RESPONSES OF MACROINVERTEBRATE COMMUNITIES TO RIVER RESTORATION IN A CHANNELIZED SEGMENT OF THE SHIBETSU RIVER, NORTHERN JAPAN

Short title: RESPONSES OF MACROINVERTEBRATES TO RIVER RESTORATION

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ABSTRACT

The effects of restoration of channel meandering and the installation of groynes on physical variables and river-dwelling macroinvertebrates were examined in a lowland river, the Shibetsu River in northern Japan. The lowland segment of the Shibetsu River, which previously meandered, had been straightened by channelization and groynes had been installed in some portions of the channelized reach. In 2002, the channelization works were partly reversed to improve the degraded river ecosystem.

Physical environment variables and the macroinvertebrate community structure and composition were compared among the reconstructed meander and channelized reaches, with and without groynes. The shear stress of the river edge in the reconstructed meander and groyne reaches was lower than that in the channelized reach. In addition, the edge habitat near the stream bank in the reconstructed meander and groyne reaches had a higher total density and taxon richness of macroinvertebrates compared with the channelized reach. Restoration provided a relatively stable edge habitat, contributing to the recovery of the macroinvertebrate communities in the channelized lowland river. The placement of groynes can be an effective method of in-stream habitat restoration for macroinvertebrates.

KEYWORDS: river restoration; reconstructed meanders; groyne structures; lowland rivers; channel straightening; macroinvertebrate community, riverbed stability.

INTRODUCTION

Rivers and streams are among the most degraded ecosystems. Worldwide, the majority of rivers have been modified by human activities, which are widely recognized as the major cause of global-scale habitat loss and degradation in the lotic environment (Allan and Flecker, 1993; Rosenberg *et al.*, 2000). Channelization alters the channel morphology and homogenizes the physical habitat across the stream (Brookes, 1994). In particular, straightening a naturally meandering river eliminates edge habitats near the shoreline, such as backwaters and edge water, which have slow current conditions. Numerous studies have shown that a loss of habitat diversity caused by channelization decreases the abundance and taxon richness of fish and macroinvertebrates (Moyle, 1976; Edwards *et al.*, 1984; Quinn *et al.*, 1992; Bis *et al.*, 2000).

In order to restore an original river ecosystem to recreate habitat diversity, the reintroduction of a meandering channel and its natural flow regime should be considered as restoration measures (Downs and Thorne, 1998). Several programmes to restore meanders have been implemented to improve stream habitats degraded by channelization (Holmes, 1998; Nakamura, 2003). However, when human interventions such as flood control, water utilization and land use are severe, the potential for implementing large-scale restoration work may be very low. In this case, river restoration has often been undertaken by placing in-stream structures such as woody debris and boulders that increase habitat complexity (Erskine and Webb, 2003; Brooks *et al.*, 2004).

A groyne is an in-stream structure that projects into the stream from a bank to manipulate the current. It is usually made of wood, stone or concrete. Two primary functions of groynes are transportation enhancement and bank protection. For stream restoration, groynes can also be used to create slow current conditions and provide edge habitat along the shore. The stable river bed created by the slow current conditions is important for maintaining the abundance and diversity of the macroinvertebrate community, particularly in a lowland river that contains a

large amount of fine sediment in its bed material (Rempel *et al.*, 1999). Thus, groynes have the potential to enhance macroinvertebrate habitat while at the same time maintaining bank protection. Shields *et al.* (1995) reported that habitat restoration by installation of groynes increased the abundance and variety of fish. However, few studies have evaluated the effects of groyne structures on lotic macroinvertebrate communities.

The Shibetsu River in eastern Hokkaido Island, northern Japan, is a lowland alluvial river. The entire lowland portion of this formerly meandering river was straightened by channelization, with groynes installed in some reaches. Recently, in cooperation with local communities and experts, an experiment involving reconstruction of a meander was conducted in a selected reach, with construction completed in March 2002. This provided an opportunity to examine the effects of restoration strategies (reconstruction of meanders and groyne placement) on macroinvertebrate communities. Although many studies have examined the effects of restoration projects on macroinvertebrates (Laasonen *et al.*, 1998; Muotka *et al.*, 2002), few studies have evaluated the individual effect of a restoration method, and none has been carried out in Japan.

This study aims to determine the effects of reconstructing a meander and the placement of groynes on the physical environment and macroinvertebrate communities, in order to evaluate their effectiveness in the recovery of macroinvertebrate communities.

STUDY SITE AND METHODS

Study site

The Shibetsu River originates at the foot of Mt Shibetsu (1061 m asl) and drains a catchment of 671 km^2. Pastureland covers nearly 40% of the catchment area of the Shibetsu River. The catchment receives approximately 1100 mm of precipitation per year, snowfall in winter and heavy rainfall in late summer. This seasonal precipitation pattern creates a major flood

associated with snowmelt in spring, and occasionally generates large floods in summer and fall. The lower segment of the Shibetsu River was straightened and channelized between the 1950s and 1970s for flood control and farmland reclamation. This caused severe degradation of the river and riparian ecosystems. The Blakiston's fish owl (*Ketupa blakistoni*) and the Japanese huchen (*Hucho perryi*), which were the symbolic species of Hokkaido, disappeared. In recent years, growing interest in river health in Japan has led to a programme to reconstruct meanders in the Shibetsu River to restore the river ecosystem (Nakamura, 2003). Due to a lack of experience in meander restoration in Japan, a small-scale demonstration project to test construction methods was carried out in 2002, about 8.5 km upstream from the river mouth. The oxbow lake K, once isolated by channelization, was reconnected to the main channel, which restored a historic meander (Figure 1). The channelized reach was retained, which allowed stream flow in the two channels to ensure flood control. Because erosive velocities in the straight canal had lowered the river elevation, the bottom sediment of the oxbow lake was excavated to the same elevation. To reinforce stream inflow to the reconstructed meander channel (the connected lake), a weir spillway to reduce the flow in the straight channel was placed just above the outlet of the meander channel. This experimental site was located in the fourth-order river at an elevation of 10 m asl. In 2003, the mean annual discharge of the Shibetsu River was 17.3 m^3/s.

Habitat measurements and macroinvertebrate sampling

Habitat measurements and macroinvertebrate sampling were carried out in June and November 2003, in three study reaches: an experimental reconstructed meander reach (the restored meander reach), a channelized reach with groyne structures (the groyne reach), and a channelized reach without groynes (the channelization reach) (Figure 1). Each study reach was further classified into an edge (within 4 m from the bank) or mid-channel habitat, resulting in six habitat types in total being surveyed. In general, a reach of stream and river was viewed as a

mosaic of mesohabitats such as woody debris, macrophytes and minerals of various grain sizes, and the community structure of the benthic macroinvertebrates is closely related to the mesohabitat type (e.g., Armitage *et al*., 1995; Brunke *et al*., 2002). However, non-mineral mesohabitats were limited and the substrates of each habitat type were homogeneous in the study reaches. Sandy gravel (0.5–6.4 cm) was dominant and particles larger than cobble size (>64 mm) were very rare in the streambed substrate of the study site. Eight macroinvertebrate samples were collected from each habitat type in June and November, using a modified T-sampler (23 cm diameter; ca 400 cm^2 area; 0.3 mm mesh). The bottom of this sampler had indentations to allow easy insertion into the riverbed. Macroinvertebrate samples were preserved in 70% ethanol in the field and then identified and counted in the laboratory. Wherever possible, identification of most faunal groups was to species and genus level, except for some dipteran families, Chironomidae to tribes and Oligochaeta to class level.

Water depth and mean velocity (at the point of 60% of depth) were measured at each macroinvertebrate sampling point. In addition, the water surface slope was measured for each reach with a level, to calculate the shear stress at the sampling point by the following equation:

$$\tau = \rho gHI$$

where ρ is the water density (102 kgf s^2/m^4), g is the gravitational acceleration (9.8 m/s^2), H is the water depth (m) and I is the slope of the water surface.

Data analyses

Physical environmental variables and community structure data were log (x+1) transformed prior to statistical analysis to normalize and stabilize variances. Differences in the macroinvertebrate community structure (total macroinvertebrate density and taxon richness), and physical environmental variables (water depth, mean velocity and shear stress), were compared among habitat types for each sampling period (June and November), using one-way

ANOVA, with habitat types as the main factors. When significant differences were apparent, multiple comparisons were made using the Holm test.

The family abundance data were log (x+1) transformed and ordinated by detrended correspondence analysis (DCA) to identify important gradients in the composition of macroinvertebrates for each sampling period, using the PC-ORD multivariate statistical package, version 4 (McCune and Mefford, 1999). Families that occurred in fewer than 1% of the samples were removed to avoid spurious variability caused by the presence of rare taxa.

RESULTS

Physical environments

All physical environmental variables were significantly different among the habitat types in June (water depth, $F_{5, 42} = 54.2$, $P < 0.0001$; mean velocity, $F_{5, 42} = 52.4$, $P < 0.0001$; shear stress, $F_{5, 42} = 48.4$, $P < 0.0001$) and November (water depth, $F_{5, 42} = 149.4$, $P < 0.0001$; mean velocity, $F_{5, 42} = 73.0$, $P < 0.0001$; shear stress, $F_{5, 42} = 167.1$, $P < 0.0001$). In the restored meander and the groyne reaches, water depth was significantly higher in mid-channel habitats, whereas it was lower in edge habitats (Figures 2A, 3A). Similarly, mean velocity and shear stress contrasted between mid-channel and edge habitats in the restored meander and groyne reaches (Figures 2B, C, 3B, C). There was no difference between edge and mid-channel habitats in the channelization reach in June. However, mean velocity and shear stress in November were different between the edge and middle of the channelized reach.

Macroinvertebrate abundance and richness

Total macroinvertebrate density and taxon richness were significantly different among habitat types in both June (density, $F_{5, 42} = 50.7$, $P < 0.0001$; richness, $F_{5, 42} = 28.6$, $P < 0.0001$) and November (density, $F_{5, 42} = 45.8$, $P < 0.0001$; richness, $F_{5, 42} = 36.1$, $P < 0.0001$). Edge habitat in

the restored meander reach had a significantly higher total density and taxon richness than other habitat types, followed by the density and richness of the edge in the groyne reach in June (Figures 2D, E) and November (Figures 3D, E). Mid-channel habitat had a low density and richness in all reaches. Macroinvertebrate density and richness did not differ between the edge and mid-channel habitats for the channelization reach in June, but in November, both were significantly greater at the edge rather than in the mid-channel habitat.

Macroinvertebrate composition

In June, the first two axes of the DCA ordination accounted for most of the variation in the family data, with eigenvalues of 0.286 and 0.155 for axis 1 and 2, respectively. The total inertia (total variation in the data) was 1.035 and the first two axes explained 43% of this variation. The macroinvertebrate community in the groyne edge habitat overlapped the restored meander edge habitat, which was clearly separated from the channelization edge and mid-channel habitats in the three reaches (Figure 4). In comparison to the other habitats, samples from the restored meander edge habitat had lower scores on DCA axis 2. The trichopteran family Glossosomatidae had the lowest score on DCA axis 2, and more than 99% individuals of this family were *Padunia forcipata*.

In November, the first two axes of the DCA ordination accounted for most of the variation in the family data, with eigenvalues of 0.185 and 0.112 for axis 1 and 2, respectively. The total inertia was 0.679 and the first two axes explained 44% of this variation. The macroinvertebrate community in the groyne edge habitat overlapped the restored meander edge habitat, which was clearly separated from the channelization edge and mid-channel habitats in the three reaches (Figure 5). In contrast to June, the channelization edge habitat was separated from the other habitats.

DISCUSSION

Few macroinvertebrates were found in the mid-channel habitats in all reaches, and the composition of the macroinvertebrate community was different in the edge habitat of the restored meander in June and November. In large rivers, the shear velocity and the Shields entrainment function increases as the water depth increases (Rempel *et al.*, 2000). The streambed in the deeper parts of a river experiences high hydraulic stress, which may result in unstable sediment conditions that disturb macroinvertebrate habitats. In this study, shear stress was higher mid-channel than at the edge. This indicates the higher hydraulic stress in the mid-channel may explain the poor macroinvertebrate colonization in this habitat. Likewise, Rempel *et al.* (1999) reported that the total density and taxon richness of macroinvertebrates were high under low hydraulic stress and stable riverbed conditions. Our results suggest that the shallow marginal habitat is more important for the abundance and diversity of macroinvertebrates than the deep mid-channel habitat in a lowland river.

The total density and taxon richness of the edge habitats in the channelization reach were lower than the restored meander edge, and the macroinvertebrate composition was different between those habitats. Channelization can cause severe streambed erosion and instability (Williamson *et al.*, 1992; Brookes, 1994). Shear stress at the channelization edge was higher than at the restored meander and groyne edges in this study, suggesting that channelization of the Shibetsu River provided a harsh environment for benthic macroinvertebrates.

Groyne structures appear to play a role in habitat enhancement for the macroinvertebrate community. Edge habitat in the groyne reach had a lower shear stress and higher density and richness of macroinvertebrates than the channelization edge. The groynes in the straight channel may have stabilized the riverbed near the bank, creating favourable conditions for macroinvertebrate colonization. Although the total density and richness of the edge habitat in the groyne reach were lower than those in the restored meander reach, the macroinvertebrate composition was similar between both habitat types. These results demonstrate that placement

of groynes is an effective method for macroinvertebrate conservation in channelized lowland rivers. While a groyne is installed for bank protection and/or transportation, its structure and function are similar to those of a deflector, which is commonly used for stream and river restoration. Deflectors are designed to diversify water velocities and depths to enhance habitat complexity for fish and macroinvertebrates (Hey, 1994), and are often applied in combination with the placement of wedge dams, boulders and large woody debris (Downs and Thorne, 1998; Laasonen *et al.*, 1998). Despite their popular use for in-stream habitat enhancement, the effects on macroinvertebrate communities of deflectors alone, independent of other structures, are poorly known. In the groyne reach in our study, the mid-channel habitat had deep and fast currents, while the channel edge had shallow and slow currents. This contrasted with the channelization reach, in which physical variables were similar between the mid- and edge habitats. This suggests that groynes may have a potential role in creating habitat diversity through the modification of current conditions. However, as evidenced by the poor colonization of the mid-channel habitat in the groyne reach, favourable habitat conditions for macroinvertebrates were created only near the shoreline. The physical environment of the mid-channel habitat was severe, with deep and fast currents that inhibited macroinvertebrate colonization, due to the flow concentration caused by the groyne structure.

In this study, the total density and richness of macroinvertebrates were highest in the edge habitat of the restored meander reach. The edge habitat was shallow and had low hydraulic stress conditions in the restored meander reach. *Padunia forcipata*, which was an indicator species for the restored meander edge habitat in June, was mainly found on the shallow margins of the channel, where the current is slow (Kagaya and Nozaki, 1998). A natural meander has an asymmetrical cross section at its channel bend, with shallow and slow flow conditions near the inside of the meander. Nakano and Nakamura (in press) reported that in-stream habitat adjacent to the stream bank of a naturally meandering lowland river had higher riverbed stability and more abundant macroinvertebrate communities than did mid-channel habitats of the same reach.

In-stream habitat restoration by reconstruction of meanders could restore macroinvertebrate communities through the creation of edge habitat with stable substrate conditions near the shoreline. Although a huge amount of engineering work and corresponding costs are involved, reconstruction of meanders may be the most effective strategy for conservation of lotic macroinvertebrates in lowland rivers.

In a lowland river with a streambed of fine sediment, riverbed stability is an important factor that determines macroinvertebrate community structure. Naturally meandering rivers have a complex topography and diverse physical habitats including edge habitat, which has stable substrate conditions. Channelization work, by straightening natural meanders, eliminates the morphological and hydraulic diversity of meandering rivers and, in particular, destabilizes and deepens the riverbed. The results of our study indicate that channelized stream habitat exhibits a low density and richness of macroinvertebrates because its substrate condition is unstable. However, reaches restored by reconstruction of meanders and the placement of groynes can increase the total density and richness of macroinvertebrates because of the presence of edge habitat that has low hydraulic stress. Habitat restoration for macroinvertebrate communities using groynes appears to be less effective than by reconstruction of meanders. However, reconstruction of meanders may not be a feasible restoration measure because of social and economic constraints, such as implementation cost, land use and flood control. In particular, it is difficult to find room for meanders in restoration projects. Restoration of a meander in the lower segment of the Shibetsu River would require a setback of artificial dykes and the agreement of landowners. Habitat restoration using groyne structures could be an alternative strategy for conservation of lotic macroinvertebrates in a severely altered stream. This study suggests that the recovery of macroinvertebrate communities in channelized lowland rivers requires the implementation of restoration programmes that allow an increase in riverbed stability.

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Figure Legends

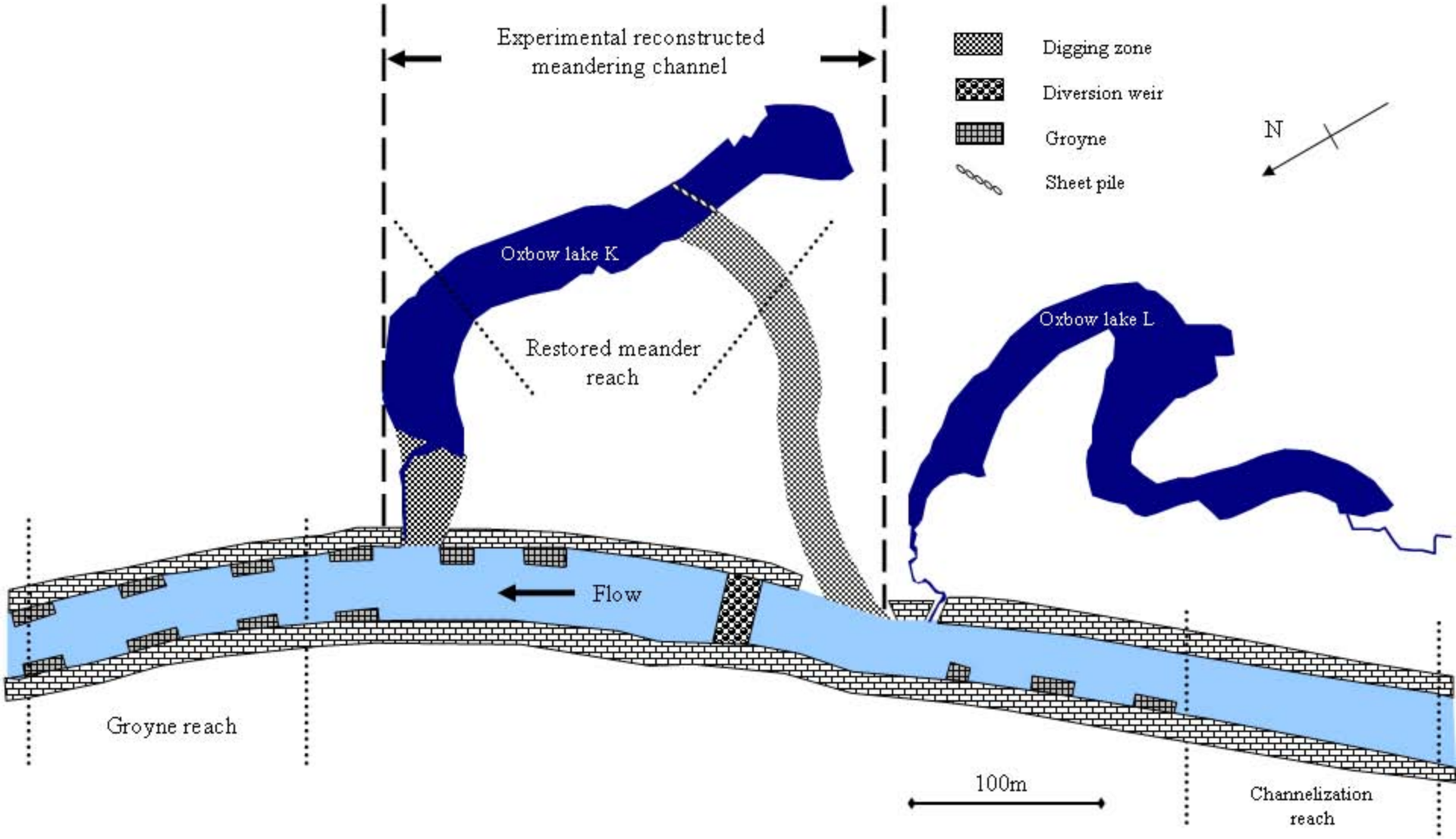
Figure 1. Location of the study reaches (channelization, restored meander, groyne) in the Shibetsu River, northern Japan.

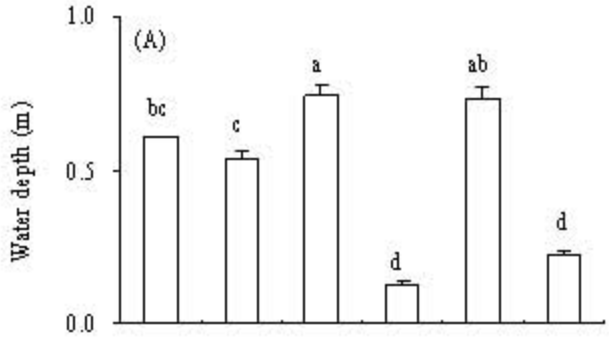
Figure 2. Physical environment (water depth (A), current velocity (B), shear stress (C)) and macroinvertebrate community structure (taxon richness (D) and total density (E)) in six habitat types in June 2003. Vertical bars indicate 1 S.E. Different letters denote significant differences (Holm test, $P < 0.05$).

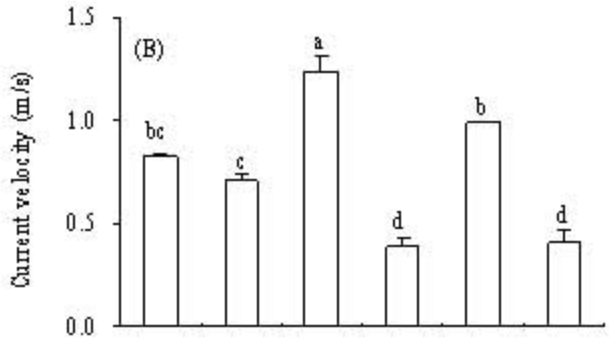
Figure 3. Physical environment (water depth (A), current velocity (B), shear stress (C)) and macroinvertebrate community structure (taxon richness (D) and total density (E)) of six habitats in November 2003. Vertical bars indicate 1 S.E. Different letters denote significant differences (Holm test, $P < 0.05$).

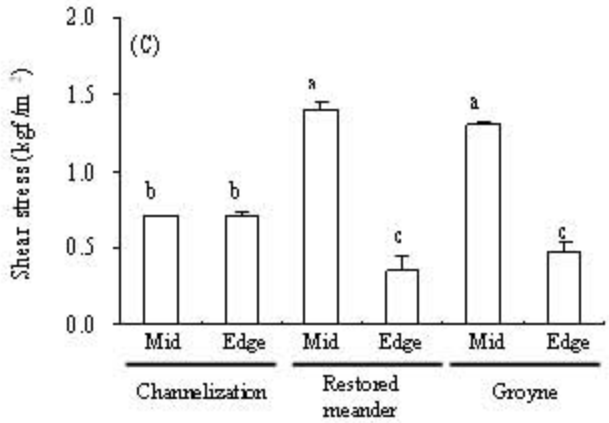
Figure 4. DCA ordination of macroinvertebrate communities from different habitat types in the Shibetsu River, June 2003. RM = restored meander mid, RE = restored meander edge, CM = channelization mid, CE = channelization edge, GM = groyne mid, GE = groyne edge. The location of each taxon is marked with •, and taxa codes are: ani = Anisogammaridae, bae = Baetidae, cer = Ceratopogonidae, chi = Chironomidae, chl = Chloroperlidae, eli = Elmidae, eph = Ephemerellidae, glo = Glossosomatidae, hep = Heptageniidae, iso = Isonychiidae, oli = Oligochaeta, per = Perlodidae and tip = Tipulidae.

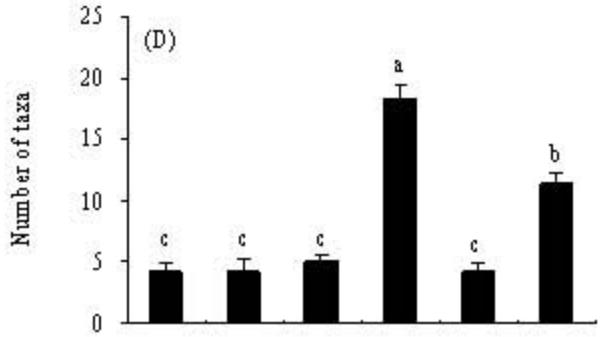
Figure 5. DCA ordination of macroinvertebrate communities from different habitat types in the Shibetsu River, November 2003. Abbreviations for habitat types are given in Figure 4. The location of each taxon is marked with •, and taxa codes are: cap = Capniidae, chi = Chironomidae, eli = Elmidae, eph = Ephemerellidae, glo = Glossosomatidae, hep = Heptageniidae, hyd = Hydropsychidae, nem = Nemouridae, oli = Oligochaeta, per = Perlodidae, rhy = Rhyacophilidae and tip = Tipulidae.

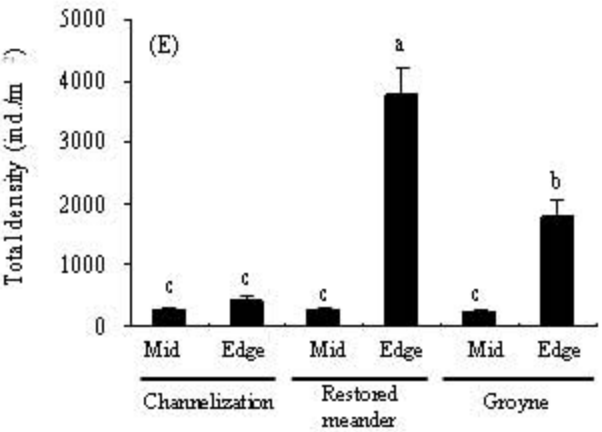

Experimental reconstructed meandering channel
Digging zone
Diversion weir
Groyne
Sheet pile
N
Oxbow lake K
Restored meander reach
Oxbow lake L
Flow
Groyne reach
100m
Channelization reach

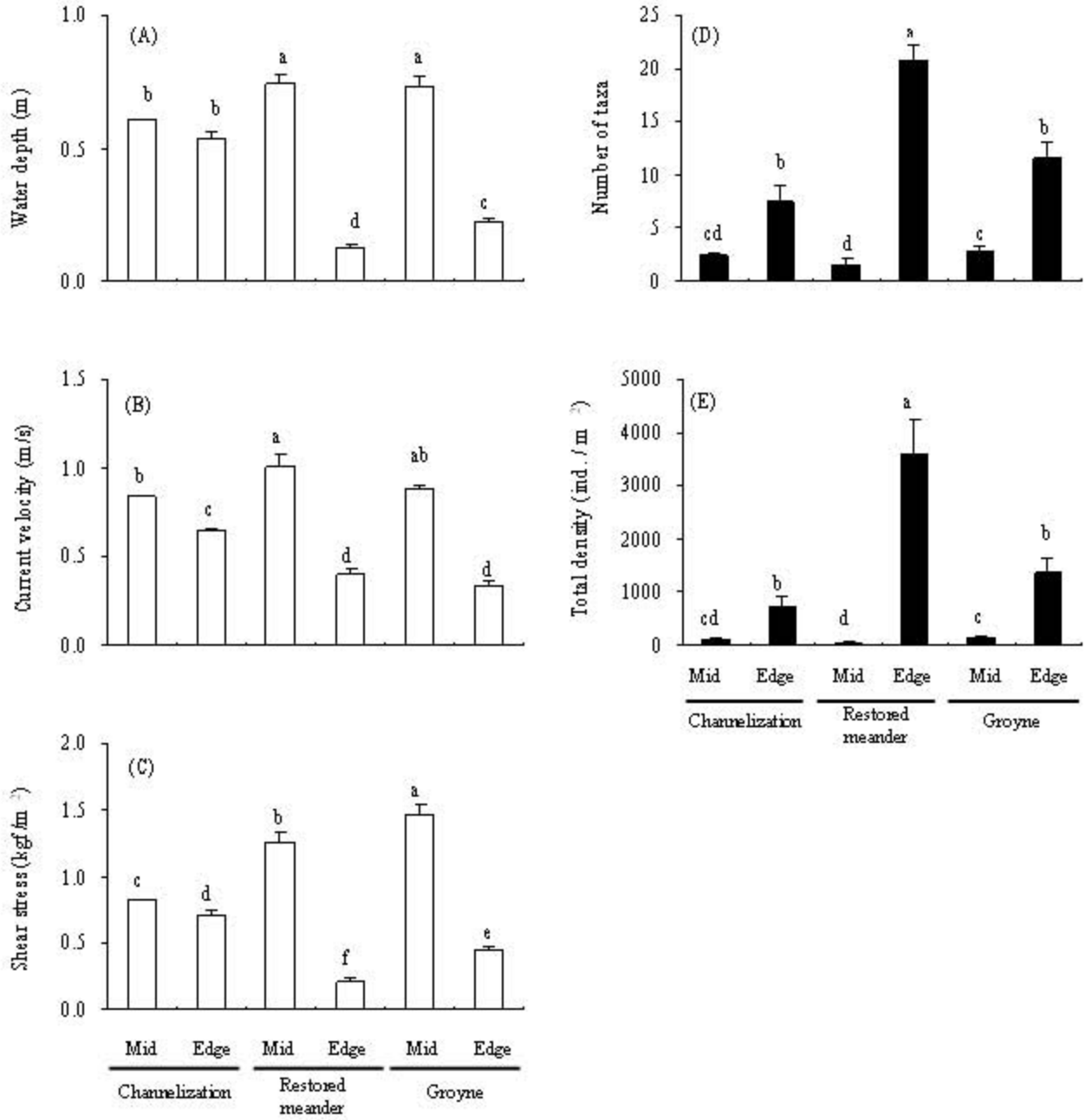

(A)
Water depth (m)
1.0
0.5
0.0
bc
c
a
d
ab
d

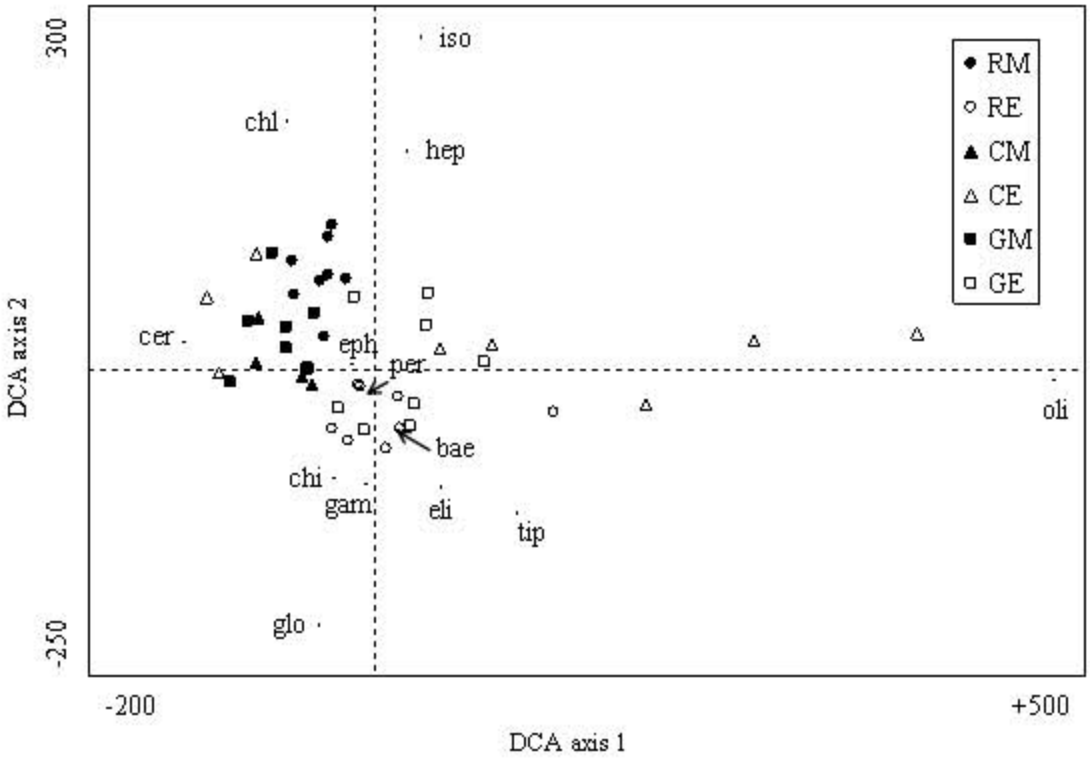

(B)
Current velocity (m/s)
1.5
1.0
0.5
0.0
bc
c
a
d
b
d


(C)
Shear stress (kgf/m²)
2.0
1.5
1.0
0.5
0.0
b
b
a
c
a
c
Mid
Edge
Mid
Edge
Mid
Edge
Channelization
Restored meander
Groyne


(D)
Number of taxa
25
20
15
10
5
0
c
c
c
a
c
b


(E)
Total density (ind./m²)
5000
4000
3000
2000
1000
0
c
c
c
a
c
b
Mid
Edge
Mid
Edge
Mid
Edge
Channelization
Restored meander
Groyne


(A)
Water depth (m)
1.0
0.5
0.0
b
b
a
d
a
c
(B)
Current velocity (m/s)
1.5
1.0
0.5
0.0
b
c
a
d
ab
d
(C)
Shear stress (kgf/m²)
2.0
1.5
1.0
0.5
0.0
c
d
b
f
a
e
Mid
Edge
Mid
Edge
Mid
Edge
Channelization
Restored meander
Groyne
(D)
Number of taxa
25
20
15
10
5
0
cd
b
d
a
c
b
(E)
Total density (ind. / m²)
5000
4000
3000
2000
1000
0
cd
b
d
a
c
b
Mid
Edge
Mid
Edge
Mid
Edge
Channelization
Restored meander
Groyne


300
-250
-200
+500
DCA axis 1
DCA axis 2
RM
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CM
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iso
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chi
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tip
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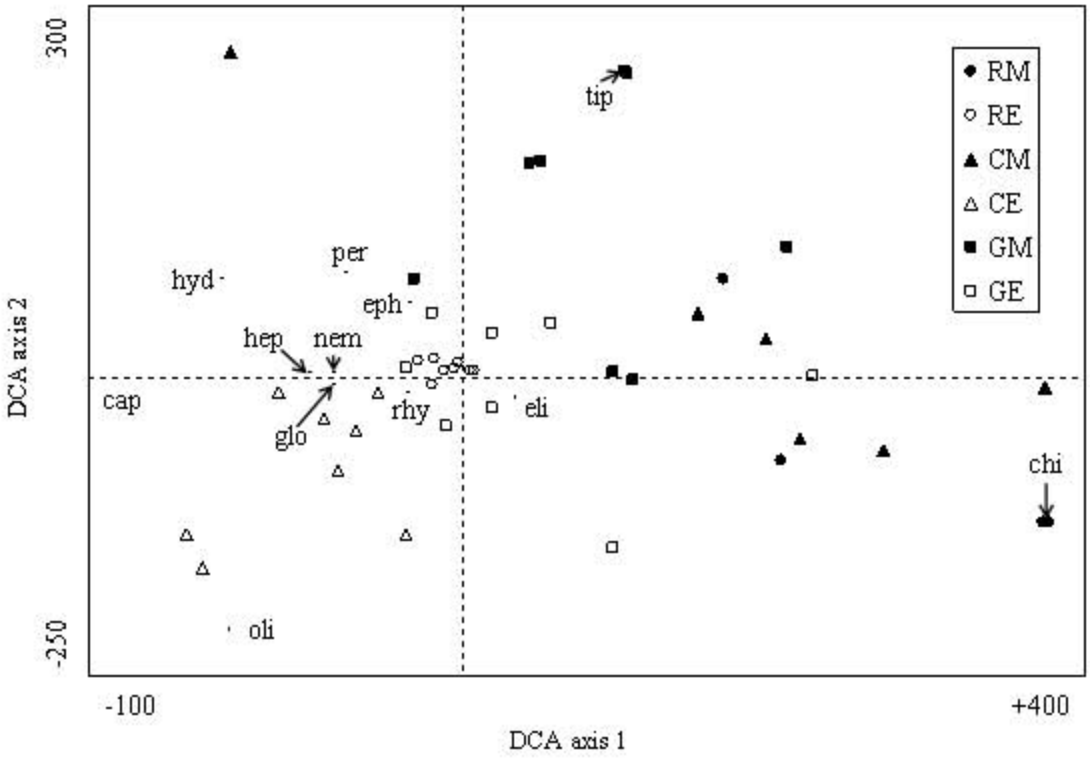
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DCA axis 1
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