Water Resour Manage (2010) 24:1313–1332
DOI 10.1007/s11269-009-9498-y

Testing a Dynamic Complex Hypothesis in the Analysis of Land Use Impact on Lake Water Quality

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Received: 10 November 2008 / Accepted: 7 August 2009 /
Published online: 18 August 2009

Abstract In this study, we proposed a dynamic complex hypothesis that the impact of land use on water quality could vary along the expansion of the buffer size, and there should be an effective buffer zone where the strongest linkage occurs between land use and water quality. The hypothesis was tested and supported by a case study carried out in four watersheds in Hanyang District, China. More specific, buffer analysis and regression model were applied for studying the impacts of land use type, area proportion of land use type, and spatial pattern of land use on water quality. We conclude that not only the proportion of land use but also the spatial pattern moderates the impact of land use on water quality. Our study indicates that the identification of the effective buffer zones can provide new information and ideas for planning and management. Moreover, this study could also partially help to explain the conflicting results on the impact of land use on water quality in buffer versus in catchments in the literatures.

Keywords Spatial pattern · Effective buffer · Land use · Water quality · Hanyang District · China

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1 Introduction

The degradation of water quality is a key global environmental issue that needs urgent attention (Palmer et al. 2004). Studies have suggested that water degradation could be caused by two general sources: the point sources which typically include household or industrial wastewater and wastewater treatment plants (Kim et al. 2005), and the non-point sources (NPS) represented by the runoff from urban area and farmland (Leitch and Harbor 1999; Wang 2001). It is evident in recent years that urbanization has been one of the leading anthropogenic activities causing the destruction of natural ecosystems in China due to its thriving economy. The continued replacement of vegetative surface has made the rainfall, which once filtered through soil, now flow through storm drains and discharges directly into streams and coastal areas. As a result of rapid urbanization, the water quality degrades quickly and extensively (Changnon and Demissie 1996; Mander et al. 1998; Palmer et al. 2004; Conway and Lathrop 2005).

Research has studied the impact of land use on water quality by spatial analysis, statistical analysis, and hydrologic modeling (Mattikalli and Richards 1996; Hanratty and Stefan 1998; Rai and Sharma 1998; Tsihrintzis and Hamid 1998; Brezonik and Stadelmann 2002; Chang 2008; Amiri and Nakane 2009). A strong relationship between land use and water quality within catchments or watersheds has been suggested by previous studies (Gburek and Folmar 1999; Brezonik and Stadelmann 2002; Ha and Stenstrom 2003; Donohue et al. 2006; Moreno et al. 2006). Land use, in many cases, has been one of the key-contributing factors for urban water pollution (Changnon and Demissie 1996; Mander et al. 1998; Foley et al. 2005; Grimm et al. 2008). For example, urban and agricultural land uses have shown positive relationship with NPS loads; on the other hand, orchard and grassland contribute to NPS loads negatively (Basnyat et al. 1999; Wang 2001; Tong and Chen 2002; Moreno et al. 2006).

While a strong linkage has been suggested between land use and water quality at the catchments or watershed scale (Wang 2001; Tong and Chen 2002; Moreno et al. 2006), a number of studies have shown conflicting results on the impact of land use on water quality in buffers versus in catchments. For example, Johnson et al. (1997) found that the whole catchments explained slightly less of the water quality variability than that in the 100 m buffer. Similar analysis of land use data by Sawyer et al. (2004) showed that agricultural practices and urbanization occurring within 30 m buffer of the stream had higher correlations to biotic community structure than that at the catchments. Conversely, Sliva and Williams (2001) used multiple regressions to show that land use characteristics at the catchment scale had slightly greater influence on water quality than that in the 100 m buffer. Lastly, Hunsaker and Levine (1995) found that the relationship between land use and water quality was distinctly stronger at catchments scale than that in the 200 or 400 m buffer. The inconsistent results can be attributed to a number of factors, such as different characteristics of study regions, inconsistent parameters of water quality used in each study, and low resolution of digitized data (Sliva and Williams 2001). We also should point out that most previous studies focusing on the relationship between land use and water quality were only carried out in one buffer and catchments. However, the complexity and variability in spatial pattern and the trend of impacts of land uses on water quality have not been explored.

In general, the greater the percentage of land use significantly and negatively related to water quality, the more the loads of total nitrogen, total phosphorus, and other water quality parameters are present in water bodies (Mehaffey et al. 2005). Whereas, the greater the percentage of land use positively to water quality, the lower the loads of water quality parameters (Basnyat et al. 1999). Within a watershed, some land use forms act as NPS source and others function as sink. In addition, land use patterns are spatially heterogeneous in general. During storm water runoff, NPS pollutants delivered from NPS sources can be absorbed, deposited, and re-separated out on different land use types. This process is a multi-step, often episodic (Phillips 1989). Therefore, we proposed the dynamic complex hypothesis that the impact of land use on water quality could vary along the expansion of the buffer size, and that there should be an effective buffer zone where the strongest linkage occurs between land use and water quality. When beyond or under the effective buffer zone, the impact of land use on water quality should become weak or insignificant (Fig. 1), given that the land use characteristics themselves varied with distance.

In this study, we applied the principle of landscape ecology, which highlights the strong link between pattern and process (Gustafson 1998), to study the relationship between land use and water quality. Our objectives are: (1) to explain that water quality is an integrated result of positive and negative influences of land uses, (2) to quantify how much the influence of spatial pattern of land use on the surface water quality (Gillies et al. 2003), and (3) to test the dynamic complex hypothesis. We used buffer analysis and pattern analysis techniques to investigate the correlation of land

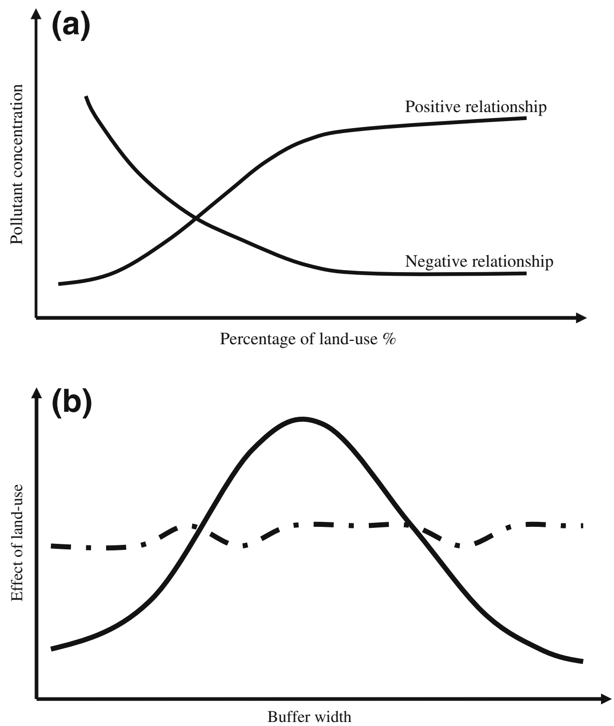


Fig. 1 Sketch of the relationship between land uses and water quality parameters. **a** The trends in positive or negative influence of land uses on water quality along the gradient of percentage of land use. **b** The effect of integrated land use on water quality along the gradient of buffer width; '——' delegates the strongest effect within a buffer width, and '– · – · –' delegates the similar effect in different buffer width. Noting: the percentage of land use and buffer width both are in a fixed studying region

uses with water quality in watershed varied with buffer distance along lakeshores by a stepwise regression model.

2 Materials and Methods

We selected four watersheds in Hanyang District in southern China (Fig. 2) as our study regions because they illustrate the process of the rapid urbanization and ecological and environmental problems caused by the urban growth during the past two decades. A previous study done by Ren et al. (2003) has suggested that a close to 94% of the variability in water quality classifications is explained by industrial land area in Shanghai which is the biggest city in the Yangtze River watershed. This study site, Hanyang District is a part of the Jianghan Plain, which is a historically famous and ecologically important wetland (Fang et al. 2005) in central China. However, only few studies have documented the interrelationship of urban land use and lake water quality in this area.

2.1 Description of the Watersheds

The study area contains four watersheds: Lake Long Yang (LY, 1,073.60 ha), Mo Shui (MS, 1,924.83 ha), Nan TaiZi (NTZ, 2503.68 ha), and San Jiao (SJ, 1,123.56 ha), as a portion of Hanyang District (2.21×10^4 ha), Hubei Province, China (E 114°3′∼114°17′, N 30°25′∼30°36′) (Fig. 2). Precipitation occurs mostly in spring and summer, especially in April to July. As a typical urban–rural area in the central of China, Hanyang has experienced significant urbanization expansion (population from 344,800 in 1989 to 536,749 in 2007) and consequently has had

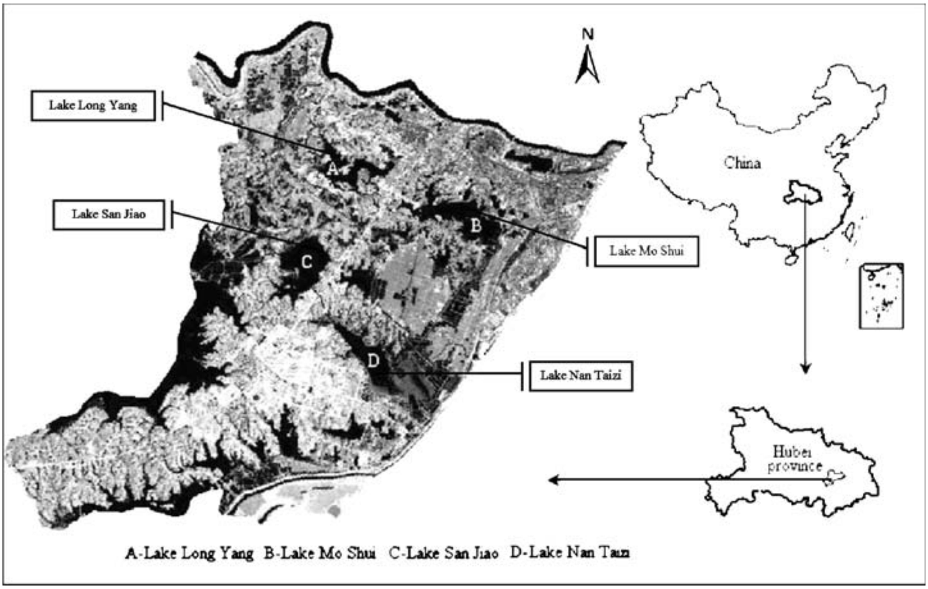


Fig. 2 Location of study sites. Hanyang District is located on the west of Yangtze River and the south of Han River

dramatic changes in urban spatial structure and residential density during the past two decades (population density from 3,768 people/km^2 in 1989 to 4,951 people/km^2 in 2007). In response to these changes, the four lakes have been providing wastewater sinks for the urban surface runoff and household wastewater. Currently, the Nan TaiZi wastewater treatment plant (WWTP) is functional and Zhuankou WWTP will be built in the near future. Under the current situation, the separation of the storm and sanitary sewer systems to prevent combined sewer overflows is weak, and the non-point sources are unregulated in the Hanyang District.

2.2 Catchments and Water Quality

Four lakes were divided into several catchments using the Soil & Water Assessment Tool (SWAT, Grassland, Soil & Water Research Laboratory 2001) model based on the 1:10,000 DEM data from National Fundamental Geographic Information System of China. Seventeen catchments were generated from watersheds: four catchments in Lake Long Yang, six in Lake Mo Shui, four in Lake Nan TaiZi, and three in Lake San Jiao (Fig. 3). Seventy sampling sites were chosen in which 15, 21, 20 and 14 sites from Lake Long Yang, Mo Shui, Nan TaiZi and San Jiao, respectively. These samples

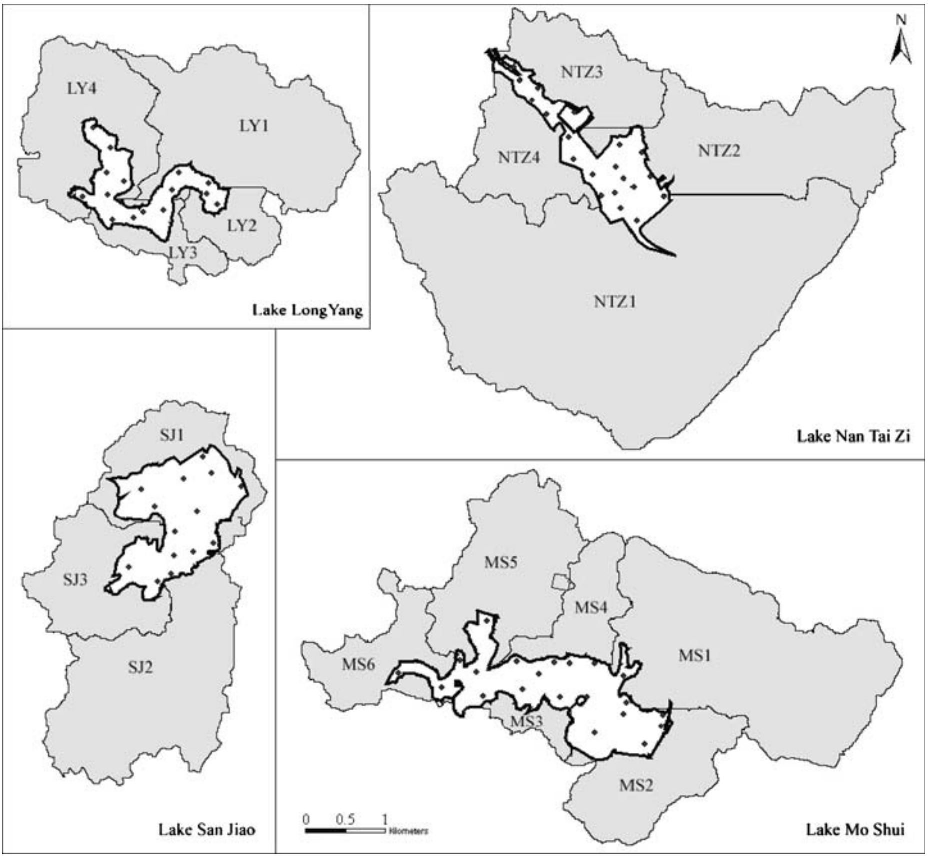


Fig. 3 Distribution of sampling sites in different catchments. *Black points* denote the sample sites

were assigned within the lakes to a particular portion of the watersheds to ensure that not less than three sampling are taken to represent the effects of land use from catchments. We assume that the sampling points are relatively independent or less affected by each other.

Sampling data were typically collected in 24∼48 h after rainstorms in July 2004. Based on the national environmental quality standard for surface water (GB3838-2002) by State Environmental Protection Administration of China (2002), the water quality parameters in this study were selected as total nitrogen (TN), total phosphorus (TP), ammonium (NH_4), chemical oxygen demand (COD), and non-metallic element, Selenium (Se). We obtained the data of NH_4 and COD in each sample site using potable water quality analyzers, 6600EDS (YSI Int.) and U-10 (Horiba Int.). In the process of field investigation, three replicates were averaged in each sample site. The alkaline potassium persulfate digestion-UV spectrophotometric method was applied to determine the measurements of TN. The ammonium molybdate spectrophotometric method was used to measure TP. The non-metallic Se data were obtained by plasma transmit spectrum instrument ICP–OES (VISTA-MPSX).

2.3 Land Use Classification

Land use data were extracted through the high-resolution Quickbird multispectral imagery (resolution of 0.6 m) acquired on January 23, 2003 (SPOT Company). The supplementary data for study were 1:50000 Relief Maps supported by National Geomatics Center of China. Auto-interpretation by computer from Quickbird imagery could meet with the disturbance of shadows in the high-resolution (0.6 m) imagery. Therefore visual interpretation method was employed in the land use classification of the high-resolution image in ArcGIS 8.1 (ESRI 2001). The satellite-derived land use data estimated from 2003 Quickbird image were calibrated by fieldwork (79 samples) to achieve a better accuracy (85%).

According to the Standard of Land use Classification of China (Table 1), the modified classification system employed fifteen general categories: canal, pond, agriculture(AG), forest, artificial grassland (Grass), rural habitation (RH), urban habitation (UH), industry, commercial, impervious road (IR), pervious road (PR), school, office and open space (Office), land leveled (LL), and bottomland (BL). We generated buffer zones through drawing a line from the edge of the lake to the furthest edge of the watershed, and then dividing that line into equal segments, with each 10% of the total distance associated with the edge of a circle around the lake by using the buffer tools in ArcGIS 8.1 (ESRI 2001). One hundred percent of a buffer zone is equal to the whole catchment. The proportion of land use type was extracted for catchments and the proportions of land use types were calculated in buffer zones.

Landscape indices were used to quantify the spatial characteristics for the buffers (McGarigal and Marks 1995). Here we used Shannon's Diversity Index (SHDI), Shannon's Evenness Index (SHEI), and Landscape Division Index (DIVISION) measured through FRAGSTATS3.3, an open software to determine the spatial pattern of land use. SHDI was applied to measure the land use diversity. SHDI should increase as the number of different land use types increases and the proportional distribution of area among land uses becomes more equitable. SHEI is expressed as an even distribution of area among land uses. SHEI approaches '1' when the distribution of area becomes increasingly even. DIVISION is interpreted as the

Table 1 Land use/land cover classification system for the Hanyang District of Wuhan, China

I	II	III	Remarks
100 Water	110 River		Yangtze River; Han River
	120 Lake		Natural and artificial lakes
	130 Canal/ditch		Natural and artificial canal/ditch
	140 Pond		Natural ponds, artificial fishes and lotus ponds
200 Agriculture			Dry lands and vegetable lands
300 Vegetated	310 Forest		Nature forests and artificial trees in parks or along the streets
	320 Natural grassland		Natural grasslands.
	330 Artificial grassland		Grasslands planted in golf course, palestra, schools and parks etc
400 Developed	410 Residential	411 Rural residential	Houses in rural area, usually low density residential
		412 Urban residential	Houses in urbanized area, usually high density residential
	420 Commercial		All kinds of shopping malls, marketplaces, stores and their corresponding parking spots
	430 Industry and quarries		Heavy industry, light industry, quarry plants etc.
	440 School		All kinds of education lands, including universities, high schools, middle schools and elementary schools
	450 Transportation	451 Impervious roads	Roads with impervious surfaces, such as asphalt
		452 Pervious roads	Roads with naked and pervious surfaces
	460 Office and open space		All kinds of office building and recreational plaza with more pervious surfaces
500 Bare	510 Land leveled		Lands for future construction
	520 Bottomland		Bare lands and wetlands which are around river and lakes

probability of land use area distribution. DIVISION achieves its maximum value (1.0) when the landscape is maximally subdivided.

2.4 Modeling the Relationship Between Land Use and Water Quality

The delivery process of pollutants from upstream contributing areas to a receiving downstream point is a multiple, often episodic process (Phillips 1989). Factors, such as land use types, soil, slope and geology, are important factors impacting the NPS pollutants transport. NPS pollutants delivered from NPS sources such as residential, urban, and agriculture areas are absorbed, deposited and re-separated out when flowing through land use types, especially through forest and grassland adjacent to water bodies.

In this study, we used the stepwise regression model to evaluate NPS pollutants attenuation in flow through various land uses to the lakes (Basnyat et al. 1999, 2000). In this model, proportions of fifteen land use types were chosen as land use variables. The pollutant concentrations of TN, TP, NH_4, COD, and Se were put into the model as dependent variables to identify the land use variables effectively impacting on water quality. Thus the NPS pollutant concentration (NPS_i) can be expressed in the following equation:

$$NPS_i = \alpha \times exp\,(\beta_1 \mathrm{Canal}_i + \beta_2 \mathrm{Pond} + \beta_3 \mathrm{AG} + \ldots\ldots \beta_{14} \mathrm{LL} + \beta_{15} \mathrm{BL}_i) \qquad (1)$$

Equation 1 can also be expressed as

$$Ln\,(NPSi) = \chi + \beta_1 \mathrm{Canal}_i + \beta_2 \mathrm{Pond} + \beta_3 \mathrm{AGi} + \ldots\ldots \beta_{14} \mathrm{LL} + \beta_{15} \mathrm{BL}_i \qquad (2)$$

Where α and χ are constants, and $\beta_1, \ldots \beta_{15}$ are coefficients that depict the direction and strength of the relationships between proportion of land use type and NPS_i. When β value is positive, it indicates that this particular land use type is exporting NPS_i. When β value is negative, this particular land use type is reserving NPS_i. The model allows us to find out the effect of land use to NPS_i within different buffers. The analyses process was carried out by linear regression in SPSS 10.0 for windows, the method chosen was stepwise, and F test was used to the stepping method criteria, more specific, the probability of F to enter was $\leq$0.100, the probability of F to remove was $\geq$0.110. T test was used to identify the significant of the coefficients of independent variables ($p \leq 0.05$) entered in the final stepwise model.

3 Results

3.1 Water Quality

The concentrations of five surface water quality parameters in seventeen catchments were monitored (Fig. 4). The levels of TN, TP, COD and Se were over the national grade V (seen in GB3838-2002 by EPA of China 2002). Specifically, the concentration of Se was ten times greater than that of the grade V. Surface water loads were higher in Lake Long Yang, but lower in Lake San Jiao (grade II). The variability of these parameters in the catchments was remarkable. For example, catchments LY1 and LY2 had the highest concentration values comparing with other catchments for TN, TP, NH_4, and COD. Reversely, these four parameters in catchments SJ1, SJ2, SJ3, NTZ3, and NTZ4 were lower.

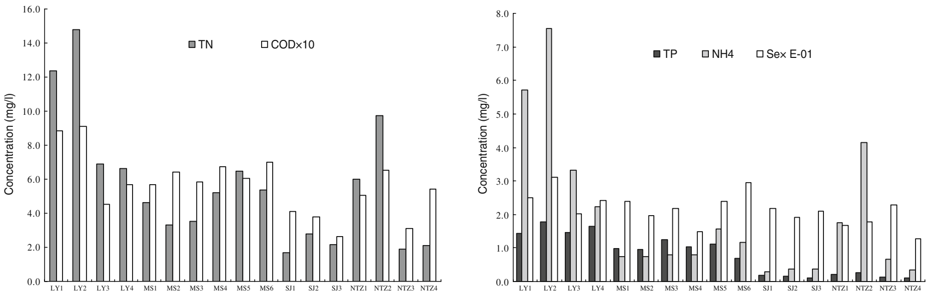


Fig. 4 Changes in surface water quality of TN, TP, COD, NH_4 and Se in 17 catchments, in which the concentration data of COD were smaller ten times than the monitoring data, and the concentration data of Se were bigger ten times than the monitoring data

3.2 Land Use Characteristics

Fifteen land use types were classified in the study. Proportions of land uses in the 10%∼100% buffer zones along the lakeshores were generated; only the results of land use classification in 10%, 50% and 100% buffer zones were listed due to the size of the datasets (Fig. 5).

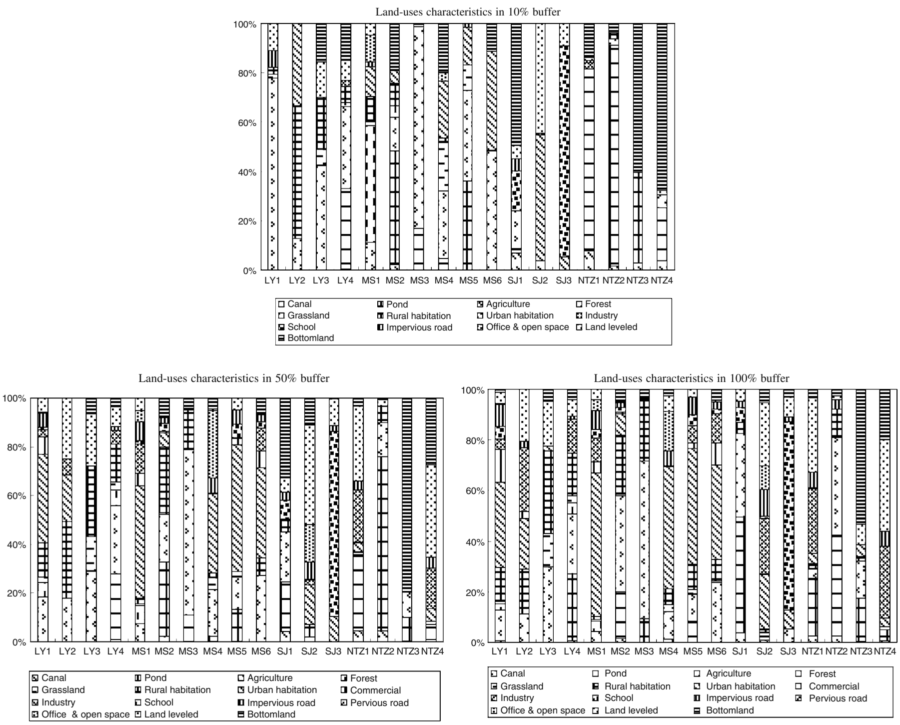


Fig. 5 Land use proportions in 10%, 50% and 100% buffers in 17 catchments. Land use proportions varied with the size of the buffer zones in 17 catchments

Land use proportions varied with the increasing of buffer zone size. The main land use type, agriculture exhibited four clear trends of proportional changes. Firstly, its proportion increased gradually with the distance to the lakeshore in catchments MS2, SJ1, and NTZ2. The area proportion increased from 2.52% in 10% buffer to 38.68% in 100% buffer in NTZ2. Secondly, the agriculture proportion decreased gradually in catchments LY1, LY2, LY4, MS1, MS3, MS6, and NTZ4. For example, the proportion increased from 77.83% in 10% buffer to 12.31% in 100% buffer in LY1. Thirdly, the proportion trend was unimodal in LY2, in particular, the peak proportion of agriculture was at 17.91% in 50% buffer. Finally, the agriculture land type was absent in some buffer zones especially near the lakeshore in catchments SJ1, SJ2, and NTZ1. There was no agriculture land type in the 40% buffer in SJ2. Other land uses had similar dynamic trends as well as agriculture land use (Fig. 5).

The spatial pattern of land uses varied in the buffer zones. The large proportion of every land use could provide a clue for land use distribution. The fluctuating values of the landscape indices with buffer distance from the lakeshore depicted the changing patterns of land use (Fig. 6). With the buffer size increasing, the values of SHDI increased gradually in LY2. Similar situations also occurred in catchments LY4, MS5, MS6, SJ2, SJ3, NTZ1, NTZ2, NTZ3, and NTZ4. A “U” shaping curve, a unimodal trend and a fluctuating pattern were also symbols of the SHDI in other catchments. The second landscape index, SHEI displayed both increasing trend and decreasing trend, “U” shaping curve, unimodal trend and fluctuating pattern with the increasing of the buffer size. The third landscape index, DIVISION also showed

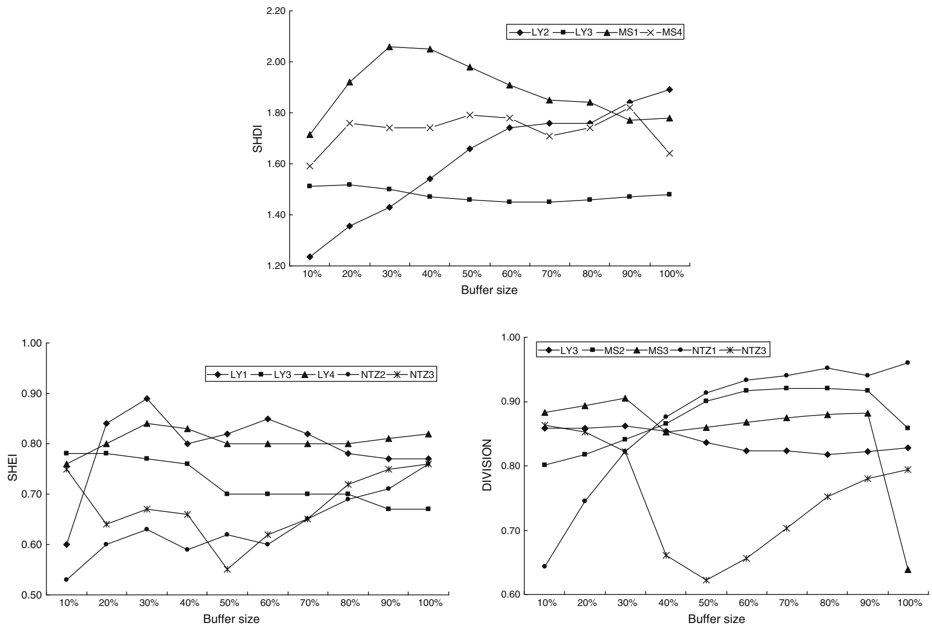


Fig. 6 Typical trends of landscape indices with buffers size increasing in 17 catchments. Four types of typical trends of SHDI, i.e. increasing trend, “U” shaping curve and unimodal trend and fluctuating pattern with buffer size increasing. And five types of typical trends of SHEI and DIVISION, i.e. increasing trend, decreasing trend, “U” shaping curve, unimodal trend and fluctuating pattern with the increasing of buffer size

Table 2 Results of stepwise multiple regression of the effect of land use types on lake water quality, within 100%~10% buffers, in 17 catchments of Hanyang District

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Ln (TN)										
RH	0.0167	0.02033	0.01769							0.0298
Commercial										0.0805
School	−0.0123	−0.0118	−0.0133	−0.0155	−0.0151	−0.0138	−0.0132	−0.0135	−0.0137	
PR			−2.062							
BL	−0.0173	−0.0175	−0.0199	−0.0218	−0.0218	−0.0239	−0.0267	−0.0296	−0.0311	
Model R^2	0.689	0.790	0.790	0.581	0.543	0.520	0.520	0.524	0.523	0.411
Ln (TP)										
AG	0.0244	0.0262	0.0288	0.0387	0.0656	0.0244	0.0229			
RH	0.0332	0.0374	0.0540	0.0590	0.0494	0.0506	0.0527	0.0723	0.0757	0.0527
UH						0.0280	0.0280	0.0232	0.0221	
IR			0.209	0.219	0.2					
PR				−3.64	−6.068					
LL			−0.0251	−0.02						
BL										−0.0344
Model R^2	0.563	0.566	0.803	0.876	0.808	0.668	0.655	0.554	0.561	0.560
Ln (NH_4)										
Canal		−0.279								
Pond	0.0204	0.0312								
AG	0.0214									
Grass									−0.15	
RH	0.055	0.0564	0.0544	0.0504	0.0525	0.0526	0.0521	0.0553	0.122	0.0740
Commercial										0.0922
IR		0.119								
PR									−8.302	−4.848
Model R^2	0.734	0.837	0.448	0.353	0.328	0.314	0.307	0.316	0.576	0.572

Table 2 (continued)

	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Ln (COD)										
RH		0.0076								
Commercial						0.0329	0.0311	0.0310	0.0330	0.0403
School	−0.0221	−0.0223	−0.0244	−0.0261	−0.026	−0.0249	−0.0247	−0.0252	−0.0254	−0.0252
IR	0.0489									
LL	−0.0124	−0.0099		−0.0063						
BL	−0.0066	−0.0057	−0.0089	−0.0093	−0.0097	−0.0093	−0.0104	−0.0115	−0.0119	−0.0114
Model R^2	0.889	0.910	0.859	0.889	0.852	0.886	0.893	0.891	0.893	0.893
Ln (Se)										
RH		0.0105	0.0099	0.0097						
UH						0.0069		0.0053		
Commercial		0.107	0.0467	0.0522	0.0644	0.0276	0.0357	0.0321	0.0392	0.0424
IR					−0.0434	−0.0597	−0.0377	−0.058	−0.0342	−0.0327
Model R^2		0.540	0.454	0.454	0.448	0.471	0.373	0.563	0.413	0.461

A negative correlation shown as "–" and no "–" data indicates a positive correlation. Significant correlation at the 0.05 level, $P \leq 0.05$

similar fluctuating trends with SHEI in the seventeen catchments at various buffer levels.

3.3 Relationship Between Land Use and Water Quality

The relationships between land use proportion and water quality at watershed scale (100% buffer) were presented in Table 2. The results indicated that proportions of rural habitation and commercial land use had a positive correlation with TN concentration ($R^2 = 0.411$, $P = 0.025$) within 100% buffer. TP concentration had a positive relationship with proportion of rural habitation, and a negative relationship with proportion of bottomland ($R^2 = 0.560$, $P < 0.001$). Proportion of rural habitation, commercial land use, and pervious road contributed to a significant relationship with NH_4 concentration ($R^2 = 0.572$, $P = 0.01$). COD concentration was positively correlated to proportions of commercial land use and school, and negatively to proportion of bottomland ($R^2 = 0.893$, $P < 0.001$). Proportion of commercial land use had a positive effect on Se concentration, while impervious road had a negative effect on Se ($R^2 = 0.461$, $P = 0.013$).

Table 3 Correlation between water quality and landscape indices

		TN	TP	NH_4	COD	Se
10% buffer	DIVISION		0.633**			
	SHDI		0.490*			
	SHEI		0.580*			
20% buffer	DIVISION		0.548*			
	SHDI					
	SHEI		0.603*		0.487*	
30% buffer	DIVISION		0.496*			
	SHDI					
	SHEI	0.509*	0.556*		0.598*	
40% buffer	DIVISION		0.527*		0.538*	
	SHDI					
	SHEI		0.503*			
50% buffer	DIVISION		0.494*		0.588*	
	SHDI				0.510*	
	SHEI		0.486*		0.642**	
60% buffer	DIVISION				0.591*	
	SHDI				0.530*	
	SHEI	0.501*	0.502*	0.485*	0.655**	
70% buffer	DIVISION				0.580*	
	SHDI				0.527*	
	SHEI	0.557*	0.494*	0.548*	0.665*	
80% buffer	DIVISION				0.565*	
	SHDI				0.504*	
	SHEI	0.554*		0.562*	0.599*	
90% buffer	DIVISION				0.574*	
	SHDI				0.530*	
	SHEI				0.541*	
100% buffer	DIVISION					
	SHDI					
	SHEI	0.518*		0.523*		

*Correlation is significant at the 0.05 level, $P \leq 0.05$; **correlation is significant at the 0.01 level, $P \leq 0.01$

Land use types related to water quality changed with the increasing sizes of buffer zones (Table 2). Proportion of school and bottomland had significant relationship with TN concentration ($R^2 = 0.523$, $P = 0.006$) in the 90% buffer, which was different with land use types in the 100% buffer. Within 40%∼90% buffers, the land use types related to TN were concurrent with the 100% buffer. However, rural habitation, school, pervious road, and bottomland all had significant relationship with TN in the 30% buffer, and then the land use types related significantly to TN only involved rural habitation, bottomland, and school in the 10%∼20% buffer. Bottomland had negative relationship with TP in the 100% buffer, whereas bottomland was insignificant with TP in the 10%∼90% buffers. Land use types were coincident within 80%∼90% buffers, similar within 60%∼70% buffers, and different in 50% buffer. Land leveled had negative effect on TP in the 40% buffer. Only rural habitation and agriculture had effects on TP in the 10%∼20% buffers. The way that various types of land uses are related to NH_4, COD, and Se also changed with buffer sizes.

Water quality was also strongly related to the spatial pattern of land use. As shown in Table 3, DIVISION had a significantly positive relationship with TP concentration in the 10%∼50% buffers and with COD concentration in 40%∼90% buffers. SHDI had a positive effect on TP concentration in the 10% buffer and on COD concentration in the 50%∼90% buffers. However, an insignificant relationship between SHDI and water quality was represented in 20%∼40% and 100% buffers. To the relationship of SHEI with water quality, our results indicated a positive relationship with TN and NH_4 in the 100% buffer, with COD in the 90% buffer, and with TN, NH_4 and COD in the 80% buffer. SHEI was also significantly related to TN, TP, NH_4, and COD in the 60% to 70% buffers.

4 Discussion

4.1 Impact of Land Use on Water Quality

Previous studies have suggested the general trend of the impact of urban land use on water quality. For example, the total suspended solids (TSS), TP, and TN concentrations from intensive agriculture and urban areas are normally 10∼100 times greater than those from the forested and idle lands in the Great Lakes region (Sonzogni 1980). Constructed sites, including commercial, industrial, high density residential, and street, are main pollutant sources in all urban land use types (Bannerman et al. 1993; Tong and Chen 2002). Our results on the correlation between water quality and land use at watershed scale (Table 2) also showed that the proportions of rural habitation and commercial land use had positive correlations to TN, TP, NH_4, COD, and Se concentrations; proportion of bottomland had negative impact on TP and COD concentrations; proportion of pervious road and school yielded negative influence on NH_4 and COD concentrations, respectively. Our results also indicated that proportion of impervious road appeared to have a negative effect on the non-metallic Se concentration. This could be due to the combination of storm and sanitary sewer systems, in particular, the negative influence of the impervious road on Se may reflect the negative relationship between sewer systems and Se. The non-metallic element could be reduced by the sediment basins and WWTPs available in the area.

Our study suggests that the correlation between water quality and land uses was due to the land use patterns in the buffers. For example, rural habitation positively contributed to TN in the 30%∼10% buffers, but this phenomenon did not occur in the 90%∼40% buffers. TN was negatively correlated to school and bottomland, and the correlation was significant in 90%∼10% buffers. Pervious road only influenced TN in the 30% buffer. There were differences in the influence of land use types on TP. For example, TP was affected by rural habitation in all buffers, by agricultural in the 70%∼10% buffers, and by impervious road in the 50%∼30% buffers. Other land uses, such as pervious road and bottomland had negative correlations with TP.

It was specially noted that the impervious road had a negative relationship with selenium (Se) in the 10%∼40% buffers. Commercial land use, rural habitation and urban habitation could provide sources for Se. The positive relationship between Se and commercial land use was analyzed along the gradient of buffers from 10% to 100%. The influence of rural habitation appeared in the buffers adjacent to lakes (10%∼30% buffers). The influence of urban habitation was significant in 60% and 80% buffers on selenium. It should not be overlooked that the relationship of land use types and Se was insignificant in the 10% buffer.

The characteristics of land use in this research suggested that agriculture, bottomland, and pond distributing around the lakes formed a "concentric circle" structure. Lake was placed in the center of the structure as the first inner circle. Agriculture, bottomland, pond, rural habitation, and land leveled around the center composed the second inner circle. It was apparent that the second inner circle functionally affected the water quality within 50% buffer. Industry, urban habitation, and commercial formed the outer circle which could influence water quality in the 60% buffer and beyond.

The results above were based not only on the area proportion of land uses but also on the spatial pattern of land uses. As shown in Table 3, the correlation of landscape indices and water quality changed in different buffers. The SHEI, representing even distribution of land use area, had a significantly positive correlation with water quality especially in the 60∼70% buffers. Clearly, the distribution pattern of land use was a critical factor affecting water quality and the even distribution of land use contributed to water pollution. The information on land use proportion exhibited the impact of land use on water quality in a two dimensional way; however it overlooked the effects of the distribution patterns of land uses. Spatial analysis addressed the deficiency of the two-dimension way with incorporating of the spatial distribution patterns of land uses.

We agree with the study of O'Neill et al. (1997) in which the spatial pattern of land use played an important role in modulating land use effects on water quality. We could literally see the "concentric circle" structure sprawling from the lakeshores to the watershed boundaries. The intermixing of land use, the landscape's poor connectivity, and the changing property of land use types contributed to the relationship of land use types with water quality within different buffers. For land use change, this could have significant impacts on runoff volume and consequently pollution concentrations (Tang et al. 2005; Van Dessel et al. 2008; Cao et al. 2009).

More realistically, the impact of land use on water quality could form a dynamic complex in a certain spatial region due to its diversity in area proportion and spatial pattern of land use. So the impact of land use on water quality happens to change along the expansion of buffers. We further explain that there is not enough land use area significantly related to water quality when the study area is under the effective buffer zone, so that the relationship between the land use and water quality appears weak. On the other hand, when beyond the effective buffer zone, other land use types intercepting into the relationship of land use with water quality can reduce the impact of land use on water quality. Our study results support the proposed dynamic complex hypothesis (Fig. 1). For instance, rural habitation had significant impact on TN in the 10%∼30% buffers; and then the impact diminished in the 40%∼90% buffers; surprisingly, it occurred at the entire watershed scale.

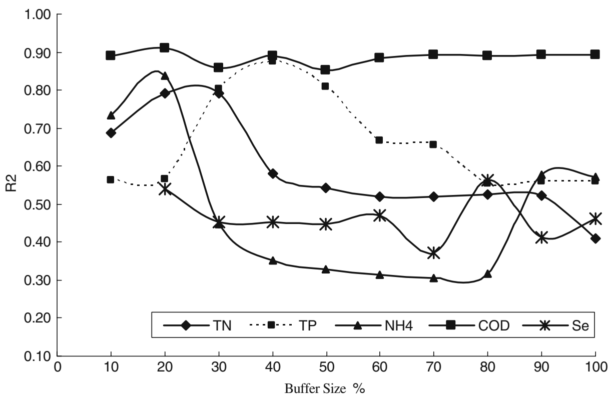
4.2 Evaluation of Correlation Between Land use and Water Quality

The next question is how to evaluate the dynamic and complex relationship between land use and water quality as discussed above. We used correlation coefficient (R^2) in the stepwise regression model as explanatory variable (Sliva and Williams 2001) to address the issue. Using R^2 to compare the relationships at catchments scale *vs.* buffers scale allowed us to determine whether land use near water body is a better predictor of water quality than that over the entire catchments (Hunsaker and Levine 1995; Johnson et al. 1997; Sliva and Williams 2001; Sawyer et al. 2004).

The curve of the correlation coefficient (R^2) could help clearly indicate the character of relationship between land use and water quality at various spatial scales (Fig. 7). R^2 of TN was lower at catchments scale ($R^2 = 0.411$) than that in other buffers; R^2 of TP at catchments was similar to R^2 in 10%, 20%, 80%, and 90% buffers. The peak values of the TN and TP curves revealed that land use had strongest influence on TN and TP in 20%∼30% and 30%∼50% buffers, respectively. Elsewhere, before or after the peak range, the influence all was weaker. This also supported the proposed dynamic complex hypothesis (Fig. 1). There were two peaks associated with the R^2 curves of Se and NH_4, suggesting that there were two regions where the land use significantly affected the concentrations of Se and NH_4. The fluctuating R^2 curve of COD might indicate similar effects of land use on COD within all buffers.

We found an irregular fluctuation in the curve of R^2 within TN, TP, NH_4, COD, and Se concentration gradient. Although the interactions among water pollutants were suggested (Shao et al. 2006), the water pollutants were independent with each

Fig. 7 R^2 curves appearing in multiple regression model from 10% to 100% buffers



other to some degree. Another reason was that these explanatory variables in the regression model referred to the proportion of land use, not to the pollutants concentration. Previous research and this study all assumed that same land use type holds same pollutant loads. In fact, anthropogenic influences could result in different pollutant concentrations on same type of land use. Therefore, it is essential to study the relationship between anthropogenic influences and water quality to a further step.

The change of land use proportion and landscape pattern along the gradient of buffer demonstrates the strong linkage between pattern and process. As suggested by Wiens (2002), the relationships of terrestrial landscape with freshwater ecosystems that are apparent at one scale may disappear or be replaced by other relationships at other scales. Furthermore, the pattern-process relationships might be a threshold phenomenon where only changes in pattern near the threshold occurs (Gustafson 1998). Clearly, our proposed dynamic complex hypothesis agrees very well with the general principle of landscape ecology. Most importantly, our study results explain why there are conflicting results on the impact of land use on water quality in buffer versus in catchments in the literatures. Furthermore, spatial pattern is the determinant factor for water quality and even for aquatic ecosystems (Alberti et al. 2007), and land use regulation should be put into critical step for urban planning.

4.3 Application in Nonpoint Source Pollution Management

Water quality of Lake Long Yang, Mo Shui, Nan Taizi, and San Jiao has all been degraded, because these lakes have received discharges of residential wastewater, industry wastewater, and multiple wastewater treatment plant effluent, combined with urban storm runoff through sewer system. WWTP alone may not significantly affect the water quality while the combined effects from point source and non-point source (urban land) can be reflected in the water quality data (Wang 2001). The results from this study can be a useful support for improving water quality of the four lakes. This study displayed that there were different effective buffer zones to lake water pollutants from urban NPS pollution. Expect for TN, NH_4 and COD, which buffer sizes were the same buffer size 20%, the effective buffer size to TN was in 40%; and the effective buffer size to Se was in 80%. The R^2 of the effective buffer zone was higher than that of watershed scale. The effective buffer zone of pollutants could provide new information and ideas for planning and management.

There is an increasing need to design and implement best management practices (BMPs) that will effectively improve water quality. Riparian buffers, constructed wetlands, porous pavement, infiltration basins, infiltration trenches, and other practices can intercept surface water runoff, treat tile drainage. In Berlin, BMPs converting existing retention tanks to soil filter tanks could offer a high effectiveness concerning stormwater treatment at relatively low costs (Sieker and Klein 1998). However, these practices are not equally effective in all locations. How to optimize the placement of these practices at a watershed scale is the key to optimize their effectiveness. Tomer (2002) has already used digital terrain analyses to identify sites best suited for riparian buffer and constructed wetland. Liu et al. (2009) developed an inexact linear programming model for optimal land use management to better protect water source and to gain maximum benefits from development. However Tomer and Liu's researches were operated only at the watershed and sub-watershed scale. As we can see there is an effective buffer zone for NPS pollutants in which the relationship between land use and water quality is the most strong and the placement of BMPs can optimize their effectiveness. This study demonstrated BMPs should be placed within 20∼40% buffer sizes as in series following the urban storm runoff rout in Hanyang District, China. Watershed approach has been used widely to manage water quality and quantity within specific drainage area or watershed; the buffer zone can be used to improve environmental protection agencies and managers' effectiveness. NPS pollution controlling planning and management in Hanyang can chose the way of integration of watershed approach with effective buffer zone to realize control goals. Consequently economical and environmental benefits can be realized through this approach.

5 Conclusions

We explored the relationship between land use and water quality in buffers at various spatial scales. We concluded that not only proportion of land use but also its spatial pattern moderated land use effects on water quality. By proposing a dynamic complex hypothesis, we further described the impact of land use types, land use proportions, and land use patterns on water quality. The impact of land use on water quality is stronger in the effective buffer than that in the catchments or watershed. Buffer analysis can provide a way to determine the effective buffer width. And our study indicated that the identification of the effective buffer zones could provide new information and ideas for planning and management.

Acknowledgements This research was supported financially by the State Key Project on Fundamental Studies (973) (2007CB407307), and the Innovation Group Program of National Natural Science Foundation of China (40621061).

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