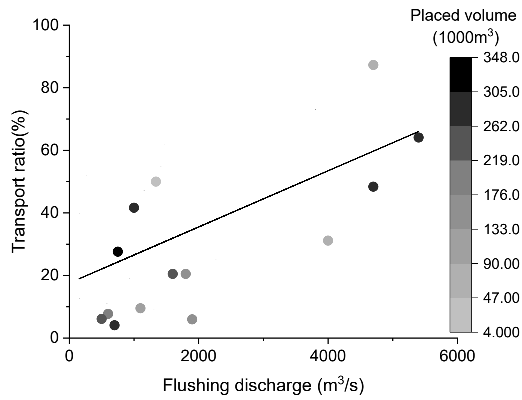

Fig.6 Correlation analysis between TR and flushing discharge with the consideration of placed volume in the Naka River

(2) Assessment of hydro-morpho-ecology

In order to evaluate the influencing area caused by SR, the distance from the replenishment site at Kohama was added in the following assessment. Indicators and indices will be calculated separately with an interval of 1.0 km reach.

The results of GUSI-R and GUSI-D are shown in Fig.7. Significant alteration of both 2 indices can be observed from 2015 to 2016 in most of reaches, while the values kept stable in 2017 and 2018. The reduction of transported sediment from SR site may be the primary reason to affect the formation of geomorphic units (150,000 m^3 in 2015, 70,000 m^3 in 2017). Furthermore, based on Fig.8, large and integral pools were transferred to small runs and rapids, and the geomorphic units tended to be equal distribution. Due to the continuous supply of sediment, the geomorphic units run to be broken up into semi units[15].

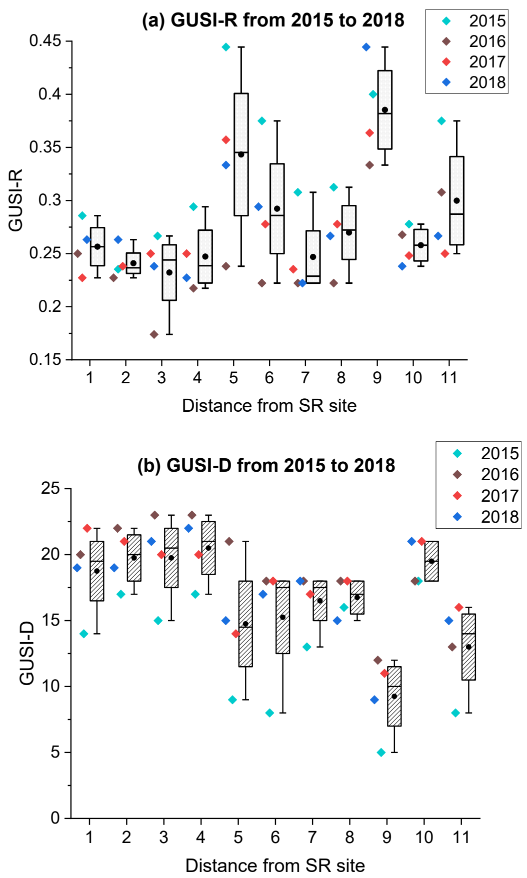

Fig.7 Indices of GUS from 2015 to 2018 with the distance from SR site ((a): GUSI-R, (b): GUSI-R)

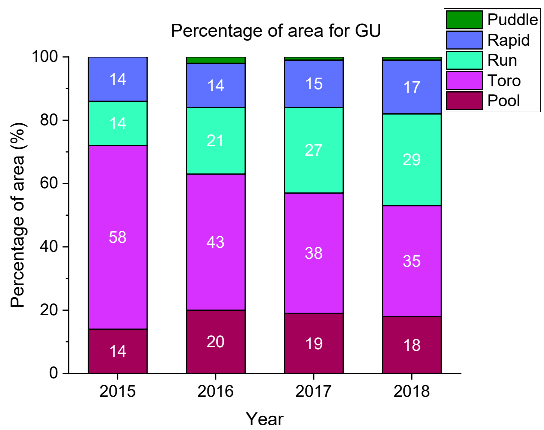

Fig.8 Percentage of area for geomorphic units from 2015 to 2018 downstream of Nagayasuguchi dam

As for the research on HMID, only results of 2015 and 2016 were determined due to the deficit of data on flow velocity. Data was collected out of the rainy season to avoid the influence of precipitation.

According to Fig.9, HMID was greater than 9 in the majority of area, which means that sediment replenishment did not destroy the pristine condition of habitat. Moreover, continuous growth of HMID can be founded in those semi-natural areas (5<HMID<9) from 7.0 km to 12.0 km, which was caused by the morphological changes here. The transformation among runs, rapids, toros, and pools (Fig.8), and significant alteration of bed level (Fig.10), will affect the water depth and flow velocity, and finally lead the fluctuant of HMID.

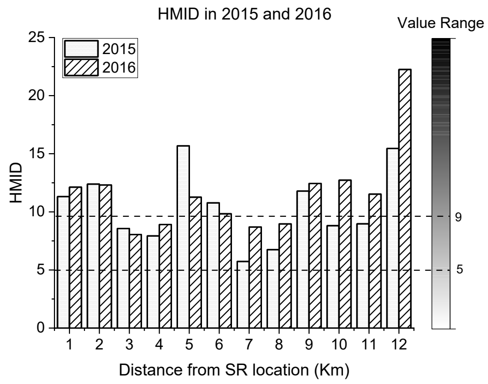

Fig.9 HMID in 2015 and 2016 with the distance from SR site

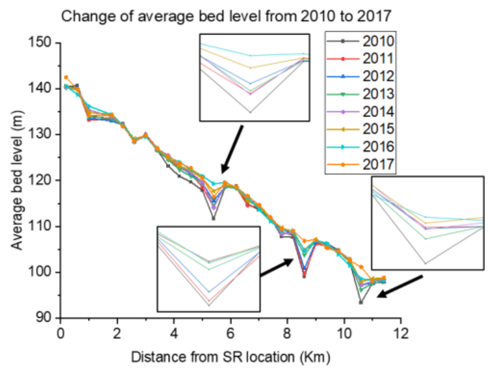

Fig.10 Change of average bed level from 2010 to 2017 with the distance from SR site

Finally, the H values were determined for 2 typical spawning grounds, which are located at 1.0 km and 12.0 km downstream of the SR site (Fig.11). Values in summer and autumn were calculated separately to avoid the influence of seasonal variation.

It can be noticed that fish diversity remained steady near the SR site, while crucially different between summer and autumn at 12.0 km, which may attributable to the results of sediment deposition. Specifically, sediment deposition is able to alter the riverbed materials and configurations, which leads to the variation of flow velocity, water depth, and geomorphic units at the same time. These morphological and hydrological changes have close correlations to the riverine habitat structures and biodiversity. However, the alteration of fish diversity does not have a direct correlation with transported sediment as sediment deposition is a long-term process and cannot influence downstream reach instantly. In a word, the SR in Naka River can be justified as a successful project since the corresponding alterations promoted the enhancement of morphological and ecological quality.

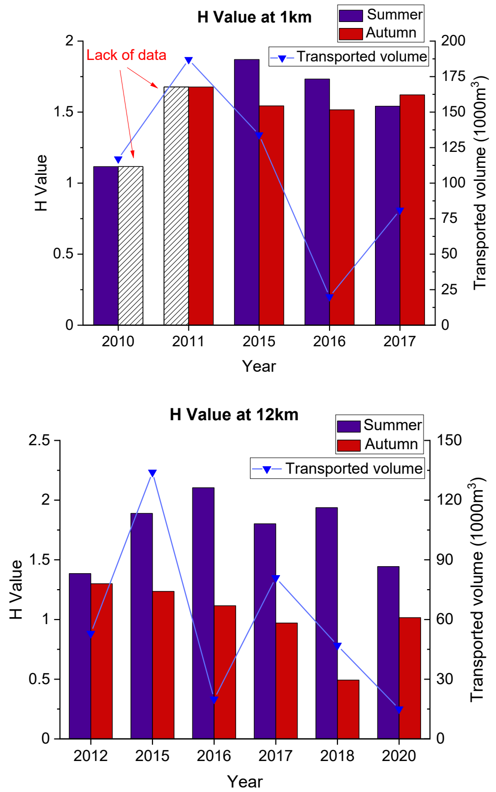

Fig.10 H value at 1.0 km and 12.0 km downstream of SR site from 2012 to 2020

5. CONCLUSION

In summary, an integrated assessment approach was developed and implemented in Naka River to investigate the hydro-morpho-ecological responses caused by SR. Particular indices were utilized to simply evaluate the morphological quality and habitat structures downstream of the dam.

It can be concluded that: (a) the replenishment efficiency was fluctuant due to the lack of integral design on operation, and further optimization regarding sediment equilibrium should be considered; (b) geomorphic units tends to be dispersed and average distribution, which is favorable for restoration of morphological quality; (c) with the continuous sediment replenishment, quality of physical habitat is promoted through the alteration of morphological conditions at spawning grounds. In the future, the assessment will be conducted to other projects if sufficient data can be obtained, and an integrated guide of SR design can be created.

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