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An index of river health for river plain network regions

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Abstract We propose a new concept – "water health" – based on ecological health to describe the degradation of aquatic ecosystems in relation to human-induced watershed alterations, and present a partial application of these ideas in a river plain network region. An indicator framework for the analysis and assessment of "water health" is presented which takes environmental, ecological, landscape and social service functions into consideration. The meaning and method of determination of each indicator is described. The entropy method was adopted to calculate the weight of index, applying the weighted sum model. These approaches were implemented to assess the four main functions of "water health" for Xinghua city, China. It was found that the water quality is inferred as being only lightly polluted – "the general stage"; ecological and landscape functions were also in this category. In addition, large-scale exploitation of the social service function has also influenced the regional environment to some extent.

Key words water health; river health; ecological integrity; indicators; river plain network regions

INTRODUCTION

River and lake ecosystems change their course and morphology over time as a result of many forces acting on their water environment and basin. These changes could be natural or human-induced, and may be gradual or rapid. Since entering the 21st century, with the sharply rising population and modernization of society, river and lake degradation have increased. Pollution, fishing pressures, habitat destruction, species introductions, and other anthropogenic stresses act simultaneously with internal and external physical, chemical and biological forces (Jordan & Vaas, 2000). These forces can have a wide variety of physical, ecological, and environmental effects in rivers and lakes, such as streambed mobilization, scouring, degradation, lake shrinkage and aggradation, and changes in hydrological regime (Kondolf, 1997; Surian, 1999; Rinaldi, 2003; Choi *et al.*, 2005; Magilligan & Nislow, 2005; Rinaldi *et al.*, 2005, Isik *et al.*, 2006b).

Based on the concept of ecosystem health, river health (Karr, 1999; Norris & Thomas, 1999) has been introduced into the field of eco-hydrology to express the status and condition of the river ecosystem. Most scholars believe that river health means the ability of the aquatic ecosystem to support and maintain the ecological integrity and process (Karr, 1999). Due to serious ecosystem degradation, there has been increasing research into the assessment of river health assessment in recent years (Norris & Thomas, 1999; Zhao & Yang, 2005; Vugteveen *et al.*, 2006). Currently, two methods for river health assessment are generally accepted: biological monitoring with representative indicator species, and the aggregative indicator method, which includes physical, chemical, biological and socio-economic information and is gradually becoming a primary method for assessing river health (Townsend & Riley, 1999; Kong *et al.*, 2002; Tang *et al.*, 2002; Zhao & Yang, 2005). The classical aggregative indicator methods are ripian, channel and environmental inventory for small streams in agricultural landscape (RCE) grading and the Index of Stream Condition (ISC) (Petersen, 1992), both of which produce a relative aggregated assessment by the filtering index system, based on assessment standards and corresponding marks by experts, and calculating the weighted sum. This assessment model is still being developed. River health is not a precise scientific concept, but a means of estimation in river management. In accordance with different problems and purposes, the definition of health is broad and researchers have proposed many new concepts, such as river ecosystem health and healthy working rivers, and watershed ecosystem health (Cai *et al.*, 2003; Dong, 2005; Vugteveen *et al.*, 2006).

Because of the lack of quantitative standards, all of the above mentioned models and methods cannot reflect the real state of aquatic ecosystems and allow comparisons between different water bodies; they only provide a relative assessment of identity of a single river. However, almost all rivers are a part of a larger river network, which is disturbed by human activities and other factors. If managers only pay attention to individual rivers management, treatment may not be very effective. To solve these problems, based on the river health view and approaches, we propose the concept of "water ability", which expresses the general condition of the aquatic ecosystem including rivers, lakes and wetlands within a region. It can be defined as the ability of the aquatic ecosystem, influenced by the regional environment and climate, to maintain and support key ecological processes, a community of organisms and sustainable service functions to human society. The "Water Health Index" (WHI) is proposed in this paper to try to quantitatively characterize "Water Health". It not only considers a single river, but also takes all the regional rivers into account, integrating river service function, the aquatic ecosystem and the regional environment. In this paper, we present a theoretical framework for generating a WAI, and a partial application of these ideas.

A river plain network region is an area with numerous lakes, low-lying relief and a high frequency of flooding. Lixia River basin is a typical river plain network region in Jiangsu province, China. With economic development and social progress, the basin land use has been greatly changed. A large number of river branches have been manually excavated, the natural flood-control capacity of the river system has been weakened, the stream structure has been simplified, the diversity of natural river forms has been reduced, and lakes and wetlands have disappeared in urbanized areas. The protection and restoration of aquatic ecosystems in the basin plays a key function in the local environment and societal development.

METHODS AND MATERIALS

Study area description

The study site for the research was Xinghua city (32°40′–33°13′N, 119°43′–120°16′E) in the Lixia river basin, Jiangsu province, eastern China. Xinghua city is in the centre of Jiangsu province, covers over 2393 km^2 and encompasses 28 towns, 6 villages and 1 provincial economic development zone, with a total population of 156 million, of which 9% live in urban areas. Xinghua is a typical river plain network region, situated approximately 2–5 m above sea level. Since the 1980s there has been a tremendous growth in manufacturing and reclamation of land from lakes for agriculture and aquaculture to increase food production. One of the most significant effects of these changes is the enrichment of aquatic bodies with phosphorous, ammonia, copper, organic matter and other nutrients, and decreases in dissolved oxygen (Hall *et al*., 1992; Wu *et al*., 1994; Leung *et al*., 1999). More seriously, the total surface area covered by water has sharply decreased to <2% of the water-covered area in the 1980s.

Candidate metrics

Candidate metrics were selected based on the feasibility of measurement and ecological relevance. They were tested using multivariate statistical techniques to determine which best indicated the "water ability" of the river plain network region ecosystem. From this the following 21 indicators in four categories were selected to evaluate the "water ability" of Xinghua city.

Indicators for environmental function

Water chemistry measurements are from water samples taken in April 2008. Figure 1 shows the location of 19 sampling sites in Xinghua city for water chemistry assessment, 16 sites along the main rivers and three sites in Dazong Lake, Guocheng Lake and Wugong Lake. Water pH, temperature, dissolved oxygen (DO), and transparency were measured *in situ* in the field. Concentrations of NO_3^-, NO_2^-, PO_4^{3-}, chemical oxygen demand (COD_{Cr}), permanganate index (COD_{Mn}), TN, TP, NH_4^+, chlorophyll (Chla) were transported to the laboratory in a cool box at 4°C immediately and measured in the laboratory using the methodology recommended by Standard Methods (GB3838, 2002). Equation (1) was used to calculate the degree of eutrophication (Jin & Liu, 1990) using the five parameters TN, TP, transparency, COD_{Mn} and Chla.

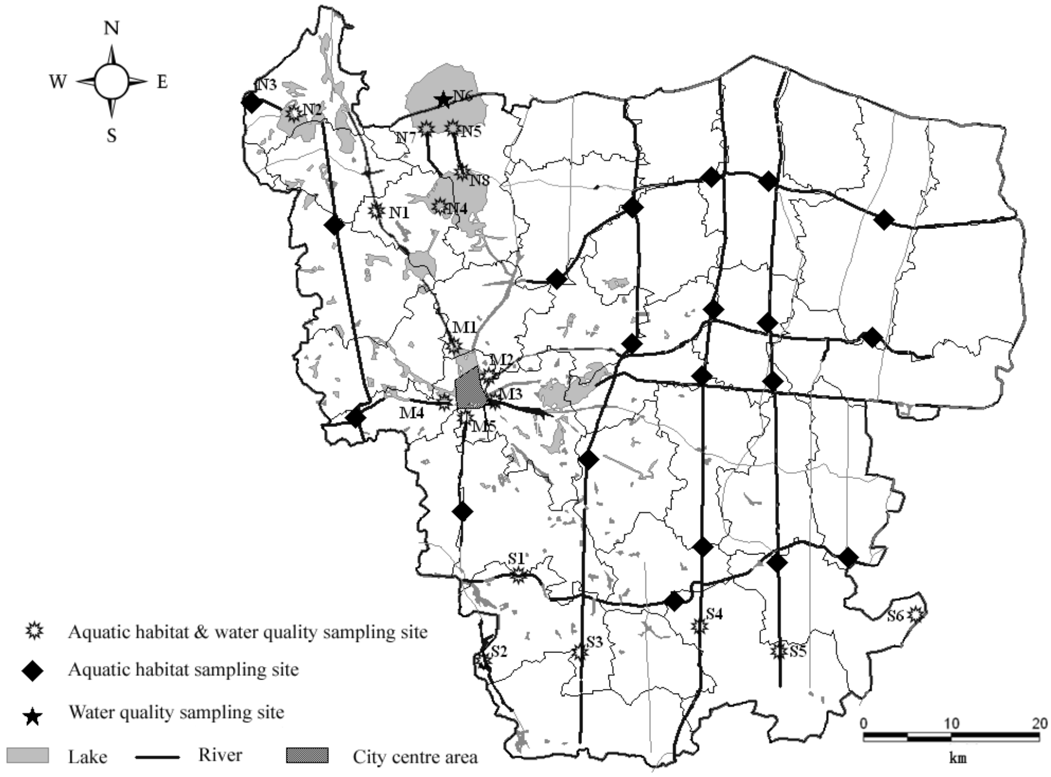

Fig. 1 Location of sampling sites in Xinghua city. N_i, M_i and S_i represent the north, middle and southwest water quality sample sites, respectively.

$$E = \sum W_j TLI_j \tag{1}$$

where E is the eutrophication index, W_j is the relative weight assigned to each parameter and TLI_j is the trophic state index of each parameter. Full details of the weighting procedure are provided by Jin & Liu (1990). The other chemical parameters were used to calculate the water quality index (WQI) using the following equation.

$$WQI = \sum_i c_i p_i / \sum_i p_i \tag{2}$$

Where c_i is the normalized value of the parameter and p_i is the relative weight assigned to each parameter. The values suggested for parameters c_i and p_i are based on standard values used in China (GB3838, 2002).

Indicators of ecological function

The aquatic habitat was studied at 16 river and three lake sites shown by the diamond symbols in Fig. 1, which also shows the location of 37 sampling sites. The integrity of aquatic habitat was assessed from four parameters – pool variability, channel sinuosity, bank vegetation protection and channel alteration – whose values were based on USGS Standards (Environmental Agency, 2003). The integrity of ecosystem community structure was calculated from the primary productivity of planktonic plants (P) and the nature reserve area (N) calculated using equations (3) (Wang & Wang, 1984) and (4). The higher the values the better the integrity.

$$P = 0.28Chla + 0.96 \tag{3}$$

$$N = \textit{nature reserve area / region area} \tag{4}$$

Assessment of the region's "water health" should take the regional environment into account. It includes two aspects: the regional ecological elasticity capability, which contains the landscape diversity index and high ecological status patch density, and the ecological disturbance force, which we expressed as hemeroby. The landscape diversity index, *H*, was calculated using equation (5).

$$H = -\sum_{i=1}^{m} P_i \log_2 P_i \tag{5}$$

where *m* is the total number of landscape types and *P* is the proportion of type *i* of the total land area. The higher the value the greater the diversity. The high ecological status patch density is calculated as the ratio of the area of landscapes with important ecological functions (here assumed to be woodland and grass) to total area. The higher the index the better the ecological system. Hemeroby is the degree of disturbance resulting from human activity, whether intentional or unintentional, and was calculated as:

$$H = \sum_{k=1}^{m} f_k \times h_k \tag{6}$$

where m is the total rank and f_k is the proportion of the total land area of rank *k*. h_k is the hemeroby factor. In this paper, on the basis of ecological landscape pattern information, we used seven values of h_k (Table 1).

Table 1 The correspondence of land use types to the values of the hemeroby factor.

Degree of Hemeroby	Degree of naturalness	Land use type	h_k
None	Natural	Un-utilized land	1
Tiny	Semi-natural	Woodland	2
Little	Relatively natural	Grass	3
Gently	Remote natural	Water area	4
Intermediate	Near natural	Garden plot	5
Strong	Semi-artificial	Farmland	6
Artificial	Artificial	Constructed land	7

Indicators of landscape function

River corridors are the most important corridors of the regional landscape and the life spring of ecosystems and human society, and therefore their landscape function cannot be ignored. The landscape function represents the influence of the aquatic body to maintain the riparian or waterfront area and its aesthetics, which was described with the following three parameters:

- Condition of aquatic/terrestrial ecotones: these form the transition zone between terrestrial and aquatic ecosystems. Materials, energy and information are exchanged within them and they play an important function in the human landscape.
- Width of riparian vegetation: a certain width of bankside vegetation is required to minimize the transport of pollutants to the waterbody and enhance the scenic value. Human activities in the riparian vegetation zone, such as building houses or farming, can destroy or decrease the landscape service.
- Aesthetics of the river/lake bank: The high landscape value of bankside areas has many functions, such as for leisure activities and increasing the mental and physical well-being of tourists.

Indicators of social service function

The social service function is the basis for sustainable development. We divided the study area into 15 sub-regions to assess this function using the following six parameters.

- Surface water ratio: the ratio of the surface water area to the total area, indicating the flood risk.

– Channel connectivity index, r: it reflects the character and degree of complexity of the river network and is calculated as:

$$r = L / L_{\max} = L / 3(V - 2) \tag{7}$$

where L is the river number, V is the node number and L_{max} is the total number of river junctions. r takes values from 0 to 1, where r = 1 means that all nodes are connected.
– Degree of flood control: the ratio of reaching the regional flood control requirement or not.
– Water supply: evaluated from GDP generated per m^3 water and the rate of change of annual runoff.
– Navigability: it is defined as:

$$s = \left(\sum_{i=1}^{n} L_i R_i \right) \Big/ A \tag{8}$$

where n is the number of navigable rivers, L_i and R_i are the navigation mileage and rank corresponding to the river i and A is the total length of the rivers in the region.

Assessment method

Information entropy describes the degree of disorder in the information system; the smaller the entropy value, the lower the degree of disorder. Information entropy is estimated from the degree of order and the utility of the system information. The coefficients of weight are derived from the available value of data reflecting the information entropy, thereby reducing the subjective judgment. The calculation approaches refer to the methods proposed by Qiu (2001). The weighted sum model was adopted.

RESULTS AND DISCUSSION

Characteristics of environmental function

Water quality results from the 19 sampling sites were divided into three subareas: northwest, central and south Xinghua (Table 2). The whole region is lightly polluted. Water quality was highest in the south area and lowest in the central area, which is closest to the township where industrial wastewater and domestic sewage is discharged into rivers or lakes without treatment. To better understand the relationships between environmental factors and the WQI, correlation coefficients (r) were calculated between the water chemistry parameters and the WQI. In the northwest and central areas NH_4^+ and COD_{Cr} were most strongly negatively correlated with the WQI, r = –0.745* and –0.935*, respectively (asterisks represent statistically significant at p<0.05). In the whole study area NH_4^+ and COD_{Cr} had the most negative effects on the WQI, whereas DO had the most positive effect, with correlation coefficients of –0.515*, –0.767* and 0.535*, respectively.

Table 2 Water quality characteristics of Xinghua city, mean values ±SE.

	Northwest area (8 sampling sites)	Central area (5 sampling sites)	South area (6 sampling sites)
pH	7.537 ± 0.0805	7.334 ± 0.0275	7.598 ± 0.056
NH_4^+ (mg L^{-1})	0.57 ± 0.121	0.828 ± 0.099	0.692 ± 0.143
COD_{Cr} (mg L^{-1})	24.3625 ± 0.8854	25.76 ± 2.865	23.367 ± 1.384
COD_{Mn} (mg L^{-1})	12.863 ± 0.6597	15.047 ± 1.354	12.289 ± 1.454
TN (mg L^{-1})	2.09 ± 0.098	2.341 ± 0.116	2.442 ± 0.278
TP(mg L^{-1})	0.0576 ± 0.00558	0.111 ± 0.014	0.095 ± 0.006
NO_3^- (mg L^{-1})	0.5988 ± 0.0656	0.948 ± 0.109	1.172 ± 0.199
DO(mg L^{-1})	5.48 ± 0.4436	4.308 ± 0.241	5.16 ± 0.224
Chla (mg L^{-1})	0.023 ± 0.0024	0.011 ± 0.0019	0.012 ± 0.001
WQI	0.723 ± 0.026	0.631 ± 0.057	0.727 ± 0.030

Figure 2 shows that the eutrophication index values of the sampling sites were all very similar at around 60, indicating moderate–mild eutrophic status. Dazong Lake (N6) had the most obviously moderate eutrophic status of the three lakes surveyed lakes. Baitu River (M2), Chelu River (M3) and Nanguan River (M5) which are all located within the main urban area were also moderately eutrophic. Overall, the problem of eutrophication in Xinghua is quite serious and unignorable.

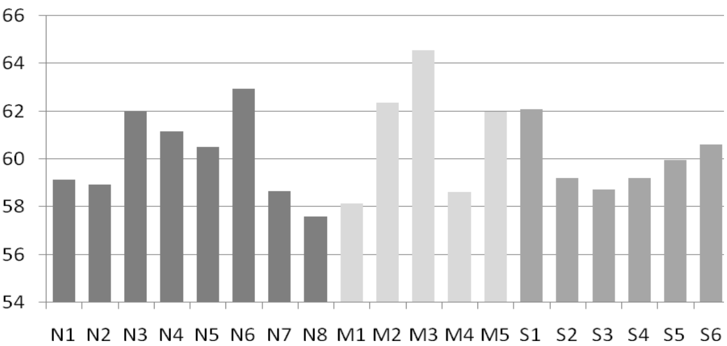

Fig. 2 Eutrophication index of sampling sites.

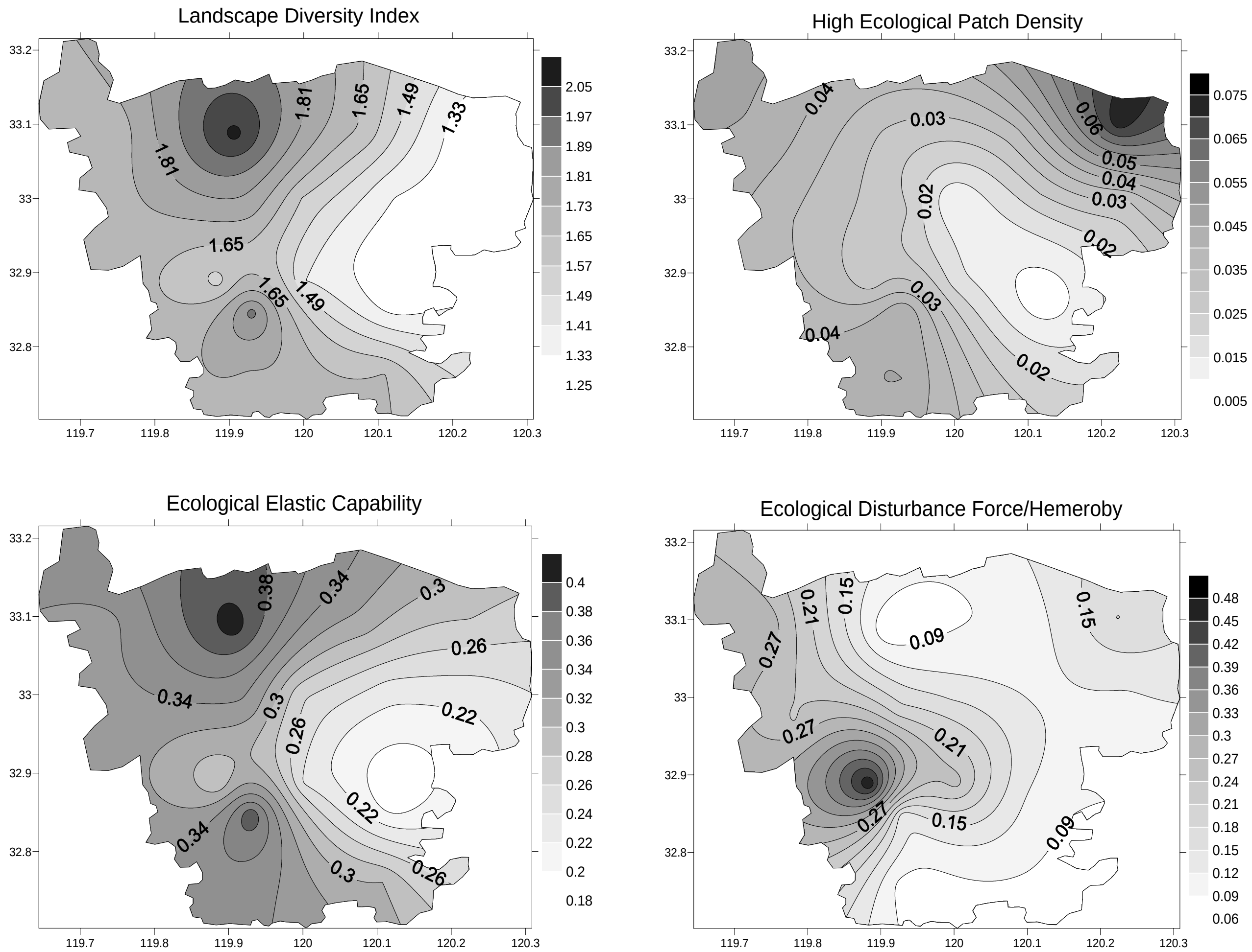

Fig. 3 The spatial distribution of the landscape diversity index, high ecological status patch density, hemoroby, and two main factors which are calculated by the three indicators using the entropy-weighted sum model.

Characteristics of ecological function

The regional ecosystem structure and stability play a key role in supporting and determining the ecological function of rivers and lakes. The self-restoration capability and degree of human interference in the regional ecosystem was represented by the indicators of ecological elasticity capability and ecological disturbance. These were assessed from the land cover classification based on data fusion and adopted unsupervised classification using ERDAS software of the Landsat7 image (resolution 15 m × 15 m). In this study, we combined the existing 35 towns into 15 subareas and calculated the indicator values of each. Figure 3 shows the contour maps derived from kriging of the values of three indicators of ecological functions (landscape diversity index, high ecological patch density, hemeroby) and two main effect factors (ecological elastic capability, ecological disturbance force).

The highest landscape diversity index score was more than 1.90 in the northwest area around Dazong Lake and Wugong Lake because land uses such as water bodies, wetland, grass and woodland, are plentiful. The high ecological status patch density was lower than 0.05 in the southeast of the study area which means that the woodland or grass cover is below the national average. The ecological elasticity capability score was calculated by combining the above two indicators. Its spatial distribution is very similar to the landscape diversity index, with good status in the northwest around Dazong Lake and lower values in the centre and southeast. On the basis of previous research, we chose just hemeroby to reflect the ecological disturbance force. As Fig. 3 shows the highest disturbance was around the central urban area and also in the northwest corner around Guocheng Lake due to disturbance from urbanization, large-scale deforestation or reclamation of land from the lake.

The ecological function also includes indicators of the integrity of aquatic habitat. From the detailed investigation of 14 rivers in Xinghua (Table 3) we found that, apart from the Chelu and Bangyan rivers, in general, key rivers, such as the Yanjing, Xitang and Weishui rivers are all of poor or bad status. Their natural morphology has disappeared and human activity has transformed them into totally straight rivers of uniform depth and width so they no longer support a diversity of habitats. Natural river bank protection is infrequent and rivers in the urban area or the main channels have been lined with stone and cement for flood protection. The riparian vegetation cover was generally poor in the study area and bank reclamation existed almost everywhere. Above all, the integrity and structure of the aquatic habitat has been severely damaged by human activity, further decreasing biodiversity.

Table 3 Scores for the integrity of aquatic habitat.

River Name	Cross-section morphological diversity	Channel sinuosity	Riparian vegetation coverage	Channel alteration
Xiaguan (M1)	0.300	0.125	0.125	0.250
Tong (N1)	0.125	0.125	0.250	0.375
Liyu (N2)	0.213	0.188	0.175	0.363
Zhongyin (N3)	0.300	0.250	0.250	0.325
Baitu (N4)	0.125	0.250	0.200	0.300
Chelu (N5)	0.350	0.500	0.125	0.250
Hengjing (N6)	0.200	0.250	0.300	0.375
Nanguan (N7)	0.225	0.125	0.250	0.250
Bangyan (N8)	0.500	0.500	0.375	0.475
Nuding (M1)	0.225	0.250	0.500	0.450
Weishui (M1)	0.200	0.100	0.125	0.400
Xitang	0.250	0.100	0.350	0.450
Yanjing	0.175	0.025	0.375	0.375
Taidong	0.250	0.250	0.250	0.500

In order to assess the biodiversity of the area, we calculated the primary productivity of plankton and the nature reserve area. Lakes had primary productivity scores greater than 6.0, with the highest value of 10.14, and had generally higher scores than rivers. Rivers in the northwest area had higher values than rivers in the middle or south area which had values less than 5.0. The primary productivity for rivers and lakes can attain average for above 5.5. The nature reserve area in Xinghua is higher than the national average including eight reserves, which account for 6.3% of the area of the whole study region.

Characteristics of landscape function

From actual site investigation and interviewing local people, we assessed the landscape function which is mainly based on the nature of the waterfront area and its scenic value. Due to severe human disturbance, natural waterfronts are very rare in Xinghua and no apparent submerged macrophytes were observed. In the dry season, bare sediment appeared between the bank and the water surface. Above all, the structure of waterfront area in Xinghua is totally at the level of the early-warning level, some channels even reached the pool level and need restoration to better conditions as soon as possible.

Rural rivers had better water quality and natural beauty. However, rivers in the urban area are almost all regulated by endless concrete banks with no waterside landscape design, and have poor water quality and contain piles of domestic waste. Among them, the aesthetics of Baitu, Hengjing, Nanguan and Xitang Rivers were the poorest. Because of the lack of water landscape and water culture concepts, there is only one famous place beside a river or lake in Xinghua; Duotian which

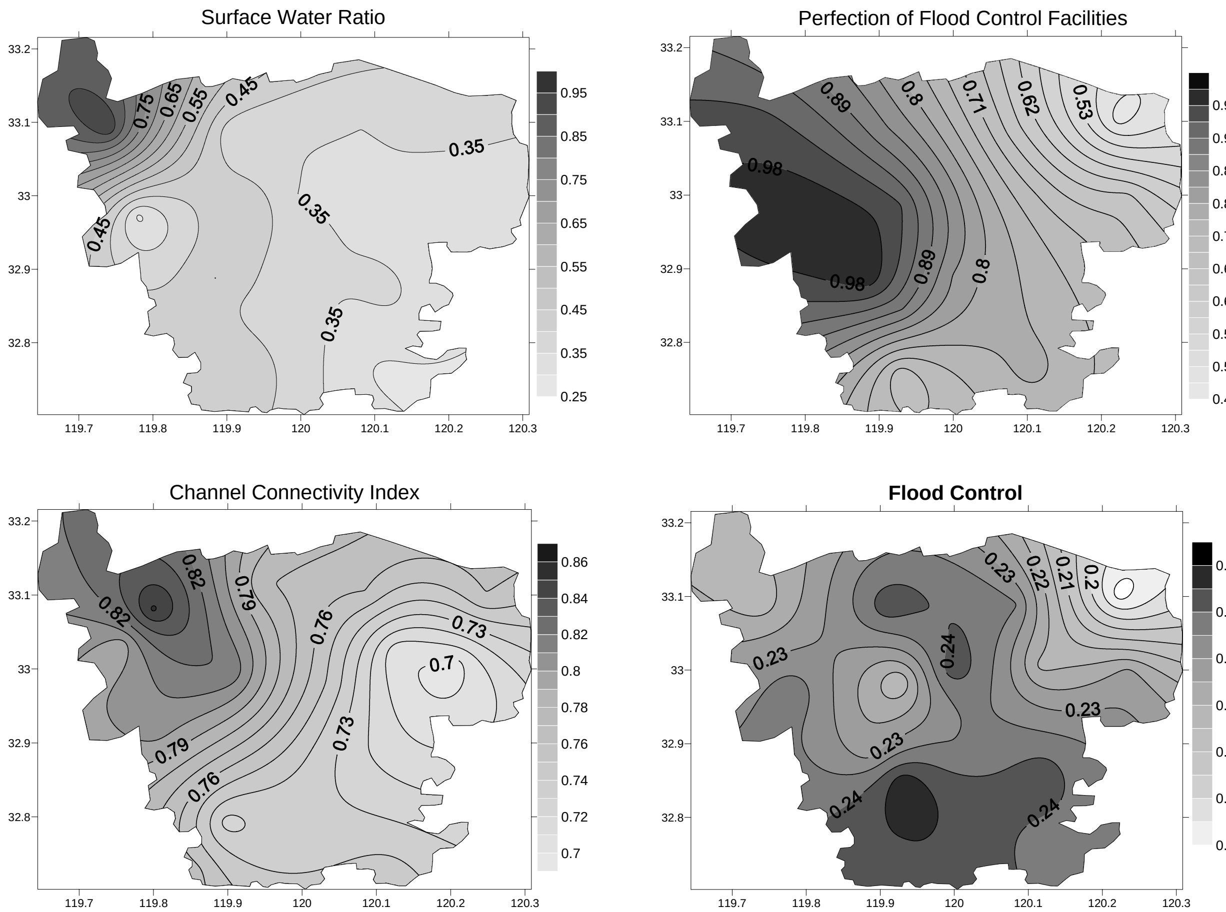

Fig. 4 The spatial distribution of the surface water ratio, perfection of flood control facilities and channel connectivity index, and the flood control index which was calculated from the previous three using the entropy-weighted sum model.

has been recently created next to the Xiaguan River and contains many streams flowing through blooming flowers, providing enjoyment for visitors. Besides that, special tourism planning has not yet been carried out in other regions, so tourism is generally lower.

The landscape conditions in Xinghua are generally lower than the average in Jiangsu Province because socio-economic development has not reached the level that can restrict construction and support water landscape planning and restrict the construction and ecological and landscape restoration. Conversely, awareness of environmental protection is low and many residents have used the riparian area for building dwellings or for agricultural land.

Characteristics of social service functions

Due to space limitations, only the flood control element is discussed here. As for assessing the ecological function, we combined the existing 35 towns into 15 subareas and calculated the indicator values of each. Figure 4 shows kriged contour maps of three indicators of flood control and the flood control index itself. The surface water ratio and channel connectivity index values were obviously higher in the northwest area where lakes are most numerous. The maximum value of perfection of flood control facilities is around west of Xinghua where the city centre is located.

CONCLUSIONS

As degradation becomes the primary problem faced by river ecosystems in countries all over the world, more attention has been paid to river restoration and sustainable river management. Nowadays most ecosystem health assessments focus on a single river or lake, which is not effective for water body protection and management. We proposed a new index, “water health”, and established a system of indicators focusing on river plain network regions. The index involved four main elements applied to Xinghua city, China. It was found that:

- The environmental function is in the stage of general conditions. The northwest area had the highest WQI and the central area near the city centre the worst water quality. NH_4-N, COD_{Cr} had the most negative effects on the WQI, whereas DO had the most positive effect.
- The ecological elasticity capability of the northwest around Dazong Lake is good status but the central urban area has suffered the highest intensity of disturbance. The ecological support ability of the whole study area is on the verge of collapse. The natural aquatic habitat has been destroyed and the biodiversity is decreasing every year.
- The landscape function is significantly lower than the normal level in Jiangsu Province. The waterfront structures of the majority of rivers are at the stage of the early-warning or pool level. The scenic aspects of the aquatic environment are poorly developed because of economic restrictions.
- The large-scale exploitation and utilization of the social service functions to meet the needs of urban development has affected the ecological health to some extent throughout the whole study area. The service function has attracted more attention than other functions as humans always attempt to exploit the service functions of rivers and ignore their other important functions.

From the conclusions above, we propose that the main countermeasures to improve the water health in Xinghua city are strict controls on wastewater discharge to improve, and at the same time enhance, environmental education. Based on this research, a suitable mathematical model should be developed to evaluate the water health ability of the whole region.

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REFERENCES

Cai, Q. H., Tang, T. & Liu, J. K. (2003) Several research hotpot in river ecology. *Chinese J. Appl. Ecol.* **14**(9), 1573–1577 (in Chinese).

Choi, S. U., Yoon, B. & Woo, H. (2005) Effects of dam-induced flow regime change on downstream river morphology and vegetation cover in the Hwang River, Korea. *River Res. & Appl*. **21**, 315–325.

Dong, Z. R. (2005) River health connotation. *China Water Resour*. **4**, 15–18 (in Chinese).

Environmental Agency (2003) River Habitat Survey in Britain and Ireland. *Field Survey Guidance Manual: 2003 version*. EA, SEPA, Environment and Heritage Service.

GB3838 (2002) *Environmental Quality Standards for Surface Water*. The Environmental Science of China Press, Beijing, China.

Hall, P. O. J., Holby, O., Kollberg, S. & Samuelsson, M. O. (1992) Chemical fluxes and mass balances in a marine fish cage farm. IV. Nitrogen. *Mar. Ecol.-Prog. Ser.* **89**, 81–91.

Hernández-Romero, A. H., Tovilla-Hernández, C., Malo, E. A. & Bello-Mendoza, R. (2004) Water quality and presence of pesticides in a tropical coastal wetland in southern Mexico. *Marine Poll. Bull*. **48**, 1130–1141.

Jin, X. C. & Liu, H. L. (1990) *Lake Eutrophication Status in China*. Environment Science Publishing Company, Beijing, China (in Chinese).

Jordan, S. J. & Vaas, P. A. (2000) An index of ecosystem integrity for Northern Chesapeake Bay. *Environmental Science & Policy*. **3**, S59–S88.

Karr, J. R. (1991) Biological integrity: a long-neglected aspect of water resource management. *Ecol. Appl.* **1**, 66–84.

Karr, J. R. (1999) Defining and measuring river health. *Freshwater Biol*. **41**, 221–234.

Kondolf, G. M. (1997) Hungry water: effects of dams and gravel mining on river channels. *Environmental Management*. vol. **21**(4), 533–551. Springer-Verlag, New York, USA.

Kong, H. M., Zhao, J. Z. & Ji, L. Z. (2002) Assessment method of ecosystem health. *Chinese J. Appl. Ecol.* **13**(4), 486–490 (in Chinese).

Ladson, A. R., White, L. J. & Doolan, J. A. (1999) Development and testing of an index of steam condition for waterway management in Australia. *Freshwater Biol.* **41**, 453–468.

Leung, K. M. Y., Chu, J. C. W. & Wu, R. S. S. (1999) Nitrogen budgets for the areolated grouper, *Epinephelus areolatus*, cultured under laboratory conditions and in open-sea cages. *Mar. Ecol.-Prog. Ser.* **186**, 271–281.

Magilligan, F. J. & Nislow, K. H. (2005) Changes in hydrologic regime by dams. *Geomorphology***71**, 61–78.

Norris, R. H. & Thomas, M. C. (1999) What is river health? *Freshwater Biol.* **41**, 197–209.

Isik, S., Sasal, M. & Dogan, E.(2006) Investigation on downstream effects of dams in the Sakarya River. *J. Faculty of Engineering and Architecture of Gazi University Ankara* **21**(3), 401–408.

Petersen, R. C. (1992) The RCE: a riparian, channel, and environmental inventory for small streams in the agriculture landscape. *Freshwater Biol.* **27**, 295–306.

Qiu, Wanhua (2001) *Management Decision and Application Entropy Science*. China Machine Press, Beijing, China (in Chinese).

Rinaldi, M. (2003) Recent channel adjustments in alluvial rivers of Tuscany, Central Italy. *Earth Surf. Processes Landf.* **28**(6), 587–608.

Rinaldi, M., Wyzga, B. & Surian, N. (2005) Sediment mining in alluvial channels: physical effects and management perspectives. *River Res. Appl.* **21**, 805–828.

Surian, N. (1999) Channel changes due to river regulation: the case of the Piave River, Italy. *Earth Surf. Processes Landf.* **24**, 1135–1151.

Tang, T., Cai, Q. H. & Liu, J. K. (2002) River ecosystem health and its assessment. *Chinese J. Appl. Ecol.* **13**(9), 1191–1194 (in Chinese).

Townsend, C. R. & Riley, R. H. (1999) Assessment of river health: accounting for perturbation pathways in physical and ecological space. *Freshwater Biol.* **41**, 393–405.

Vugteveen, P., Leuven, R. S. E. W. & Huijbregts, M. A. J. (2006) Redefinition and elaboration of river ecosystem health: perspective for river management. *Hydrobiologia* **565**, 289–308.

Wang, J. & Wang, J. (1984) Some problems on the calculation among chlorophyll concentration, biomass and production of phytoplankton. *Wuhan Botany Res.* **2**(2), 249–258 (in Chinese).

Wu, R. S. S., Lam, K. S., Mackay, D. W., Lau, T. C. & Yam, V. (1994) Impact of marine fish farming on water quality and bottom sediment: a case study in the sub-tropical environment. *Mar. Environ. Res*. **38**, 115–145.

Zhao, Y. W. & Yang, Z. F. (2005) River health: concept, assessment method and direction. *Scientia Geographica Sinica* **25**(1), 119–124 (in Chinese).