Research article

Comparison of Macroinvertebrate Community Structures between Artificial Environments and Natural Streambeds in Mountain Streams

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Received 29 December 2023 Accepted 17 February 2025 (*Corresponding Author)

Abstract In mountain streams, artificial structures like restoration dams and culverts help maintain forests, roads, and streams. However, while their negative impact on aquatic ecosystem is known in lower river reaches, their effects in mountain streams are less understood. To assess this, we compared benthic macroinvertebrate communities in natural and artificial streambeds in the Ishite River headwaters, Ehime, Japan. We studied benthic macroinvertebrates in pools, riffles, and rapids in natural streambeds and in culverts, dam walls, open ditches, a levee crown and a sedimentary zone associated with a mountain restoration dam. Results demonstrate that benthic macroinvertebrate community densities, taxon richness, and diversity tended to be greater in the natural streambeds than in the artificial environments. In all but the culverts, ordination using non-metric multidimensional scaling revealed that the benthic macroinvertebrate community structure of the natural streambeds and the artificial environments were characterized by their type. For the culverts, the community composition varied among sampling sites. For the dam walls, it was characterized by relatively small taxa such as Chironomidae and Diamesinae. Unlike all other sampling sites, the sedimentary zone tended to show lentic taxa. For the open ditches, the diversity and density were similar to that of natural streambeds. However, the results for the sedimentary zone and open ditches should be interpreted with caution due to the small number of sites examined. The results of this study indicate that the benthic macroinvertebrate communities in artificial environments in mountain streams differ in composition from those in natural streambeds, although the species present are not substantially different.

Keywords benthic macroinvertebrate, erosion control dam, culvert, mountain stream, headwaters

INTRODUCTION

In mountain streams, erosion control dams and mountain restoration dams play a role in storing sediment and preventing stream erosion. In addition, culverts and open ditches intended to manage erosion, are constructed to protect forest roads which cross streams and these artificial structures contribute directly and indirectly to forest maintenance and management. However, it has been demonstrated that such artificial structures are associated with modification of the river environment and that they have an impact on a river's ecosystem. Bylak and Kukuła (2018) reported that concrete slabs altered and degraded downstream benthic macroinvertebrate community. Kanazawa and Miyake (2006) reported that concrete substrate channels altered the community structure in the upper reaches of rivers. Conversely, Nukazawa et al. (2016) found that slit installation on a check dam did not lead to an increase in benthic macroinvertebrates.

Artificial structures contribute to the complexity and diversification of river structure and habitat, and they are thought to have an impact on biodiversity, although the actual impact on increasing species diversity is thought to be small (Palmer et al., 2010). Few studies, however, have assessed the effects of artificial structures on benthic macroinvertebrate communities in river headwaters associated with mountain restoration dams. There is also little knowledge of the structures used to manage forest roads, such as culverts and open ditches. Events in the upper reaches of rivers can have a strong influence on downstream areas, and such knowledge in the headwaters is important.

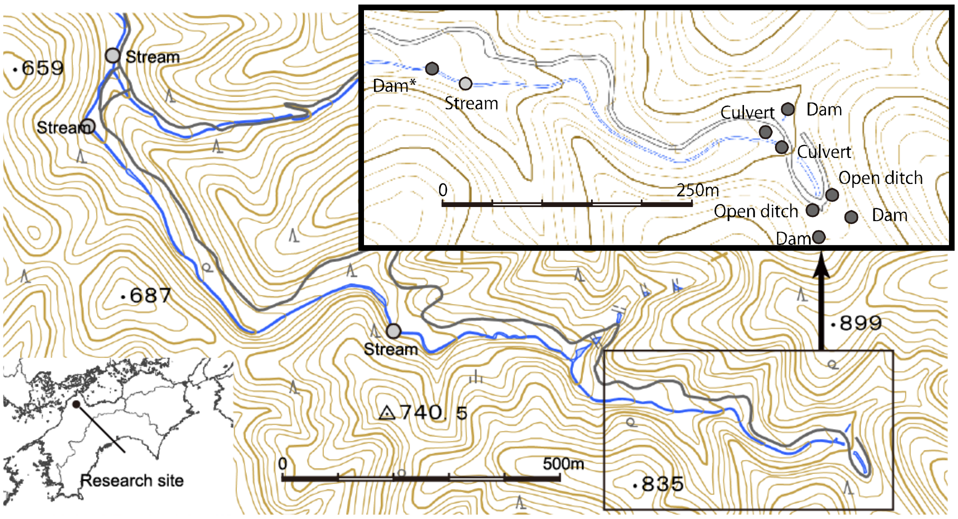
OBJECTIVE

This study aimed to elucidate the effects created by artificial structures on benthic macroinvertebrate communities in a mountain stream in the upper reaches of the Ishite River, Takanawa Peninsula, Ehime Prefecture, Japan. To this end, the benthic macroinvertebrate fauna in natural streams and artificial environments were studied and compared.

METHODOLOGY

Study Area

The study was conducted in two periods, from 28 April to 28 June 2022, the spring period, and from 24 October to 14 November 2022, the autumn period. The study was conducted in a stream flowing through the Experiment Forest attached to the Faculty of Agriculture, Ehime University, which corresponds to the upper reaches of the Ishite River (Fig. 1). Geologically, the upper reaches of the Ishite River are primarily composed of granite. The surrounding forest contains a mixture of Japanese cedar (*Cryptomeria japonica*) and Japanese cypress (*Chamaecyparis obtusa*) plantations and secondary forest dominated by fir (*Abies firma*) and tsuga (*Tsuga sieboldii*).



*Notes: *the dam of which levee crown and sedimentation zone were surveyed. Map modified from GSI map. URL: https://www.gsi.go.jp/tizukutyu.html*

Fig. 1 Map of the study area

Mountain restoration dams were constructed on the stream that runs through this forest. There is sediment on the upstream side of a dam where the river gradient becomes gentler and the river width widens, decreasing water flow. The dams contain culverts, levee crown, and walls. Under and beside the forest road there are culverts and open ditches. All artificial structures were made from concrete (Fig. 2).

Four dams in the river were selected as study sites. At each dam, surveys were carried out at the dam wall where the water was flowing and near the outlet of the culverts installed into each dam wall. For one dam, in addition to the culvert and wall, the survey was carried out at the levee crown of the dam and in the upstream sedimentation zone. Apart from culverts installed in the dam wall, surveys were also carried out in two culverts used to pass water under forest roads. In addition, two open ditches that direct water from dams were surveyed. Then, the number of study areas artificially affected was 14. Study sites were established at four locations in the river to compare the benthic macroinvertebrate communities of natural riverbeds with those of artificial environments. At each site in the natural streambed, three microtopographic locations were selected: a rapid riffle (shallow, fast-moving sections with white caps), a riffle (rippling flow sections), and a pool (deeper and slower-moving sections) (Fig. 1). The number of natural riverbeds studied was 12.

Fig. 2 Images of stream (a), sediment (b), mountain restoration dam (c), open ditch (d) and culvert (e)

During sampling, measurements were taken for both EC (Electrical Conductivity) and pH using an EC meter (AS-EC-33, AS ONE CORPORATION, Osaka, Japan) and a pH meter (AS-pH-11, AS ONE CORPORATION, Osaka, Japan), respectively. In natural streams, the mean values of EC (SSD: Sample Standard Deviation)) were found to be 0.126 (0.011) mS/cm, and in the artificial stream bed, it was 0.128 (0.0085) mS/cm. The mean values of pH (SSD) were 7.8 (0.20) in the natural stream and 7.5 (0.26) in the artificial streambed. Kanazawa and Miyake (2006), who conducted a survey in October 2005 in the watershed immediately downstream of the study site, recorded EC and pH values of 0.102-0.111 mS/cm and 7.3-7.4, respectively, which were lower than the results of the present study. These differences in water quality may be attributed to the higher density of concrete structures in the upper reaches of the study site. The General Linear Model analysis did not identify any significant difference with regard to EC; a significant difference was identified between the artificial and natural riverbeds with regard to pH. However, the pH values were neutral at both sites and do not significantly affect benthic macroinvertebrate communities in this range (Yuan 2004).

Methods

Field survey: At each sampling site, except for dam wall and culvert, a 30 cm square metal frame was placed on the surface of the streambed. A D-frame net (2 mm mesh) was positioned downstream of the frame, and sand, gravel, and debris were disturbed in the frame using the kick and sweep sampling method to flush suspended benthic macroinvertebrates into the D-frame net. This was done by disturbing sand, gravel, and debris to a depth of 5 cm or to the concrete surface from the streambed. In the culvert survey, a metal frame was placed 30 cm from the culvert outlet, benthic macroinvertebrates were swept into the downstream net by hand. For the dam wall survey, a 30 cm square frame was placed on the wall where the water was flowing, a net was positioned under the frame to disturb attached algae and other organisms in the frame, and large benthic macroinvertebrates were washed by hand into the net. The collected benthic macroinvertebrates were preserved in 80% ethanol. Benthic macroinvertebrates in each sample were identified and measured to the lowest possible taxonomic class using a stereomicroscope. After the removal of benthic macroinvertebrates, the sand and organic matter samples were dried at 40°C to a constant mass and weighed to determine the amount of sand and organic matter in the 5 cm surface layer.

Data analyses: To analyze benthic macroinvertebrate community structure, individual density (individuals/m^2), number of taxa, and Shannon-Wiener species diversity were calculated for each of 26 samples. Generalized Linear Model (GLM) analyses were performed to determine the effect of stream bed type on sand, litter, and benthic macroinvertebrate community. The mass of sand and organic matter and the density, number of taxa, and Shannon's diversity index of benthic macroinvertebrates were used as dependent variables. The effect of season and artificial environments (culverts, dam walls, open ditches, bank tops, and sediments) compared to natural streambeds (pools, riffles, and rapids) were used as independent variables. For each analysis conducted, the variance ratio (F value), numerator degrees of freedom, error degrees of freedom, and p value are presented. For the analyses of density and number of taxa, the distribution of the error term is assumed to follow a Poisson distribution, while those of the other dependent variables follow a normal distribution. In each analysis assuming a Poisson distribution and normal distribution, we present the absolute values of the Z-score and F value, respectively along with the p value.

Non-metric dimensional scaling (NMDS) analyses were used to compare benthic macroinvertebrate community structure. Bray-Curtis distances, derived from the abundance of each taxon, were used as a measure of dissimilarity between samples and coordinates were assigned by performing 51 and 108 iterations for spring and autumn, respectively (Kruskal and Wish, 1978). Kendall's rank correlation coefficients (τ) were calculated between the values of each axis and the abundance of each taxon to determine whether the axes obtained by NMDS reflected changes in the absolute abundance of each taxon. All statistical analyses were performed using R 4.3.2 (R Core Team, 2016) and Vegan 2.6-4.

RESULTS

Benthic Macroinvertebrate Fauna

A total of 1,119 benthic macroinvertebrates from 47 taxonomic groups were collected from the samples. Of these, 718 individuals representing 38 taxa were found in the natural streambeds, while 401 macroinvertebrates belonging to 35 taxonomic groups were found in the artificial environments. Of the 47 total taxa, 12 were found only in the natural streambeds and 9 were found only in the artificial environments (Table 1).

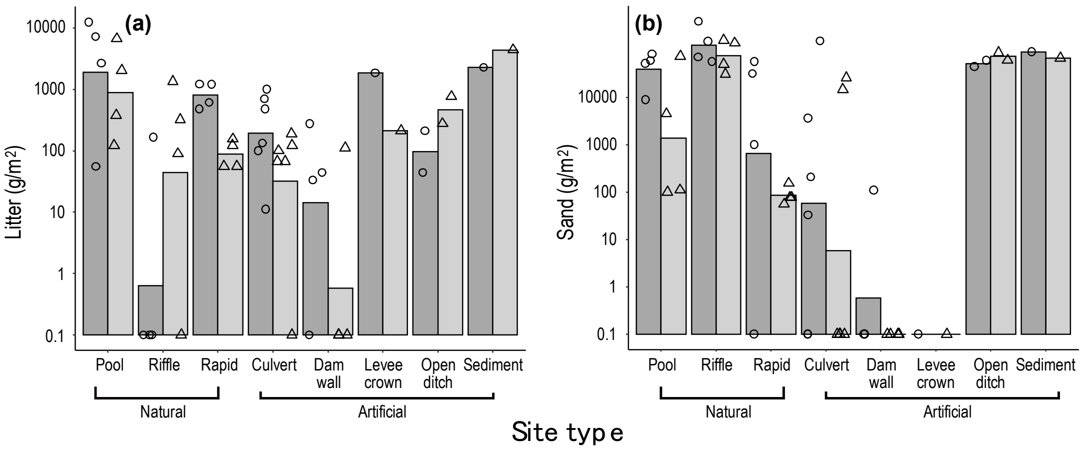
Sand and Litter

Comparing sand and litter mass in artificial and natural streambeds by GLM, a significant difference ($F_{1,48}$=4.3, $p < 0.05$) was found for sand mass, but no significant effect was found for litter mass. No significant effects of season or interaction (artificial influence and season) were found. For litter mass, the variation was greater in rapids, culverts, and on the dam wall. For sand mass, the variation was greater in rapids and culverts. Both litter and sand mass were higher in the open ditches, sedimentation zone and in the pools (Fig. 3).

Table 1 Individual number of dominant macroinvertebrate taxa found in the study sites

Taxon	Natural				Artificial			
	rpd	rfl	pl	clv	dmw	lvc	opd	sdm
Ephemeridae	11	36	93	35		2	37	
Baetidae	27	2	8	44	18	20	22	3
Hydropsychinae	31	1	59	15			6	
Gomphidae	6	4	45	1			3	5
Tipulidae	21	1	23	3			7	1
Chironomidae		1	12		21	6		8
Heptageniidae	18	2	15	1	2		8	
Neoperla sp.	4		31	2			6	
Lepidostomatidae	33		9				1	
Geothelphusa dehaani	10	13	7	3			8	
Psychomyiidae	14	1	1					
Lepidostoma japonicum	12							
Amphipoda	2		4					
Leptophlebiidae	1		3					
Uenoidae	3	1						
Colymbetinae								4
Baetis thermicus				3				
Ephemera japonica				2				
Macrostemum radiatum				2				
Notonectidae								2
Number of taxon observed	20	15	20	14	8	5	15	9

Notes: The top 10 taxa in total and the top 5 taxa found only in artificial environments or natural streams are only shown. Abbreviations are as follows: rpd: rapid riffle, rfl: riffle, pl: pool, clv: culvert, dmw: dam wall, lvc: levee crown, opd; open ditch, and sdm: sedimentation zone.



Notes: Dark grey bars/circles = spring data, light grey bars/triangles = autumn data

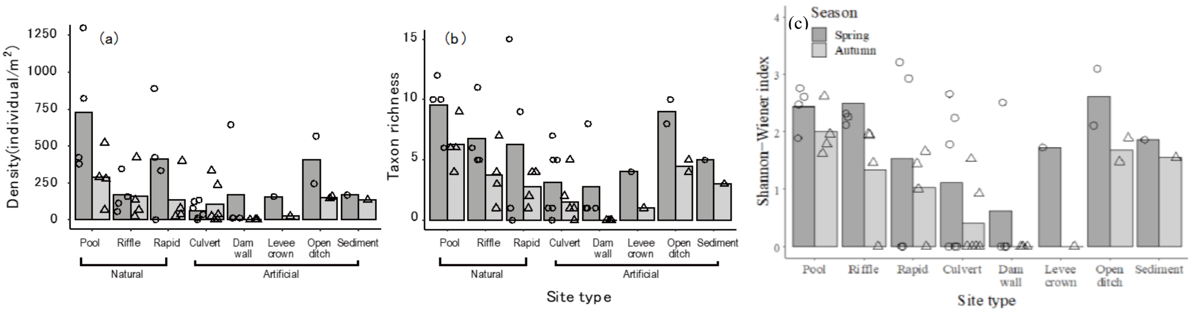
Fig. 3 Mass of litter (a) and sand (b) (g/m²)

Individual and Taxon Number and Diversity

Generalized Linear Model analyses revealed significant differences in density ($|Z|$=3.9, $p < 0.001$), number of taxa ($|Z|$=7.5, $p < 0.001$) and diversity ($F_{1,48}$=10.9, $p < 0.001$) of in all cases, no significant effects of the interaction between season and streambed type were found. Density, number of taxes and diversity were all higher in spring. Differences between sampling sites showed that these values tended to be lower at culverts and dam walls and higher at pools, open ditches and sedimentary zones. Taxon numbers and diversity were high in riffles and rapids (Fig. 4).

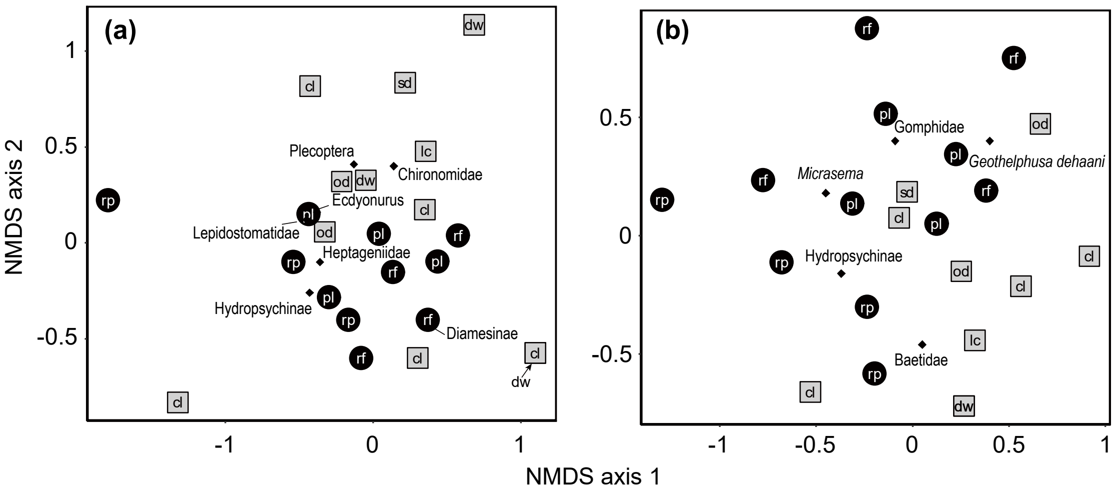
The NMDS Analyses

The NMDS analyses of the two axes based on the abundance of each taxon showed that the areas plotted in spring and autumn tended to be different in the streambeds and the artificial environments, respectively. The NMDS stresses in spring and autumn were 0.14 and 0.19 respectively. Artificial environments in spring tended to be located in areas where one of the two axes were higher than the other. Natural riverbed sites tended to be located in the region of lower values for the second axis. There was a significant correlation ($p < 0.05$) between the first axis and the densities of Diamesinae ($\tau = 0.37$), Heptageniidae ($\tau = -0.36$), Hydropsychinae ($\tau = -0.43$), Ecdyonorus ($\tau = -0.38$), and Lepidostomatidae ($\tau = -0.45$). There was a significant correlation ($p < 0.05$) with the second axis between Plecoptera ($\tau = 0.41$), Damesinae ($\tau = 0.44$), and Chironomidae ($\tau = 0.40$) (Fig. 5a).



Notes: Dark grey bars/circles= spring data, light grey bars/triangles = autumn data

Fig. 4 Density (/m²) (a), taxon number (b), and diversity index (*H*) (c)



Notes: A black circle represents a natural stream bed, while a grey rectangle represents artificial environments. Abbreviations are as follows: pl: pool, rf: riffle, rp: rapid, cl: culvert, dw: dam wall, lc: levee crown, od; open ditch, and sd: sediment.

Fig. 5 Plots of axis 1 versus axis 2 for the non-metric multidimensional scaling (NMDS) of the density of benthic macroinvertebrates at each study site for (a) spring and (b) autumn, with taxa showing significant correlations.

A tendency was observed for artificially influenced environments in the autumn period to appear in areas with higher values on the first axis and lower values on the second axis. Significant correlations ($p < 0.05$) with the first axis were observed for the number of Hydropsychinae ($\tau = -0.37$), *Geothelphusa dehaani* ($\tau = 0.40$), and *Micrasema* ($\tau = -0.45$). Significant correlations ($p < 0.05$) with the second axis were found for the number of Baetidae ($\tau = -0.46$), Gomphidae ($\tau = 0.40$), and *Geothelphusa dehaani* ($\tau = 0.40$) (Fig. 5b).

DISCUSSION

In general, many benthic faunal species are known to grow mostly during specific seasons (Hynes, 1970), and such growth periods influence the seasonal variation in distribution. No seasonal variation in litter abundance was observed in the present study (Fig. 3). The density, number of taxa, and diversity of benthic macroinvertebrate taxa were significantly higher in spring than in autumn (Fig. 4). Species that showed significant correlations to the NMDS axes in the Kendall's rank correlation coefficient analyses in spring or autumn were six and five taxa, respectively. The only taxon common to spring and autumn was Hydropsychinae. With the exception of this, the taxa characterizing the NMDS co-ordinates for each season differed. These results indicate that seasonal differences in the dominant taxa led to seasonal differences in the NMDS coordinates. It was suggested that this may not have resulted from seasonal variations in litter mass, but from other factors such as growing seasons.

The results of this study showed that taxa dominated in artificial environments were often found in natural streambeds. Densities were higher in natural streams for most of these common taxa, suggesting that natural streambeds are more productive than artificial environments. With the exception of open ditches and sedimentation zones which showed a similar number of taxa to natural streambeds, these results suggests that artificial environments have a limited contribution to the maintenance of benthic macroinvertebrate community diversity in mountain streams. For some taxa, such as Baetidae and Chironomidae, densities were higher in artificial environments (Table 1). It has been reported that the density of individuals belonging to Baetidae and Chironomidae is higher on concrete substrates with artificial environments. This is attributed to the increased flow velocity on concrete substrates (Kanazawa and Miyake 2006). It has also been reported that the number of taxa that can occur in habitats with high flow velocities is limited (Boyero and Bosch, 2004). The results of the high abundance of Baetidae and Chironomidae identified in this study in artificial environments may also be related to increased flow velocities in concrete environments, as in these previous studies.

Of the artificial environments examined in this study, the culverts, dam walls, levee crowns, and open ditches have concrete as substrates. Of these, the dam walls and levee crown were environments with low amounts of sand and litter. The culverts were a type of environment where the amount of litter and sand varied from point to point. The open ditches and sedimentation zone had high amounts of litter and sand, comparable to the natural streambed. The sedimentation zone not only had a high amount of litter and sand, but also had a lentic environment, which was different from any of the other study sites.

The sedimentary zone, an artificial environment characterized by high litter and sand deposition, was the only environment where taxa such as Colymbetinae and Notonectidae were observed. These taxa are lentic and carnivorous, suggesting that the community composition of this sedimentary zone may be unique. Lentic benthic macroinvertebrates such as *Platambus pictipennis* and *Anotogaster sieboldii* were also observed outside the sampling frame during the survey (M. Hamguchi personal observation). This observation supports the possibility that this habitat may provide environments that are significantly different from others. On the other hand, it has been suggested that the establishment of lentic habitats and changes in biota in such sedimentary zones may merely establish a downstream environment leading to a reduction in diversity (Takemon, 1997). However, it should be noted that only one site was surveyed in this study. The autumn NMDS coordinates are not far from other sites, suggesting that further research is needed to elucidate the role of these depositional zones.

The benthic macroinvertebrate community in the open ditches showed a higher density, number of taxa, and diversity than in other artificial environments, and the positions of the NMDS coordinates were close to those of the natural streambeds, indicating that the community structure was similar to that of the natural streambed. The substrate of the open ditch in the study was concrete, but it was located on a gentle slope and its substrate was not well exposed due to litter and sand deposition (Fig. 2d, Fig. 3). As a result, the open ditches may have had an environment similar to a natural riverbed, which may have led to the observed community structure in these open ditches.

Regarding the dam wall, the water flowed vertically, and algae and other organisms were attached to the wall surface, and although almost no benthic macroinvertebrates were observed during the autumn season, some organisms were observed during the spring season. According to Ota et al. (2023), small body size taxa such as Chironomidae are reported to be present amongst the algae growing on the concrete riverbed, and indeed small body size Chironomidae and Diamesinae were observed on this wall, and these taxa have also been identified in NMDS analyses of spring data as taxa with a preference for artificial environments. As for culverts, not only do litter/sand levels vary widely between sites, but the extensive plotting of culverts in the MNDS analysis indicates that community structure here varies from site to site. The reasons for this are not clear but may be influenced by the environment around the culverts and the upstream structure.

CONCLUSION

The results of NMDS analyses indicate that community composition differs between artificial environments and natural riverbeds. Many of the taxa identified in the artificial environments were also found in the natural streambeds. These results suggest that the benthic macroinvertebrate communities in artificial environments in mountain streams differ in composition from those in natural streambeds, although the species present are not substantially different. In the sedimentary zone, however, unique species were identified that differed from those in natural riverbeds and other artificial environments. These results indicate that artificial environments in mountain streams do not significantly increase the diversity of benthic communities throughout the watershed. It should be noted that our results suggest that unique communities possibly exist in the sedimentary zone, but previous studies have indicated that such communities may be more similar to those in the lower reaches of the watershed.

ACKNOWLEDGEMENTS

This work was partly supported by JSPS KAKENHI Grant Number JP 19H00560 and 23H03622. We thank K. Haikawa, D. Takeda, and members of the laboratory of forest resource biology, department of Forestry, Ehime University, for field assistance.

REFERENCES

Boyero, L. and Bosch J. 2004. The effect of riffle-scale environmental variability on macroinvertebrate assemblages in a tropical stream. Hydrobiologia, 524, 125-132, Retrieved from DOI https://doi.org/10.1023/B:HYDR.0000036127.94781.3c

Bylak, A. and Kukuła K. 2018. Concrete slab ford crossing, An anthropogenic factor modifying aquatic invertebrate communities. Aquatic Ecosystem Health and Management, 21 (1), 41-49, Retrieved from DOI https://doi.org/10.1080/14634988.2017.1329604

Hynes, H.B.N. 1970. The ecology of running waters. University of Toronto Press, Canada, ISBN 0802016898.

Kanazawa, K. and Miyake, Y. 2006. Comparison of stream invertebrate assemblages between concrete and natural substrates. Ecology and Civil Engineering, 9 (2), 141-150, Retrieved from DOI https://doi.org/10.3825/ece.9.141 (in Japanese)

Kruskal, J.B. and Wish, M. 1978. Multidimensional scaling. Quantitative Applications in the Social Sciences, SAGE Publications, Inc., Newbury Park, USA, Retrieved from DOI http://dx.doi.org/10.4135/9781412985130

Nukazawa, K., Hayashi, T., Kazama, S. and Takahashi, S. 2016. Temporal variation of stream invertebrates and habitat after the slit construction of a check dam. Journal of Japan Society of Civil Engineers, Ser. G (Environmental Research), 72 (7), III_553-III_558, Retrieved from DOI https://doi.org/10.2208/jscejer.72.III_553 (in Japanese)

Ota, K., Kumagai, Y. and Miyake, Y. 2023. Comparison of invertebrate assemblages between concrete and natural beds in lowland streams. Ecology and Civil Engineering, 25 (2), 51-61, Retrieved from DOI https://doi.org/10.3825/ece.21-00025 (in Japanese)

Palmer, M.A., Menninger, H.L. and Bernhardt, E. 2010. River restoration, habitat heterogeneity and

biodiversity, A failure of theory or practice? Freshwater Biology, 55 (s1), 205-222, Retrieved from DOI https://doi.org/10.1111/j.1365-2427.2009.02372.x
R Core Team. 2016. R, A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, Retrieved from URL https;//www.R-project.org/
Takemon, Y. 1997. Conservation of aquatic insect habitats in mountain streams. Journal of the Japan Society of Erosion Control Engineering, 50, 52-60, Retrieved from DOI https://doi.org/10.11475/sabo1973.50.52 (in Japanese)
Yuan, L.L., 2004. Assigning macroinvertebrate tolerance classifications using generalized additive models. Freshwater Biology, 49 (5), 662-677, Retrieved from DOI https://doi.org/10.1111/j.1365-2427.2004.01206.x