Environ Geol (2009) 58:937–942
DOI 10.1007/s00254-008-1573-9

ORIGINAL ARTICLE

The influence of topography and land use on water quality of Xiangxi River in Three Gorges Reservoir region

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Received: 7 January 2008 / Accepted: 23 September 2008 / Published online: 25 October 2008

Abstract A self-organizing map (SOM) was used to cluster the water quality data of Xiangxi River in the Three Gorges Reservoir region. The results showed that 81 sampling sites could be divided into several groups representing different land use types. The forest dominated region had low concentrations of most nutrient variables except COD, whereas the agricultural region had high concentrations of NO_3N, TN, Alkalinity, and Hardness. The sites downstream of an urban area were high in NH_3N, NO_2N, PO_4P and TP. Redundancy analysis was used to identify the individual effects of topography and land use on river water quality. The results revealed that the watershed factors accounted for 61.7% variations of water quality in the Xiangxi River. Specifically, topographical characteristics explained 26.0% variations of water quality, land use explained 10.2%, and topography and land use together explained 25.5%. More than 50% of the variation in most water quality variables was explained by watershed characteristics. However, water quality variables which are strongly influenced by urban and industrial point source pollution (NH_3N, NO_2N, PO_4P and TP) were not as well correlated with watershed characteristics.

Keywords Land use · Redundancy analysis (RDA) · Self-organizing map (SOM) · Topography · Water quality

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Introduction

Although the majority of recent freshwater eutrophication research has mainly focused on lakes and reservoirs, the quality of flowing waters is also of great concern (Smith et al. 1999). Rivers constitute the main inland water resources for domestic, industrial and irrigational purposes, and play an important role in the hydrological and biogeochemical cycles (Singh et al. 2004). River water quality is controlled by numerous natural (such as topography, geology and climate) and anthropogenic (such as urban, agriculture, and deforest) factors (Perona et al. 1999). Understanding the state of river water quality and the influencing factors is important for establishing an effective water management system.

Early studies on river water quality were mainly focused on the influence of geomorphic characteristics such as drainage area, gradient and stream order on river physical characteristics (such as turbidity, dissolved oxygen concentration and temperature), understanding elemental dynamics, and quantifying diffuse sources of pollutants in catchments (Johnson et al. 1997). Recently, the increasing availability of geographic information system (GIS), remote sensing (RS), and multivariate statistics techniques have allowed researchers to quantify watershed characteristics and assess the influences of terrestrial ecosystems on river systems (Richards et al. 1996; Johnson et al. 1997; Fritch et al. 2000; Jarvie et al. 2002). Many current researches indicate that changes in land use, such as from forest to agricultural land, can dramatically alter the nature of particulate and dissolved material inputs to river (Cooke and Prepas 1998). At the same time, topographical features, such as slope and catchment area, are important factors that affect watershed hydrology as well as river water quality (Arnold et al. 1998).

Though there have been many studies linking watershed characteristics to river water quality, few studies have been conducted in Three Gorges Reservoir region, where a distinct landform and geologic characteristics may make river water quality different to other regions. In addition, after the filling of the Three Gorges Reservoir in 2003, numerous bays formed in downstream tributaries are facing serious eutrophication problems (Cai and Hu 2006; Ye et al. 2006; Ye et al. 2007). Understanding the spatial pattern of water quality and its relationships with watershed characteristic is important for watershed and reservoir management. This study herein focuses on describing the spatial pattern of water quality in a typical tributary of Three Gorges Reservoir, and linking the relationship between river water quality and the watershed characteristics.

Materials and methods

Study area and the data

The Xiangxi River system, located in the north-west of Hubei Province, P. R. China, is one of the longest tributaries (94 km long) in the Three Gorges Reservoir region (Ye et al. 2003). The elevation in the watershed is ranged from 60 to 3,087 m, and there are four main tributaries running into main channel of Xiangxi River (XX River): Guanmenshan River (GMS River), Jiuchong River (JCH River), Gufu River (GF River) and Gaolan River (GL River) (Fig. 1).

Field surveys were carried out at 81 sampling sites in June 19–23, 2004. Fourteen environmental variables were measured at each site. Latitude and longitude were measured with a hand-held GPS (Magellan GPS 315), water temperature (WT) was measured in situ. Other chemical variables, conductivity (Cond.), ammonium nitrogen (NH_3N), nitrite nitrogen (NO_2N), nitrate nitrogen (NO_3N), total nitrogen (TN), phosphate phosphorus (PO_4P), total phosphorus (TP), dissolved silicate (SiO_2), chemical oxygen demand (COD), alkalinity (Alk.), and Hardness (Hd.) were measured in the field laboratory according to the environmental quality standards for surface water of China (Wei et al. 1989) and the standard methods for observation and analysis in China (Huang et al. 1999).

Land use and topography data

To calculate the watershed characteristics of each sampling site, the catchment boundaries of all sampling sites were delineated on 1:50,000 digital elevation model (DEM) using the soil and water assessment tools (SWAT, http://www.brc.tamus.edu/swat/). Land use data in Xiangxi watershed was acquired through the Landsat 7 ETM + data (125/38, 28 November 2002). The classification of land use categories was based on a modified version of the Anderson et al. (1976) scheme, which was constructed specifically for natural resource applications. A supervised classification was performed using the maximum likelihood algorithm. Reference sites for the classification were identified on the image based on the field knowledge and 1990–1995 government land use maps. Land use was categorized into five classes: forest, grass and scrub, permanent vegetation (including forest, grass and scrub), agriculture, and urban (Table 1). The topographical variables of included sub-catchment area, mean sub-catchment

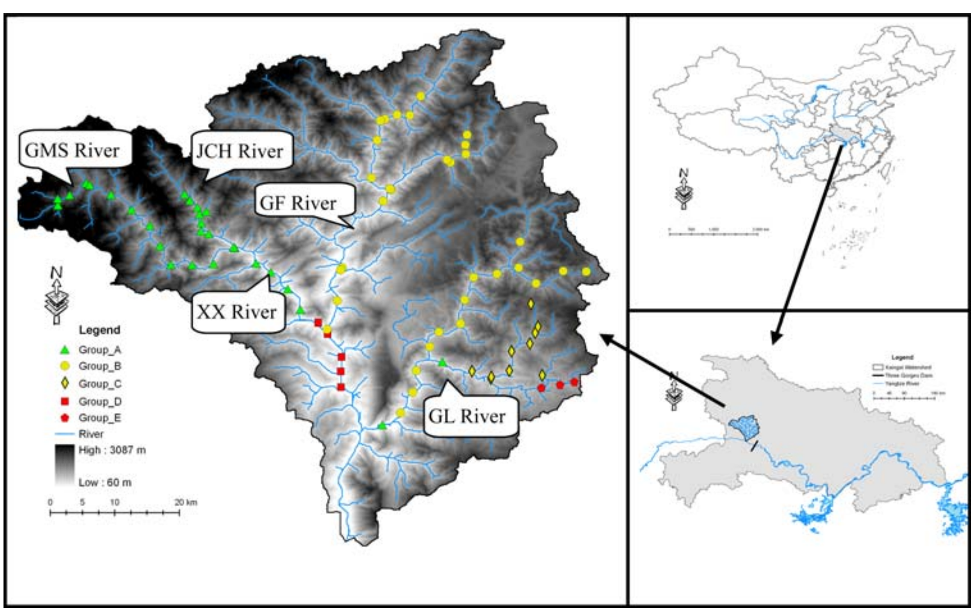

Fig. 1 The location of Xiangxi River, variation in watershed elevation, and the spatial pattern of river water quality derived by the self-organizing map (SOM)

Table 1 Basic statistic information of watershed characteristics, which was used to describe influence of land use (anthropogenic) and topography (natural) on river water quality

Parameters	Range	Mean ± CV
Land use		
Forest (%)	36.4–92.0	64.0 ± 22
Shrub and grass (%)	0.86–43.0	19.8 ± 56
Permenant vegetation (%)	75.4–95.5	83.7 ± 6.15
Agriculture (%)	0.00–24.6	14.3 ± 47
Urban (%)	0.00–0.51	0.10 ± 144
Topography		
Catchment area(km^2)	4.97–1963	346 ± 134
Mean catchment slope (°)	14.3–28.4	23.2 ± 16
Mean elevation (m)	1153–2424	1541 ± 20

slope, and mean sub-catchment elevation were derived from the DEM with the aid of spatial analysis function of GIS (Table 1). All the spatial data were projected onto a common coordinate system (WGS 1984) and analyzed in ArcGIS (ESRI, USA).

Non-supervised artificial neural networks

The spatial pattern of water quality in Xiangxi River system was partitioned by a non-supervised artificial neural networks, self-organizing map (SOM), developed by Kohonen (2001). SOM is the most popular non-supervised ANN which can be applied to ordination, clustering and visualization of high dimensional data and has been proved to be a useful tool in ecosystem research (Recknagel et al. 2006).

Redundancy analysis (RDA)

Redundancy analysis (RDA) was employed to assess the effects of watershed characteristics on river water quality. RDA is a form of direct gradient analysis to explore the relationships between two matrixes (Ter Braak and Prentice 1988; Leps and Smilauer 2003). Specifically, a matrix of predictor variables (e.g. watershed characteristics) is used to quantify variation in a matrix of response variables (e.g. river water quality). In general, two important outputs that may be obtained with this method: (1) the fraction of the water quality variables that are explained by the RDA axes; (2) the relationship between the water quality variables and the watershed characteristics. River water quality is hypothesized to be co-determined by land use (anthropogenic factors) and topography (natural factors). Therefore, the partial RDA (Liu 1997) was employed to determine the independent influences of anthropogenic and natural features on river water quality. Three sites (Group E in Fig. 1) were excluded from the RDA because they were polluted by local pyrites mining, which could interfere with the measurement of some water quality variables (Wei et al. 1989).

Results

Watershed characteristics

The catchment area of the sampling sites was ranged from 4.97 to 1,963 km^2, with a mean value of 346 km^2 (Table 1). The mean slope and elevation were ranged from 14.3 to 28.4°, 1,153 to 2,424 m, respectively.

Land use in the study region was dominated by forest, with the value ranged from 36.4 to 92.0% (mean 64.0%) among sampling sites. Shrub + grass was the next most prevalent cover, ranging from 0.86 to 43.0% (mean 18%). The mean values of agriculture and urban were 14.3 and 0.10%, respectively. The GMS River and JCH River watersheds had the highest forest coverage, whereas the GF River, GL River and the downstream of XX River watershed have larger agriculture area due to their relatively flat topography and lower elevation (Fig. 2). The agriculture in the upland of the study region watershed is dominated by tea, corn and tobacco, whereas the middle and lower regions are typified by orchards and paddy. Urban areas were mainly distributed in the middle and lower region of the watershed near the river bank.

Spatial pattern of water quality

The SOM algorithm clustered 81 sampling sites into five groups according to the similarity in water quality (Fig. 3a).

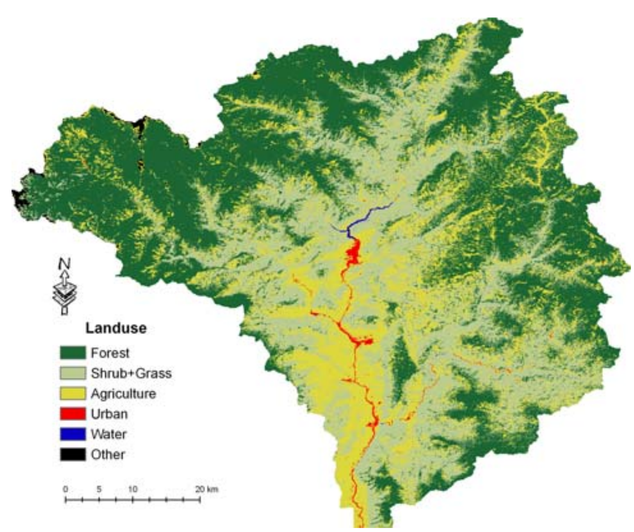

Fig. 2 The spatial distribution of forest, shrub + grass, agriculture, urban, water and other types in Xiangxi watershed (classified form Landsat 7 ETM + data, 125/38, 28 November 2002)

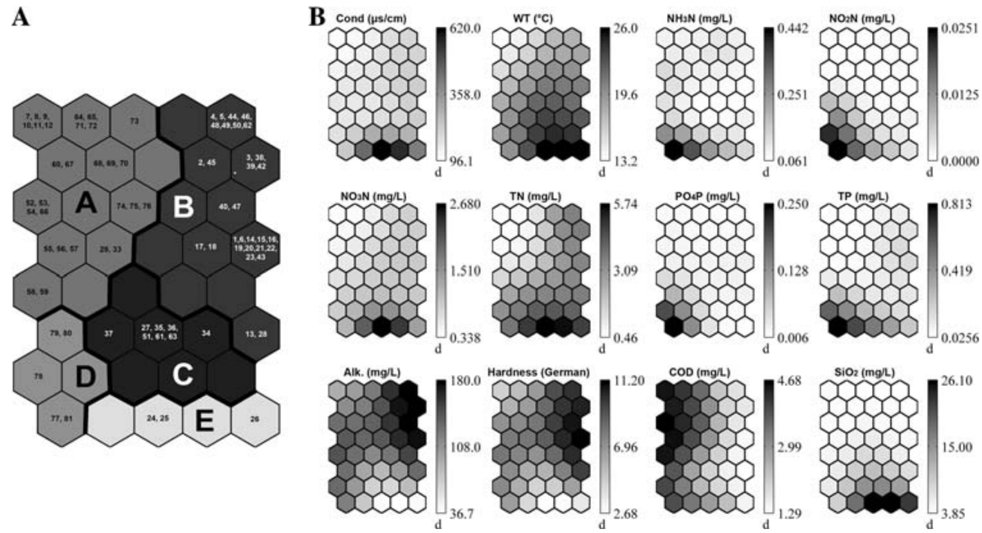

Fig. 3 Ordination and clustering of sampling sites by SOM (**a**), and the concentration of different water quality variables on the trained SOM map with a *gray scale* (**b**). *Dark* represents high values, while *light* represents low value

Table 2 Percentage of variance accounted for by land use and topography, partitioned by partial redundancy analysis

Variance component	Explanation (%)
Land use	10.2
Topography	26.0
Shared: land use + topography	25.5
Total explained	61.7
Unexplained	38.3

According to the spatial distribution of field sampling sites (Fig. 1), sites in the top-left cluster of the SOM (Group A) are located in the northwest of Xiangxi River watershed with higher forest coverage and less human land use. The sites in right cluster of the SOM (Group B and C) are distributed in the GL River and GF River, the main agricultural region in this watershed. The sites in bottom-left cluster (Group D) are in the downstream of Xiangxi River, which was polluted by the phosphorus related industry and urban waste water. The sites in bottom-right (Group E) are in a tributary of the Gaolan River, which was polluted by local pyrites mining seriously.

The twelve water quality variables are presented in the trained SOM (Fig. 3b). The region of Group A is characterized by low concentrations of Cond., WT, NO_2N, NO_3N, TN, PO_4P and TP, and a high concentration of COD. Group B was characterized by high NO_3N, TN, Alk., and Hardness. Group C was similar to Group B, with a high concentration of NO_3N and TN. The region of Group D was characterized by high concentrations of NH_3N, NO_2N, PO_4P and TP. The region of Group E was characterized by high concentration of Cond., and WT. High concentration of other chemical variables in this group, such as NO_3N, TN, SiO_2, may be a result of high ion concentrations which would cause inaccurate measurements (Wei et al. 1989).

Table 3 Mean and coefficient variation (CV) of water quality variables and their variances accounted by watershed characteristics

Parameters	Mean ± CV	Explanation (%)
Cond. (μs/cm)	195.2 ± 84	59.42
WT (°C)	18.8 ± 22	77.77
NH_3N (mg/L)	0.11 ± 161	3.99
NO_2N (mg/L)	0.004 ± 160	46.68
NO_3N (mg/L)	0.85 ± 93	59.48
TN (mg/L)	2.49 ± 69	68.17
PO_4P (mg/L)	0.03 ± 198	39.67
TP (mg/L)	0.14 ± 181	35.21
Alk. (mg/L)	133.2 ± 37	65.22
Hardness (German)	7.95 ± 40	59.71
COD (mg/L)	18.89 ± 8	59.21
SiO_2 (mg/L)	6.47 ± 104	52.71

Influence of watershed characteristics on water quality

The redundancy analysis indicated that watershed characteristics accounted for 61.7% variation of water quality in Xiangxi River (Table 2). When variance for the entire set of water quality parameters was partitioned between land use and topography by the partial RDA, topographical variables explained 26.0% and land use information alone explained 10.2% of the variance independently. The shared information of topography and land use explained 25.5% variation of water quality.

For specific water quality variables, more than 50% of the variations in Cond., WT, NO_3N, TN, Alk., COD and SiO_2 were accounted for by watershed characteristics (Table 3). More than 35% variations of NO_2N, PO_4P and TP were explained by watershed characteristics. NH_3N was poorly correlated with watershed characteristics. According to the relationships between water quality and watershed characteristics derived by RDA (Fig. 4), it could be found that water temperature and conductivity have negative correlation with altitude. NO_3N and TN were positively correlated with agriculture and shrub and grass, and a negatively correlated with the altitude and forest. SiO_2 was positively correlated with agriculture and a negative correlation to slope. COD was positively correlated with altitude and forest area. Hardness and alkalinity have a positive correlation to permanent vegetation and negative to altitude.

Discussion

This study has demonstrated that water quality in the Xiangxi River is strongly related to land use. The forest dominated region has low concentrations of most nutrient variables except COD, whereas the agricultural subwatershed has high concentration of NO_3N, TN, Alk., and Hardness. This pattern of good water quality in forested areas and high concentrations of nitrogen in agricultural areas has been demonstrated in many related studies (Hunsaker and Levine 1995; Allan 2004). The high concentration of COD in forest region may be caused by high levels of terrestrial organic matter (branches and leaves) enter into river channel. The region downstream of the urban area has high concentrations of NH_3N, NO_2N, PO_4P and TP, which may be a result of point source discharges of

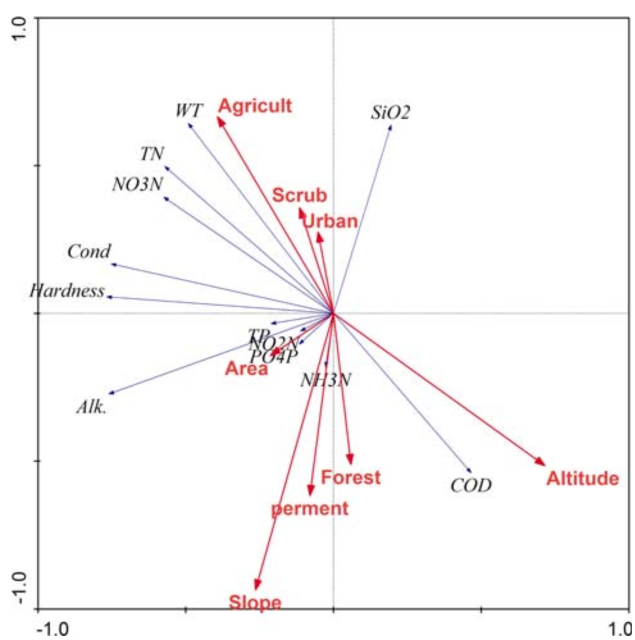

Fig. 4 Biplots of the river water quality and watershed characteristics in Xiangxi watershed by the redundancy analysis. Correlations between watershed characteristics and water quality variables can be obtained by projecting watershed characteristics on each water quality variable; the higher values mean higher correlations

sewage as well as the pollution from the phosphorus industry in watershed. The high value of Cond. in this region was due to the pollution of upstream pyrite mining.

More than 61% of water quality variation was explained by watershed characteristics (land use and topography). Surprisingly, the land use information only accounted 10.2% variance in water quality independently. Topographical characteristics could explain 26.0%, and the joint effect of land use and topography is 25.5%. In field observations, agriculture fields were mainly observed where the topography is relatively flat, whereas forest was distributed in high elevation regions. This indicates that the topography may constrain certain land use patterns in the Xiangxi watershed. The regression analysis indicated that altitude is significantly correlated with forest ($r = 0.66$, $P < 0.001$), shrub and grass ($r = -0.64$, $P < 0.001$), agriculture ($r = -0.82$, $P < 0.001$), and urban ($r = -0.43$, $P < 0.001$) land use. Slope was also significantly correlated with forest ($r = 0.57$, $P < 0.001$), shrub and grass ($r = -0.39$, $P < 0.001$), and agriculture ($r = -0.63$, $P < 0.001$).

River water quality is influenced by the watersheds through which they flow (Allan 2004). Our study indicates that topography and land use information can explain the majority of variation in water quality variables except for NH_3N, NO_2N, PO_4P and TP (Table 3). A study carried out in 62 catchments in the central Michigan achieved similar results (Johnson et al. 1997). They found that more than 50% variance in alkalinity, TN and NO_3N, and >40% variance in PO_4P were accounted for by watershed characteristics. TP and ammonium were poorly correlated with watershed characteristics, which they suggest is due to their strong relationship to particulate dynamics and the temporal scale of transport dynamics (Johnson et al. 1997). In our case, statistical analysis showed these variables have very large variation with a CV value more than 160% (Table 3). SOM indicated that the sites with the highest values of PO_4P, TP, NH_3N, and NO_2N were in group D (Fig. 3) and were located downstream of the phosphorus related factory and an industrial town which was polluted by the point source pollution. Hence, they could not be well explained by the watershed characteristics.

The present study demonstrates that the SOM and RDA techniques can be successfully used to study the relationship between water quality patterns and watershed characteristics. Through the SOM, the sampling sites in Xiangxi watershed could be grouped according to the similarity of their water quality. Partial RDA was then used to quantify the effects of different watershed characteristics on the river water quality. This study found that the water quality of the Xiangxi River was restrained by topography and land use. Future watershed management activities should considered the effects of both topographical characteristics and land use on river water quality.

Acknowledgments This work was funded by National Natural Science Foundation of China (No. 30330140, 40671197), Key Project of Knowledge Innovation Program of CAS (No. KZCX2-YW-427), and "973" Programme (No. 2002CB412300). The authors would like to thank the members of system and watershed ecology group for their assistance in field sampling. We also thank anonymous reviewers for their valuable comments in improving this manuscript and Rebecca Hale for her help in improving English presentation.

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