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Spatiotemporal patterns of geomorphological processes determine characteristics of riverine habitat heterogeneity

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ABSTRACT: Riverine habitat structure and its heterogeneity are determined by spatiotemporal patterns of geomorphological processes. However, only a few researches have quantitatively analyzed geomorphological changes and resultant spatial distributions of habitat structures in a shifting habitat mosaic. We conducted a case study in a middle reach of the Tenryu River in Japan to identify how these changing patterns determine habitat heterogeneity. A set of interval-recording-cameras has been installed at 60 m above riverbed on the electric supply tower located in the middle of the river corridor. Firstly, we identified different types of habitat structures in a reach and analyzed characteristics of flood inundation processes for each habitat type. Secondly, we analyzed, at a micro scale, hardening and softening processes of habitat structures, using a riverbed softness measurement. Thirdly, we developed a 2-D model using the photogrammetric method and quantitatively analyzed erosion and deposition processes at macro and reach scales.

1 INTRODUCTION

Riverine habitat is structured with various habitat types, e.g., riffles and pools, back waters, and side pools, and these habitat structures are formed by erosion and deposition processes. Such geomorphological processes are determined by flood intensity and frequency, and sediment volumes with various grain sizes (Poff et al. 1997, Sumi & Kantoush 2010), thereby characterizing habit diversity and heterogeneity. Depending on flow and sediment regimes, habitats are recurrently created and eliminated and they are structured as a result of spatiotemporal patterns of geomorphological processes (Hyodo et al. 2013a). Habitat structures include nutrients and vegetation and they are influenced by flow and sediment regimes as well (OCK et al. 2010, OCK & Takemon 2011). In order to restore the riverine ecosystem, it is important that spatiotemporal patterns be appropriately evaluated. However, current ecological evaluation tools, e.g., HEP (US FWS 1981), PHABSIM (US FWS 1989), AUSRIVAS (Parsons et al. 2001), RIVPACKS (Wright et al. 2000), IBI (Karr 1981, Karr & Dudley 1981), etc., does not address this perspective. Recent researches implicated that, in order to optimize biodiversity, it requires presence of various habitat types with different habitat age (Takemon 1997, Ward et al. 2002). For example, there are several researches looking at spatiotemporal patterns of riverine habitats, e.g., shifting habitat steady state (Arscott et al. 2002) and habitat age (Tockner et al. 2010) in the Tagliamento River. However, only a few researches have tracked changing patterns of each habitat and quantitatively analyzed geomorphological changes and resultant spatial distributions of habitats. The objective of this study is to analyze spatiotemporal patterns of geomorphological processes that determine characteristics of riverine habitat heterogeneity. We analyze spatiotemporal patterns from a perspective of flood inundation, riverbed hardening and softening, and erosion and deposition processes.

2 METHODOLOGY

We conducted a case study in a middle reach of the Tenryu River in Japan. The Tenryu River has the catchment area of 5090 km^2 and river length of 213 m in the Nagano, Shizuoka, and Aichi prefecture. The study area is at 16.4 k-point from its river mouth, the slope is 1/520 to 1/650, 60% representative grain diameter is 60 to 73 mm, riverbed configuration is co-exiting of alternate and braided bars, and channel width is 1000 km. The lowest dam at the downstream reach is called Funagira dam located at 30 k-point for hydropower. A discharge gauging station has been set at Kashima at 25 k-point. There is an electric supply tower located in the middle of the river corridor. We have installed on the tower a set of interval-recording-cameras at 60 m above the riverbed since 8 August 2012, after we conducted camera testing on 17 May 2012. The study are and camera-recording sites, which are directed to upstream and downstream, are shown in Figure 1, and the photo data are shown in Figure 2. A number of habitat types were identified within the camera-recording sites at the beginning on 8 August 2012, summarized as: three riffles (2 in upstream and 1 in downstream sites, also referred to as Rfs), six side pools (4 in upstream and 2 in downstream sites, also referred to as SPs), and three back waters (3 in upstream and 4 in downstream sites, also referred to as BWs). SPs and BWs are classified by defining that SPs are disconnected to main or secondary channels by surface water under low flow conditions, and on the other hand BWs are connected. Exceptionally, in case when surface waters are connected but flow direction of pools goes to main or secondary channels rather than influenced by backwater, these habitats are classified as SPs in this article, i.e., Up-SP-2 and Up-SP-3 in Figure 2. This classification was made by photo data and field surveys.

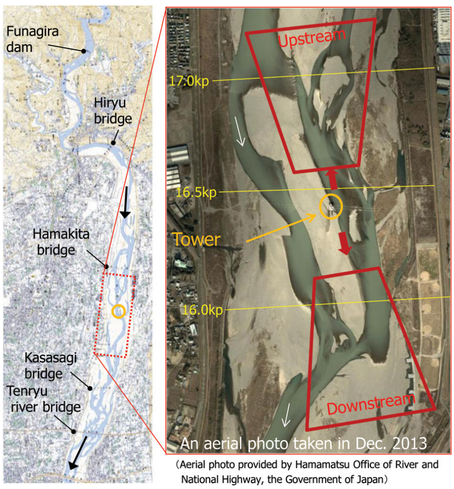

Figure 1. Study area and camera-recording sites, Tenryu River.

Figure 2. Habitat distributions within the camera-recording sites at the beginning, as of 8 August 2012.

This case study conducted the following by which how geomorphological processes determine characteristics of riverine habitat heterogeneity is discussed: to analyze inundation processes during floods with different intensity via interval-recording cameras; to quantitatively analyze changing patterns of riverbed softness at a micro habitat scale; and to quantitatively analyze erosion and deposition patterns at a macro habitat and reach scale.

2.1 *Inundation processes during floods*

Two flood events with different intensity were selected for the inundation analysis. Figure 3 shows hourly discharge of recent years in relation to surveys conducted. It is noted that hourly discharge at the Kashima gauging station is used throughout this article, when providing information relating to discharge. As maximum annual discharge since 1939 to 2013 is 4500 m^3/s, one is a small flood occurred on 23 October 2012 with the discharge of 510 m^3/s, and another is a middle flood occurred on 16 September 2013 with the discharge of 4900 m^3/s. Reasons for selecting these two floods were because not only they have different flood intensity, but also a riverbed softness survey was conducted around these periods to analyze their relations. Sequence photos taken via interval-recording-cameras were used to analyze inundation processes including flow directions according to water level rise.

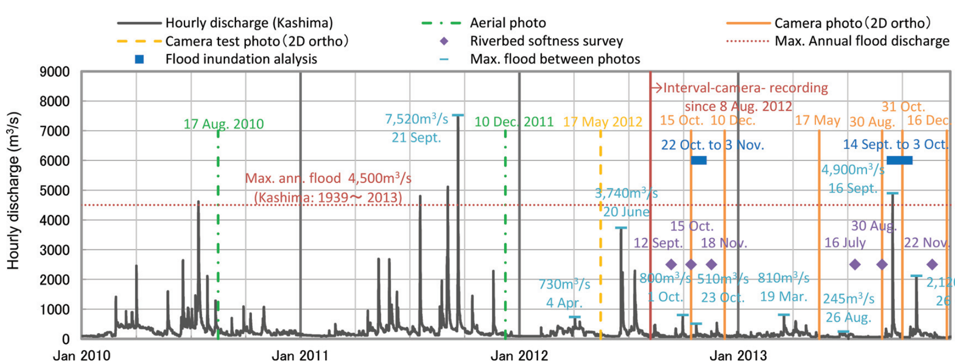

Figure 3. Hourly discharge at the Kashima gauging station located at 25 k-point, in relation to surveys conducted.

2.2 *Changing patterns of riverbed softness at a micro habitat scale*

In order to analyze changing patterns of hardening and softening processes of the riverbed, a riverbed softness survey was conducted six times in total, i.e., three times in 2012 (12 September, 15 October, and 18 November) and three times in 2013 (16 July, 30 August, and 22 November 2013) as shown in Figure 3. A small flood occurred during the former three times in 2012, while a middle flood occurred during latter three times in 2013. Methodologies for this survey are that firstly a matrix was developed for each habitat, ranging from 3 to 12 longitudinally along and 3 to 16 laterally against flow direction respectively, depending on the habitat size. The riverbed softness was measured at lattice points in matrixes. The measurement is called "shino" and was made with a small steel pipe, of which one edge is sharp. The sharp side edge is penetrated into the riverbed with a certain load by hand, and the depths under the riverbed surface were measured and recorded. For each lattice point of the matrix, the penetrated depth below the riverbed was recorded five times and their average values were used as the riverbed softness. When the riverbed is soft, a value of the riverbed softness shows a high number and vice-versa. In order to measure the riverbed softness, there is a tool called "Hasegawa riverbed cone penetration testing". Since numerous lattice points need to be continuously measured, easy-to-use shino was adopted to effectively measure them in this study.

2.3 *Erosion and deposition patterns at a macro habitat scale*

Firstly, we developed a 2-D model applying a photogrammetric method, i.e., transforming photo data to 2-D images with the orthogonal coordinate system, in order to quantitatively analyze erosion and deposition processes (see also Hyodo et al. 2013b). Secondly, erosion and deposition areas were measured by orthogonal 2-D images developed, which were superposed to identify geomorphological changes of surface-terrestrial boundaries. Then relations between flood intensity and erosion and deposition processes were analyzed.

A basic theory of the photogrammetric methods is formed by an equation (1).

$$X = \frac{b_1 x + b_2 y + b_3}{b_7 x + b_8 y + 1}, \quad Y = \frac{b_4 x + b_5 y + b_6}{b_7 x + b_8 y + 1} \qquad (1)$$

This equation is obtained from objectives to be transformed, which need to be a plane geometry, but they do not necessarily be a non-plane geometry, e.g., vertical and slope planes. 8 unknown quantities from b_1 to b_8 in equations of (2) and (3) can be obtained based on the least squares method by transforming more than 4 pairs of coordinate target bench marks as (X_i, Y_i, x_i, y_i) ($i = 1, 2 \ldots, n$: $n \geq 4$) to liner equations.

$$x_i b_1 + y_i b_2 + b_3 - x_i X_i b_7 - y_i X_i b_8 = X_i \qquad (2)$$

$$x_i b_4 + y_i b_5 + b_6 - x_i Y_i b_7 - y_i Y_i b_8 = Y_i \qquad (3)$$

In this case study, we have installed 8 target bench marks having coordinate values within camera recording sites, of which 4 were used for developing a 2-D model, i.e., a set of orthogonal images. Figure 4 shows an image of superposing an orthogonal image developed and aerial photo taken both in December 2012. This result describes well the accuracy of the 2-D model and showed approximately the 1 m accuracy. Considering a fact that a river width of this study area is about 800 m, this accuracy is appropriate enough to quantitatively measure erosion and deposition areas. However, it is noted that modeling of around photo edges used extrapolation and reduced its accuracy. This fact does not discuss in this article, but will be treated as a future challenge to enhance accuracy of this model.

A period for the quantitative analysis was from 17 August 2010 to 16 December 2013 (see Fig. 3). Even though interval-recording-cameras have been installed since 8 August 2012, camera testing was conducted prior to its installation on 17 May 2012. This photo data enables to obtain geomorphological change by a middle flood on 20 June 2012 with the peak discharge of 3740 m^3/s. In addition, orthogo-

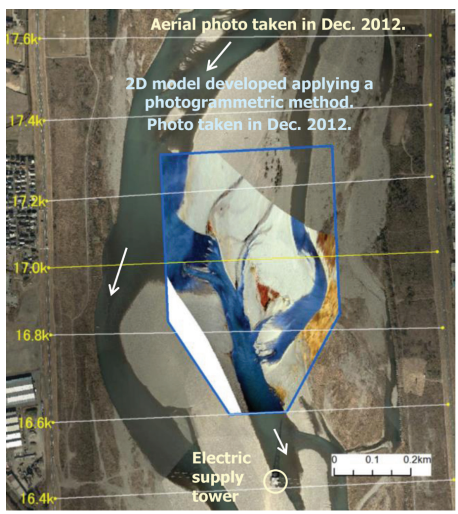

Figure 4. An image of superposing an orthogonal image developed and aerial photo taken both in December 2012.

nal aerial photo data on 10 December 2011 and 17 August 2010 were used to obtain changes due to a large flood occurred on 21 September 2010 with the peak discharge of 7520 m^3/s. These orthogonal aerial photo data were taken and developed by the Hamamatsu Office of Rivers and National Highways, Ministry of Land, Infrastructure, Transport and Tourism. Based on these data, geomorphological changes by a set of small, middle, and large floods could be used for the quantitative analysis on erosion and deposition processes.

3 RESULTS AND DISCUSSIONS

3.1 *Inundation processes during small and middle floods*

Figure 5 shows upstream photo sequences of a small flood from 22 October to 2 November 2012, taken by upstream interval-recording-cameras. As for Up-BW-1 and Up-SP-2, flood water passed through old channels followed by its water level rise. This old channel played a role as an active channel during a small flood, referred to as a "lotic system". On the other hand, as for Up-SP-1, it got inundated by backwater followed by its water level rise around Up-Rf-1, referred to as a "lentic system". In simplification, habitats have different inundation processes during small floods, which can be categorized as two types of lotic and lentic systems. Only Small geomorphological change has occurred by the small flood, such as integrating Up-BW-1 and Up-SP-2 into Up-BW-11.

Figure 6 shows upstream photo sequences of a middle flood from 14 September to 3 October 2013. At an earlier stage of the middle flood, inundation processes are similar with small floods. When the water level reached to the flood peak at 13:00, 16 September 2013, a part of woody canopies is above the water level except of which were totally inundated. In the recession stage of floods, river geomorphology appeared to have changed. Habitats were newly created such as Up-Rf-21, 22 and 23, Up-BW-22, Up-SP-21, etc. This implicates that middle floods have the potential to create new habitats, while small floods cause only geomorphological changes at a very small scale.

3.2 *Changing patterns of riverbed softness at a micro habitat scale in relation to floods*

This section analyzes changing patterns of micro habitat structures, focusing on the riverbed softness, and how their hardening and softening processes are related to geomorphological and inundation processes, which can be represented by lotic and lentic systems. Figure 7 shows results of a riverbed softness survey conducted in September, October, and November 2012 and July, August, and November 2013. A middle flood occurred between August and November 2013. Higher the numbers indicate the riverbed is soft and vice-versa.

As for Rfs, the riverbed softness is averaged longitudinally, i.e., riffle head, middle, and tail. The result shows that the riverbed has got continuously hardened especially at riffle heads. The riverbed of Up-Rf-2 once got softened, but it again started to get hardened. At Dn-Rf-1, unique change has occurred. While the riffle head got harder, the tail became softer until November 2012 and then again got harder. This process may be explained that small floods can transport a small portion of sediment to limited distance downstream, since small floods erode sediment at riffle heads and deposit it on their tails. For middle floods, we expected that they can deposit sediment on existing Rfs and its riverbed gets renewed and softened, according our assumptions (Hyodo et al. 2013b). However, rel-

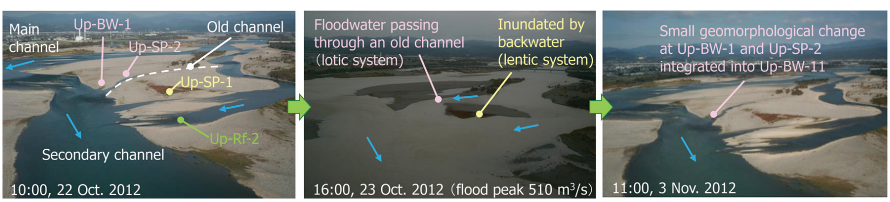

Figure 5. Upstream photo sequences of a small flood from 22 October to 2 November 2012.

Figure 6. Upstream photo sequences of a middle flood from 14 September to 3 October 2013.

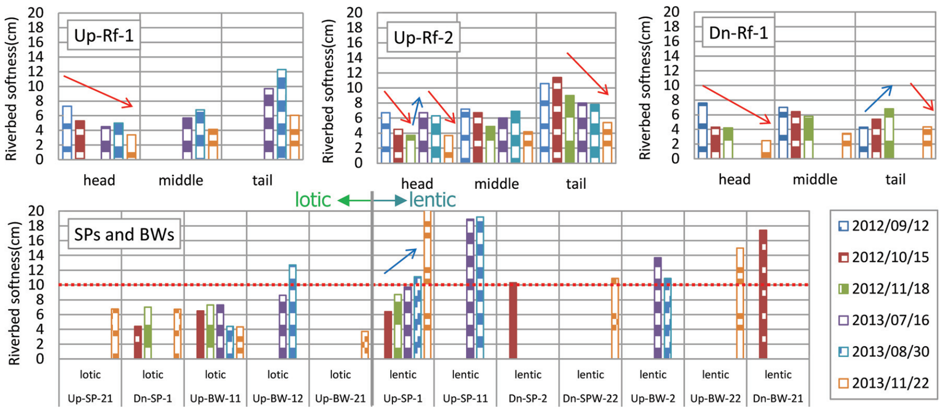

Figure 7. Results of the riverbed softness survey. Higher the numbers indicate the riverbed is soft and vice-versa.

evant results explaining this assumption could not be obtained from this survey. One reason for this is that since we could not conduct the survey between a middle flood in September 2013 and a relatively small flood in October 2013, but could conduct only after the small flood. As of November 2013, renewing processes of habitats by the middle flood may be completed and hardening processes by the small flood may have already started. These processes are discusses in Section 3.3.

As for SPs and BWs, the riverbed softness is averaged for each habitat. As shown in Figure 7, lotic and lentic systems correspond to the riverbed softness. Habitats with lotic systems showed lower values of the riverbed softness mostly below 10 cm, while those with lentic systems showed higher mostly above 10 cm. Lentic systems of SPs and BWs are inundated by backwater, assuming that in flood recession stages fine sediment is likely to be deposited on their habitats. This explains why lentic systems showed the riverbed is softer than lotic systems. On the other hand, even if habitat types are SPs and BWs, those of lotic systems have the harder riverbed than those of lentic systems. This result also leads to an assumption that small floods induce a sediment move of the riverbed of such habitats at a micro habitat scale, causing erosion as same as Rfs. Giving a detailed look at Up-SP-1 of lentic systems, the riverbed softness got higher over the period from 2012 to 2013, experiencing both small and middle floods. Figure 8 shows softening processes of Up-SP-1, representing well how lentic systems deposit fine sediment and form the softened riverbed.

3.3 *Flood intensity and erosion and deposition processes at a macro habitat scale*

Figure 9 shows a temporal series of spatial distributions of erosion and deposition areas within camera photo frames upstream. 2-D models for the orthogonalization of photo data were developed under conditions of low-enough flows. Area of erosion and deposition means changes of terrestrial and surface water boundaries in plane shapes above low-enough water levels.

A period between August 2010 and December 2011 experienced a large flood with the discharge of 7520 m^3/s. Large area of erosion and deposition were identified. Up-Rf-1 was developed by deposition of up- and down-stream sides on the right bars created. A new secondary channel was created on the left bars due to deposition and neighbor erosion. As a result of significant geomorphological changes, bar waterfront was formed by the large flood.

A period between May 2012 and September 2012 experienced a middle flood with the discharge of 3740 m^3/s. relatively large geomorphological changes occurred. Right bars were deposited and extended to downstream, thus renewing Up-Rf-1. Secondary channels on the left bars were deposited and eroded further downstream, thus creating Up-Rf-2.

A period between August and October 2013 experienced a middle flood with the discharge of 4900 m^3/s. On the right bars, a large ratio Up-Rf-1 was replaced by deposition with a new habitat of Up-BW-22.

A period between October and December 2013 experienced a relatively small flood with the discharge of 2120 m^3/s. A tail of the bar waterfront was eroded and shifted further downstream.

A set of these results explains that creation, elimination, renew of habitats can occur through erosion and deposition processes, and these changing patterns can be characterized by flood intensity.

3.4 *Erosion and deposition processes extended to a reach scale and discussions*

Figure 10 shows geomorphological changes at a reach scale in August 2010, December 2011, and December 2012. After experiencing a large flood, this reach has significantly changed the channel configuration, Up-Rf-1 was newly created as a result of such significant change, and the bar waterfront was formed as of December 2011. After experiencing a middle flood, the channel configuration has not changed, but changes to creating and renewing habitats have occurred at a macro habitat scale within the bar as of December 2012. When experiencing only small floods, habitat changes at a micro habitat scale, for example Rfs get continuously hardened (see Figs. 7 and 9). This result shows that geomorphological processes and resultant habitat heterogeneity are characterized more or less by flood intensity.

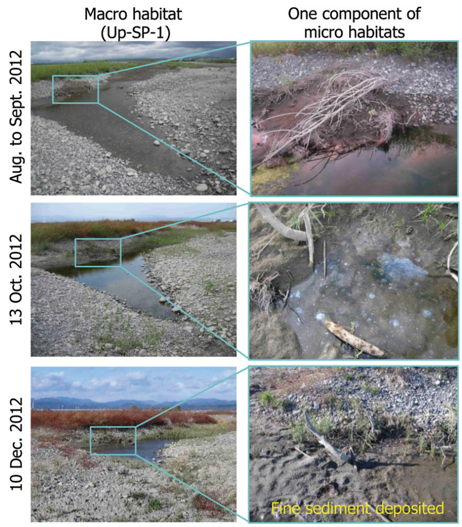

Figure 8. Micro habitat photos of Up-SP-1. These photos represent well how fine sediment is deposited by a backwater effect, leading to softened riverbed.

Using the results of 2-D models developed (see Fig. 9), relations between flood intensity and erosion and deposition processes were analyzed. We measured area of being eroded, deposited, unchanged, and surface water for each result. Figure 11 shows relations between flood intensity and the area measured. In comparison with the total area of 272,000 m^2 for the analysis, in relatively small and middle to large floods (larger than 2000 m^3/s), active area for geomorphological changes, where erosion and deposition are subject to occurring, is 19,000 to 89,000 m^2 (17% to 33% against the total area). On the other hand, in small foods (lower than 1000 m^3/s), active area is 4100 to 14,200 m^2 (2% to 5%), explaining that small floods less contribute to geomorphological changes.

In comparison with a ratio between erosion and deposition area in small floods lower than 1000 m^3/s (see Fig. 11), erosion is dominant in most of cases. During small floods, sediment adjacent to bar waterfront did not change. Based on this fact and hardening processes of the riverbed at riffle heads (as discussed in Fig. 7), it is assumed that sediment is not supplied from upstream bars onto the riffle heads, and within a riffle unit sediment is transported by

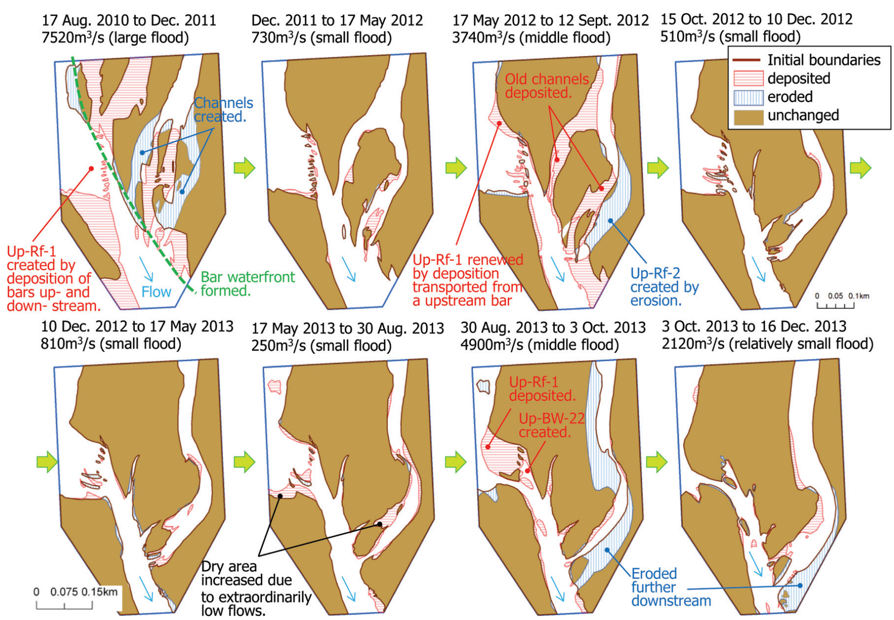

Figure 9. Results of orthogonalization of photo data, showing a temporal series of erosion and deposition areas, since 17 August 2010 to 16 September 2013.

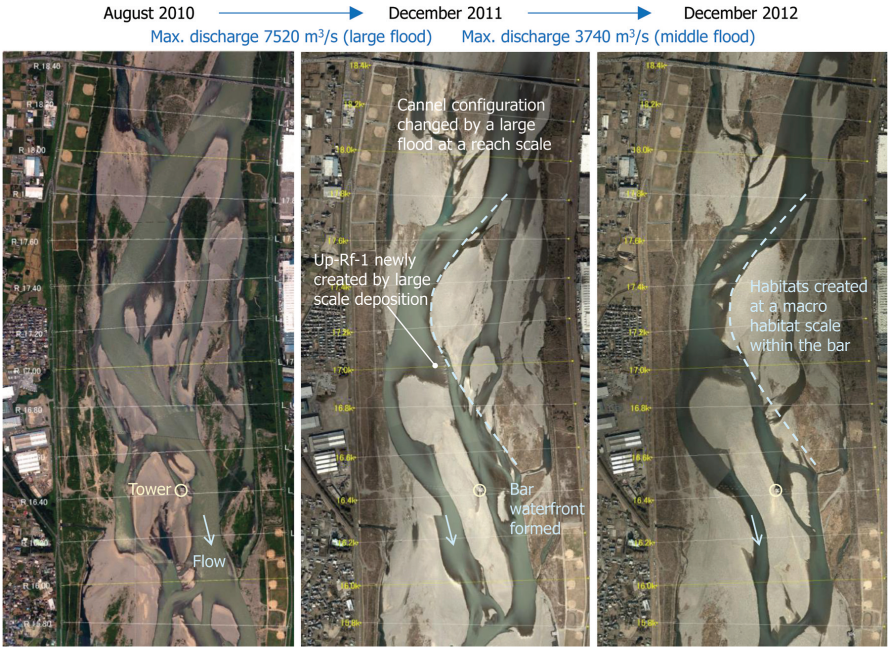

Figure 10. Aerial photos at a reach scale in August 2010, December 2011, and December 2012.

eroding its heads and depositing it on its tails. This process created the erosion dominant and hardening of the riverbed at Rfs during small floods.

Taking an example of spawning redds for Ayu fish species (*Plecoglossus altivelis*), it is known that Rfs are important and they should be composed of relatively small gravels. Our recent studies showed that especially riffle heads are more frequently used for spawning redds and soft riverbed is one of important components creating suitable redds (Sumi et al. 2011). Our case study showed that absence of middle and large floods reduces the suitability by eroding riffle heads and showed quantitatively processes of how the riverbed gets hardened. It also showed that presence of middle floods create new Rfs and induce deposition onto existing Rfs by a mass movement around bar waterfront located upstream of riffles. Large floods change significantly the channel configuration, creating new Rfs as summarized in Figure 11.

As for Rfs, it is assumed that the Rf suitability can be classified by flood intensity (see Fig. 11). Small floods have a deterioration effect (–) by changing habitats limited to a micro scale, middle floods have a relatively positive effect (+) by renewing riffle heads by deposition of sediment within a macro habitat scale, and large flood have a recovery effect (++) by significantly changing channel configuration and thus creating soften riverbed suitable for spawning redds of Ayu species. As for SPs and BWs, small and

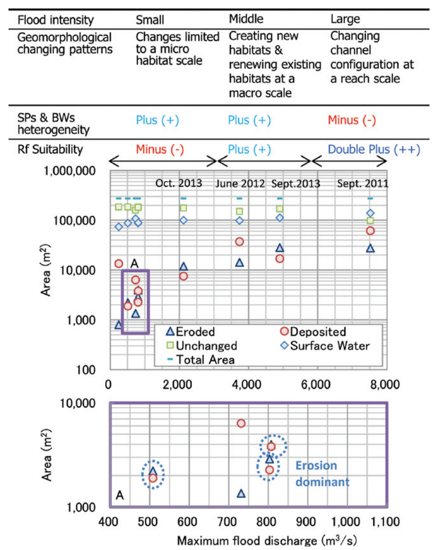

Figure 11. Relations between flood intensity and riverbed erosion and deposition areas. This figure also depicts geomorphological changing patterns and resultant SPs & BWs heterogeneity and Rf suitability.

middle floods enhance habitat heterogeneity over inundation processes of lentic and lotic systems, while large floods may reduce habitat heterogeneity by changing significantly the channel configuration.

Although we need to accumulate data and another effect influencing suitability and heterogeneity, e.g., timing and frequency of floods, vegetation effects, etc., it is revealed that they can be explained by a spatial hierarchy at reach, macro habitat, and micro habitat scales, and its temporal changing patters caused by floods with different intensity.

4 CONCLUSIONS

Monitoring by a set of interval-recording-cameras revealed that during small floods inundation processes of SPs and BWs are classified with two types of lentic and lotic systems and these systems determine the riverbed softness at a micro habitat scale. Riverbed softness is high in lentic systems and low in lotic systems. We developed a 2-D model applying a photogrammetric method. This model showed effectiveness to quantitatively analyze erosion and deposition processes with certain accuracy, by transforming photo data to 2-D images with the orthogonal coordinate system. This result showed large floods significantly change channel configuration, as a result of which new habitats are created. Middle floods do not have the potential to change the channel configuration, but change can occur at a macro habitat scale and renew existing habitats such as Rfs by deposition within a bar formed after large floods. Small floods can change at a micro habitat scale, for example Rfs get continuously hardened. These results showed that geomorphological processes and resultant habitat suitability and heterogeneity are characterized more or less by flood intensity. Even though we need to accumulate data and another effect influencing suitability and heterogeneity, e.g., timing and frequency of floods, vegetation effects, etc., it is revealed that they can be explained by a spatial hierarchy at reach, macro habitat, and micro habitat scales, and its temporal changing patters due to floods with different intensity.

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