Quantitative Assessment of River Environment by Focusing on Benthic Biota

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Abstract
River ecosystem is a fragile environment because it can be a primal receptor of wastewater from human society. However, there are few studies evaluating the factors which lead to the loss of biodiversity of river benthos from multiple dimensions. In this study, we try to clarify the interrelation among biodiversity, structure of river ecosystem, and water quality. Field research on benthic species (mainly aquatic insects) was carried out at 17 different sites in the Gunma prefecture in Japan. Sample collection was carried out twice at each station during March 2015 to May 2016 by a Beck-Tsuda β method. In total, we identified 5,141 benthos of 145 species. Biodiversity was calculated by Simpson's diversity index. Structure of river ecosystem was checked at each stations and principal component analysis was carried out for score matrix on structure of river ecosystem. Database of water quality was obtained from website of Gunma prefectural government and principal component analysis was carried out for data matrix on water quality. After that, structural equation modeling (SEM) was carried out. Values of Simpson's diversity index were defined as the objective variable, and scores of respective principal components were defined as explanation variables. As a result, increase in water pollution level causes negative effect to the biodiversity of benthos. On the other hand, increases in submerged plants and litter pack provide positive effects to the biodiversity. Therefore, the improvement of water quality and conservation of habitat will be the important aspects to establish the preferable management program of river environment.

Keywords: Biodiversity, River ecosystem, Structural equation modeling (SEM)

Introduction

Our life is supported by various kinds of ecological services from biodiversity such as resource supply, stabilization of the living environment, and a chance of recreation. Costanza et al. (1997) reported that the world's ecological services account for 33 trillion US dollars. Therefore, the conservation of biodiversity which provides ecological services is one of the important issues in recent environmental interests. However, recent extinction rate of species is estimated to be accelerated in 1,000 to 10,000 times of the natural situation in today's fast-changing environment. Island region originally has high biodiversity but most of them face a crisis of damage. Japan is one of the hot spots of biodiversity as with the other island countries (Myers 1988).

Several types of ecosystem such as forest, river, agricultural land, and ocean play prominent roles in preserving biodiversity. Among them, river ecosystem is fragile environment because it is a primal receptor of wastewater from human society. However, there are few studies evaluating the factors which lead to the loss of biodiversity of river benthos from multiple dimensions.

Katoh et al. (1995) evaluated the changes in benthic biota in the river by using multivariate analysis. This study shows that flow velocity and sediment characteristics are the important factors effecting species composition of aquatic invertebrates. They concluded that the diversity in channel morphology should be considered to conserve ecological community. Nakajima et al. (2007) showed that the physica1 structure of river environment had a positive influence on macroinvertebrate communities via the mode1 with multip1e indicators. In particular, the number of loose stones, depth, flow velocity, and distance from river bank has referred to the significant positive effects to the diversity of benthos. These studies provide important aspects for the conservation of river ecosystem. However, effects by diversity of vegetation and water contaminants were not discussed in detail.

In this study, we try to evaluate the factors which lead to the loss of biodiversity in river ecosystem. We focus on two factors. One is the structure of river ecosystem which dominates the habitat of benthos. The other one is water quality, because benthos have specific pollution tolerance by species (Noguchi et al. 1997). In order to conserve the biodiversity, it is essential to clarify the interrelation among these factors. This study is intended to establish the preferable management program of river environment by focusing on the interrelation among the biodiversity, structure of river ecosystem, and water quality.

Method

A. Monitoring stations

We set up seventeen monitoring stations of ten rivers in Gunma prefecture (see Fig. 1, Table 1). Gunma prefecture located in the northwest area of 100 km away from the central Tokyo. These rivers have important role as the reservoir suppling water resource to the Tokyo Metropolitan Area. Blue solid lines in Fig. 1 indicate the river flow, and red markers indicate the monitoring stations set upped. In case the river has long flow channel, we set up the stations in the upper and lower reaches. The Tone River (Station ID: TN (U), TU (L)) is the main river in this area. It runs from north area to southeast area. The Katashina River (KT (U), KT (L)) flows north area in

Gunma. There are five rivers flow west area in Gunma. From the north, the Agatsuma River (AG (U), AG (L)), the Karasu River (KR (U), KR (L)), the Usui River (US (U), US (L)), the Kabura River (KB (U), KB (L)), and the Kanna River (KN (U), KN (L)). In the east area, we focus on three rivers, The Ishida River (IS), the Watarase River (WT), and the Yada River (YD).

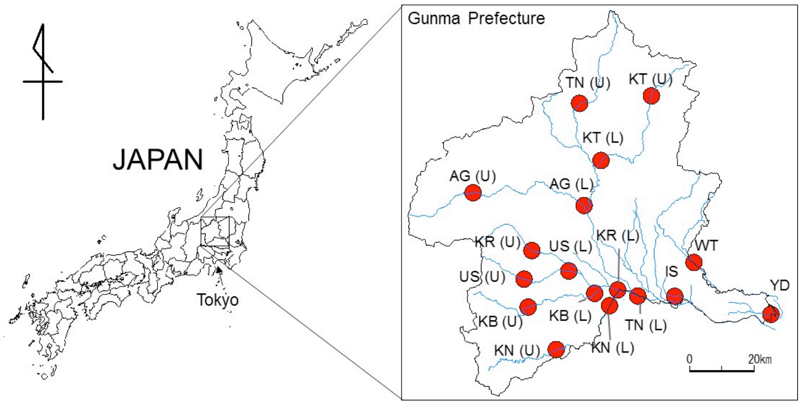


Fig. 1: Location of monitoring stations

Table 1 List of monitoring stations

River	Area	Station ID
Tone River	Upper	TN (U)
	Lower	TN (L)
Katashina River	Upper	KT (U)
	Lower	KT (L)
Agatsuma River	Upper	AG (U)
	Lower	AG (L)
Karasu River	Upper	KR (U)
	Lower	KR (L)
Usui River	Upper	US (U)
	Lower	US (L)
Kabura River	Upper	KB (U)
	Lower	KB (L)
Kanna River	Upper	KN (U)
	Lower	KN (L)
Ishida River	-	IS
Watarase River	-	WT
Yada River	-	YD

(U): Upper, (L): Lower

B. Collection of benthos

Sample collection of benthos was carried out twice at each station during March 2015 to May 2016 by a Beck-Tsuda β method. A Beck-Tsuda β method is a sampling method which enables to collect benthos from various points in the river ecosystem. Kick swipe and stirring are the main ways. In this study, sample collection was carried out in one hour by one parson. Collected benthos were fixed with 75% alcohol and identified species by using a microscope. We refer “Aquatic Insects of Japan: Manual with Keys and Illustrations (Kawai et al. 2005)” for identifying species. *Ephemeroptera*, *Plecoptera*, *Trichoptera*, and *Odonate* are the major species in Japan.

C. Evaluation of biodiversity

Diversity index enables quantitative evaluation on biodiversity, and is often used for environmental assessment (Peet 1974, Nakamura 2000). In this study, we used Simpson’s diversity index which is defined as the function indicates below (Simpson 1949). Here, S indicates the number of species. *Pi* indicates *ni /N,* where *ni* indicates the number of the *i* th species and *N* indicates total number of collected benthos. *D* measures the probability that randomly selected two individuals will belong to the same (function (1)). Therefore, diversity index can be defined as the reciprocal of *D* (function (2)).If many species are well balanced, the index tends to increase. On the contrary, if poor species are out of balance, the index tends to decrease.

$$D = \sum_{i=1}^{S} (P_i)^2 \quad \cdot \cdot \cdot (1)$$

$$\frac{1}{D} \quad \cdot \cdot \cdot (2)$$

D. Evaluation for structure of river ecosystem

We prepare the check list consists of “Flow”, “Structure”, and “Bottom sediment”. From the view point of “Flow”, the items of rapid, slow, and stagnate were specified. Rapid indicates the flow with waves. Stagnate indicates stopped or almost stopped flow. Slow indicates intermediate of rapid and stagnate. From the view point of “Structure”, the items of riffle, lateral pool, and deep pool were specified. Riffle indicates shallow area. Lateral pool indicates side area like a pond which was separated from the main flow. Deep pool indicates deep area. From the view point of “Bottom sediment”, the items of embedded stones, loose stones, gravels, mud, litter pack, moss mat, and submerges plants were specified. Two types of stones can be found. Embedded stones hold tight each other. Loose stones are generally on the other stones, and easy to move. Twenty sites were randomly selected in respective monitoring stations. We filled the check list by presence or absence. The score appeared from zero to 20 by each item.

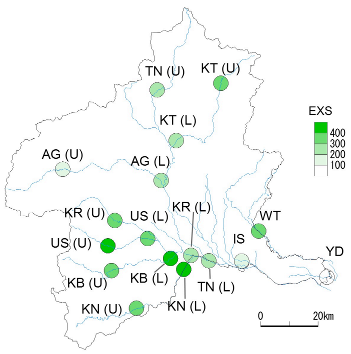
E. Evaluation of water quality

Database of water quality was obtained from website of Gunma prefectural government. In Japan, the water quality of the river is researched by Local government regularly, and disclosed as Database of Water Quality Survey of Public Water. We focus on dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), Total coliform, T-P, T-Zn, T-N, NO_3-N, NO_2-N, NH_3-N, and electrical conductivity (EC). These items are the indicators of the water pollution.

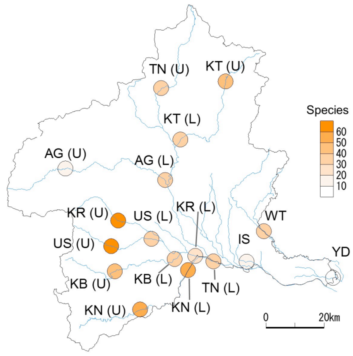
Result and discussion

A. Benthic biota

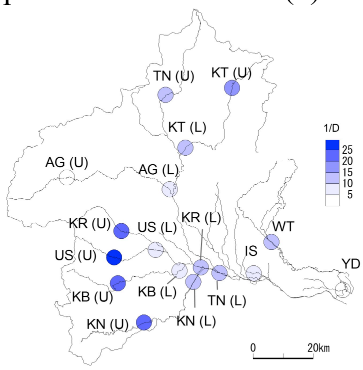
In total, we identified 5,141 benthos of 145 species. Except for AG (U), IS, and YD stations, large variety of benthos was generally observed in each station (see Fig.2 (a)). The result in number of benthos also showed similar distribution. Remarkably small number of benthos was observed at AG (U), IS, and YD stations (see Fig.2 (b)). From the viewpoint of Simpson’s diversity index, relatively high values were shown in the upper reaches of southwest basin (KR (U), US (U), KB (U), and KN (U)). On the other hand, notably low values were obtained at AG (U), IS, and YD stations (see Fig.2 (c)). Interrelation among the biodiversity, structure of river ecosystem, and water quality will be discussed below in detail.



(a) Number of species



(b) Number of benthos



(c) Simpson's diversity index

Fig. 2 Distribution of biological indices

B. Structure of river ecosystem

The score matrix characterized the difference in structure of river ecosystem among respective stations (see Table 2). Stations located in the upper reaches (e.g. TN (U) and KR (U)) can be characterized as rapid flow with loose stones on bottom. Stagnated sites were frequently observed at the stations located in the lower reaches (e.g. KN (L) and YD). Moss mat were typically shown on the bottom of slow flow at the stations located in the lower reaches (e.g. TN (L) and KR (L)).

Table 2 Score matrix on structure of river ecosystem

River	Area	Station ID	Flow			Structure			Bottom sediment						
			Rapid	Slow	Stagnate	Riffle	Lateral pool	Deep pool	Embedded stones	Loose stones	Gravels	Mud	Litter pack	Moss mat	Submerged plants
Tone River	Upper	TN (U)	10	8	2	18	2	0	7	15	0	0	2	0	0
	Lower	TN (L)	0	11	9	11	9	0	17	0	0	3	0	17	0
Katashina River	Upper	KT (U)	7	7	6	14	6	0	10	11	0	0	1	0	2
	Lower	KT (L)	7	8	5	15	5	0	7	13	1	0	0	6	4
Agatsuma River	Upper	AG (U)	2	6	12	8	5	7	11	6	0	5	0	0	0
	Lower	AG (L)	6	9	5	15	5	0	7	13	0	2	0	0	2
Karasu River	Upper	KR (U)	8	6	6	14	6	0	7	11	0	1	2	0	2
	Lower	KR (L)	0	16	4	16	4	0	17	10	0	0	0	20	0
Usui River	Upper	US (U)	5	12	3	17	0	3	11	7	0	2	0	2	5
	Lower	US (L)	4	8	8	12	8	0	7	10	1	2	0	15	2
Kabura River	Upper	KB (U)	5	13	2	18	2	0	15	5	2	1	1	17	3
	Lower	KB (L)	7	10	3	17	3	0	8	9	1	0	0	8	4
Kanna River	Upper	KN (U)	6	7	7	13	3	4	6	10	2	0	4	0	0
	Lower	KN (L)	0	0	20	0	5	15	10	3	4	0	3	0	3
Ishida River	-	IS	4	11	5	15	0	5	7	5	3	4	0	0	4
Watarase River	-	WT	6	7	7	13	7	0	6	11	0	2	0	11	4
Yada River	-	YD	0	0	20	0	0	20	14	5	2	6	0	14	0

In order to elucidate the major factors of river ecosystem, a principal component analysis was carried out to the score matrix obtained. As a result, structure of river ecosystem was aggregated into four components (see Table 3). Respective components were interpreted as follows.

● 1st component: Water stagnation (Stagnate (+), Deep pool (+), Rapid (-), Riffle (-)) .
● 2nd component: Embedded stones with moss mat (Embedded stones (+), Moss mat (+), Rapid (-). Litter pack (-)).
● 3rd component: Submerged plants (Submerged plants (+), Gravels (+), Lateral pool (-)).
● 4th component: Litter pack (Litter pack (+), Mud (-)).

Table 3 Principal component profile of river ecosystem

	Component			
	1	2	3	4
Rapid	-0.80	-0.49	0.01	-0.13
Slow	-0.64	0.64	0.25	0.23
Stagnate	0.94	-0.20	-0.20	-0.10
Riffle	-0.94	0.20	0.20	0.10
Lateral pool	-0.10	0.17	-0.77	-0.07
Deep pool	0.92	-0.26	0.18	-0.05
Embeded stones	0.40	0.78	-0.01	0.32
Loose stones	-0.71	-0.38	-0.26	-0.20
Gravels	0.56	-0.38	0.47	0.41
Mud	0.59	0.28	0.17	-0.62
Litter pack	0.07	-0.68	-0.23	0.64
Moss mat	0.14	0.80	-0.07	0.18
Submerged plants	-0.30	-0.17	0.65	-0.17

C. Water quality

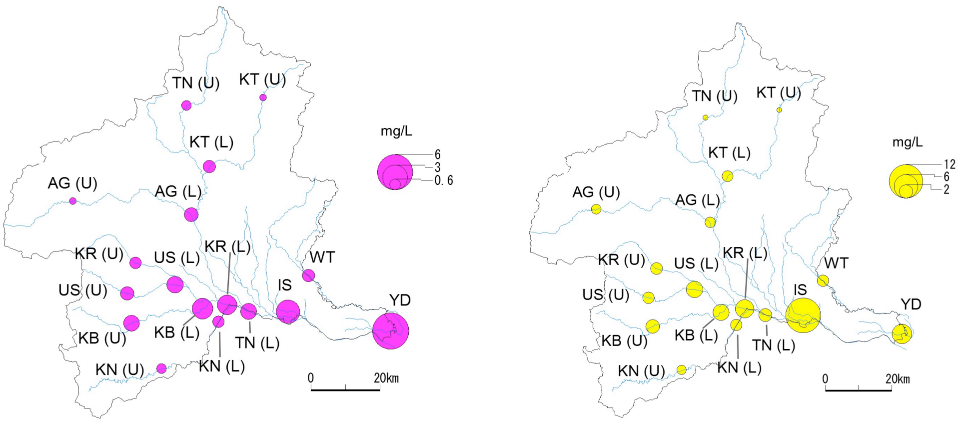
The data matrix characterized the difference in water quality among respective stations (see Table 4). Stations with low diversity index (AG (U), IS, and YD) had unique characteristics in water quality. AG (U) station was situated in relatively low pH condition. It might be due to the contamination of runoff from volcanic hot springs. High concentration of BOD (surrogate of organic pollution) was observed at the lowest YD station (see Fig. 3 (a)) due to a large population who has insufficient sewage treatment system. Remarkably high concentration of T-N (causing an eutrophication) was observed at IS station (see Fig. 3 (b)) located in the extensive farming zone.

Table 4 Data matrix on water quality

River	Area	Station ID	Temperature (ºC)	Water temperature (ºC)	pH	DO (mg/L)	BOD (mg/L)	COD (mg/L)	SS (mg/L)
Tone River	Upper	TN (U)	15.7	9.8	7.09	11.0	0.5	2.1	3.0
	Lower	TN (L)	17.8	12.8	7.40	12.0	1.3	3.0	9.5
Katashina River	Upper	KT (U)	14.8	8.5	7.40	11.0	0.3	1.6	1.0
	Lower	KT (L)	16.5	11.1	7.62	12.0	0.8	2.0	4.0
Agatsuma River	Upper	AG (U)	14.8	10.8	5.18	12.0	0.3	2.2	21.0
	Lower	AG (L)	17.3	14.6	7.41	11.0	1.0	2.5	13.0
Karasu River	Upper	KR (U)	16.2	13.1	7.69	11.0	0.7	1.6	3.3
	Lower	KR (L)	16.8	15.3	7.61	10.3	1.9	4.2	9.0
Usui River	Upper	US (U)	18.4	13.1	7.97	12.0	0.9	2.6	3.0
	Lower	US (L)	17.5	15.1	8.14	12.0	1.4	3.6	4.0
Kabura River	Upper	KB (U)	17.9	14.1	8.24	13.0	1.3	2.9	2.0
	Lower	KB (L)	20.0	16.2	8.33	13.0	2.1	4.7	9.0
Kanna River	Upper	KN (U)	18.2	12.6	8.14	12.0	0.5	1.6	2.0
	Lower	KN (L)	13.9	13.5	7.89	11.0	0.7	2.1	3.0
Ishida River	-	IS	20.2	18.5	7.66	10.0	2.7	5.4	14.3
Watarase River	-	WT	18.9	14.9	7.63	12.0	0.8	2.5	3.0
Yada River	-	YD	19.3	17.4	7.66	9.3	6.4	11.0	22.0

Table 4 Data matrix on water quality (continue)

River	Area	Station ID	Total coriform (MPN/100ml)	T-P (mg/L)	T-Zn (mg/L)	T-N (mg/L)	NO3-N (mg/L)	NO2-N (mg/L)	NH3-N (mg/L)	Electric conductivity (μS/cm)
Tone River	Upper	TN (U)	540	0.01	0.00	0.33	0.23	0.01	0.01	42.8
	Lower	TN (L)	7225	0.09	0.01	1.90	1.50	0.03	0.08	177.5
Katashina River	Upper	KT (U)	138	0.01	0.00	0.30	0.26	0.01	0.01	58.8
	Lower	KT (L)	1625	0.03	0.00	1.38	1.25	0.01	0.02	110.0
Agatsuma River	Upper	AG (U)	33	0.05	0.01	1.10	1.00	0.01	0.05	230.0
	Lower	AG (L)	3300	0.06	0.01	1.28	1.30	0.01	0.04	240.0
Karasu River	Upper	KR (U)	4900	0.02	0.00	1.60	1.50	0.01	0.04	120.0
	Lower	KR (L)	22000	0.16	0.02	3.70	3.10	0.12	0.28	280.0
Usui River	Upper	US (U)	4275	0.03	0.00	1.50	1.40	0.01	0.02	180.0
	Lower	US (L)	33000	0.08	0.09	3.00	2.60	0.05	0.11	402.5
Kabura River	Upper	KB (U)	8250	0.03	0.00	2.10	2.20	0.01	0.06	365.0
	Lower	KB (L)	3300	0.10	0.00	2.90	2.70	0.05	0.08	360.0
Kanna River	Upper	KN (U)	455	0.01	0.00	1.00	1.00	0.01	0.01	180.0
	Lower	KN (L)	5425	0.03	0.00	1.50	1.48	0.01	0.01	220.0
Ishida River	-	IS	132500	0.28	0.02	13.00	10.25	0.18	0.27	552.5
Watarase River	-	WT	2550	0.08	0.01	1.50	1.30	0.01	0.02	120.0
Yada River	-	YD	45500	0.48	0.02	4.18	2.95	0.16	0.94	730.0



(a) BOD (b) T-N

Fig. 3 Concentration distribution of water contaminants.

In order to elucidate the major factors of water contamination, a principal component analysis was carried out to the data matrix of water quality. As a result, water quality was aggregated into two components (see Table 5). Respective components were interpreted as follows.

- 1st component: Water pollution level (BOD (+), T-P (+), T-N (+), EC (+), DO (-)).
- 2nd component: Type of contaminants (T-N (+), BOD (-)).

Table 5 Principal component profile of water quality

	Component 1	Component 2
DO	-0.65	0.12
BOD	0.90	-0.36
COD	0.91	-0.36
SS	0.69	-0.29
Total coliform	0.82	0.55
T-P	0.96	-0.22
T-Zn	0.35	0.19
T-N	0.79	0.59
NO_3-N	0.76	0.63
NO_2-N	0.96	0.13
NH_3-N	0.88	-0.44
Electric conductivity	0.91	-0.06

D. Interrelation among the biodiversity, structure of river ecosystem, and water quality

To identify the interrelation among the biodiversity, structure of river ecosystem, and water quality, structural equation modeling (SEM) was carried out. Values of Simpson's diversity index were defined as the objective variable, and scores of respective principal components were defined as explanation variables (see Table 6). It is known that well fitted model has RMSEA with 0.08 or less and the lower in AIC.

Table 6 Variables for structural equation modeling (SEM)

			Biodiversity	Structure of river ecosystem				Water quality	
River	Area	Station ID	Simpson's diversity index	Water stagnation	Embedded stones with moss mat	Submerged plants	Litter pack	Water pollution level	Type of contaminants (Nitrogen or Organics)
Tone River	Upper	TN (U)	14.02	-1.12	-0.97	-0.59	0.28	-0.71	-0.23
	Lower	TN (L)	13.76	0.66	2.04	-1.2	0.44	-0.2	-0.18
Katashina River	Upper	KT (U)	15.91	-0.57	-0.41	-0.8	-0.05	-0.78	-0.11
	Lower	KT (L)	11.97	-0.76	-0.39	0.18	-0.43	-0.6	0.04
Agatsuma River	Upper	AG (U)	2.25	0.89	0.27	-0.68	-1.4	-0.33	-0.49
	Lower	AG (L)	9.39	-0.66	-0.23	-0.34	-1.08	-0.24	-0.4
Karasu River	Upper	KR (U)	23.51	-0.58	-0.86	-0.89	-0.19	-0.53	0.1
	Lower	KR (L)	10.6	-0.31	1.96	-0.46	1.34	0.65	-0.05
Usui River	Upper	US (U)	27.74	-0.52	0.33	1.75	-0.45	-0.51	0.02
	Lower	US (L)	6.92	-0.11	0.35	-0.8	-0.54	0.28	0.82
Kabura River	Upper	KB (U)	20.67	-0.33	1.01	1.23	1.58	-0.37	0.22
	Lower	KB (L)	9.91	-0.78	-0.01	0.85	0.03	0.09	-0.17
Kanna River	Upper	KN (U)	23.56	-0.08	-1.45	-0.53	1.64	-0.69	0.07
	Lower	KN (L)	11.59	2.03	-1.56	0	1.49	-0.45	0.06
Ishida River	-	IS	5.14	0.16	-0.21	2.35	-0.43	2.24	2.85
Watarase River	-	WT	11.02	-0.46	-0.02	-0.39	-1.2	-0.51	0
Yada River	-	YD	4.22	2.53	0.15	0.33	-1.04	2.67	-2.57

As a result of SEM (see Fig. 4), the biodiversity is dominated by structure of river ecosystem and water quality. According to the standard partial regression coefficients indicated on the path, increase in water pollution level causes negative effect ($p<0.05$) to the biodiversity of benthos. On the other hand, increases in submerged plants and litter pack provide positive effects ($p<0.10$ and $p<0.05$, respectively) to the biodiversity. Watanabe et al. (2006) suggested that removal of the natural reed riverbed has negative effect to the biological indices. Therefore, the improvement of water quality and conservation of habitat will be the important aspects to establish the preferable management program of river environment.

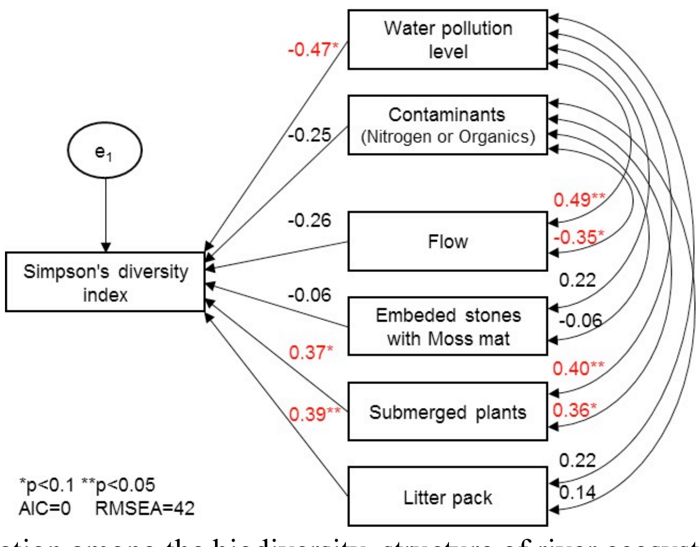


Fig. 4 Interrelation among the biodiversity, structure of river ecosystem, and water quality

Conclusion

Biodiversity of river benthos is dominated by various elements of the ecosystem. To establish the preferable management program of river environment, we need to understand the interrelation among the biodiversity, structure of river ecosystem, and water quality. In terms of the conservation of biodiversity in the river ecosystem, following two efforts will be needed. One is the improvement of the water quality particularly in the lower reaches of the research area. The other one is the conservation of habitat containing submerged plants and litter pack in abundance. To achieve a symbiosis with nature, we hope for evidence-based policy and decision making.

Acknowledgements

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