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Assessing the effects of landscape pattern on river water quality at multiple scales: A case study of the Dongjiang River watershed, China

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ABSTRACT

Understanding how land use and land cover change influences the flow and water quality of rivers is critically important for river management and restoration. Human activities have transformed the landscapes in southern China where damaged river systems need to be restored and better managed for achieving environmental sustainability. Toward this end, we quantified the land use and land cover pattern of the Dongjiang River watershed, China between 1990 and 2006 based on remote sensing data and field measurements. We then analyzed how river flow and several water quality variables were related to landscape attributes at three scales: subwatershed, catchment, and buffer. Our results show that the water quality of the Dongjiang River differed among the upper, middle, and lower reaches and also changed significantly during the recent decades. These changes in space and time indicate a trend of accelerating deterioration in water quality. Also, land use and land cover pattern had major impacts on the flow and water quality of the Dongjiang River at multiple spatial scales. In particular, urban land use, although small in percent cover, exerted a disproportionately large influence both locally and over distance. We also found that most water quality variables (Cl^-, EC, NH_3–N, and NO_3–N) were correlated with landscape pattern on all three spatial scales although the correlation was stronger at the subwatershed scale than at the catchment and buffer scales. This scale multiplicity suggests that, while water-monitoring and river restoration need to adopt a multi-scale perspective, particular attention should be paid to the subwatershed scale. In addition, the control of pollution sources associated with socioeconomic activities ought to be explicitly incorporated in landscape management practices.

1. Introduction

Land use and land cover change is one of the major anthropogenic influences on ecosystems (Dale et al., 2000), which affects the water flow and quality of rivers in particular. For example, land use and land cover change can both modify the geomorphologic features and intensify the pollution sources of river systems. Rivers are recipients of pollutants from adjacent landscapes, acting as integrators of land-water interactions. Thus, river conditions such as flow and water quality are not only indicative of the health of the river ecosystems themselves but also the surrounding landscapes.

A number of studies have shown that changes in landscape pattern induced by human activities had major impacts on river conditions (Allan, 2004; Bhat et al., 2006; Hopkins, 2009). For example, land use and land cover change was strongly correlated with water chemistry parameters (Hunsaker and Levine, 1995; Tran et al., 2010), the species diversity of freshwater fish and macroinvertebrates (Hopkins, 2009; Weijters et al., 2009), and sediment metal concentrations (Hollister et al., 2008). The effects of land use and land cover change may take place at different spatial scales, including the watershed, catchment, and riparian zone. For instance, studies have shown that land use pattern adjacent to a stream was a better predictor of water quality than the spatial pattern of the entire watershed (Johnson et al., 1997; Dodds and Oakes, 2008), while others found that the proportions of land use types at the watershed scale better accounted for the variability in river water quality (Hunsaker and Levine, 1995; Sliva and Williams, 2001).

The scale dependence of the relationship between landscape pattern and water quality has important implications for both watershed research and management. River research and riparian management are often based on the idea that a catchment is a topographically and hydrologically defined unit (Hobbs, 1995; Allan et al., 1997). Administrative areas also have been used frequently because they represent the scales at which most

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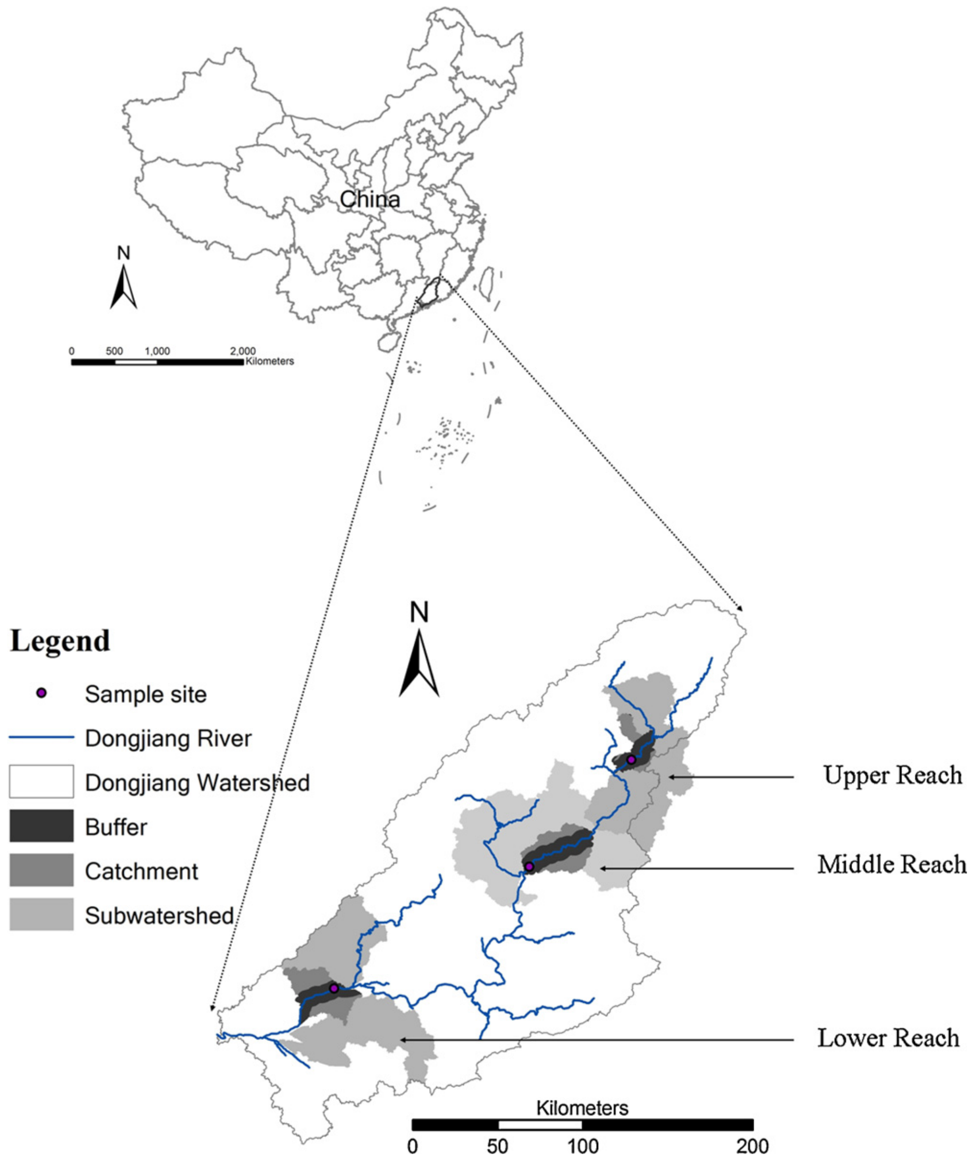

Fig. 1. Landscape pattern and socioeconomic factors on water quality at three scales: the subwatershed delineated by matching a drainage area and an administrative unit; the catchment defined by a land area that drains directly to the river within each subwatershed; and the buffer with different widths (500 m, 1000 m,. . ., 5000 m) on each side of the mainstream.

environmental policies, planning activities, and implementation actions usually take place. However, recent studies have suggested that a range of scales beyond the local catchment and across administrative units are needed if a fuller understanding of river systems is to be achieved (Allan, 2004; Hopkins, 2009; Johnson and Host, 2010). Also, river water quality is influenced by both the biophysical and socioeconomic factors in the adjacent landscape.

To improve our understanding of the multi-scale relationship between river water conditions and landscape pattern, we have investigated how land use and land cover change has affected the flow and water quality of the Dongjiang River in southern China from the local to watershed scales. Our main objectives were to (1) quantify the spatial and temporal patterns of river water characteristics, (2) explore the key landscape and socioeconomic factors influencing this pattern on the buffer zone, catchment, and subwatershed scales, and (3) discuss the implications of our study for sustainable river restoration.

2. Methods

2.1. Study area

The Dongjiang River is a tributary of Pearl River, located in the Guangdong Province, southern China (22°21′–25°12′ N, 113°04′–115°50′ E). It is the major source of the drinking water for Hong Kong downstream and also other parts of the Pearl River Delta in China (Liang et al., 2008). The mainstream of the Dongjiang River is 523 km long and encompasses a watershed area of 35,340 km^2 (Fig. 1). Based on the gradient in terms of both key biophysical and anthropogenic features (Table 1) along the river, we divided the river into three sections – the upper, middle, and lower reaches.

We explicitly recognized three distinctive spatial scales within the regional watershed: subwatershed, catchment, and buffer (Fig. 1). The subwatersheds were delineated by matching the boundary of drainage areas with that of administrative units in order to facilitate the use of socioeconomic information together with biophysical data. The subwatershed in the upper reach is

Table 1
The characteristics of the upper, middle and lower reaches in the Dongjiang River watershed in 2007.

Reach	Area sizes (km^2)	Percentage of land use/cover (%)		Topography	Mean discharge (m^3/s)	Inhabitants (million)
Upper	3387	Urban	0.41	Predominantly hill	302.9	0.92
		Agriculture	10.60			
		Forest	63. 17			
Middle	4588	Urban	2.34	Relatively flat	692	0.81
		Agriculture	9.18			
		Forest	61.41			
Lower	4273	Urban	22.42	Mainly alluvial plains	1187.6	8.36
		Agriculture	22.92			
		Forest	36.11			

Longchuan County, in the middle reach contains Yuancheng District and Dongyuan County, and in the lower reach is composed of Zengcheng city and Dongguan city. Within each subwatershed, a catchment encompassing the river was delineated. Within each catchment, we conducted analysis with a series of buffers of different widths, ranging from 500 m, 1000 m, 1500 m, to 5000 m on each side of the river. The subwatershed, catchment, and buffers with different widths provided a hierarchy of spatial scales for analyzing the relationship of the river flow and water quality to land use and land cover pattern.

2.2. Data acquisition and processing

The flow and water quality were measured at the hydrological stations (Longchuan, Heyuan and Shilong) in three subwatersheds of the study region in November of 1989, 1990, 1991, 1997, 1998, 1999, 2005, 2006 and 2007 over a span of 18 years (Fig. 1). These data were acquired from the Hydrological Bureau of Guangdong Province. Hydrological and chemical variables include flow, pH, Cl^-, sulfate ion ($SO_4{}^{2-}$), electrical conductivity (EC), total hardness (TH), biochemical oxygen demand (BOD_5), dissolved oxygen (DO), ammoniacal nitrogen (NH_3–N), and nitrate nitrogen (NO_3–N).

For each sampling site, the values of each variable were averaged for three time periods: 1989–1991, 1997–1999, and 2005–2007, which corresponded to the approximate dates of satellite imagery used to generate the land use and land cover maps. Most of the water quality variables appeared normally distributed according to the Sharpio–Wilk test, and were not transformed prior to analysis (except NH_3–N, NO_3–N, and EC). The concentrations of NH_3–N, NO_3–N, and EC were log-transformed to meet the assumptions of normality (as determined by the Sharpio–Wilk test with a significance level of p-value smaller than 0.05).

Recognizing that climatic conditions, particularly precipitation, may significantly affect river flow and thus water quality from year to year, our analysis only used data for the dry season (November) when the influence of precipitation on river flow was minimal. Our assumption is supported by the annual hydrographs for the Dongjiang River region, showing that precipitation significantly affected river flow between April and August, but not between October and January.

Social and economic data of the cities and counties across the three subwatersheds, including population and gross domestic product (GDP), were obtained from the Statistical Yearbooks published by the local governments between 1990 and 2007 (Dongguan Statistics Bureau, 1997, 2008; Heyuan Statistics Bureau, 1997, 2008; Zengcheng Statistics Bureau, 1999, 2006).

2.3. Quantification of landscape pattern

The mainstream and catchments of the Dongjiang River were delineated from a digital elevation model (DEM; Shuttle Radar Topography Mission, SRTM) with a spatial resolution of 90 m using Arc GIS 9.0. Landsat 5 Thematic Mapper (TM) images in December of 1990, 1998 and 2006, with a spatial resolution of 30 m, were used for landscape pattern characterization. Image preprocessing, including geometrical rectification, image registration, radiometric and atmospheric corrections, was conducted by Satellite Remote Sensing Ground Receiving Station in Beijing. The accuracy was improved to be within 0.5 pixel of root mean square error (RMSE). The processed TM images were used to create land use and land cover maps through a supervised maximum likelihood classification after a low-pass filtering with the ENVI 4.2 (The environment for Visualizing Images, Research System Inc.). The classification was revised according to visual interpretation and ground survey. Accuracy assessment was conducted with more than 30 ground control points (GCPs) evenly distributed, indicating that the overall accuracy of each land cover map was above 85%.

Five land use and land cover types were classified: water, urban, forest, agriculture, others. To quantify the land use and land cover pattern, we selected two landscape pattern metrics: percentage of landscape (PLAND) and patch density (PD) using the software package FRAGSTATS 3.3 (McGarigal and Marks, 1995). These metrics were calculated at each spatial scale described above for the three years for which remote sensing data were obtained (1990, 1998, and 2006).

2.4. Statistical analysis

A one-way balanced ANOVA was performed to explore if there were differences in river flow and water quality among the three reaches in the three periods. Paired t-test was performed at the 5% level of significance to test whether water quality variables differed between the same locations over time. The stepwise regression approach was employed to identify a final model with only significant ($p < 0.05$) independent variables included. Water quality variables were considered as dependent variables, while landscape variables, including percent cover of each land use type (e.g., urban, forest, agriculture) and patch density, as well as population and GDP were treated as independent variables. We compared the correlations between river water characteristics and landscape pattern varied with the spatial scale of analysis using the adjusted R^2. We calculated the average adjusted R^2 of the buffers from 500 m to 2500 m to represent narrower buffer, and the average value in the buffers from 3000 m to 5000 m to represent wider buffer. All statistical analyses were done with SPSS for Windows (version 16.0).

3. Results

3.1. Spatial variability and temporal change in river flow and water quality

Most of the water quality measures in the upper and middle reaches did not change much from 1989 to 2007, except for a significant increase in $SO_4{}^{2-}$, NH_3–N, NO_3–N, and TH (Table 2).

Table 2
T-test results for the differences in water quality variables (mean values) at the level 0.05 among different time periods in the upper, middle and lower reaches. "–" denotes no data. pH was measured by handheld pH meters; Cl^- by ion chromatography; SO_4^{2-} by flame atomic absorption spectrophotometry; EC by portable conductivity meter; TH by EDTA titration; BOD_5 by dilution and inoculation method; DO by iodometry; NH_3–N by salicylic acid spectrophotometry; and NO_3–N by chromophotometric phenoldisulfonic acid method. Flow is measured in m^3/s, pH is unitless, electrical conductivity is measured in μS/cm, all the other variables are measured in mg/L.

Upper reach	1989–1991	1997–1999	*t*-Statistic	df	Significance (2-tailed)
Flow	86.43	134.97	−2.01	2	0.182
pH	7.17	7.00	1.147	2	0.370
EC	65.33	63.0	0.123	2	0.914
Cl^-	2.45	4.62	−4.285	2	**0.05**
SO_4^{2-}	2.56	3.16	−0.961	2	0.438
DO	7.57	8.0	−0.407	2	0.724
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	–	–	–	–	–
TH	12.39	26.2	−2.865	2	0.103

Upper reach	1997–1999	2005–2007	*t*-Statistic	df	Significance (2-tailed)
Flow	134.97	109.87	1.356	2	0.308
pH	7.0	7.42	−2.392	2	0.139
EC	63.0	86.47	−2.025	2	0.18
Cl^-	4.62	5.33	−0.955	2	0.44
SO_4^{2-}	3.16	6.03	−2.467	2	0.132
DO	–	–	–	–	–
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	0.43	4.01	−1.981	2	0.186
TH	26.2	43.23	−4.801	2	**0.041**

Upper reach	1989–1991	2005–2007	*t*-Statistic	df	Significance (2-tailed)
Flow	86.43	109.87	−0.723	2	0.545
pH	7.17	7.42	2.73	2	0.112
EC	65.33	86.47	−2.762	2	0.11
Cl^-	2.45	5.33	−2.439	2	0.135
SO_4^{2-}	2.56	6.03	−4.28	2	**0.05**
DO	7.57	8.0	−0.816	2	0.500
NH_3–N	0.047	0.16	−6.8	2	**0.021**
NO_3–N	0.037	0.88	−5.345	2	**0.033**
BOD_5	–	–	–	–	–
TH	12.39	43.23	−22.34	2	**0.002**

Middle reach	1989–1991	1997–1999	*t*-Statistic	df	Significance (2-tailed)
Flow	201.67	352.67	−2.872	2	0.103
pH	7.13	7.0	1.512	2	0.27
EC	65	61.67	0.195	2	0.863
Cl^-	2.24	3.57	−2.882	2	0.102
SO_4^{2-}	2.68	1.88	1.05	2	0.404
DO	6.67	7.5	−1.255	2	0.336
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	–	–	–	–	–
TH	12.94	30.63	−5.261	2	**0.034**

Middle reach	1997–1999	2005–2007	*t*-Statistic	df	Significance (2-tailed)
Flow	352.67	323.37	0.447	2	0.698
pH	7	7.38	−3.152	2	0.088
EC	61.67	74.7	−0.669	2	0.573
Cl^-	3.57	5.51	−1.264	2	0.334
SO_4^{2-}	1.88	7.63	−7.33	2	**0.018**
DO	7.5	7.59	−0.14	2	0.901
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	0.23	3.89	−1.996	2	0.184
TH	30.63	37.35	−1.067	2	0.398

Middle reach	1989–1991	2005–2007	*t*-Statistic	df	Significance (2-tailed)
Flow	201.67	323.67	−4.169	2	0.053
pH	7.13	7.38	−3.496	2	0.073
EC	65	74.7	−3.218	2	0.084
Cl^-	2.24	5.51	−2.888	2	0.102
SO_4^{2-}	2.68	7.63	−3.218	2	0.084
DO	6.67	7.59	−1.104	2	0.385
NH_3–N	0.06	0.11	−0.896	2	0.465
NO_3–N	0.04	0.37	−6.089	2	**0.026**
BOD_5	–	–	–	–	–

Table 2 (*Continued*)

Middle reach	1989–1991	2005–2007	*t*-Statistic	df	Significance (2-tailed)
TH	12.94	37.35	−7.637	2	**0.017**
Lower reach	**1989–1991**	**1997–1999**	***t*-Statistic**	**df**	**Significance (2-tailed)**
Flow	307.33	462.67	−2.205	2	0.158
pH	7.03	7.13	−1.0	2	0.423
EC	55.33	75.33	−1.473	2	0.279
Cl^-	3.25	6.25	−4.672	2	**0.043**
$SO_4{}^{2-}$	1.93	4.89	−1.275	2	0.33
DO	7.47	7.73	−0.857	2	0.216
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	–	–	–	–	–
TH	10.77	30.83	−13.473	2	**0.05**
Lower reach	**1997–1999**	**2005–2007**	***t*-Statistic**	**df**	**Significance (2-tailed)**
Flow	462.67	449.67	0.171	2	0.880
pH	7.13	7.41	−1.508	2	0.271
EC	75.33	125.63	−2.285	2	0.15
Cl^-	6.25	11.03	−3.578	2	0.07
$SO_4{}^{2-}$	4.89	10.6	−1.988	2	0.185
DO	7.73	6.19	4.130	2	0.054
NH_3–N	0.32	0.54	−2.23	2	0.156
NO_3–N	1.45	1.31	1.051	2	0.403
BOD_5	0.60	2.75	−3.723	2	0.065
TH	30.83	62.82	−3.639	2	0.068
Lower reach	**1989–1991**	**2005–2007**	***t*-Statistic**	**df**	**Significance (2-tailed)**
Flow	307.33	449.67	−2.229	2	0.156
pH	7.03	7.41	−4.308	2	**0.05**
EC	55.33	125.63	−7.445	2	**0.018**
Cl^-	3.25	11.03	−4.03	2	0.056
$SO_4{}^{2-}$	1.93	10.6	−7.389	2	**0.018**
DO	7.47	6.19	1.183	2	0.359
NH_3–N	–	–	–	–	–
NO_3–N	–	–	–	–	–
BOD_5	–	–	–	–	–
TH	10.77	62.82	−7.004	2	**0.02**

The significance of bold values is at the level 0.05.

However, substantial changes were observed in the lower reach especially periods of 1989–1991 and 2005–2007. Generally, TH changed significantly very often (Table 2). During 1989–1991, no differences in water quality measures were detected among the three reaches, suggesting that water quality was similar from upstream to downstream. However, differences occurred in the following two periods (Fig. 2). As expected, flow changed along the river, but the differences in flow between reaches tended to increase during the three study time periods (Fig. 2). The concentration of Cl^- became much higher in the lower reach than the middle and upper reaches by 1997–1999 (Fig. 2). The concentration s of Cl^-, EC, NH_3–N, NO_3–N, and TH all showed considerable variations among the reaches in 2005–2007, with the highest values occurring in the lower reach. In contrast, the concentration of DO decreased from the upper to lower reach (Fig. 2).

3.2. Impacts of land use and land cover on river flow and water quality

The results of stepwise multiple linear regression showed that the water attributes of the Dongjiang River were correlated with certain landscape characteristics, but not others (Table 3). At least one urban landscape metric was significant as an explanatory variable in each regression relationship. Specifically, the PLAND occupied by urban land use was positively correlated with the concentrations of Cl^-, EC, NH_3–N, and NO_3–N and negatively with the concentration of DO. The PD of urban land use was positively correlated with water flow and negatively with DO.

In contrast with urban land use, the percentage of agricultural land use was positively correlated with the concentrations of DO at the subwatershed scale and with flow at the buffer scale (1000 m and 1500 m in buffer width). The patch density of agriculture was negatively correlated with DO at the scales of subwatershed, catchment, and buffer (3000–5000 m in buffer width). The landscape metrics of forested land cover were not significantly correlated with water quality variables. None of the landscape metrics used in our analysis was significantly correlated with pH, $SO_4{}^{2-}$, TH, and BOD_5 at any scale although, as mentioned earlier, Cl^-, NH_3–N, and NO_3–N were positively correlated with urban land use at all scales (Table 3).

3.3. Correlations at different spatial scales

Our results showed that the correlations between river water characteristics and landscape pattern varied with the spatial scale of analysis (Table 4). For example, river flow was more strongly correlated with landscape pattern at the scale of buffers of 1000 m and 1500 m in width (adjusted R^2 = 0.82 and 0.83, respectively). For DO, the adjusted R^2 increased from 0.43 to 0.93 when buffer width increased from 500 m to 5000 m. The values of adjusted R^2 for DO were similarly high at the scales of the widest buffer, catchment, and subwatershed (Table 4). Similar scale effects were also found with other water quality variables. The regression coefficients for

Cl^-, $SO_4{}^{2-}$, EC, NH_3–N, and NO_3–N varied as the spatial scale of analysis was changed, with the strongest correlations found at the subwatershed scale (Table 4). The effects of landscape pattern on water quality variables at larger spatial scales appeared more pronounced than at smaller scales (Fig. 3).

3.4. Effects of socioeconomic factors

The addition of population and GDP resulted in more water quality variables (e.g., $SO_4{}^{2-}$ and TH) in the stepwise multiple linear regressions and improved adjusted R^2 for water quality variables (Cl^-, $SO_4{}^{2-}$, EC, TH, NH_3–N, and NO_3–N) except DO (Table 5). GDP was positively correlated with Cl^-, $SO_4{}^{2-}$, EC, TH, NH_3–N, and NO_3–N at the subwatershed scale. At the same time, urban patch density was positively correlated with river flow but negatively with DO. In contrast with GDP, population did not make a statistically significant contribution to explaining the variations of water quality, so the data of population were excluded during stepwise regression.

4. Discussion

4.1. Water quality deterioration in Dongjiang River watershed

This spatiotemporal pattern of water quality in the Dongjiang River exhibits a trend of accelerating river deterioration. This corroborates the previous finding that the water quality in the upper and middle reaches has declined in recent years (Lee et al., 2007). Previous studies in this region suggest that changes in water quality have been influenced mainly by waste discharge (Jiang et al., 2009). Our study suggests that most of the pollution sources were related to human activities. TH changed significantly during the study period (Table 2), indicating high levels of calcium, magnesium, and other mineral salts such as iron. Similarly, urban streams had higher denitrification rates probably due to high $NO_3{}^-$ concentration (Mulholland et al., 2008; Silva et al., 2011).

High input of nitrogen into the river from wastewater in urban areas and fertilizers in farmland affects water quality (Broussard and Turner, 2009; Zhang et al., 2010). In our study region, pesticide application increased 2.4% annually in the middle reach between

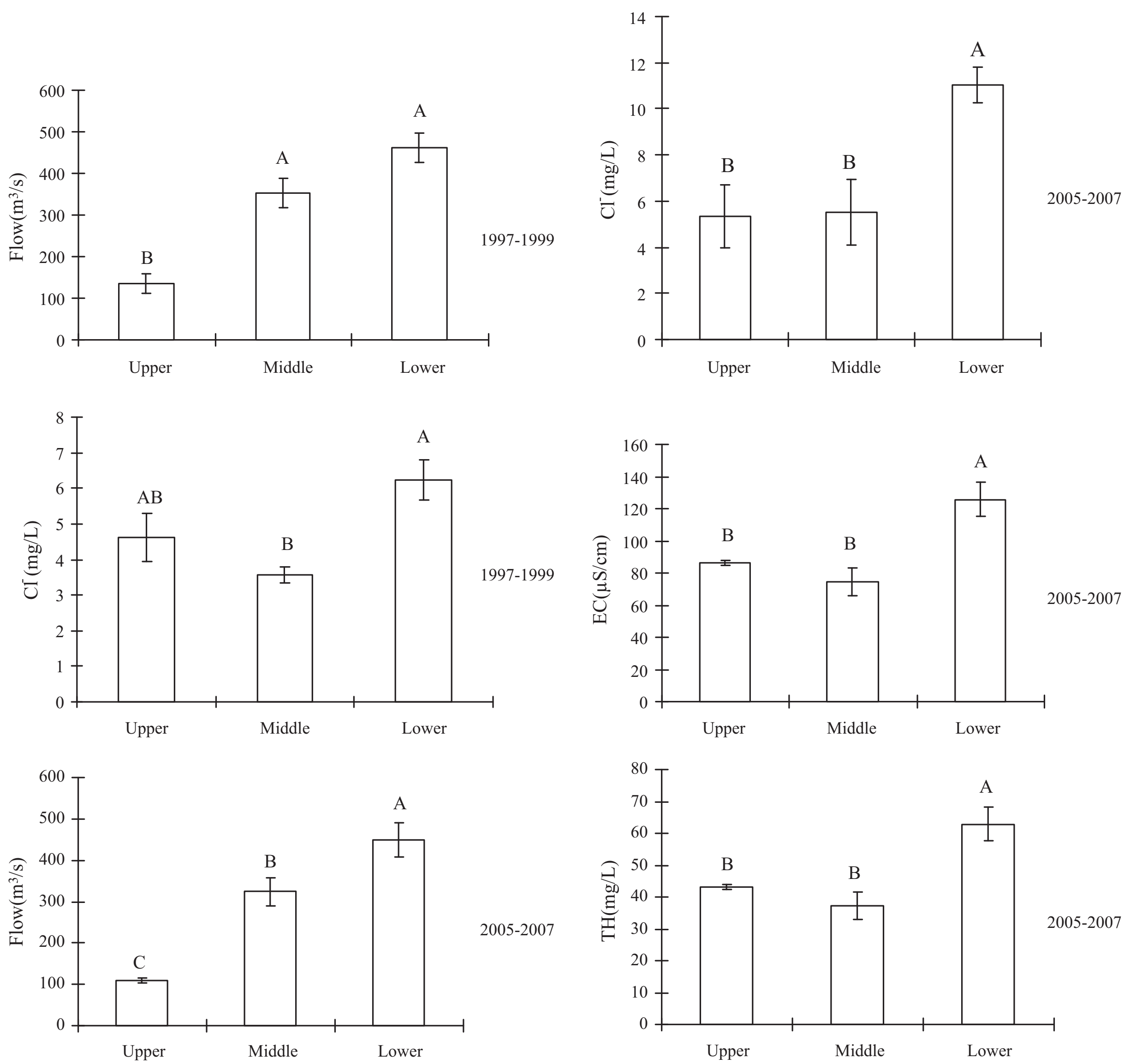

Fig. 2. One-way ANOVA test for differences in water quality variables among the three reaches in time periods of 1997–1999 and 2005–2007 (mean ± SE). Flow was measured in m^3/s, electrical conductivity in μS/cm, and all the other variables in mg/L. Different letters indicate significant differences among reaches at the level of 0.05. Vertical bars represent standard errors.

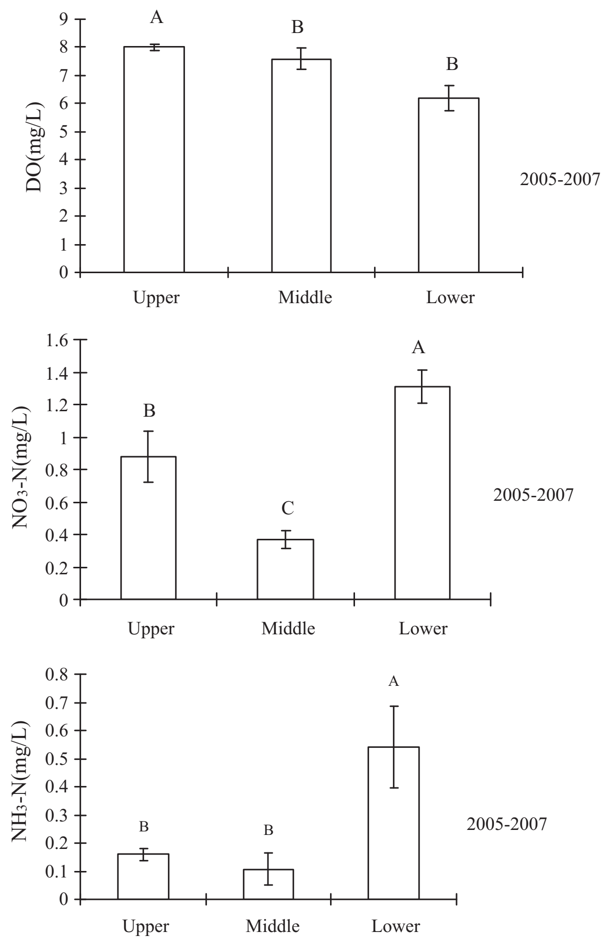

Fig. 2. (*Continued*)

2001 and 2007, and the domestic wastewater in Longchuan County in the upper reach was largely untreated (Jiang et al., 2009). Previous studies showed that nutrient inputs (N, P) increased from upstream to downstream along the Dongjiang River (Liang et al., 2008).

4.2. *Effects of land use and land cover pattern on river degradation*

Our results suggest that land use and land cover pattern has major impacts on the flow and water quality of the Dongjiang River at multiple spatial scales (subwatershed, catchment, and buffer zone) during the recent decades. In particular, urban land use, although small in percent coverage, exerted a disproportionately large influence both locally and over distance. Degraded streams and rivers that drain urbanized landscapes often have higher nutrient loads and contaminant concentrations, as well as altered stream morphology and reduced biodiversity (Meyer et al., 2005). Our results in the Dongjiang River watershed support this general observation. Expanding satellite cities like Dongguan and Zengcheng in the lower reach of the Dongjiang River have profoundly transformed the regional landscape. Urbanization-related activities have been found to increase N, P, alkalinity, and the total dissolved solids in surface waters (Johnson et al., 1997; Boyer et al.,

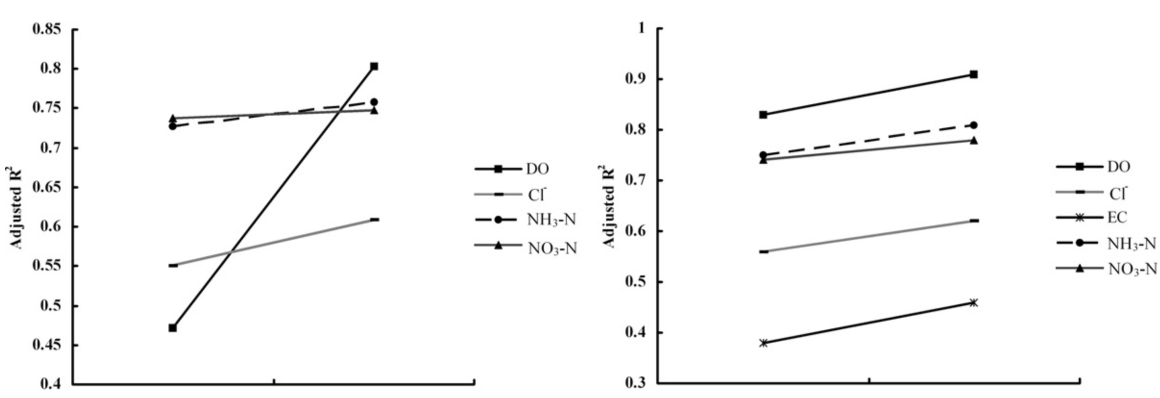

Fig. 3. The correlations between river water characteristics and landscape pattern at different spatial scales of analysis. Narrower buffers included those whose width ranged from 500 m to 2500 m, and wider buffers were those with a width ranging from 3000 m to 5000 m.

Table 3
Results of stepwise regression of water quality variables against landscape metrics at different spatial scales. Landscape metrics include the percentage of urban area (PLAND_urban), the patch density of urban land (PD_ urban), the percentage of agriculture area (PLAND_ agriculture), the patch density of agriculture land (PD _ agriculture). Flow is measured in m^3/s, and electrical conductivity is measured in μS/cm, all the other variables are measured in mg/L. "+" indicate the positive relationship, "–" indicate the negative relationship, and blank no correlation. The significance level is 0.05.

	PLAND_urban	PD_urban	PLAND_ agriculture	PD_ agriculture
Subwatershed				
Flow		+		
DO	–		+	–
Cl^-	+			
EC	+			
NH_3–N	+			
NO_3–N	+			
Catchment				
Flow		+		
DO		–		–
Cl^-	+			
EC	+			
NH_3–N	+			
NO_3–N	+			
500 m				
Flow	+			
DO	–			
Cl^-	+			
EC	+			
NH_3–N	+			
NO_3–N	+			
1000–1500 m				
Flow		+	+	
DO		–		
Cl^-	+			
EC				
NH_3–N	+			
NO_3–N	+			
2000–2500 m				
Flow		+		
DO		–		
Cl^-	+			
EC				
NH_3–N	+			
NO_3–N	+			
3000–5000 m				
Flow		+		
DO	–			–
Cl^-	+			
EC				
NH_3–N	+			
NO_3–N	+			

2002; Gergel, 2005). Highly fragmented urban land uses, with a large amount of impervious surfaces, tend to increase river flow and negatively affect water quality (Sliva and Williams, 2001; Brabec, 2009; Lee et al., 2009). The problem of soil erosion was severe in some parts of our area because of rapid urban development in recent decades (Ho and Hui, 2001).

When the widths of buffers are 1000 m and 1500 m, the percentage of agriculture positively correlated with flow. The water conservation function of agriculture is weak relatively, so the increase of agriculture area will induce the reduction of flow. We did not find significant effects of agricultural land use on most water quality measures, except for a positive correlation between the PLAND of agriculture and DO at the subwatershed scale and a negative correlation between PD of agriculture and DO at the subwatershed, catchment, and 3000–5000 m buffer scales. However, this does not mean that agriculture has positive effects on water quality. In our study area, paddy fields were the primary form of agricultural land use, and it is possible that the photosynthesis of crops enriched O_2 in water. Tran et al. (2010) found that DO levels were positively correlated with the presence of agriculture for maintaining a flow regime that consisted of either riffle/run or riffle/pool sequences, and the presence of the riffle sequences

Table 4
Adjusted R^2 of the stepwise regression analysis at multiple spatial scales. The independent variables are the percent cover of each land use type (urban, forest, agriculture) and patch density of each land use type. The numbers in bold and italic style indicate they are the highest value among several scales. Flow is measured in m^3/s, pH is unitless, EC is measured in μS/cm, and all the other variables are measured in mg/L. The significance level is 0.05.

	Subwatershed	Catchment	Buffer (m)									
			500	1000	1500	2000	2500	3000	3500	4000	4500	5000
Flow	0.70	0.65	0.65	0.82	***0.83***	0.73	0.73	0.73	0.73	0.72	0.71	0.70
DO	0.91	0.83	0.43	0.44	0.48	0.50	0.51	0.92	0.92	0.92	0.92	***0.93***
Cl^-	***0.62***	0.56	0.57	0.56	0.55	0.54	0.53	0.53	0.52	0.52	0.53	0.54
EC	***0.46***	0.38	0.38									
NH_3–N	***0.81***	0.75	0.75	0.74	0.73	0.71	0.71	0.71	0.71	0.71	0.72	0.73
NO_3–N	***0.78***	0.74	0.76	0.75	0.74	0.72	0.72	0.72	0.72	0.72	0.73	0.73

Table 5
Results of the stepwise regression of water quality variables against landscape metrics and socioeconomic factors at the subwatershed level. We analyzed the year of 1989, 1990, 1991, 1997, 1998, 1999, 2005, 2006 and 2007 here. PD_urb means the patch density of urban. "+" denotes a positive correlation, "−" a negative correlation, and blank no correlation. Flow is measured in m^3/s, pH is unitless, EC is measured in μS/cm, and all the other variables are measured in mg/L. The significance level is 0.05.

	Adjusted R^2	PD_urb	GDP
Flow	0.70	+	
DO	0.86	−	+
Cl^-	0.78		+
SO_4^{2-}	0.53		+
EC	0.80		+
TH	0.50		+
NH_3–N	0.85		+
NO_3–N	0.93		+

could result in high oxygen levels. In addition, Snyder et al. (2003) observed a positive relationship between the extent of agriculture and biological integrity scores in catchments because of the negative correlation between the extent of agriculture and urban land uses. This may also be part of the explanation for the relationship between agricultural land and DO found in our study. However, numerous studies have found that water quality, habitat, and biological diversity decline as the extent of agricultural land increases (Allan, 2004). The lack of significant effects of agriculture on water quality measures in our study may have to do with the particular cropping practices, interactions among multiple factors, and impacts of point sources of pollution that were not identified.

4.3. Scale multiplicity of the relationship between landscape pattern and water quality

Our study has demonstrated that the influence of land use and land cover on water quality is scale dependent, as reported elsewhere (Hunsaker and Levine, 1995; Sliva and Williams, 2001; Sponseller et al., 2001). Our finding suggests that key topographical and anthropogenic factors interact with water quality in this region mainly at the subwatershed scale.

The effects of land use and land cover on water quality (except DO) were much weaker on the catchment and buffer scales. Recent studies have suggested that the distance over which land-use pattern affects water quality depends on the size of the streams (Tran et al., 2010). Buck et al. (2004), for example, reported that upstream land use had stronger influences on large rivers, whereas local land use and other factors were more important to small streams. Dodds and Oakes (2008) found that riparian zone and land use/land cover close to streams were more important to water quality than the landscape pattern of the entire catchment. Other studies, however, showed that land use pattern close to the river was not a better predictor of water chemistry than land use pattern away from the river (Houlahan and Findlay, 2004; Meynendonckx et al., 2006).

A major advantage of multi-scale analysis, as done here in our study, is to identify the appropriate scales at which relationships between different kinds of variables ought to be examined (Wu, 2004; Wu et al., 2006). Our study suggests that the proper scale ranges for assessing the effects of land use and land cover on river water quality in the study region should include: the 1500 m buffer scale for river flow, the 5000 m buffer scale for DO, and the subwatershed scale for Cl^-, EC, NH_3–N, and NO_3–N. Flow and DO were influenced by direct factors in surrounding landscape mostly, so the proper scale is small relatively. For example, Xie et al. (2011) used the monthly runoff data of Longchuan Station at Dongjiang River, and they found that about 60% of the alteration is induced by the human activities, especially the construction and operation of Fengshuba Reservoir. Higher DO concentrations may be due to factors such as higher cross section of streams with consequent increased surface of interaction with atmosphere, and higher algae activity, rapid flows, and turbulent mixing (Silva et al., 2011). However, higher nutrient concentrations of dissolved inorganic forms were observed in rural and urban streams in relation to those in areas under natural cover (Silva et al., 2011), and chloride is a robust indicator of urban impact (Riva-Murray et al., 2010), and has been linked to road de-icing salts that are transported to the stream in surface runoff (Kelly et al., 2008). The concentrations of Cl^-, EC, NH_3–N, and NO_3–N were impacted by point and non-point pollution, and the influence can be transported for a large area. In our study, these water quality variables were better assessed at large scales.

4.4. Effects of socioeconomic factors on river water quality

GDP was an important factor affecting water quality variables. While the percentage of urban land use describes the spatial extent of urbanization, GDP provides additional information on the intensity of human activities that lead to the generation of pollutants. In our study region, the rapid increase in GDP reflected the soaring economic development in the past several decades. In particular, the lower subwatershed (Dongguan) of the Dongjiang River is part of the Pearl River Delta which is one of the economically fastest growing regions and the largest manufacturing centers in China. The total number of Township and Village Enterprises (TVEs) in Dongguan increased from 8154 in 1990 to 25,103 in 2006 (Dongguan Statistics Bureau, 2007). The factors that drove the success of local economy were also responsible for the water pollution of rivers in this area (Wang et al., 2008).

5. Concluding remarks

Our study shows that the water quality of the Dongjiang River in southern China declined between 1989 and 2007 mainly because of changes in land use and land cover pattern. In particular, urban land use had major impacts on river flow and water quality on multiple scales (subwatershed, catchment, and buffer zone), whereas the effects of agriculture appeared to be localized. Our results suggest that the subwatershed is a key spatial scale on which landscape pattern affects most of the river water variables in the Dongjiang River region. In the same time, many river water variables were also affected by factors on smaller scales. These findings have several implications for river restoration and management in the Dongjiang River region.

First, for a given study area, selected landscape pattern metrics that are correlated with river water characteristics may be used as indicators to assist with the monitoring and management of river systems. Our study shows that those landscape metrics closely related to urban land use are particularly useful for the Dongjiang River watershed when used together with water quality measures. Second, river monitoring and restoration must consider land use and land cover patterns on multiple scales, ranging from buffer zones, catchments, subwatersheds, to the entire watershed. The management practices in the Dongjiang River area have often had a local focus, lacking a regional watershed perspective. Our study suggests that focusing only on smaller scales (e.g., catchments or riparian corridors) may have been a main reason for the apparent failure of river management in the region during the past several decades. Future management plans should consider multiple scales, and landscape planning at the subwatershed and watershed scales seems particularly important, as indicated by our study.

Third, urbanization must be curtailed in and around the riparian areas of the Dongjiang River if its flow and water quality are to be protected. As our study shows that urbanization was a key factor affecting the river water, future river restoration or management efforts should focus on restricting urban land expansion, reducing urban sources of pollution, and planning more sustainable urban landscapes in the region. Fourth, river restoration requires interdisciplinary collaborations and engagement with policy makers. Our study indicates that, while natural environmental setting is important, anthropogenic factors have played an increasingly dominant role in influencing the flow and water quality of the Dongjiang River. This means that natural and social scientists must work together in order to fully understand and successfully restore degraded river systems in this region. In addition, scientists must actively engage policy makers if restoration efforts are to achieve long-term success on the ground. This is a grand challenge for river management and restoration in the Dongjiang region in particular and elsewhere in general.

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