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Integrated assessment of river health based on water quality, aquatic life and physical habitat

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Abstract

The health conditions of Liao River were assessed using 25 sampling sites in April 2005, with water quality index, biotic index and physical habitat quality index. Based on the method of cluster analysis (CA) for water quality indices, it revealed that heavily polluted sites of Liao River are located at estuary and mainstream. The aquatic species surveyed were attached algae and benthic invertebrates. The result showed that the diversity and biomass of attached algae and benthic index of biotic integrity (B-IBI) were degrading as the chemical and physical quality of water bodies deteriorating. Physiochemical parameters, BOD_5, COD_{Cr}, TN, TP, NH_3-N, DO, petroleum hydrocarbon and conductivity, were statistically analyzed with principal component analysis and correlation analysis. The statistical results were incorporated into the integrated assessing water quality index, combining fecal coliform count, attached algae diversity, B-IBI and physical habitat quality score. A comprehensive integrated assessing system of river ecological health was established. Based on the systimetic assessment, the assessed sites are categorized into 9 “healthy” and “sub-healthy” sites and 8 “sub-sick” and “sick” sites.

Key words: Liao River; river health assessment; benthic-index of biotic integrity; water quality; physical habitat conditions

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Introduction

As the important channel of substance cycle in biosphere, a whole river eco-system should have the functions of providing the food and water for living, industry and agriculture, amusement, shipping and commerce. Over the past century, it have been being seriously destroyed by various human activities including contaminant discharge, damming, solidifying riverside, destroying vegetation in the riparian zone and etc., resulting in deterioration of water environment, degradation of biological communities and riverbed atrophying. Therefore, the restoration and maintenance of “healthy” river ecosystems have become important objective of river management (Norris and Thoms, 1999).

For the assessment of river health, the basis of river management, using biologic index to assess river eco-system has become the mainstream method of studying the river health, because the physiological function, species abundance, population density, and community construction and function of aquatic life are impacted by all the changes of water ecosystem. We can make judgments of river health according to its biotic diversity and quantity through the bio-assay. Many species of aquatic lives such as fish (Harris and Silveira, 1999; Belpaire *et al*., 2000), algae (Stevenson and Smol, 2003), plankton (Reynolds, 2003) and benthic macroinvertebrates (Yoon *et al*., 1992; Brain *et al*., 2002; Silvera *et al*., 2005) are common biologic indicators of water pollution in stream, which have been used in typical assessment indices including benthic index of biotic integrity (B-IBI) (Butcher *et al*., 2003; Davis *et al*., 2003; Wang *et al*., 2005; Zhang *et al*., 2007) and O/E index (O: the number of taxa collected at the test site; E: the number of taxa expected to occur). For example, there are RIVPACS (River Invertebrate Prediction and Classification System) (Wright *et al*., 2000) and AUSRIVAS (Australian River Assessment System) (Smith *et al*., 1999; Hart *et al*., 2001).

However, because the river is a complex eco-system, using single factor such as biologic index to assess river health is not able to completely reflect a river regime. Particularly, when assessing method only using one species such as RIVPACS and AUSRIVAS and the species used is not sensitive to the external disturbance. Moreover, it has been proved that IBI system may not be regarded as the only factor impacting the river environment (An *et al*., 2002). For example, being the living space of instream aquatic organisms, physical habitat describes the ecomorphological appearance of the river. If it has more nature structure, it will gain more ecological value

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(Maddock, 1999; Kamp *et al*., 2004). Based on this kind of cognition, many integrated assessing index systems, such as IBI (index of biotic integrity) (Karr, 1981), RCE (riparian, channel environment inventory) (Petersen, 1992), ISC (index of stream condition) (Ladson *et al*., 1999), RHP (the river health programme) (Roux, 2000), were founded by collecting extensive data. The advantages of an integrated assessment method based on multi-index are that the character of river eco-system can be generally reflected under the disturbance from human activities and it is helpful to reveal the inner relationships among different indices. However, because of different ecosystem structures and functions resulting from land use change, it is necessary to find a proper multi-metrics system to assess river health according to the characters of a river basin.

In this study, 24 indices on water quality, biology and physical habitat were analyzed using statistic methods to set an integrated assessing index system of river health. In these indices, water quality indices reflect the degree of river pollution and the stress onto water eco-system. Biological indices include hygienic indices reflecting the risk of human health, attached algae indices responding rapidly to short-term environment changes, and benthic invertebrate providing more information of the environment change in specifically river reach habitat. At last, the physical habitat quality index was used, of which the alternation is one of five major factors from human activities (Karr *et al*., 1986; Karr, 1991). In analyzing and assessing process for each index, we tried to answer the three following questions. (1) What relationships occur among the water quality, biology and physical habitat? (2) Is the individual index able to completely characterize river health? (3) Can we use multi-metric system to assess the river health for Liao River Basin?

1 Materials and methods

1.1 Study area and sampling sites

The Liao River Basin is located in the northeast of China (38°43′–45°10′N, 116°30′–125°47′E), which is markedly influenced by temperate and warm temperate continental climate (Fig. 1). There are two main rivers in Liao River Basin, the east one is the Daliao River, which estuary is located at Yingkou City, and the other one is the Liao River, which estuary is located at Panjin City. During April 23–30, 2005, samples were collected at 25 sites. Of them, eight sampling sites including PJ2, SY1, PJ1, YK1, AS1, SY2, TL6, and LR1, are located in the agricultural and urban area, and the other 17 sites are located in the vegetation area. For all sites, the conditions of physical habitat, water quality, macroinvertebrate and attached algae were surveyed following different methods and standards.

1.2 Water quality index, biotic index, and physical habitat index

The water quality analyses include chemical and physical analysis, consisting of twenty parameters. Chemical parameters include the dissolved oxygen (DO), chemical oxygen demand (COD_{Cr}), permanganate index (COD_{Mn}), five-day biological oxygen demand (BOD_5), petroleum hydrocarbon, volatile phenols, sulfide, lead, mercury, cadmium, total nitrogen (TN), total phosphorous (TP), ammonia-nitrogen (NH_4^+-N), nitrate-nitrogen (NO_3^--N), and nitrite-nitrogen (NO_2^--N). Physical parameters include pH value, suspended solids (SS), and conductivity. In these parameters, DO, pH and conductivity were measured at field using portable instrument, and the remaining were determined in laboratory according to Monitoring and Analysis Methods for Water and Wastewater (SEPA, 2002). In order to discover the relationship between water quality and biotic parameters easily, the comprehensive pollution index (CPI) was used in this study (Eq. (1)).

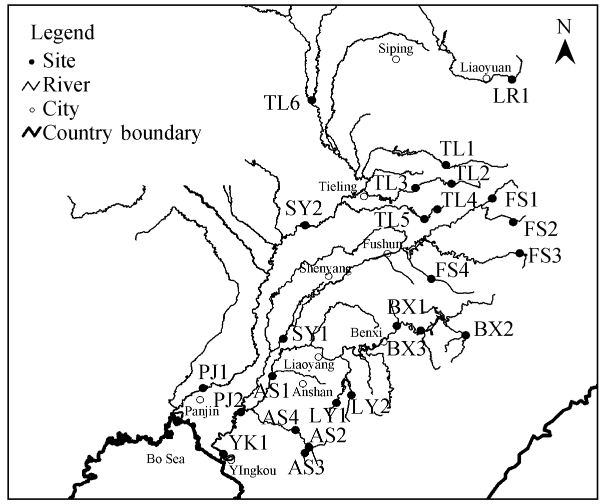

Fig. 1 Map of Liao River and sampling sites.

$$P_j = \sum_{i=1}^{n} \frac{C_{ji}}{C_{si}} \quad (1)$$

where, P_j is the value of CPI at j site, C_{ji} is the value of i parameter at j site including BOD_5, volatile phenols, NH_3-N, TP, COD_{Cr}, petroleum hydrocarbon, mercury, and C_{si} is the category III value of i parameter. The higher CPI, the more serious water pollution is.

Biotic parameters consist of three parts, hygienic parameters, attached algae and benthic of biotic integrity index. Hygienic parameter only includes fecal coliform and total bacterial. The sample collection, preservation, and analysis are conducted following Monitoring and Analysis Methods for Water and Wastewater.

Attached algae diversity index (Shannon-Weaver diversity index) and biomass index were used in this study based on the qualitative and quantitative determinations. In order to reflect water quality differences among streams, single habitat sampling approach was used. The attached algae on the natural substrates including cobble, silt and gravel, was sampled three times for living observation and restoration and preserved with 1% Lugol's solution at field. The bioassay process was strictly followed the procedures of rapid bioassessment protocols (RBPs) of USA (Barbour *et al*., 1999).

The collection of benthic invertebrate samples was guided by RBPs. According to the assembling method of

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IBI in USA (Barbour *et al*., 1996, 1999), twenty metrics were selected as the B-IBI candidate metrics. Based on the analysis of the range of index value distribution, Pearson correlation and judgment ability, six biological metrics are selected to establish B-IBI, which are total number of taxa, EPT taxa, three dominant taxa individual relative abundance, intolerant taxa individual relative abundance, clingers individual relative abundance, and chironomidae taxa (Table 1). Total number of taxa, EPT taxa and chironomidae taxa indicate community abundance, and three dominant taxa individual relative abundance reflects the proportion of individual amount, and intolerant taxa individual relative abundance is the indicator of tolerance towards water pollution, and clingers individual relative abundance indicates the quality of micro habitat.

In this study, the habitat assessment index system was developed based on modified Barbour's system (Barbour *et al*., 1999) considering the characters of river ecosystem in northern China. This system consists of ten parameters, including substrate, habitat complexity, velocity-depth combination, bank stability, bank conservation, vegetation cover, vegetation diversity, intensity of human activities, water cognition and riverside land use. Every parameter was divided into four different levels as optimal (score 20–16), sub-optimal (15–11), marginal (10–6), and poor (5–1) condition. The integrated habitat assessment index (I) was obtained as the sum of ten parameters scores.

Table 1 Six metrics score calculation by ratio scoring method

Metric	Score formula
Total number of taxa (A)	A/14
EPT taxa (B)	B/6
Three dominant taxa individual relative abundance (F)	(0.86–F)/(0.86–0.32)
Intolerant taxa individual relative abundance (H)	H/0.79
Clingers individual relative abundance (G)	G/0.43
Chironomidae taxa (I)	I/9

1.3 Integrated assessment method

The principal component analysis (PCA) was employed in this study to discriminate the main water quality factors of river health regime. In order to interpret the principal components easily, the maximum variance rotation method was used to discriminate the factors which have larger load values. When the principal factors were selected, the only factor would be determined in two factors which have high correlation based on the correlation analysis. Through the steps above, we will determine some parameters to construct the river health index system.

After river health index system established, each component value of index was calculated and accumulated to generate the river health assessment score (RH) according to Eq. (2).

$$RH = \sum_{i=1}^{n} (EH_i \times W_i) \quad (2)$$

where, EH_i is the value of the ith assessing index; W_i is the weight value of the ith assessing index. The index whose value decreases as the increase of the human disturbance was conversed according to Eq. (3), and oppositely, the other indices were divided by the value of water quality standards of III class (Eq.(4)).

$$EH = \frac{EH_{max} - EH_{fact}}{EH_{max} - EH_{III}} \quad (3)$$

$$EH = \frac{EH_{fact}}{EH_{III}} \quad (4)$$

where, EH_{max} is the maximum of the index; EH_{fact} is the actual value of the index; EH_{III} is the category III value of the index. The weight value, W_i, is determined by the PCA method. In addition, cluster analysis (CA) was used to obtain the spatial distribution of water quality and physical habitat quality, where the Ward's amalgamation method and squared Euclidean distances measure method were used.

The statistic analyses in this study were conducted in SPSS 13.0 system. The CA was executed in Statistica 6.0 system.

2 Results and discussion

2.1 Water quality condition

It is easy to identify the main pollutants, such as BOD_5, COD_{Mn}, COD_{Cr}, NH_4^+-N, TP, and petroleum. In some sites, the water quality were even worse than the criteria of the poorest category V according to Surface Water Quality Norm (GB3838-2002) of China (Table 2), which can only be used for agriculture and landscape. Except COD_{Mn}, the highest values were almost at the same site (SY1), which is located at the downstream of Shenyang City, a heavily industrial polluted area. Especially for DO value of SY1, it is so low (3.1mg/L) that fish can not live in the water body. There is a little change on the concentrations of volatile phenol, sulfide, Cd, Hg, and Pb, which are almost under the category I standard, safe to aquatic life and human health.

By using CA method as only chemical index with standardized data, all sites are grouped in three classes at $(D_{link}/D_{max})\times100 < 55$, where D_{link}/D_{max} represents the quotient of the linkage distance for a particular case divided by the maximum distance (Fig. 2). SY1 is the independent class with the maximum on organic and trophic indices beyond the standards of category V compared to the other sites. LR1, YK1, SY2, TL6, AS1, PJ1 and PJ2 were grouped into the second class with the values of organic and trophic pollution indices reaching to or exceeding the category IV standard and they are all located at the mainstream of Liao River except TL6, where the water and soil loss is very serious. The other sites, mainly located at tributaries of Liao River, are grouped into the third class with relatively light pollution.

In order to select right parameters to form the integrated assessing index system of river health, PCA and correlation analysis were performed using raw data. Before the PCA, the Kaiser-Meyer-Olkin test and Bartlett's of Sphericity test were performed on the parameter correlation matrix

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Table 2 Observation of chemical and hygienic indices at all sites of Liao River Basin (mg/L)

Site	BOD_5	COD_{Mn}	DO	Volatile phenol	NH_4^+-N	Sulfide	TN	TP	Conductivity (μS/cm)
LR1	10.1	17.8	9.3	0.002	0.297	0.002	4.68	0.586	110
FS1	1	2.59	12.9	0.001	0.025	0.002	3.74	0.068	200
FS2	1	2.37	11.8	0.001	0.025	0.002	0.89	0.056	90
FS3	1	2.47	11.5	0.001	0.025	0.002	2.44	0.047	158
FS4	1	1.61	12.3	0.001	0.025	0.002	1.92	0.043	110
TL1	1	2	11.8	0.001	0.78	0.002	2.38	0.01	202
TL2	1	3	12.6	0.001	0.81	0.002	2.58	0.03	337
TL3	1	2.1	12.3	0.001	0.9	0.002	2.42	0.03	358
TL4	1	2.4	12	0.001	0.9	0.002	2.21	0.02	149
TL5	1	2.1	10.4	0.001	0.87	0.002	2.28	0.07	188
TL6	5	13.7	11.4	0.014	8.857	0.002	10.4	0.49	532
SY1	30	15.1	3.1	0.045	26.9	0.027	28.3	1.65	850
SY2	13	26.3	5.3	0.01	4.95	0.009	8.51	0.26	600
BX1	1.8	2.24	7.7	0.001	0.38	0.003	1.62	0.005	193
BX2	0.9	1.9	11.8	0.001	0.025	0.003	1.37	0.005	68
BX3	1.8	2.7	11.6	0.001	0.025	0.003	1.103	0.005	193
AS1	3.83	10.32	8.02	0.004	4.043	0.006	8.21	0.277	820
AS2	0.891	1.64	10.8	0.001	0.025	0.002	2.93	0.005	354
AS3	0.33	1.8	10.9	0.001	0.025	0.002	2.38	0.005	368
AS4	0.218	2.05	11	0.001	0.159	0.002	3.58	0.005	353
PJ1	9.28	13	5.49	0.007	6.513	0.042	7.8	0.291	740
PJ2	6.27	12	3.41	0.007	13.393	0.047	16.01	0.375	1073
YK1	4.33	12.8	7.03	0.001	17.128	0.002	19.37	0.14	6100
LY1	1	1.69	9.6	0.001	0.02	0.003	2.01	0.005	311
LY2	1	1.08	11.2	0.001	0.02	0.003	2.82	0.005	304
Mean	3.950	6.270	9.81	0.004	3.485	0.007	4.96	0.179	590.44

Site	Cd	Pb	Hg	COD_{Cr}	Petroleum	SS	pH	NO_3^--N	NO_2^--N
LR1	0.0005	0.005	0.00002	77.2	0.17	53	7.48	2.14	0.005
FS1	0.0005	0.005	0.00002	5	0.02	6	8.62	2.45	0.005
FS2	0.0005	0.005	0.00002	5	0.01	8	7.64	1.91	0.005
FS3	0.0005	0.005	0.00002	5	0.01	10	8.1	0.72	0.005
FS4	0.0005	0.005	0.00002	5	0.01	4	7.62	1.78	0.005
TL1	0.0005	0.005	0.00002	5	0.02	45	8.12	1.71	0.018
TL2	0.0005	0.005	0.00002	12	0.02	48	7.81	1.74	0.011
TL3	0.0005	0.005	0.00002	5	0.03	54	7.93	1.51	0.012
TL4	0.0005	0.005	0.00002	5	0.005	61	7.89	0.05	0.01
TL5	0.0005	0.005	0.00002	17	0.01	50	7.7	1.79	0.007
TL6	0.0005	0.01	0.00002	47.67	0.627	65	8.01	0.25	0.04
SY1	0.0025	0.005	0.00002	124	0.86	246	8.18	0.63	0.107
SY2	0.0014	0.005	0.00002	108	0.05	89	8.55	0.26	0.031
BX1	0.0005	0.005	0.00002	10.93	0.005	2	8.13	0.843	0.013
BX2	0.0005	0.005	0.00002	9.51	0.005	2	7.53	1.71	0.004
BX3	0.0005	0.005	0.00002	14.1	0.005	2	7.98	1.48	0.013
AS1	0.0005	0.005	0.00018	44	0.683	156	7.98	1.33	0.18
AS2	0.0005	0.005	0.00002	5	0.01	23	7.58	2.48	0.019
AS3	0.0005	0.005	0.00002	5	0.01	31	7.7	3.03	0.031
AS4	0.0005	0.005	0.00002	12.1	0.01	25	8.3	2.89	0.034
PJ1	0.0005	0.005	0.00004	29.9	0.225	122.7	8.02	0.647	0.203
PJ2	0.0005	0.005	0.00004	33.87	0.405	133.7	7.99	0.86	0.18
YK1	0.0005	0.005	0.00002	44.33	0.07	558	7.19	0.39	0.06
LY1	0.0005	0.005	0.00002	5	0.02	27.2	7.02	1.25	0.012
LY2	0.0005	0.005	0.00002	5	0.03	39.2	7.05	1.76	0.007
Mean	0.00062	0.0052	0.000028	25.58	0.1328	74.43	7.84	1.42	0.041

to exam the validity of the PCA. The result of KMO test is 0.541, indicating that PCA can be used for extracting the important ones of water quality parameters. The PCA extracted three components with the cumulative 73.66% of variance (Table 3). The first rotated component includes BOD_5, COD_{Mn}, DO, volatile phenol, NH_4^+-N, TN, TP, Cd, COD_{Cr} and petroleum hydrocarbons with high loading values (> 0.6), indicating that organic, trophic and life-supported substance contribute most to water quality change and these ten parameters are main restricting factors. The other principal components including conductivity, SS, Hg, NO_2^--N, and sulfide, reflect the information of suspended solid and toxic substance. Under the standard (loading value > 0.6), 15 parameters were selected as the candidate parameters for integrated assessment of river health.

Before the correlation analysis, there were only three parameters, DO, pH and NO_3^--N, passing the normal distribution test. Therefore, the Spearman rank correlation analysis was used, whereas the Pearson correlation analysis was used among DO, pH and NO_3^--N. The results of correlation analysis show that there are high correlations ($p < 0.01$) among organic pollutant parameters, trophic substance indices and suspended solid (Table 4).

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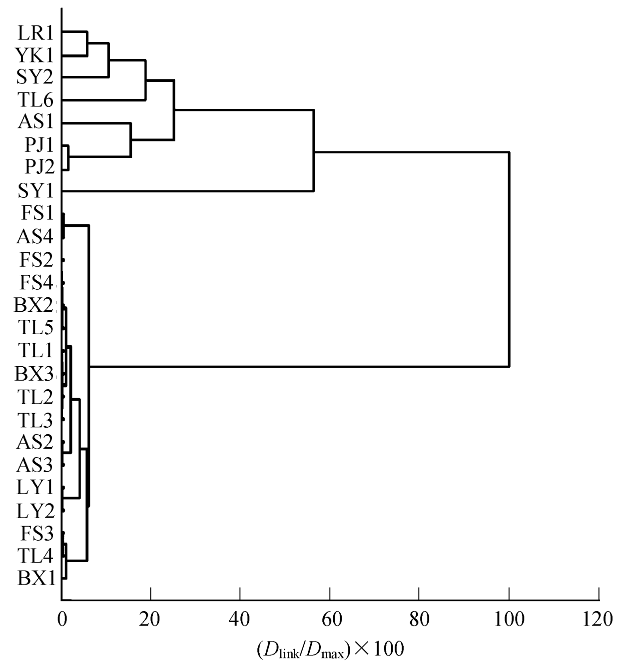

Fig. 2 Dendrogram showing the clustering of monitoring sites on the water quality indices.

Table 3 Rotated principal components and loading values of water quality indices

	Significant principal components		
	VF1	VF2	VF3
BOD_5	0.973	0.150	0.060
COD_{Mn}	0.649	0.300	0.240
DO	–0.674	–0.528	–0.311
Volatile phenol	0.943	0.099	–0.029
NH_4^+-N	0.782	0.253	0.489
Sulfide	0.465	0.660	0.055
TN	0.783	0.290	0.485
TP	0.927	0.160	0.027
Conductivity	0.087	0.081	0.961
Cd	0.950	–0.063	–0.042
Pb	0.076	–0.051	–0.031
Hg	–0.125	0.795	–0.020
COD_{Cr}	0.872	0.146	0.145
Petroleum	0.633	0.534	0.023
SS	0.343	0.204	0.888
pH	0.325	0.224	–0.488
NO_3^--N	–0.367	–0.207	–0.361
NO_2^--N	0.293	0.917	0.174
Variance (%)	41.931	16.328	15.404
Cumulative (%)	41.931	58.259	73.664

VF: Varimax factor

According to the principles of alternative between two high-correlative index and completely characterizing the river health using the selected parameters, BOD_5, COD_{Cr}, petroleum, TN, TP, NH_4^+-N, DO and conductivity were regarded as the water quality parameters for integrated assessment of river health. Because of the low observing values and un-obvious change, Hg and Cd, two heavy metal pollutants, were not brought into the integrated assessing index system.

2.2 Biotic index

2.2.1 Hygienic index

The fecal coliform count and total bacterial count were used in hygienic assessment. The fecal coliform count was an indicator of pollution of human and animal fecal material, implying the pestiferous risk through drinking, recreation or aquatic product consuming. Among data measured in this study the maximum value 5.4×10^6 colonies/L was found at site AS1, which was 5.4×10^5 times of the maximum allowable value (10 colonies/L) and 140 times as the standard value of category V (4×10^4 colonies/L), resulting in very high risk of pathogen infection. This causes the mean fecal coliform count in Liao River basin as high as 3.6×10^4 colonies/L. The sites with high fecal coliform count include SY1 (3.5×10^6 colonies/L), AS3 (1.6×10^4 colonies/L), PJ1 (1.1×10^4 colonies/L), and PJ2 (1.8×10^4 colonies/L), where a plenty of untreated waste may be discharged. The Spearman rank correlation coefficient between fecal coliform colony count and total bacterial colony count is 0.66 ($p < 0.01$). In order to precisely indicate the degree of fecal pollution, fecal coliform count was selected as one of the biotic indices of integrated assessing index system because the living of fecal coliform colony is limited in intestinal canal, whereas the total bacterial colony may have self-multiplication under the some probable condition of water quality.

2.2.2 Attached algae index

At 25 sites, 178 attached algae species were collected involving 5 phyla (Cyanophyta, Xanthophyta, Chlorophyta, Bacillariophyta, and Euglenaphyta), 7 classes, 17 orders, 25 families and 53 generas. There are 122 species in Bacillariophyta, which is the most in all phyla. We believe there should be a direct relationship between attached algae species and substance. At all sites, *Achmanthes* sp. was mainly collected with cobble substance, while the other species with silt and gravel substance are different, such as *Fragilaria* sp., *Navicula* sp., *Euglena* sp., *Synedra* sp. and so on.

Apparently, the water quality also affects the distribution of attached algae species (Table 5). In the water body with higher value of CPI (> 10), the main dominant species are *Fragilaria* sp., *Navicula* sp., *Synedra* sp., *Euglena* sp., *Achmanthes* sp., *Melosira* sp., *Navicula* sp. and Cocconeis sp., whereas the dominant species is mostly simple, *Achmanthes* sp., in clean water body with lower CPI (Table 5). Particularly, there are three sites, LR1, TL1, and YK1, obtaining no or little sample, where it was not able to compute the diversity index and biomass. The values of diversity index of attached algae are ranged from 25.0 to 73.9, and did not show the obvious correlation with CPI values (Fig. 3a). The biological density of attached algae shows the good correlation with it, decreasing with deterioration of water quality (Fig. 3b). It can be concluded that the main pollution types are organic and trophic pollution at serious polluting sites. The organic substance can restrain the photosynthesis of algae cell and impact the nucleic acid composition and heredity. The trophic

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Table 4 Spearman correlation coefficient of physical and chemical indices of water quality in Liao River Basin

	BOD_5	COD_{Mn}	DO	Volatile phenol	NH_4^+-N	Sulfide	TN	TP	Conductivity
BOD_5	1.000								
COD_{Mn}	0.839**	1.000							
DO	–0.602**	–0.434*	1.000						
Volatile phenol	0.800**	0.751**	–0.625**	1.000					
NH_3-N	0.671**	0.731**	–0.476*	0.672**	1.000				
Sulfide	0.546**	0.299	–0.637**	0.569**	0.261	1.000			
TN	0.454*	0.511**	–0.418*	0.787**	0.485*	0.335	1.000		
TP	0.775**	0.806**	–0.396*	0.784**	0.712**	0.187	0.599**	1.000	
Conductivity	0.415*	0.408*	–0.590**	0.553**	0.640**	0.402*	0.595**	0.366	1.000
Cd	0.492*	0.448*	–0.452*	0.570*	0.399*	0.441*	0.432*	0.379	0.350
Pb	0.207	0.255	0.057	0.393	0.259	–0.161	0.283	0.288	0.170
Hg	0.387	0.321	–0.438*	0.514**	0.412*	0.594**	0.442*	0.414*	0.477*
COD_{Cr}	0.774**	0.811**	–0.671**	0.777**	0.722**	0.444*	0.503**	0.678**	0.488*
Petroleum	0.673**	0.589**	–0.487*	0.774**	0.606**	0.353	0.753**	0.758**	0.713**
SS	0.608**	0.609**	–0.540**	0.670**	0.833**	0.266	0.592**	0.698**	0.736**
pH	0.260	0.424*	–0.154[a]	0.362	0.389	0.196	0.464*	0.255	0.258
NO_3^--N	–0.647**	–0.544**	0.487*[a]	–0.481*	–0.615**	–0.437*	–0.157	–0.387	–0.347
NO_2^--N	0.432*	0.406*	–0.660**	0.582**	0.666**	0.460*	0.509**	0.301	0.902**

	Cd	Pb	Hg	COD_{Cr}	Petroleum	SS	pH	NO_3^--N	NO_2^--N
BOD_5									
COD_{Mn}									
DO									
Volatile phenol									
NH_4^+-N									
Sulfide									
TN									
TP									
Conductivity									
Cd	1.000								
Pb	–0.061	1.000							
Hg	–0.110	–0.075	1.000						
COD_{Cr}	0.492*	0.266	0.323	1.000					
Petroleum	0.358	0.287	0.488*	0.585**	1.000				
SS	0.371	0.170	0.462*	0.608**	0.805**	1.000			
pH	0.407*	0.113	0.159	0.248	0.131	0.085	1.000		
NO_3^--N	–0.366	–0.311	–0.217	–0.417*	–0.313	–0.507**	–0.114[a]	1.000	
NO_2^--N	0.281	0.199	0.564**	0.537**	0.560**	0.658**	0.348	–0.386	1.000

* Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); [a] Pearson correlation.

substance is necessary for algae multiplication. These two aspects both impact the multiplication of algae. From the observed data of water quality, at heavily polluted sites where the CPI values are more than 10, the values of diversity index at TL6, AS1, PJ1, PJ2 are higher and the concentrations of BOD_5 and COD_{Cr} are lower than that at SY1 and SY2. Therefore, it is believed that the serious organic pollution may be the main limiting factor for attached algae living. At last, we select the attached algae diversity index as one of the integrated assessing indices of river health because the biomass is reflected in Shannon-Weaver diversity index.

2.2.3 Biotic integrity

Benthic invertebrate has a long life and limited moving rang, including sensitive species and pollution tolerant species, therefore, it can be used to monitor the long term impact of organic pollutant discharge. At 25 sites, 130 benthic invertebrate species were collected involving 4 phyla (Arthropod, Annelida, Mollusca, Crustacean), 7 classes, 16 orders, 37 families and 92 genera, and the arthropod is the main phyla. The species of chironomid and ephemerid are the main indicators for clean and light-polluted water body, whereas leech, oligochaeta and nereis are the main indicators or pollution-tolerant species for moderate- and heavy-polluted waterbody (Table 6). The mean percentage of dominant species in all species, discovered in each site, is 36.4%, and becomes bigger as the deteriorating of water quality condition. It suggests that there is an obvious degenerating trend for water eco-system under the external disturbance. At site LR1, no species was discovered, thereby the percentage of dominant species is null. The maximum of this index occurred at sites YK1 and SY1, where only one species (*Nereis* sp.) was discovered.

In the assessment of benthic biotic integrity, the values of B-IBI of all sites are ranged from 0 to 4.47 (mean is 2.81, standard deviation is 1.40). Obviously, the B-IBI scores decrease with the deterioration of water quality condition (Table 7, Fig. 4), proved by that there are significant minus correlations between it and some physical-chemical parameters, such as conductivity, SS, organic pollution parameters and trophic substance parameters and significant plus correlation only occurred between B-IBI and DO (Table 7).

Noticeably, there are three sites, LR1, SY1, and YK1, given the zero mark indicating that no or little benthic invertebrate could be collected at sampling sites. Based on the survey data of three sites, we find that the COD_{Mn},

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Table 5 Attached algae at all sites under different water quality conditions

Site	Dominant species	Dominant species (%)	Diversity index	Biological density (ind/cm^2)	CPI
LR1	Non	Non	0	0	13.61
FS1	*Navicula* sp.	32.3	2.65	87837.84	1.67
FS2	*Achmanthes* sp.	32.4	2.63	120652.2	1.41
FS3	*Achmanthes* sp.	28.6	3	127826.1	1.36
FS4	*Oscillatoria* sp.	37.6	2.53	109302.3	1.34
TL1	Non	Non	0	0	2.13
TL2	*Achmanthes* sp.	35.1	2.71	155033.6	2.61
TL3	*Achmanthes* sp.	47	2	135616.4	2.55
TL4	*Synedra* sp.	69.9	1.64	254347.8	2.00
TL5	*Achmanthes* sp.	43	2.54	890476.2	2.92
TL6	*Fragilaria* sp., *Navicula* sp.	25.0	2.46	24827.59	30.48
SY1	*Euglena* sp.	61.5	1.68	43333.33	75.25
SY2	*Synedra* sp.	73.9	1.56	234444	18.10
BX1	*Achmanthes* sp.	37.7	2.65	252221	1.90
BX2	*Achmanthes* sp.	73.3	1.26	177193	1.25
BX3	*Achmanthes* sp.	39.1	2.47	251908.4	1.71
AS1	*Achmanthes* sp.	35.2	3.2	59663.87	24.85
AS2	*Achmanthes* sp.	52.8	2.4	364469.9	1.12
AS3	*Navicula* sp., *Achmanthes* sp.	29.5	2.28	650704.2	0.98
AS4	*Cymbella* sp.	58.7	2.03	707692.3	1.44
PJ1	*Cocconeis* sp.	31.6	2.47	24782.61	18.08
PJ2	*Melosira* sp., *Navicula* sp.	27.3	2.41	11000	28.43
YK1	Non	Non	0	0	22.93
LY1	*Achmanthes* sp.	41.9	2.44	100722	1.35
LY2	*Achmanthes* sp.	70.5	1.69	112000	1.55

CPI: comprehensive pollution index.

Table 6 Dominant species of benthic invertebrate at all sites under different water quality conditions

Site	Dominant species	Dominant species (%)	B-IBI	CPI
LR1	Non	Non	0	13.61
FS1	*Orthocladius* sp.	19	4.47	1.67
FS2	*Eukiefferiella gracei*	20	4.38	1.41
FS3	*Tabanus* sp.	31	3.49	1.36
FS4	*Diamesa* sp.	20	4.23	1.34
TL1	*Hydropsyche* sp.	20	3.76	2.13
TL2	*Orthodladius* sp.	30	2.87	2.61
TL3	*Orthodladius* sp.	24	3.33	2.55
TL4	*Orthodladius* sp.	25	3.15	2.00
TL5	*Orthodladius* sp.	21	3.68	2.92
TL6	*Cryptochironomus digitatus*	50	2.36	30.48
SY1	*Limnodrilus udekemi*	100	0	75.25
SY2	*Lipinilla* sp.	60	1.06	18.10
BX1	*Ephemera lineata*	17	4.28	1.90
BX2	*Sympotthastia fulva*	38	3.96	1.25
BX3	*Micropsectra* sp.	24	3.59	1.71
AS1	*Herpobodella* sp.	75	1.57	24.85
AS2	*Epeorus* sp.	21	3.39	1.12
AS3	*Epeorus* sp.	22	2.82	0.98
AS4	*Herpobodella* sp.	23	3.32	1.44
PJ1	*Nereis* sp.	91	1.16	18.08
PJ2	*Einfeldia dissidens*	26	2.39	28.43
YK1	*Nereis* sp.	100	0	22.93
LY1	*Ephemerella* sp.	16	3.29	1.35
LY2	*Hydropsyche* sp.	38	3.73	1.55

COD_{Cr}, and BOD_5 values are very high and even higher than criteria of V class, the worst grade of water quality standards according to GB3838-2002, which is the main reason resulting in zero B-IBI in these sites. Moreover, sites with B-IBI values above mean are located at the upstream of the tributaries of Liao River. These sites are less disturbed by human activity, and mean value of human activity intensity in physical habitat assessment is 10.18, as sub-optimal level. The water quality at these sites is better as well. The sites with poor water quality are located at mainstream of Liao River, where human activity intensity, such as agricultural and traffic activity is relatively high (3.38) and water body is heavily polluted. Especially at LR1, serious water run-off and soil erosion result in the high concentration of SS and continuous accumulation of sediment, which seriously disturb the habitat of benthic invertebrate. Theses impacts deteriorate the living conditions of benthic invertebrate, resulting to low B-IBI values.

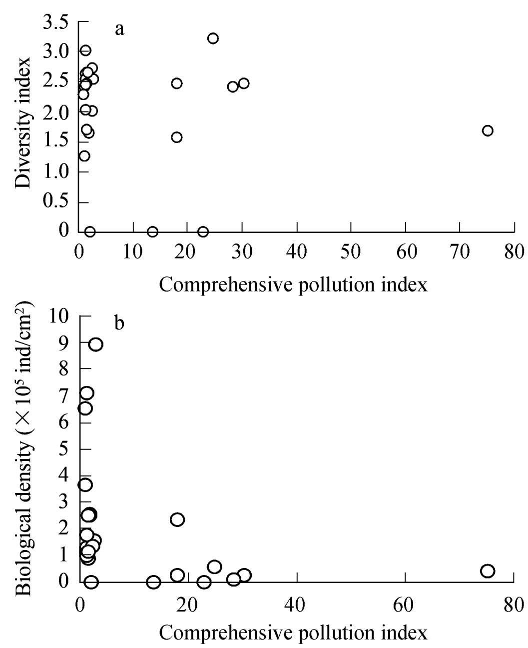

Fig. 3 Scatter diagram for CPI and diversity index (a) and biological density (b) of attached algae.

Besides the water chemistry conditions, the species and

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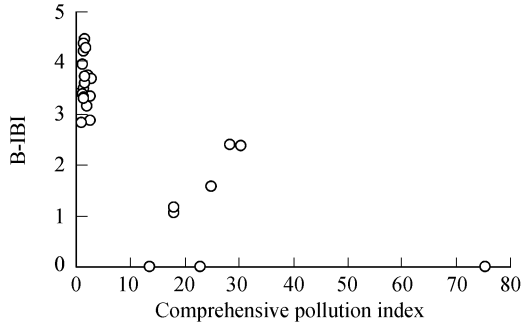

Fig. 4 Scatter diagram for B-IBI and comprehensive pollution index.

biomass of benthic invertebrate are also related to substrates, water depth and flow velocity in the river. In order to isolate the impact of water chemistry conditions, some B-IBI values at those sites with relative clean conditions (less than 2.0 for comprehensive pollution index) were used as reference to assess the impact on benthic invertebrate from river regime. During this study, no regulatory criteria are available as reference. Therefore, it is assumed that only water chemistry conditions impact the living and reproduction of benthic invertebrate in study area.

At the same time, the correlation analysis was conducted between B-IBI and physical habitat quality assessing score. The Pearson correlation coefficient is 0.900 at 0.01 significant levels, indicating that the river regime change impacts the community structure and abundance of benthic invertebrate.

Table 7 Spearman correlation coefficient between B-IBI and physical-chemical parameters

Item	Coefficient	Item	Coefficient
BOD_5	–0.595**	Conductivity	–0.684**
COD_{Mn}	–0.671**	Cd	–0.411*
DO	0.698**[a]	Pb	–0.170
Volatile phenol	–0.693**	Hg	–0.342
NH_3-N	–0.668**	Petroleum	–0.683**
Sulfide	–0.284	SS	–0.834**
TN	–0.565**	pH	0.016[a]
TP	–0.572**	NO_3-N	0.401*[a]
COD_{Cr}	–0.715**	NO_2-N	–0.648**

* Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); [a] Pearson correlation.

2.3 Physical habitat

The physical habitat assessment scores are ranged from 16 to 138 (the mean value is 96.6 and the standard deviation is 33.83). There is no site with physical habitat assessment score above 150, which is 75% of the full score. Of the 25 surveyed sites, 60% of sites are with scores above 100 (Fig. 5). For each metric, there are about 60% of sites having sub-optimal and optimal levels on substrate, habitat complexity, velocity-depth combination and water cognition, suggesting that the natural condition of water body is acceptable for maintaining water ecosystem at most of sites. But for metrics of bank stability, bank conservation, vegetation cover, vegetation diversity, intensity of human activities, and riverside land use, more than 75% sites are below sub-optimal level. At these sites soil erosion occurred on more than 30% and vegetation cover is less than 50% of bank area. It suggests the bank stability is not sufficient and exceeding amount of suspended solid is generated. The vegetation diversity, intensity of human activities, and riverside land use are three main metrics related to human activities. The metric of intensity of human activities indicates that 84% of sites are suffered from intensive disturbance from human, mainly agricultural activities. Thus, the type of vegetation is less diversified farm crop. This is also reflected on riverside land use metric.

In order to understand the relationship between the physical habitat and water quality, the correlation analysis was performed using ten parameters of physical habitat and eighteen of water quality parameters (Table 8). It is showed that six parameters of physical habitat, such as substrate, habitat complexity, bank conservation, vegetation cover, intensity of human activities and water cognition, correlate well to most of water quality parameters, and thus impact the water quality predominately. The other parameters of physical habitat are subdominant because there are only several water quality parameters correlating to them significantly. Therefore, except heavy metal and pH, almost all water quality parameters are significantly

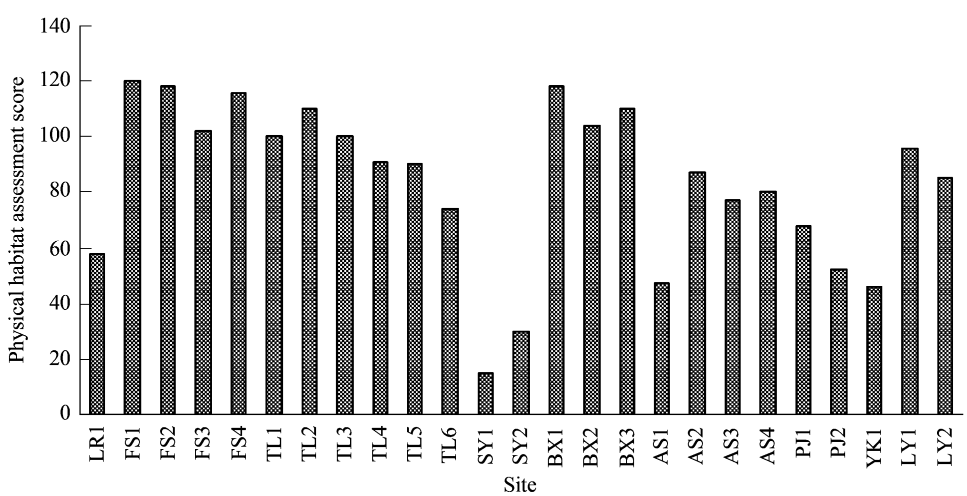

Fig. 5 Histogram of physical habitat assessment score.

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Table 8 Spearman correlation coefficient between physical habitat parameters and physical-chemical parameters

	Substrate	Habitat complexity	Velocity-depth combination	Bank stability	Bank conservation
BOD_5	–0.699**	–0.518**	–0.063	–0.229	–0.413*
COD_{Mn}	–0.660**	–0.470*	–0.100	–0.318	–0.455*
DO	0.744**[a]	0.769**[a]	0.356[a]	0.409*[a]	0.636**[a]
Volatile phenol	–0.745**	–0.724**	–0.317	–0.510**	–0.452*
NH_4^+-N	–0.607**	–0.596**	0.056	–0.448*	–0.572**
Sulfide	–0.378	–0.345	–0.247	–0.086	–0.477*
TN	–0.714**	–0.877**	–0.243	–0.466*	–0.486*
TP	–0.660**	–0.581**	–0.014	–0.443*	–0.280
COD_{Cr}	–0.704**	–0.621**	–0.194	–0.358	–0.603**
Conductivity	–0.594**	–0.779**	–0.326	–0.393	–0.581**
Cd	–0.474*	–0.474*	–0.481*	–0.457*	–0.350
Pb	–0.257	–0.185	–0.014	–0.103	0.159
Hg	–0.376	–0.409*	–0.004	–0.203	–0.438*
Petroleum	–0.668**	–0.798**	–0.226	–0.427*	–0.310
SS	–0.696**	–0.792**	–0.189	–0.583**	–0.597**
pH	–0.176[a]	–0.115[a]	–0.046[a]	–0.029[a]	–0.062[a]
NO_3^--N	0.496*[a]	0.346[a]	–0.025[a]	0.198[a]	0.274[a]
NO_2^--N	–0.607**	–0.712**	–0.282	–0.363	–0.663**
	Vegetation cover	**Vegetation diversity**	**Intensity of human activities**	**Water cognition**	**Riverside land use**
BOD_5	–0.648**	–0.178	–0.618**	–0.643 **	–0.357
COD_{Mn}	–0.729**	–0.262	–0.599**	–0.564**	–0.335
DO	0.477*	0.518**[a]	0.795**[a]	0.708**[a]	0.563**
Volatile phenol	–0.573**	–0.322	–0.722**	–0.689**	–0.459*
NH_4^+-N	–0.755**	–0.450*	–0.563**	–0.512**	–0.470*
Sulfide	–0.334	–0.290	–0.598**	–0.554**	–0.297
TN	–0.547**	–0.483*	–0.627**	–0.634**	–0.500*
TP	–0.658**	–0.220	–0.403*	–0.554**	–0.404*
COD_{Cr}	–0.585**	–0.374	–0.776**	–0.714**	–0.504*
Conductivity	–0.514**	–0.446*	–0.642**	–0.577**	–0.331
Cd	–0.422*	–0.426*	–0.479*	–0.402*	–0.486*
Pb	0.031	0.043	–0.158	–0.088	0.058
Hg	–0.458*	–0.161	–0.399*	–0.500*	–0.164
Petroleum	–0.425*	–0.274	–0.531**	–0.661**	–0.425*
SS	–0.673**	–0.575**	–0.578**	–0.559**	–0.568**
pH	–0.368	–0.029[a]	–0.165[a]	–0.134[a]	0.052
NO_3^--N	0.551**	0.410*[a]	0.489*[a]	0.306[a]	0.377
NO_2^--N	–0.530**	–0.435*	–0.699**	–0.569**	–0.294

* Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed); [a] Pearson correlation.

correlated to the above-mentioned key parameters of physical habitat and can be impacted by them easily.

2.4 Integrated assessment of river health

According to the analysis of water quality index, biotic index and physical habitat quality index, 12 assessing indices, nearly completely describing the characters of the river, were assigned to assess the Liao River health. Using the principal components analysis method, each index was attached to different weight value from 0.060 to 0.096 (Table 9). It was indicated that the contribution of water quality and physical habitat quality indices to river health are more than that of biotic indices except B-IBI.

For setting assessing standards, the same method for generating the integrated assessment score was used based on five levels, where the EH_{fact} in Eqs. (2) and (3) was replaced by the values of the standards of category I, II, III, or V standards for each parameter. The less score, the higher level gotten (Table 10). Finally, there were 9 sites categorized in healthy and sub-healthy levels, accounting for 36% of all sites. Only eight sites, 32% of all sites, which almost locate on the mainstream of Liao River, were categorized in sub-sick and sick levels. It is necessary to point out that because of very large fecal coliform count, the assessing scores of the sites, SY1 (32.97) and AS1 (37.72), are very high and are 7.4 and 8.5 times, respectively, as the standard of sick level threatening human health (Fig. 6).

Table 9 Integrated assessing index system of river health

Index type	Assessing index	Weight value
Physical and chemical index		
Organic pollution	BOD_5	0.092
	COD_{Cr}	0.087
	Petroleum	0.090
Trophic substance	TN	0.096
	TP	0.093
	NH_4^+-N	0.087
Living metric	DO	0.074
Water physics	Conductivity	0.068
Biotic index		
Hygienics	Fecal coliform count	0.060
Attached algae	Attached algae diversity	0.071
Benthic invertebrate	B-IBI	0.090
Physical habitat quality index		
Physical habitat quality for aquatic life	Physical habitat quality evaluation index	0.092

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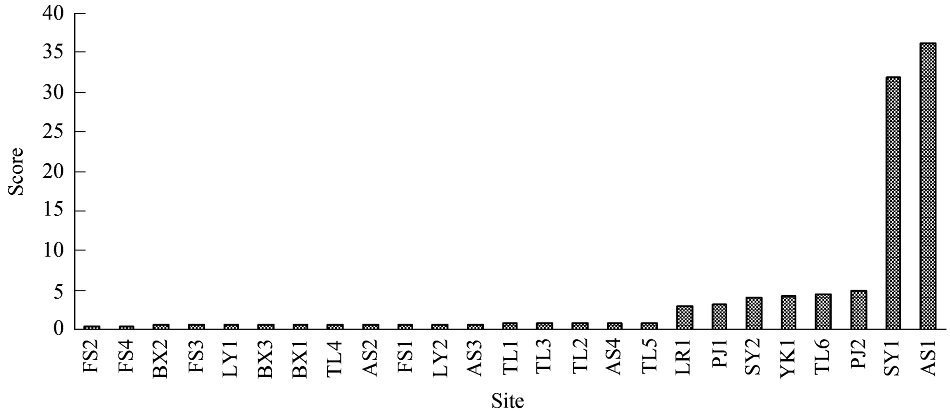

Fig. 6 Histogram of integrated assessment score of river health.

Table 10 Integrated assessing standard and result of river health

Quality	Standard	Number of sites	Site
Healthy	⩽ 0.50	1	FS2
Sub-healthy	0.50–0.70	8	FS4, BX2, FS3, LY1, BX3, BX1, TL4, AS2
Fair	0.70–1	8	FS1, LY2, AS3, TL1, TL3, TL2, AS4, TL5
Sub-sick	1–3.64	2	LR1, PJ1
Sick	⩾ 3.64	6	SY2, YK1, TL6, PJ2, SY1, AS1

3 Conclusions

In present study, the indices of water quality, hygiene, attached algae, benthic invertebrate, and physical habitat quality were used to assess the health conditions of Liao River. Generally, the water quality of main stream, where industrial and agricultural activities are intense, is much worse than that of the tributaries, which is clearly demonstrated in the spatial distribution analysis of water quality parameters.

Similarly, B-IBI and physical habitat show the same pattern in spatial distribution. Data analysis also reveals the correlation between the impact on aquatic life and water quality conditions. However, different from many studies mentioned in introduction section, in our integrated assessing index system of river health, the bigger weight values were not assigned to the biotic indices.

According to the PCA analysis results, water quality and physical habitat quality indices play rather important roles in river eco-system health. Based on this result, an assessing standard system was established. Finally, nine of studied sites are categorized into healthy and sub-healthy levels. Eight with heavy organic and trophic pollution are at sub-sick and sick levels. Therefore, the pollution control may be feasible and effective for improving the status of river ecosystem. These results provide objective and rational assessment on health conditions of Liao River ecosystem.

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