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ASSESSING THE IMPACT OF LAND USE CHANGES ON WATER QUALITY ACROSS MULTIPLE SPATIAL SCALES IN EASTERN MASSACHUSETTS

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ABSTRACT: *A study of water quality, land-use changes, and population growth trends in several watersheds of eastern Massachusetts since the 1970s has been conducted to examine the impact of land use changes on water quality at sub-watershed and stream buffer-zone scales through GIS and statistical analyses. GIS analyses are used to delineate sub-watersheds of water sampling sites from Digital Elevation Models, to generate buffer zones with different distances from the streams, and to derive land use indicators such as forest, agricultural land, residential use, and population density for different scales. Statistical analyses are used to examine, quantify, and compare the relationships between water quality and the land use indicators, to study the changes across space and over time at a sub-watershed scale and within different buffer zones, and to find good predictors of water quality changes in response to the spatial and temporal variations of land use patterns. Results from this study will contribute to a better understanding of not only the impact of historical land use changes on water quality, but also the appropriate scale for effective watershed management in the future.*

Keywords: *Land use changes, Water quality, Geographic Information System, Watershed, Spatial scale*

INTRODUCTION

Over decades, land uses in the United States have been changing rapidly, causing a sharp decline of agricultural area and forest and a significant increase of urban land (Alig et al., 2003). Such changes alter the surface characteristics of watersheds and can have considerable influence on runoff quality and quantity, and may be responsible for the increase of various pollutants. The spatial relationship between land use and water quality has been examined by some previous studies (Tong and Chen, 2002; Ngoye and Machiwa, 2004). Tong and Chen (2002) found that rises in agricultural land had a strong positive correlation with conductivity and pH but a negative correlation with heavy metals, while rises in residential land had a positive correlation with heavy metals, BOD (Biological Oxygen Demand), and conductivity in the watersheds of Ohio State. However, the long-term impact of land use changes on water quality has not been well understood. Furthermore, land use change, the physical environment, and social and economic development are not uniform in different places. Thus, the extent and characteristics of the impact also vary. It is critical to study the impact of long-term land use changes on water quality at a local scale.

Many previous studies have also found that the impact of land use change on water quality and stream biological communities is scale dependent (Sliva and Williams, 2001; Jarvie et al., 2002). Sliva and Williams (2001) reported that the urban land within stream buffer zones, which are the riparian areas along the stream, had a stronger influence on water quality than that within the entire watershed in three southern Ontario watersheds of Canada. In contrast, Jarvie et al. (2002) found stronger correlations between some water quality parameters and land characteristics at a watershed scale than in the buffer zones of sampling sites in the Humber watershed of the UK.

This study assessed the impact of land use changes on water quality over the past thirty years in eastern Massachusetts through analysis of the relationships between land use, population variables, and water quality indicators at multiple spatial scales using GIS and statistical analyses. Two different types of spatial scales were used: (1) sub-watershed scale: the whole upstream drainage area of each water quality sampling site; and (2) stream buffer scale: the riparian area within a certain distance to major streams and ponds in each sub-watershed. Seven different land use types and three related variables, including percentage of developed land use (PDLU), population density (PD), and per capita developed land use (PCDLU), were used to measure the extent and rate of land use changes caused by urban sprawl. PCDLU reflects the combined effect of population and land use changes. Because of the limited availability of long-term water quality data, only specific conductance (SC) was used as a water quality indicator, which reflects the dissolved ionic concentration in water. The objectives were threefold: (a) analyze the relationship between land use change and water quality across space and over time; (b) assess the sensitivity of water quality to different land use types and population variables; and (c) examine the influences of spatial scale on the spatial and temporal relationships between land use change and water quality.

STUDY AREA

The study area is within 80 km of the City of Boston in Massachusetts, covering metropolitan Boston and its surrounding areas (Figure 1). Compared to most parts of New England, it is more densely populated and urbanized. Although the metropolitan Boston and Worcester areas are mainly urban and suburban, it also contains a high percentage of forest and other land use types. The land use change in this area was mainly caused by urban sprawl.

This area consists of 15 watersheds defined by the U.S. Geological Survey (USGS) and the Massachusetts Department of Environmental Management (MADEM) (Simcox, 1992). Most of the area is within the U.S. Environmental Protection Agency (USEPA) Level III Ecoregion 59, so the watersheds are relatively homogeneous in their natural characteristics such as geology, soils, and climate (Omernik, 1987). Therefore, the water quality change could be largely attributed to anthropogenic factors (e.g., urbanization) rather than to natural variability.

DATA SOURCES AND METHODS

Land use and population data were obtained from the website of the Massachusetts Geographic Information System (MassGIS; URL http://www.mass.gov/mgis/). Land use data for 1971, 1985, and 1999, population data by census block for 2000, and population data aggregated by municipality for 1970, 1980, 1990, and 2000 were used. The original land use data set with 21 land use types were aggregated into seven broad categories, including agriculture, forest, open undeveloped land (defined as abandoned agricultural fields, power-line corridors, and areas of no vegetation), commercial land, industrial/transportation/mining areas, recreation use, and residential land, by combining several similar land use types into one broad category. For example, the amount of residential land is the sum of high, medium, and low density, and multi-family residential lands from the original 21 types. Residential, commercial, industrial, and recreation areas were further aggregated into developed land use.

Specific conductance data from 1970 to 2004 were retrieved from the USGS National Water Information System Web (NWISWeb; URL http://waterdata.usgs.gov/nwis/). Based on the data availability, 18 USGS water sampling sites were selected. The mean concentrations of SC were calculated for the 1970s, the 1980s, and the 1990s and beyond (1990 – 2004, henceforth referred to as the 1990s).

In order to study the relationships between land use and population variables for areas and SC for points, the drainage area (sub-watershed) for each water-sampling site was delineated from digital elevation data, which was provided by the USGS National Elevation Dataset (NED), using ArcGIS spatial analysis tools. All the sub-watersheds are mutually exclusive, and their sizes range from 28 to 778 km^2 (Figure 1).

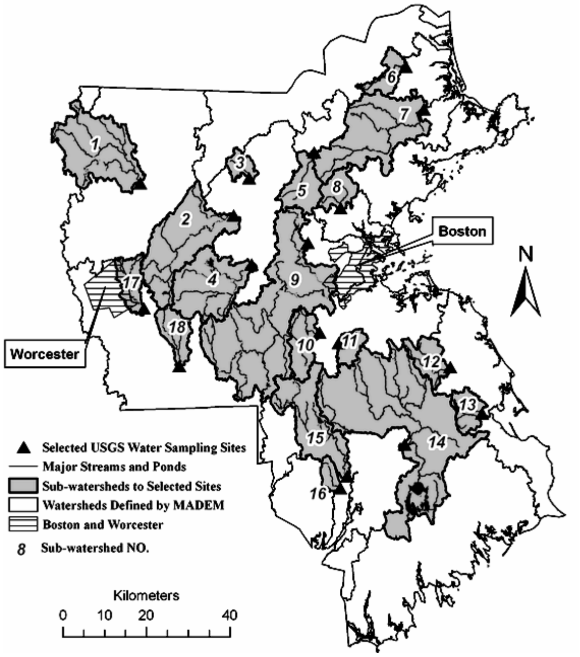

Figure 1. Location of the study area.

In each sub-watershed, three stream buffer zones with different distances to streams and ponds, 250, 500, and 1,000 meters, were delineated using ArcGIS buffer analysis tool. The land use and population data for each of the four spatial zones (sub-watershed, 250 m, 500 m, and 1,000 m stream buffers) were obtained by overlaying the land use and population data layers on the delineated spatial zone layers in ArcGIS.

The impact of land use changes on water quality was assessed by analyzing both spatial and temporal relationships between land use, population variables, and SC. In this study, the spatial relationship refers to how SC varies with land use and population changes over space, while the temporal relationship refers to how SC evolves with land use change over time.

Percentages of different land use types and PCDLU for 1999, PD for 2000, and SC for the 1990s were used for spatial relationship analysis. The Kolmogorov-Smirnov test was used to examine the normality of distribution of the variables. After appropriate transformations (e.g. natural log) were performed on the variables that were not normally distributed, a simple linear bivariate regression was used to analyze the correlations between land use, population variables and SC at different spatial scales. For each combination of variables, coefficients of determination (r^2) and significance levels (p) were compared to determine the relative importance of land use and population variables affecting water quality and the relative significance of different scales in terms of the impact on water quality. When r^2 and p were similar for the combination of the same variables at different scales, the regression slopes were further compared, with higher slopes indicating higher levels of impact.

Percentages of change in land use and PCDLU from 1971 to 1999, PD from 1970 to 2000, and SC from the 1970s to the 1990s were used for temporal relationship analysis. Because too many variables were not normally distributed, a nonparametric correlation, Spearman rank correlation analysis (rho), was used to quantify the temporal relationships between SC and land use and population variables.

RESULTS AND DISCUSSION

Spatial Variation between Sub-watersheds of Land Use, Population Variables, and SC

Land use and population variables showed great variability over the 18 sub-watersheds (Figure 2). In 1999, the most dominant land use type was forest, ranging from 18.8% to 72.7%, followed by residential land, which was 14.1% to 48.4% of the

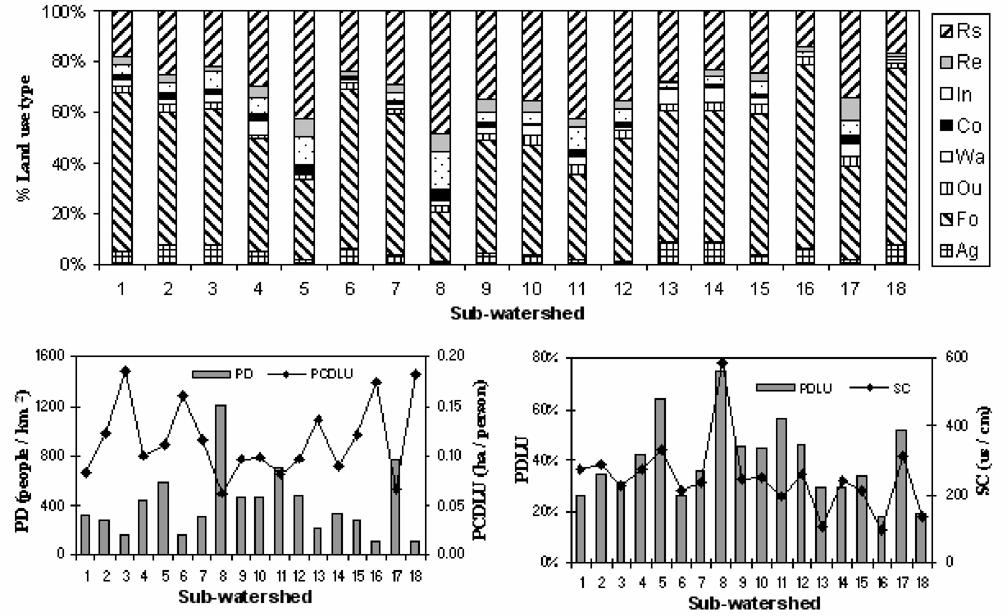

Figure 2. Comparison of land use, population variables, and SC among the 18 delineated sub-watersheds (Ag = % agricultural land; Fo = % Forest land; Ou = % open undeveloped land; Wa = % water body; Co = % commercial land; In = % industrial, transportation and mining land; Re = % recreation use; Rs = residential land; Land use types, PDLU, and PCDLU are for 1999; PD is for 2000; SC is for the 1990s).

sub-watersheds. In most sub-watersheds, the percentages of the other land use types, such as agricultural, open undeveloped, recreational, and commercial lands, were generally less than 10%. PDLU, PD, and PDLU ranged from 18.0 to 74.9%, 103 to 1,209 people/km^2, and 0.062 to 0.186 ha/person, respectively.

Pearson correlation coefficients (r) among land use and population variables are shown in Table 1. Except for open undeveloped land (Ou), all other variables were highly correlated. Significant positive correlations existed among % agriculture land, % forest, and PCDLU ($r = 0.62 – 0.72$, $p < 0.01$). Higher values of these variables indicate less urbanization. Significant positive correlations were also found among % commercial land, % industrial, transportation, and mining land, % recreation use, % residential land, PDLU, and PD ($r = 0.73 – 0.97$, $p < 0.01$). Higher values of these variables indicate higher levels of urbanization. In contrast, significant negative correlations were found between these two groups of variables, i.e., % forest vs. PDLU ($r = -0.53$, $p < 0.05$ to $r = -0.97$, $p < 0.01$). PDLU was the most highly correlated variable with the others, so it could be regarded as the best indicator of urbanization in the study area. Based on the values of PDLU, the sub-watersheds with PDLU higher than 50%, including sub-watersheds 5, 8, 11, and 17, were classified as highly-urbanized sub-watersheds, while sub-watersheds 16 and 18 with PDLU lower than 20% were classified as less-urbanized sub-watersheds, and all the others with PDLU between 20% and 50% were grouped into moderately-urbanized sub-watersheds. As expected, the highly-urbanized sub-watersheds had high PD, but their PCDLUs were relatively low. On the contrary, the less-urbanized sub-watersheds had high PD, but their PCDLUs were relatively high, indicating that in the less urbanized areas, usually rural areas, each person occupied more developed land than in highly urbanized areas. SC also showed great variability, ranging from 97.5 μs/cm to 586.8 μs/cm. As shown in Figure 2, the highly-urbanized sub-watersheds tended to have high SC, while the less-urbanized sub-watersheds were associated with low SC.

Spatial Relationships between Land Use and Population Variables and SC

The plots of SC concentration versus each land use or population variable for the 18 sub-watersheds are shown in Figure 3. Except open undeveloped land, all the variables had significant correlations with SC. PCDLU, % agricultural land, and % forest had significant negative correlations with SC. Percentage of forest explained 57% of the spatial variation in SC, while PCDLU and % agricultural explained 40% and 29%, respectively. The other variables showed significant positive relationships with SC. Percentage of commercial land had the strongest correlation and explained 76% of the spatial variation in SC, followed by PD that explained 70%. This result confirms that the more urbanized drainage areas with higher PD and higher percentage of developed land, including residential, commercial, industrial lands, tend to have higher SC.

Except % open undeveloped land, % agricultural land had the weakest relationship with SC among all the variables; however, its negative correlation was significant. This result is opposite to the findings of many early studies in intensive agricultural areas (Tong and Chen, 2002; Vondracek et al., 2005). In those studies, agricultural land was usually related to poor water quality, since agricultural land was an important non-point pollution source in those areas. In contrast, the agricultural land was not a considerable water pollution source in this area because of its sparse

Table 1. Pearson Correlation Coefficients Among Land Use and Population Variables [a]

	AG	FO	OU	CO	IN	RE	RS	PDLU	PD	PCDLU
AG	1.00									
FO	**0.67** [b]	1.00								
OU	-0.30	-0.21	1.00							
CO	**-0.64**	**-0.88**	0.06	1.00						
IN	**-0.66**	**-0.88**	0.10	**0.91**	1.00					
RE	**-0.73**	**-0.80**	0.24	**0.82**	**0.74**	1.00				
RS	**-0.76**	**-0.95**	0.19	**0.77**	**0.80**	**0.73**	1.00			
PDLU	**-0.79**	**-0.97**	0.18	**0.88**	**0.90**	**0.83**	**0.97**	1.00		
PD	**-0.74**	**-0.92**	0.29	**0.90**	**0.84**	**0.82**	**0.88**	**0.93**	1.00	
PCDLU	**0.62**	**0.72**	-0.29	**-0.69**	*-0.53* [c]	**-0.68**	**-0.68**	**-0.70**	**-0.79**	1.00

[a] AG = % agricultural land; FO = % forest land; OU = % open undeveloped land; CO = % commercial land; IN = % industrial, transportation, and mining land; RE = % recreation use; RS = residential land. Land use types, PDLU, and PCDLU are for 1999; PD is for 2000.

[b] Bold numbers indicate values significant at $P < 0.01$ (n=18).

[c] Italic numbers indicate values significant at $P < 0.05$ (n=18).

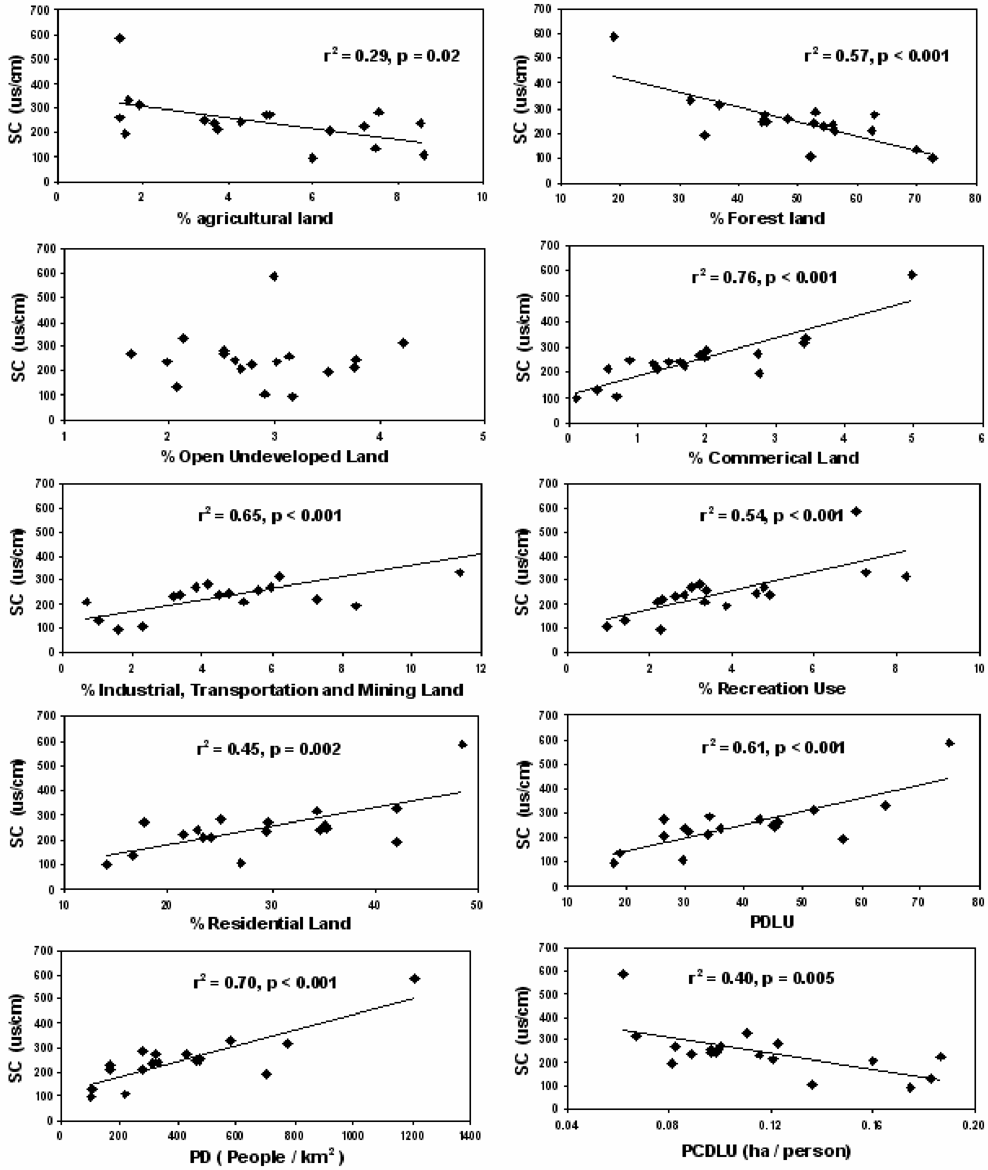

Figure 3. Relationships between SC and land use and population variables (SC is for the 1990s; Land use types and PCDLU are for 1999; PD is for 2000).

distribution. Therefore, agricultural land was generally associated with better water quality in this area. This result also suggests that urban sprawl related to the increasing residential, commercial, and industrial lands, and population density in suburbs was an important cause of water quality degradation in the study area.

Influence of Spatial Scale on Spatial Relationships

Table 2 shows the simple linear regression results for SC and land use and population variables spatial changes at different scales. It can be seen that % open undeveloped land was not significantly correlated with SC at both sub-watershed and stream buffer scales. On the other hand, the other variables showed significant relationships with SC at the sub-watershed scale as well as at all three stream buffer scales. However, differences in the correlations among the spatial scales for all the variables were shown by r^2 and slope. For most of the variables, the correlations at stream buffer scales, especially at the 1,000 m buffer scale, were stronger than that at the sub-watershed scale. The highest r^2 for % forest, % commercial, % residential land, PD, and PDLU were found at the 1,000 m buffer scale; the highest r^2 for %

Table 2. Simple Linear Regression Results Between SC and Land Use and Population Variables

Variables	Sub-watershed		1000 m stream buffer		500 m stream buffer		250 m stream buffer	
	r^2	Slope	r^2	Slope	r^2	Slope	r^2	Slope
AG	*0.29* [a]	*-22.71*	*0.32*	*-24.13*	*0.36*	*-24.53*	*0.34*	*-25.87*
FO	**0.57** [b]	**-5.88**	**0.63**	**-6.60**	**0.60**	**-6.90**	**0.52**	**-6.65**
OU	0.00	1.96	0.04	31.53	0.08	36.64	0.20	51.76
CO	**0.76**	**73.88**	**0.88**	**81.38**	**0.77**	**71.78**	**0.68**	**57.66**
IN	**0.65**	**24.09**	**0.46** $^{\mathrm{Ln}}$	**85.98**	**0.65** $^{\mathrm{Sqrt}}$	**90.82**	**0.69**	**19.98**
RE	**0.54**	**38.74**	**0.60**	**39.42**	**0.46**	**33.47**	*0.25*	*22.66*
RS	**0.45**	**7.49**	**0.42**	**8.85**	*0.34*	*8.43*	*0.34*	*9.96*
PDLU	**0.61**	**5.40**	**0.68**	**6.32**	**0.65**	**6.39**	**0.65**	**7.11**
PD	**0.70**	**0.32**	**0.72**	**0.37**	**0.71**	**0.38**	**0.69**	**0.43**
PCDLU	**0.40**	**-1745.44**	*0.34*	*-1618.92*	*0.37*	*-1640.65*	*0.24*	*-1392.10*

[a] Italic numbers indicate values significant at $P < 0.05$ (n=18).

[b] Bold numbers indicate values significant at $P < 0.01$ (n=18).

Ln indicates that variable was natural log transformed; Sqrt indicates that variable was square root transformed.

agricultural land was discovered at the 500m buffer scale, and the highest r^2 for % industrial, transportation, and mining land was present at the 250m buffer scale. The r^2 for % agricultural land, PDLU, and PD at different scales were fairly close, but their slopes increased steadily from larger scale to smaller scale (sub-watershed to 250 m stream buffer scale). For % residential land, the r^2 was a little higher in the sub-watershed (0.45) than that in the 1,000 m buffer (0.42), but the slope also increased from larger scale to smaller scale. This result suggests that the population and land use adjacent to streams had stronger influence on water quality. PCDLU had a stronger correlation with SC at the sub-watershed scale. However, it only weakly explained the SC spatial change compared to most of the variables.

Temporal Changes of Land Use and Population Variables and SC Concentration

Forest and residential land were the only two dominant land use types in this area, so only the temporal changes of these two land use types, PD, PDLU, and PCDLU were analyzed to assess their impacts on SC temporal variation. The temporal changes in land use and population variables showed great variability over the 18 sub-watersheds (Figure 4). Forest area decreased and residential land increased in all the sub-watersheds from 1971 to 1999. The decrease in the amount of forest ranged from 7.8% to 30.3%, while the increase in residential land ranged from 14.9% to 131.2%. PDLU, PD, and PCDLU increased in all the sub-watersheds. The increases in PD and PDLU ranged from 0.3% to 80.4% and from 16.9% to 147%, respectively, which represents different rates of urban sprawl. PCDLU increased from 7.4% to 47.8%, indicating that land development was faster than population growth.

SC also increased in all the sub-watersheds. The rate of increase ranged from 0.3% to 71.5%. As shown in Figure 4, with the exception of sub-watershed 5, the highly-urbanized sub-watersheds had the lowest increase in SC associated with low increase in PDLU, PD, and PCDLU, while most of high SC increases happened in moderately-urbanized sub-watersheds, such as sub-watersheds 3 and 6, which had high increases in PDLU, PD, PCDLU.

Temporal Relationships between Land Use and Population Variables and SC

The plots of SC temporal change versus temporal variation of land use and population variables are presented in Figure 5. No significant linear correlations were found, which suggests that water quality long-term change did not have consistent response to the rate of urban sprawl since some other factors such as policy and climate change may also have some effect on water quality. However, some patterns can still be identified from the plots. All the high increases in SC (> 30%) were associated with medium decreases in forest (10% - 20%), while the sub-watersheds with high (> 20%) and low (< 10%) decreases in forest had low increases in SC temporal change (< 30%). Most of the high increases in SC were also related to medium increases in residential land (50% - 80%), while most of the sub-watersheds with high (> 80%) and low (< 50%) increases in residential land had low increases in SC. Similar patterns were also observed for PD and PDLU temporal changes. The lowest land development rate was related to the lowest water quality degradation, which happened in most of highly-urbanized sub-watersheds (e.g. sub-watersheds 8 and 17). The water quality degradation became faster with the land development rate increasing until the increase in PDLU reached about 60% and the water quality degradation reached the highest level correspondingly, usually within

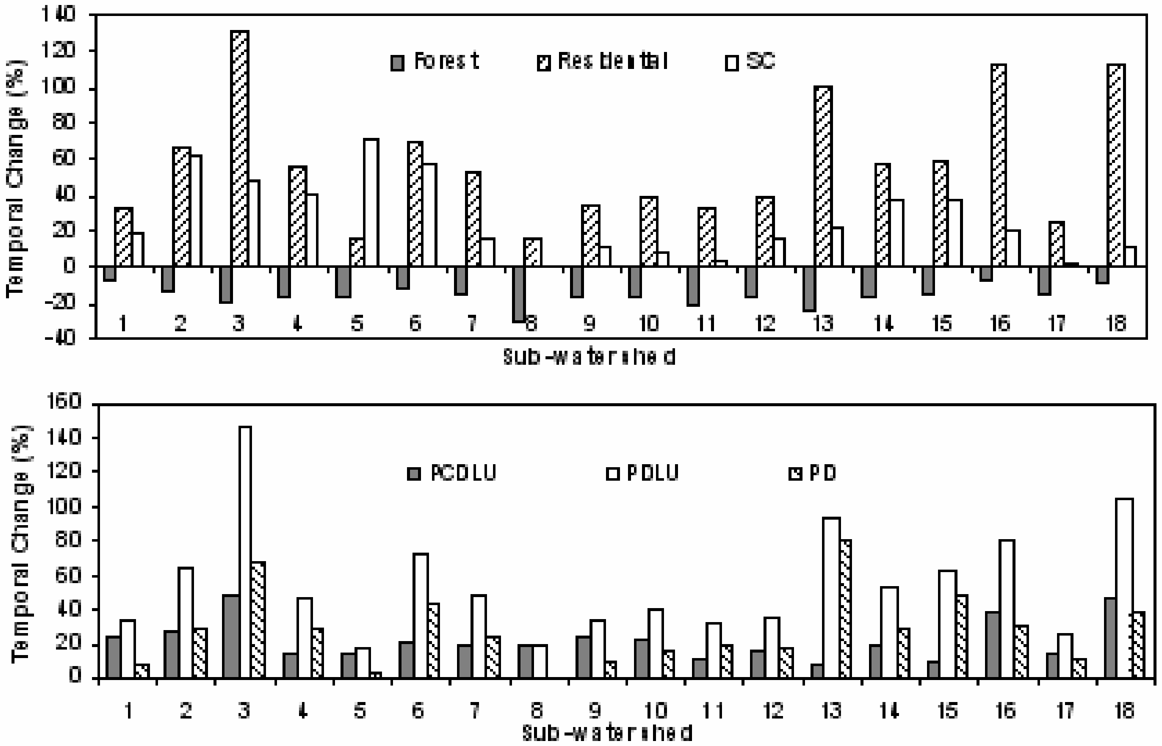

Figure 4. Comparison of temporal changes in land use and population variables and SC among the 18 delineated sub-watersheds (Temporal changes in forest, residential land, PDLU, and PCDLU are from 1971 to 1999; change in PD is from 1970 to 2000; change in SC is from the 1970s to the 1990s).

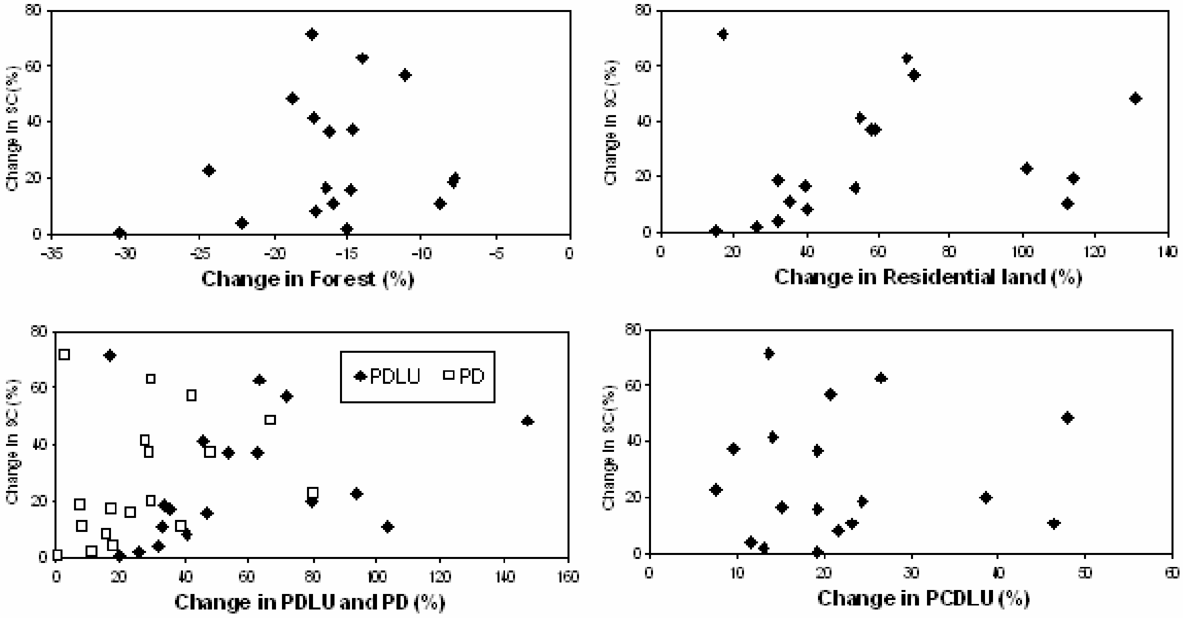

Figure 5. Relationships between SC temporal change and changes of land use and population variables over time (Temporal changes in forest, residential land, PDLU, and PCDLU are from 1971 to 1999; change in PD is from 1970 to 2000; change in SC is from the 1970s to the 1990s).

moderately-urbanized sub-watersheds (e.g. sub-watersheds 2 and 6). Most of the sub-watersheds with the fastest land development, usually within less-urbanized sub-watersheds such as sub-watersheds 16 and 18, were associated with a low water quality degradation rate, which might be attributed to the lower number of pollution sources in these sub-watersheds since they were still mainly rural areas.

Influence of Spatial Scale on Temporal Relationships

Table 3 shows the Spearman rank correlations between SC temporal change and the spatial and temporal variations of land use and population variables at different scales. Except residential land temporal change in the 250 m stream buffer, which showed a significant positive correlation with SC change over time, no significant linear correlations were found between temporal variations of land use and population variables and SC temporal change for all the four scales. However, slightly significant positive correlations between SC temporal change and each of residential land, PDLU, and PD temporal changes at all the scales suggests that water quality degradation might be attributed to population growth and land development (rho =0.30 – 0.47, p = 0.05 – 0.15).

For all the spatial scales, slightly significant or significant negative correlations were found between SC temporal change and residential land, PD, and PDLU change over space (rho = -0.23 to -0.49, p = 0.04 – 0.35), while slightly significant positive correlations were found for forest change over space in all the time periods (rho = 0.26 – 0.36, p = 0.14 – 0.30). SC temporal change had significant positive correlations with PCDLU change over space in each time period at the sub-watershed and 1000 m stream buffer scales (r = 0.48 – 0.58, p = 0.01 – 0.04). In other words, high % residential land, PD, and PDLU, low % forest and PCDLU sub-watersheds, mainly within highly-urbanized areas, tended to have low SC increase, while low % residential land, PD, and PDLU, high % forest and PCDLU sub-watersheds, mainly within moderately-urbanized areas, tended to have high SC increase. Stronger correlations for PCDLU changes over space than other variables confirm that urban sprawl is a combined effect of population and land use change. The stronger correlations at larger scales (sub-watershed and 1,000 m buffer scales) than those at smaller scales for PCDLU indicate that land development and population change at larger scales were more important to assess the impact of long-term land use change on water quality. In contrast, as described in section 4.3, population change and land development at smaller scales (stream buffers) were more important to evaluate the impact of land use change on spatial variability of water quality.

Table 3. Spearman Rank Correlations Between SC Temporal Change and Spatial and Temporal Variations of Land Use and Population Variables

Variables		Sub-watershed		1000 m buffer		500 m buffer		250 m buffer	
		rho	p	rho	P	rho	p	rho	p
Forest	1971	0.33	0.18	0.33	0.19	0.36	0.14	0.35	0.15
	1985	0.34	0.17	0.26	0.30	0.32	0.20	0.29	0.25
	1999	0.30	0.22	0.27	0.28	0.32	0.19	0.30	0.23
Residential	1971	-0.38	0.12	-0.37	0.13	-0.32	0.20	-0.36	0.14
	1985	-0.41	0.09	-0.35	0.15	-0.30	0.22	-0.32	0.19
	1999	-0.34	0.17	-0.37	0.13	-0.36	0.14	-0.23	0.35
PD	1970	-0.45	0.06	-0.44	0.07	-0.43	0.08	-0.44	0.07
	1980	-0.45	0.06	-0.41	0.09	-0.41	0.09	-0.41	0.09
	1990	-0.45	0.06	-0.43	0.08	-0.43	0.08	-0.41	0.09
	2000	**-0.47**	**0.05**	**-0.49**	**0.04**	**-0.49**	**0.04**	-0.45	0.06
PDLU	1971	-0.38	0.14	-0.27	0.11	-0.34	0.11	-0.41	0.11
	1985	-0.39	0.11	-0.36	0.14	-0.37	0.13	-0.42	0.08
	1999	-0.33	0.18	-0.35	0.15	-0.38	0.11	-0.43	0.08
PCDLU	1971	**0.48**	**0.04**	**0.50**	**0.04**	0.32	0.19	0.33	0.18
	1985	**0.55**	**0.02**	**0.50**	**0.04**	0.42	0.08	0.37	0.13
	1999	**0.57**	**0.01**	**0.58**	**0.01**	**0.48**	**0.04**	**0.49**	**0.04**
Forest change (1971-2000)		0.14	0.58	-0.04	0.87	0.10	0.70	0.02	0.94
Residential change (1971-2000)		0.44	0.07	0.30	0.23	0.40	0.10	**0.47**	**0.05**
PDLU change (1971-1999)		0.40	0.10	0.32	0.19	0.35	0.15	0.40	0.10
PD change (1970-2000)		0.45	0.06	0.44	0.07	0.43	0.08	0.40	0.10
PCDLU change (1971-1999)		0.07	0.79	-0.18	0.47	-0.10	0.69	-0.08	0.77

* Bold number indicates value significant at $P < 0.05$ (n=18).

CONCLUSIONS

Over the past three decades, land use change caused by urban sprawl had a considerable impact on water quality in eastern Massachusetts. High spatial correlations existed between SC and land use and population variables. PCDLU, % agricultural land, and % forest had significant negative correlations with SC, while PDLU, PD, % commercial land, % industrial, transportation, and mining land, % recreation use, % residential land showed significant positive relationships with SC. The more urbanized drainage areas tended to have higher SC. The spatial relationship was also scale dependent. Population and developed land adjacent to streams had stronger influence on water quality. Population change and land development at smaller scales (steam buffers) were more important to evaluate the impact of land use change on spatial variability of water quality.

SC concentration has increased in all the selected watersheds since the 1970s. High increase happened in moderately-urbanized areas, while low increase was found in highly-urbanized sub-watersheds. No significant correlation existed between SC temporal change and the changes of land use and population variables over time, indicating that water quality long-term change did not have consistent response to the rate of urban sprawl. However, significant correlations were found between SC temporal change and PCDLU changes over space for all the time periods at sub-watershed and 1,000 m stream buffer scales, which suggests that SC temporal change due to urban sprawl was the combined effect of population and land use change. This result also indicates that land development and population change at larger scales (sub-watershed and 1,000 m stream buffer scales) were more important to assess the impact of long-term land use change on water quality.

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