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Missing link of coarse sediment augmentation to ecological functions in regulated rivers below dams: Comparative approach in Nunome River, Japan and Trinity River, California, US

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ABSTRACT: This study investigated gravel augmentation activities undertaken in Nunome River and Trinity River in relation to ecological functions of instream geomorphological features from the empirical perspectives of habitat diversity and organic matter interactions. It was found that riffles supplemented by high-flow stockpile in Nunome River functioned as an important natural filter for removing reservoir-derived plankton, and then subsequently contributed to macroinvertebrates species richness and functional feeding group. In the Trinity River, we found that an island and a point bar, which recreated by high-flow injection and direct placement respectively, had a distinct retention capacity for suspended particulate organic matter, and played an important role in inducing hyporheic flows providing simplified habitat with hydrological and thermal heterogeneity. These findings of the ecological roles of inchannel riffles and gravel bars could yield insights that will inform environmental management of design, implementation of rehabilitation activity and their maintenance.

1 INTRODUCTION

1.1 *Sediment starvation in regulated channels below dams*

Discontinuity of sediment transport by reservoir sedimentation and subsequent sediment deficit downstream have triggered a chain of riverine geomorphic changes such as riverbed degradation, channel incision and bank erosion. Such sediment starvation downstream is reported to cause loss of in-channel geomorphological features (Kondolf 1997, Graf 2006), accompanied by a subsequent simplification of habitat structure to aquatic communities and degradation of ecological functions in riverine ecosystem (Ligon et al. 1995, Power et al. 1996). In particular, loss of shallow geomorphic features such as riffle-pool sequence and several types of riverine bars is known to lead to degrade fish spawning habitat (Kondolf 2000) and to elongate a transport distance of reservoir derived plankton leading to disturb trophic balance in riverine foodweb system (Ock & Takemon 2010).

In response to the sediment deficit downstream, sediment augmentation, which artificially introduce coarse sediment into regulated channels in a variety ways, has been increasingly applied worldwide. Nunome River in Japan has performed the sediment augmentation activities, and a total of 2,585 m^3 of sediment were replenished downstream for 6 years since 2004, and resulted in lengthening riffle zones in the regulated channel (Kantoush et al. 2010, Ock et al. 2010). In the Trinity River in northern California, a total of about 122,000 m^3 of coarse sediment has been added to stream channels since 1972 (Gaeuman 2012). In recent years, the Lowden Rehabilitation project in the Trinity River recreated gravel bar features through coarse sediment augmentation (TRRP 2012).

There has been a missing link in much river restoration projects between geomorphological changes caused by gravel augmentation and subsequent contribution to ecological functioning. The study provides an opportunity to interpret the link by evaluating the effects of the long riffles in Nunome River and new gravel bars in Trinity River on ecological benefit for the downstream ecosystems. Better understanding of the ecological role of inchannel riffles and gravel bars in relation to river sedimentation could yield insights that will inform environmental management of design, implementation of rehabilitation activity, and their maintenance.

1.2 *Ecological importance of POM retention*

The trophic origin and composition in riverine Particulate Organic Matter (POM) is important indicator as an integrated record of natural and anthropogenic activities in river basins (Kendall et al. 2001, Hamilton et al. 2004). POM retention functioning, an ability of the channel to reduce the POM concentration, plays a role in supporting river and stream ecosystems as a primary energy resource (Tockner et al. 1999). However, in regulated rivers below dams, input of large amount of plankton from dam outflows influences POM quantity and quality, and subsequently could disturb downstream ecosystem foodweb (Richardson & Mackay 1991, Akopian et al. 1999). Thus, the retention efficiency of reservoir derived plankton can be important component for recovering a normal state of trophic structure. In this sense, this 'natural filtering' function, that is, to reduce POM concentrations and reservoir plankton from running water, is significant for enhancing self-purification along channels and restoring downstream ecosystem foodweb.

1.3 *Objectives*

This study focuses on evaluation for gravel augmentation activities undertaken in Nunome River and Trinity River in relation to ecological functions of instream geomorphological features such as riffles-pools and gravel bars. The objectives of this study are to make a general review of implementation process of gravel augmentation applied in the Nunome River by comparative approaches with Trinity River, and to investigate the instream features' ecological functions in relation to particulate organic matter retention and hyporheic exchange in the regulated channel.

2 CLASSIFICATION OF COARSE SEDIMENT AGUMENTATION

Comprehensive sediment management in dams and rivers has been developed worldwide including 'sediment replenishment', 'sediment bypassing tunnel', 'flood mitigation dam' without impoundment and 'dam removal' (Sakamoto et al. 2005, Sumi & Kantoush 2010). Compared with sediment bypassing tunnel and flood mitigation dam, the gravel augmentation is likely unsustainable for maintenance because of repetitive needs periodically. However this approach has merits to be relatively cost efficient and to provide immediate benefit, for instance, improvement of spawning habitat.

Despite conceptual strategies for satisfying both objectives to prevent reservoir sedimentation and to mitigate downstream impacts of dams and reservoirs, there remains still something to be systematically developed in stages of planning, implementation techniques, monitoring and evaluation, and adaptive management (Harvey et al. 2005); i.e., magnitude and frequency of flushing flow, quality and quantity of coarse sediment, source of evacuated sediment, sediment treatment; selecting appropriate methods; monitoring and evaluation for physical and ecological changes; adaptive management for feedback via science-based progress in the face of uncertainty.

Coarse sediment can be replenished mainly through some different injection types, each with specific advantages (Kondolf & Minear 2004, Harvey et al. 2005). First, 'direct placement' is relatively past implementation method where over-size sediment larger than 15 cm is directly placed within low-flow channel normally to build permanent features, e.g. constructed riffles, grade control structures or constructed point bars, which are largely immobile under the current flow regime. Second, 'high-flow stockpile' placed gravel along the channel bank margin to be distributed downstream by high flows. It is common type currently applied in Japan. This approach can add relatively large amounts of gravel at relatively low cost, but limited to volume piled and the number of suitable sites. Third, 'inchannel bed Stockpile', as a variant on the high-flow stockpile, spread gravel on the river bed to facilitate transport even

Figure 1. Sediment augmentation methods depending on implementation techniques.

by lower flows than the flow volume needed for high-flow stockpile. But it involves inchannel work at low flows, which may increase turbidity downstream. Fourth, 'high-flow injection' introduces directly gravel to river channel during a high flow event. Comparing high-flow stockpile that is quickly exhausted in a large flow, high-flow injection can allow new sediment to replace the material already transported, and larger volume can be introduced during the course of a flood. Finally, the gravel augmentation can be combined with mechanical floodplain reshaping work to increase bed mobility, so-called 'bank rehabilitation' (Fig. 1).

3 COMPARATIVE ANALYSES OF GRAVEL AUGMENTATION IN THE NUNOME RIVER AND TRINITY RIVER

Table 1 summarized the sediment augmentation applied in Nunome River and Trinity River with comparison of the purposes, implementation, flooding flow and added sediment characteristic.

Table 1. Comparisons of coarse sediment augmentation activities between Nunome River and Trinity River.

Factors of sediment augmentation	Nunome River	Trinity River
River and Dam		
River		
Basin and location	Kizu River basin in Nara, Japan	Klamath River basin in California, US
Length/basin area	30 km long/86.2 km^2	266 km long/7,389 km^2
Upstream dam		
Name/year built/height/storage capacity	Nunome Dam/1994/72 m high/17.3 MCM*	Trinity Dam/1962/164 m high/3,019 MCM Lewiston Dam/1963/28 m high/18.1 MCM
Type/purpose	Concrete gravity/mainly flood control	Earthfill/diversion, hydropower
Reservoir sedimentation risk	High	Low
Sediment augmentation		
Objectives		
Physical objectives	To reduce reservoir sedimentation rate To protect riverbed degradation To improve bed mobility	To recreate gravel bar features in part through natural fluvial forming process
Ecological objectives	To detach nuisance attached algae	To make complex habitat structure for salmonids fish
Implementation characteristics		
Year started	2004	1972
Frequency	Variable (once or twice a year in summer) depending on flooding events	Once a year in spring (April)
Main methods applied	High-flow stockpile	High-flow injection Bank rehabilitation Direct placement
Number of sites	A single site just below dam	Four sites along channel below dam
High-flow discharge characteristics		
Discharge released	Flood-control discharge release by peak cutting	Environmental flow release set up by water year types
Peak magnitude	Approx. 80 m^3/s, but varied depending on inflow volume intensity in monsoon climate	Max to 311 m^3/s in extremely wet year
Peak duration	2–4 hours	Over 5 days
Sediment added characteristics		
Source excavated	From check dam located at end of reservoir	From floodplain rehabilitation work
Amount added per a year	Max 500 m^3	Max 51,224 m^3
Grain size	Mixed sand and gravel (0.075–19 mm)	Mixed gravel and boulder (15–102 mm)

*MCM means a million cubic meter.

3.1 *Purposes specific to reservoir sedimentation and sediment deficit downstream*

Nunome River was a tributary of Kizu River basin in Nara Prefecture in Japan. The concrete gravity dam (72 m high and 17.3 mcm storage capacity) built in 1994 was planned to set sedimentation capacity to 100 years (1,900,000 m^3), but sedimentation in the reservoir had been progressed faster than that of original plan, and sedimentation rate in 2006 already reached to 13 percent (243,000 m^3) of the planned sedimentation (Kantoush et al. 2010). The rate would be accelerated unless appropriate sediment management in reservoir and upstream basin had been employed. As an objective for reducing reservoir sedimentation rate, inflowing sediment to reservoir has been trapped at the check dam located at upstream end of reservoir, and then the excavated sediment has been used for source of downstream augmentation. For objectives in downstream river channels, mitigation for bed degradation and improvement of nuisance attached algae were expected.

The Trinity River located in northwest California is the largest tributary to the Klamath River. Since Trinity Dam and Lewiston Dam construction in 1962, about more than 50 percent of water in the Trinity Basin was diverted to the Sacramento River basin. Subsequent reduction of both flow and sediment downstream have resulted in the loss or degradation of salmon habitats and caused naturally produced salmon populations to decline up to 60 to 96 percent (USDOI 2000). Trinity River Restoration Program (TRRP) have made much of efforts to restore salmonids habitats requiring hydro-geomorphological complexity corresponding to diverse stages of spawning, incubation, rearing and outmigration, and adopted restoration strategies to induce fluvial process morphologically for gravel bar restoration by coarse sediment augmentation (USFWS & HVT 1999, USDOI 2000).

3.2 *Implementation characteristics*

3.2.1 *High flow stockpile in the Nunome River*

The sediment mechanically excavated at upstream check dam moved to downstream river below dam by dump truck, and then placed down on the right bank far from 300 m below Nunome Dam (Fig. 2). The placed sediment consist mainly of sand and gravel with 0.38 mm median size (d_{50}) ranging 0.25 to 19 mm. The volume of replenished sediment in a single implementation varied 80 to 500 m^3, which depended on magnitude and duration of flushing flow. Based on the event in October 2009, the amount of 500 m^3 of coarse sediment were transported downstream by high flow recorded of 81 m^3/s of peak flow for 4 hours (Kantoush et al. 2010).

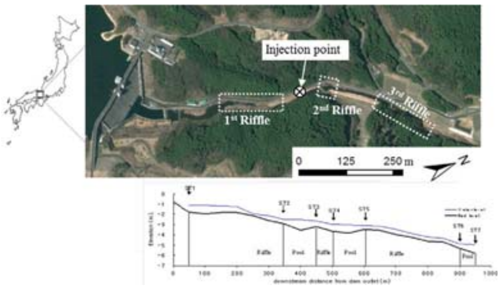


Figure 2. Nunome River project site; high-flow stockpile was done at the 300 m downstream form dam, and three riffles were developed along about 1000 m channel.

For the magnitude of flushing flow and amount of coarse sediment added, the largest amount of coarse sediment replenished in a single event was recorded as 500 m^3 on August and October of 2009. The grain size consisted mainly of mixed sand and gravels less than 10 mm. The frequency and amount of the sediment replenishment has been dependent of flushing flow released downstream during flooding season in July to October. The replenishment activities have been available in the aspects of riverbed degradation and detachment of attached algae. Despite deposition of sand bar at meandering bend, the amount and grain size of sediment replenished is likely to be insufficient to create gravel bar feature in channel. Occasionally sand bed could be problematic in habitat condition to make spawning bed buried and to let rearing pool filled. And thus in order to transport the coarser sediment much farther downstream, the much higher magnitude of the flushing flow and longer duration time of the peak flow should be considered.

It has mainly used the high-flow stockpile during the flooding event by intensive rainfall and typhoon. Although the method is effective for large amount of stocked sediment to be replenished downstream in a single event with relatively short peak duration, the downstream length for added sediment to be transported was relatively short comparing to the high-flow injection. Major deposition was actually found at just 300 m below the implementation site below Nunome Dam. To maximize transport distance of replenished sediment, the high-flow injection would be effective, because the method is able to add sediment directly to strong thalweg of the channel using a heavy equipment like conveyor machine. It also has merits to control total amount of gravel added depending on peak duration and thus enables much more amount of gravel supplied downstream than high-flow stockpile (Kondolf & Minear 2004).

3.2.2 *High-flow injection and direct placement at the Lowden rehabilitation project in Trinity River*

The Lowden Ranch rehabilitation project reaches, located 11 km downstream from Lewiston Dam. A mid-channel bar (island) was deposited in 2011 downstream from a high-flow gravel injection site. The highest peak flow of 311 m^3/s to date was released from Lewiston Dam and approximately 1,567 m^3 of gravel was injected from upstream site and distributed downstream by the high flows. Another point bar with an alcove at the downstream end was mechanically constructed by 'direct gravel placement' in 2010 (Fig. 3). About 6,880 m^3 of gravel was placed in a straight channel in order to force a meander bend in the main channel (TRRP 2011, TRRP 2012).

For the flooding flow downstream, TRRP determined the five water year types based solely on Trinity Reservoir inflow. The probability of these water year types occurring is based on historical data over eight decades past. Total allocation ranges from 1,005 mcm in an 'extremely wet year' to 455 mcm in a 'critically dry year'. Based on average inflow to Trinity Reservoir, allocation to Trinity River represents 43 percent of total inflow into Trinity Reservoir. Once the water year type was designated and the allocation to Trinity River has been established, the discharge pattern proposed (USFWS & HVT 1999). Peak discharge varies depending on water year type. Volume and grain size of sediment added were considered of pre dam topography and sediment transport capacity reduced under the current flow regime (Kondolf & Minear 2004). Gravel added used over size of 15 mm after removing fine sediments, ranging approximately 25 to 102 mm of large cobble size, which is able to mobile under anticipated flow regimes (Gaeuman 2008). In addition, four sites were selected as implementation locations for gravel augmentation in consideration of sediment delivery from tributary, sediment transport capacity below injection site.

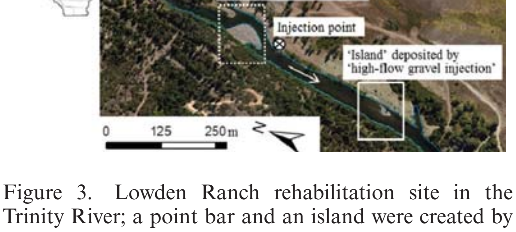


Figure 3. Lowden Ranch rehabilitation site in the Trinity River; a point bar and an island were created by direct placement and high-flow injection, respectively.

4 EFFECTS OF GRAVEL AUGMENTATION ON DOWNSTREAM ECOLOGICAL FUNCTIONS

4.1 *Field sampling and laboratory analyses*

In order to investigate how the riffles elongated by high-flow stockpile in the Nunome River and the gravel bars recreated by high-flow injection and direct placement in the Trinity River influence downstream ecosystems, i.e., natural filtering functions, quality and quantity of POM were longitudinally analyzed in the both river sites. In addition, thermal diversity within gravel bar features was investigated in relation to hyporheic flow among mainstem and side channel, alcove in the Trinity River.

Suspended POM samples were collected at either border of riffles or gravel bars using a POM net sampler with 100 μm in mesh size, in January to February 2009 in Nunome River and July 2012 in Trinity River. Three replicates were collected at each site. Each suspended fine POM samples was filtered in situ using the sieve of 1.0 mm mesh size to separate it from suspended coarse POM. Terrestrial plant leaves, epilithic algae and reservoir phytoplankton were also collected as potential POM source origins.

We traced the downstream changes in POM trophic sources (composed of allochthonous terrestrial inputs, autochthonous instream production and reservoir plankton from dam outflows), and estimated POM concentration (Ash Free Dry Matter (AFDM) of POM in a unit water volume) and qualitatively analyzed stable isotope values (δ^{15}N and δ^{13}C) to effectively identify the three sources and longitudinally estimate their relative contributions. The concentrated-weighted mixing model using dual δ^{13}C-δ^{15}N were applied (Phillips 2001, Phillips & Koch 2002). In the Trinity River, water temperatures were monitored using thermometer installation along the wetted margins of the both gravel bars. The temperature readings were taken every 10 minutes continuously for approximately one week in summer 2012.

4.2 *Suspended POM retention capacity of riffle features in the Nunome River*

Geomorphological monitoring research for cross section bed deposition and grain size distribution showed that downstream riffle was developed along channel where riffles percentage accounts for 68% as shown in Figure 2 (Ock et al. 2010), and tiny sand bar was deposited 300 m downstream from the implementation site (Kantoush et al. 2010). But the research on ecological response to the geomorphological changes was little investigated.

In three riffles distributed longitudinally, there was a downstream change in $\delta^{15}N$-$\delta^{13}C$ values of suspended POM samples (Fig. 4). $\delta^{15}N$ decreased and $\delta^{13}C$ increased in the riffles, and such downstream characteristics resulted in downstream contribution changes of three trophic sources of reservoir plankton derived from reservoir, terrestrial plant leaves and instream algae (Fig. 5). Interestingly, the contributions of reservoir plankton were found to be decreased in all riffles. Almost 60% of reservoir plankton contributed to suspended POM at the uppermost site near dam outlet point, but the contribution gradually decreased along three riffles to 52% (1st riffle), 46% (2nd riffle) and 37% (3rd riffle) within just 1 km channel length.

This finding indicates riffles have a retention capacity for removing reservoir-derived plankton in the downstream regulated channels, and subsequently change gradually trophic source in downstream foodweb system more balanced by increasing contributions of terrestrial plant and instream algal sources (Takemon 2005). Assuming that aquatic macroinvertebrates communities could response to the downstream trophic source changes in the channel, the species richness and functional feeding group were analyzed in the three riffles. Number of species increased downstream almost more than two times from 13 species at 1st riffle and 20 at 2nd riffle to 31 at 3rd riffle. It seems not to be immediate response of functional feeding groups. Species of filterers increased downstream in spite of plankton contribution reduction, whereas the rate and number of collectors and predators increased, showing gradually downstream shifting to more balanced foodweb condition (Fig. 6).

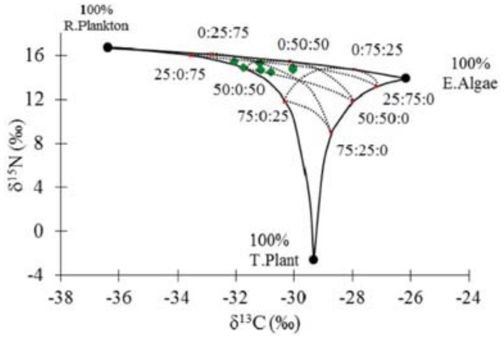


Figure 4. Downstream changes in stable isotope ratios of suspended POM surrounded by nonlinear mixing triangle composed of three trophic sources. The values of ratios composed of three sources are in order of terrestrial plant: epilithic algae: reservoir plankton.

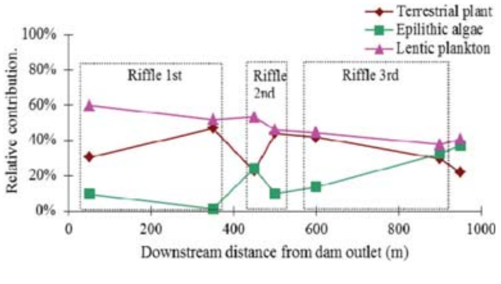


Figure 5. Downstream changes in relative contributions of the three sources to suspended POM.

4.3 *Suspended POM retention capacity of gravel bar features in the Trinity River*

It was found of reduction pattern in SPOM concentration estimated from the upstream end to downstream end in both gravel bars. In both the first and second samplings, the concentration was reduced 4 to 10% in the constructed point bar, whereas 17 to 14% in the deposited island (Fig. 7a). The difference could be differentiated in a length-normalized (100 m) retention rate, the

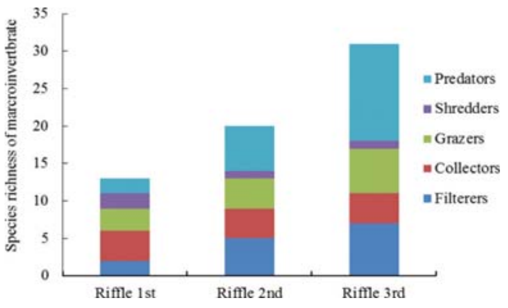


Figure 6. Downstream distribution of species richness and functional feeding group for macroinvertebrates communities.

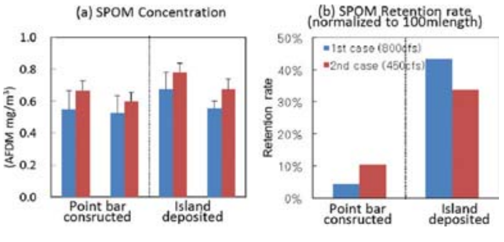
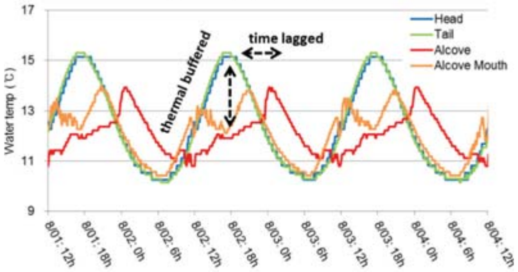


Figure 7. Suspended POM concentration along gravel bar reaches (a) and retention rate normalized to a length of 100 m (b) in the first and second samplings.

island formed by natural fluvial processes showed about 3 times higher retention rate than the constructed point bar (Fig. 7b).

The results are a clear evidence that the gravel bar features in the reaches have a retention capacity and can act as a sink for suspended POM. The reduction of POM concentration, which is an indicator for enhancing material exchange in river ecosystems, was found in both bars for the two sampling times. Also the finding that the higher retention efficiency occurred at the deposit island bar could probably attribute to an active trapping process in the shallow near-boundary along the island bar, because of the relatively long boundary length due to the contribution of side channels and wide shallow area (McNair 2006, Hunken & Mutz 2007). In contrast to island bars, point bars that occur on the inside meander bends, and are more likely to have passive deposition of suspended POM in slackwater, whose retention efficiency is expected to vary with the sinuosity of the inshore zone (Schiemer et al. 2001). Consequently, our results indicate that gravel bars created through gravel augmentation activities contribute to enhancing suspended POM retention, and suggest the importance of boundary length, and shallow area in gravel bar management and restoration.

(a) Point bar constructed



(b) Island deposted

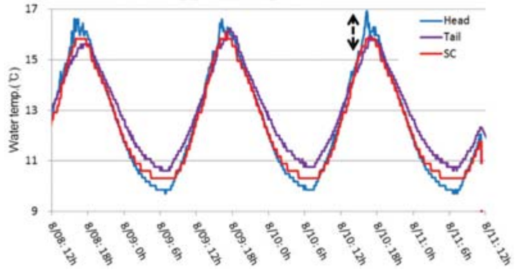


Figure 8. Spatial and temporal variations of water temperature along a gravel bar shore. Data were recorded at 10-minute intervals.

4.4 *Hyporheic flow effect between mainstem and subsurface waters beneath gravel bar*

Water temperature data acquired showed distinct thermal regimes inter-intra gravel bar features. Diel fluctuation patterns interpreted by a sine function showed the same 24 hour frequency with amplitudes and lag times specific to each feature (Arrigoni et al. 2008). In the island bar, the temperature in the tail was slightly cooler than that in the head during the daytime, resulting in the smallest amplitude of diurnal temperature (2.8°C) of the thermometers placed in the head, side channel (Fig. 8a). On the other hand, water temperatures in the point bars showed a diverse magnitude of amplitude and shifting time in the fluctuation function, mainly due to the influences of alcoves derived from hyporheic flows The alcove was about 3.1°C cooler than the mainstem at the time of mainstem maximum temperature of 15.1°C, whereas it was much warmer at the time of mainstem minimum temperature in the constructed point bar (Fig. 8b).

There was a time lag in temperature signals between alcove and mainstem in the point bar, and between head and tail in the island. The time lags were shown differently in the two bars; the point bar alcove had a longer time lag of about 6.2 hours than the island tail with 0.2 hours. Also, the temperature signal measured close to the mouth of the alcoves appeared to converge with that of the mainstem, showing a different time lag than that observed between mainstem and alcoves.

For maximum hyporheic cooling benefit in summer, it is a strategy to increase hyporheic flow rate which is a function of hydraulic gradient and substrate permeability (Tonina & Buffington 2007). Because both island and point bar were formed mainly by coarse sized gravel from coarse sediment augmentation indicating allow a high permeability, the extent of hyporheic flow rate among the bars is likely dependent on a hydraulic gradient. Field observation showed that the island showed higher hydraulic gradient between head and tail, whereas the constructed point bar showed high hydraulic gradient between mainstem and alcove. It indicates that naturally deposited islands with longitudinally steep hydraulic gradients could induce high hyporheic flow rates, while point bar with laterally steep hydraulic gradient induce high hyporheic flow rate into alcove. Likewise, from a perspective of gravel bar management, hyporheic flow contribution to thermal heterogeneity can be promoted by maintaining high permeability through regular substrate replacement and by increasing hydraulic gradients within a gravel bar (Boulton 2007).

5 CONCLUSION

Recent river restoration has shown a growing concern for the instream features management and restoration through sediment augmentation, however recognition of recovering ecological functions have not been assessed enough from the empirical perspectives of physical habitat diversity and organic matter interactions. This study summarized augmentation processes by comparison of two different cases in Nunome River and Trinity River. Then, POM trophic composition results estimated by stable isotope mixing model showed that riffles in Nunome River functioned as an important natural filter for removing reservoir plankton in the dam tailwater ecosystem, subsequently contributed to macroinvertebrates species richness and functional feeding group. Also newly created gravel bars in the Trinity River not only functioned as a strong natural filter for suspended POM, but also play a role in inducing hyporheic flows, providing simplified habitat with hydrological and thermal heterogeneity.

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