Impact of Suburbanization on Water Quality at Multiple Spatial Scales

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Abstract A study of water quality, land-use patterns, and population data is conducted at several watersheds in eastern Massachusetts to examine the impact of urban sprawl on water quality at three different spatial scales: watersheds, buffered streams, and buffered water sampling sites. GIS analysis is used to delineate the drainage areas using digital elevation models for the water flow passing the corresponding water sampling sites; to generate buffers of different distances for the streams and the sampling sites; and to derive the indicators of suburbanization such as developed land and population density for different scales. Statistical analyses are used to examine and quantify the relationships between water quality parameters and the indicators of suburbanization. Results from this study will contribute to a better understanding of not only the impact of urban sprawl on water quality but also the appropriate scale for effective management of watersheds.

KEY WORDS: Water quality; Suburbanization; Geographic information system; Specific conductance; Population growth; Land development

1 Introduction

Suburbanization, also called urban sprawl, is the land-consumptive pattern of suburban development characterized by increasing population density and rising scattered, low-density residential and commercial areas outside of the urban centers caused by population growth, increasing incomes, and decreasing commuting costs (Wilson 2003; Interlandi and Crockett 2003; Robinson et al. 2005). It has been the dominant development pattern throughout much of the United States over the recent decades.

Stream degradation due to the increasing developed land and human activities in the process of suburbanization in watersheds has become an increasing concern (Wang and Yin 1996; Finkenbine et al. 2001; Interlandi and Crockett 2003; Holland et al. 2004; Schoonover et al. 2005). In these studies, significant relationships were found between the increasing concentrations of water quality parameters, such as nutrients, dissolved solids, fecal coliform, specific conductance, sediments, and turbidity, and the increasing values of suburbanization indicators over time and space. For example, a study on water quality change in the Schuylkill River, Pennsylvania from 1973 to 1999 found that the annual mean concentrations of alkalinity, specific conductance, Cl^-, and Na^+ all showed significant positive trends, which were attributed to watershed development (Interlandi and Crockeet 2003)

Most of these previous studies mainly used land use measures, including percentage of urban land use, percentage of developed land, and percentage of impervious surface as suburbanization indicators. Conversion from undeveloped land such as agriculture land, forestland, and wetlands into developed areas such as residential, commercial, industrial and transportation uses was considered as the most significant feature of suburbanization. However, suburbanization is a pattern of not only the expansion of urban land use but also the outward movement of population from central cities to suburban areas. Usually in suburban areas land development is faster than population growth, since low-density development tends to occupy far more land than higher-density urban centers (Robinson et al. 2005).

Many studies also found that the impact of land use change on the watershed environment is scale dependent (Sliva and Williams 2001; Wang et al. 2001; Jarvie et al. 2002; Houlahan and Findlay 2004; Pan et al. 2004; Deacon et al. 2005; Frimpong et al. 2005; McBride and Booth 2005). Those studies took the advantage of GIS to examine the impact of land use change on watershed environments such as water quality and stream biological communities at multiple spatial scales, including watershed and stream riparian scales, and found that the effect of land use change varied across different spatial scales. In a study on the impact of land use on water quality in three southern Ontairo watersheds of Canada, Sliva and Willams (2001) found that urban land use within stream buffer zone had stronger influence on water quality than that in entire watershed, while forest land use was a better predictor of water quality at watershed scale. Deacon et al. (2005) studied the effects of urbanization on stream quality in the seacoast region of New Hampshire from 2001 to 2003. They found that the correlations between measures of urbanization and water quality were stronger in buffer zones near and upstream of a sampling site than that in entire watershed. In contrast, stronger correlations were found between some water quality parameters and land characteristics at watershed scale than those in the buffer zones of sampling sites by Jarvie et al. (2002). Therefore, to find an appropriate scale for assessing the impact of suburbanization on water quality is important for regional watershed management.

This study assessed the impact of suburbanization on water quality over the past thirty years in eastern Massachusetts through analyzing the relationship between suburbanization indicators and water quality indicator at multiple spatial scales using GIS analyses and statistical analyses. Three different spatial scales were used in this study: (1) sub-watershed scale: the whole upstream drainage area of each water quality sampling site; (2) stream buffer scale: the buffer zone within a certain distance to major streams and ponds in each watershed; (3) site buffer scale: the buffer zone within a certain distance to each water quality sampling site within its watershed. Population density (PD) and percentage of developed land use (PDLU) were used to measure suburbanization. Per capita developed land use (PCDLU) was used to reflect the combined effect of population and land use change. Specific conductance (SC) was used in this study as a water quality indicator. This parameter reflects the dissolved ionic concentration in water and has been used in many studies to examine the relationship between water quality and land use change (Wang and Yin 1996; Dow and Zampella 2000; Interlandi and Crockett, 2003; Deacon et al. 2005). The objectives were threefold: first, analyzing the relationship between suburbanization and water quality over space and time; second, assessing the sensitivity of water quality to different suburbanization indicators; third, comparing the impact of suburbanization on water quality at various spatial scales.

2 Study Area

The study area covers the metropolitan Boston and its surrounding areas in Massachusetts. This region, with a population of about 5.2 million in 2000 and an area of 10,000 km^2, consists of 208 municipalities within an 80 km (50 miles) buffer of the City of Boston (Figure 1). This area is more densely populated, urbanized and industrialized compared to most parts of New England. Although mainly urban and suburban in the metropolitan Boston and the third largest city in New England, Worcester, the study area also includes a high percentage of forest and agriculture lands.

The study area covers 15 watersheds defined by the U.S. Geological Survey (USGS) and the Massachusetts Department of Environmental Management's (MADEM) Division of Water Resources (Simcox 1992). The majority of the watersheds are within the U.S. Environmental

Protection Agency (USEPA) Level III Ecoregion 59, the Northeastern Coastal Zone, which means that the watersheds are relatively homogeneous in their natural characteristics such as geology, vegetation, physiography, soils, and climate (Omernik 1987). Therefore, the water quality change in this area could be mainly attributed to anthropogenic factors (e.g., urbanization) rather than to natural variability.

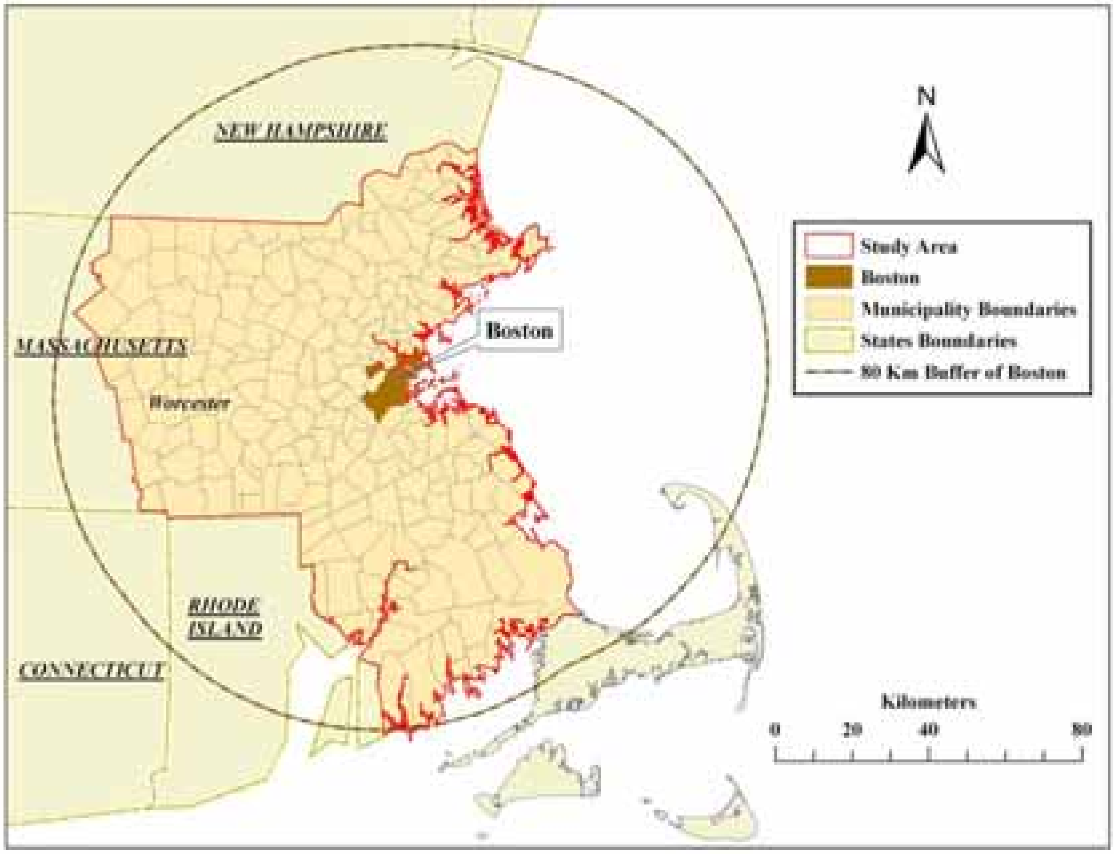

Figure 1 Location of the study area

3 Data Sources and Methods

Land use and population data were obtained from the website of the Massachusetts Geographic Information System (URL http://www.mass.gov/mgis/). Developed land use data aggregated by municipality 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 in this study. Developed land use was aggregated based on residential, commercial, industrial, transportation, recreation, urban open, and waste disposal land use, which were interpreted from 1:25,000 aerial photographs by the Resource Mapping Project at the University of Massachusetts, Amherst (MassGIS 2005).

Water quality data from 1970 – 2004 were retrieved on-line from the USGS National Water Information System Web (NWISWeb; URL http://waterdata.usgs.gov/nwis/). 33 USGS water quality sampling sites were selected based on the data availability (Figure 2). The mean concentrations of specific conductance were calculated for three time periods: the 1970s, the 1980s, and the 1990s and after.

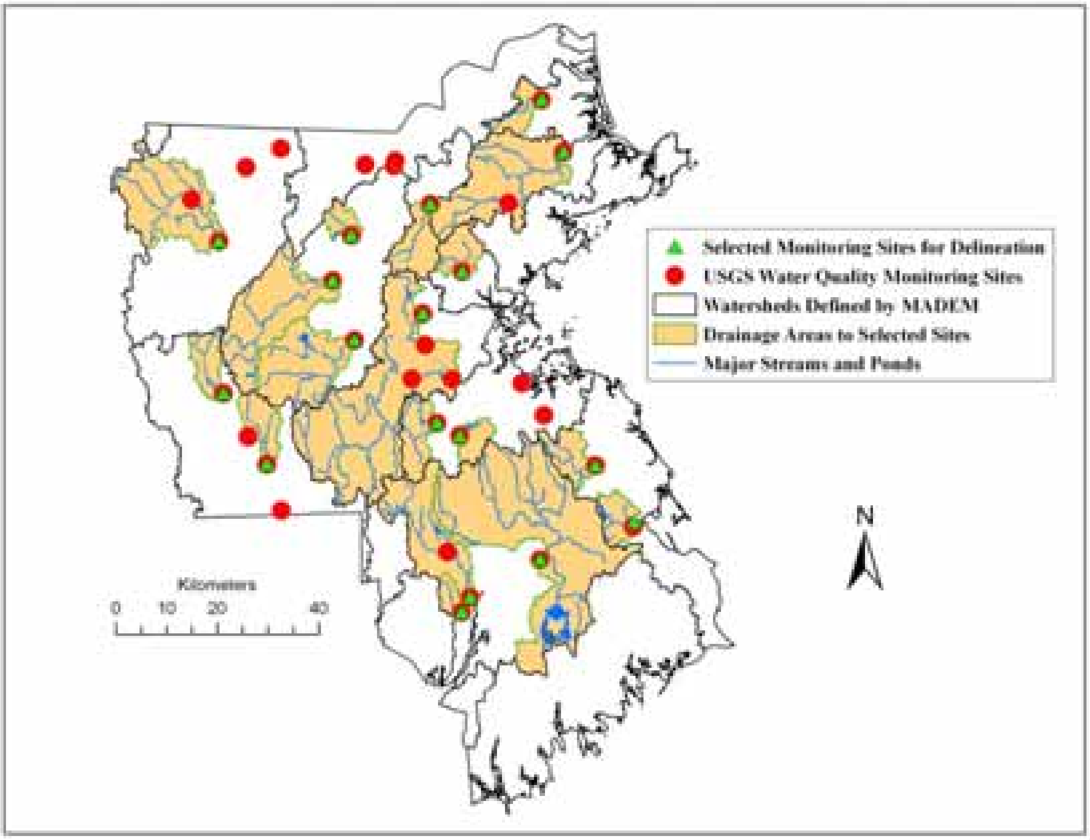

Figure 2 Delineated sub-watersheds to selected sites for statistical analyses

The relationship between suburbanization and water quality was analyzed through two phases. First, the general spatial pattern of the impact of suburbanization on water quality was mapped using ArcGIS 9.0. In this phase, population distribution in 2000, developed land use in 1999, and specific conductance in the 1990s and after were mapped to show the general spatial relationship between suburbanization and water quality. Specific conductance change from the 1970s to the 1990s and after, and population density change from 1970 to 2000, percentage of developed land use change from 1971 to 1999 were mapped to show spatio-temporal relationship between suburbanization and water quality.

Second, the relationship between suburbanization indicators and specific conductance at different spatial scales was quantified using simple linear bivariate regression. Simple linear bivariate regression requires at least two corresponding data sets. Water quality of a sampling site is affected by the physical characteristics and human activities in its upstream drainage area rather than within the limits of administrative region. The drainage area (sub-watershed) for a site can be delineated from digital elevation data. In the process of delineation, the site becomes the lowest point in its drainage area; in other words, all the water at a particular site comes from its feeding sub-watershed. Thus, water quality data at the site could be used to represent the water quality of its feeding sub-watershed. The drainage area or sub-watershed for each selected site was delineated from digital elevation data provided by the USGS National Elevation Dataset (NED) (about 30 meter resolution, URL http://seamless.usgs.gov/website/Seamless/) using ArcGIS spatial analysis tools. The procedure for delineating a sub-watershed is shown in Figure 3.

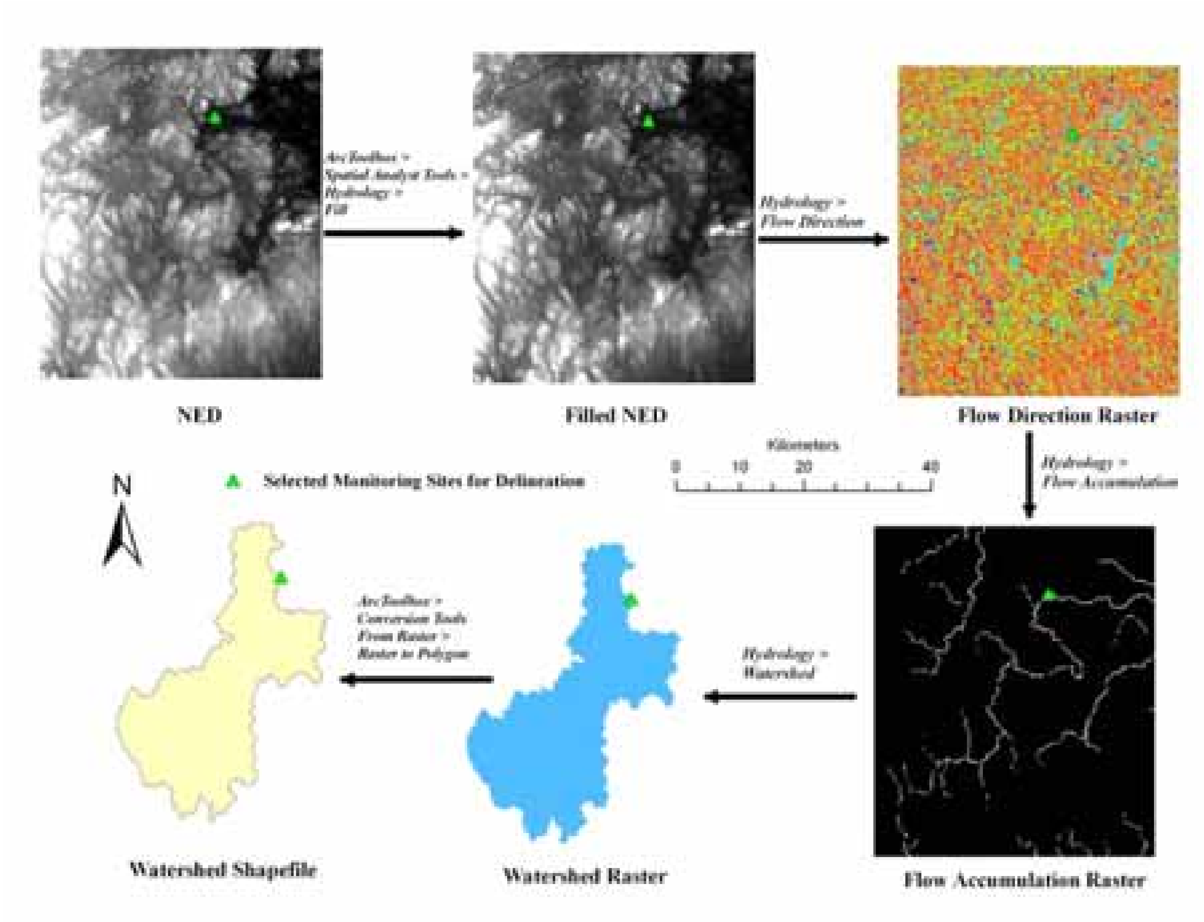

Figure 3 Procedure of sub-watershed delineation

In order to make the sub-watersheds exclusive of each other, only 18 of the 33 USGS water quality monitoring sites were selected for watershed delineation, and they are within 10 of the 15 watersheds defined by the USGS and the MADEM (Simcox 1992). The size of drainage areas ranged from 28 to 778 km^2 (Figure 2).

In these 18 delineated sub-watersheds, three stream buffer zones with different distances to streams and ponds, 250 meters, 500 meters, and 1000 meters, and three site buffer zones with different radii around the sampling sites, 1000 meters, 2000 meters, and 4000 meters, were delineated using ArcGIS buffer analysis tool. The major streams and ponds shape file was obtained from the website of the Massachusetts Geographic Information System. Figure 4 shows the delineated buffer zones and sub-watershed for one particular water quality sampling site.

Following the delineation of the seven spatial zones (sub-watershed, 250 m, 500 m, and 1000 m stream buffer, 1000 m, 2000 m, and 4000 m site buffer), the total population and developed land within each spatial zone were obtained by overlaying land use and population layers on the delineated sub-watershed and buffer zone layers in ArcGIS. To estimate the total population within a spatial zone, the proportion of each block or municipality that fell within the spatial zone was calculated, and then the proportion was multiplied by the population in the entire block or municipality. Clearly, this will introduce some error in population data because the calculation assumes that population is evenly distributed over a block or municipality, especially when municipality population data was used to calculate population change over time for small scales such as site stream buffers as there was no block population data for 1970 available. However, when block population data was used to calculate the population within each spatial zone in 2000, the error is relatively small. Afterwards, population density and percentage of developed land use for a spatial zone were calculated through dividing the total population and the amount of developed land within the spatial zone by the total area of that zone, respectively. Population density change was calculated by comparing population density in 2000 with that in 1970, and percentage of developed land use change was calculated by comparing the land use in 1999 with that in 1971. Per capita developed land for a spatial zone is calculated through dividing the amount of developed land use by population within the same zone. The procedure of calculating population and developed land data for a spatial zone of a water quality sampling site is shown in Figure 5.

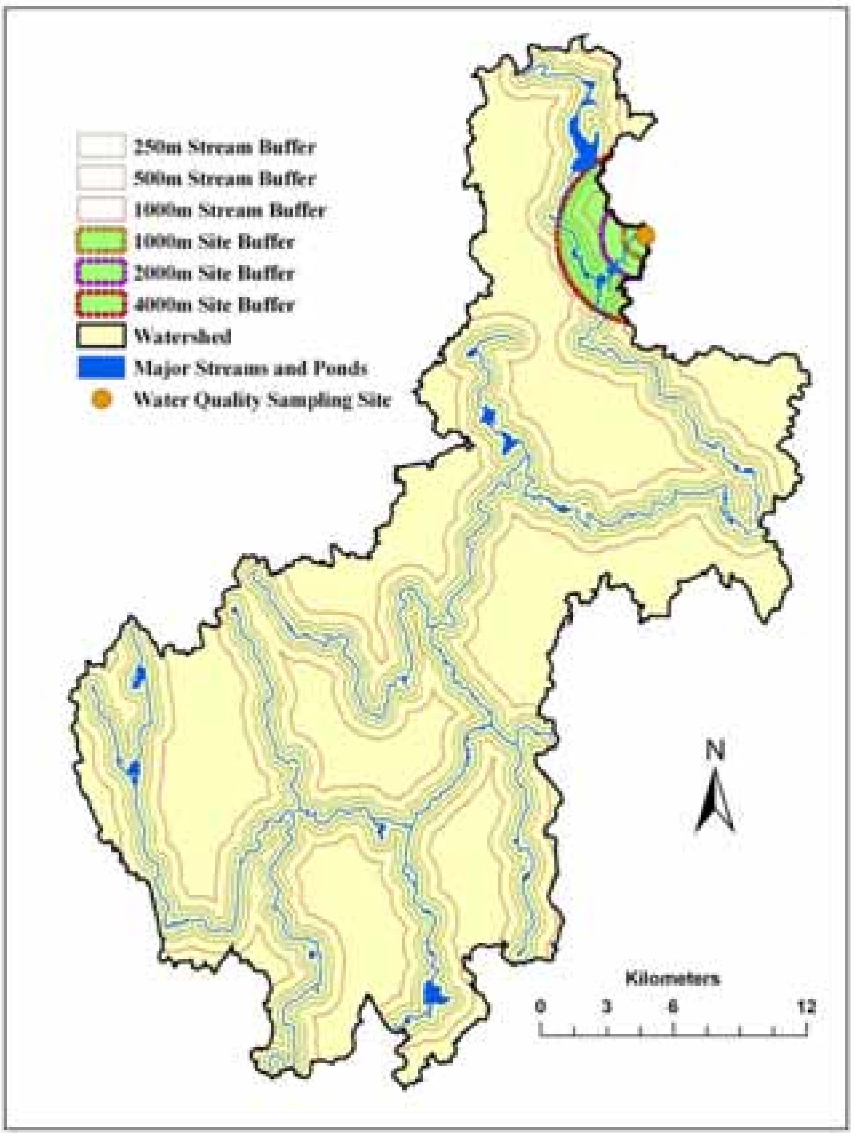

Figure 4 Delineated buffer zones and sub-watershed for a water quality sampling site

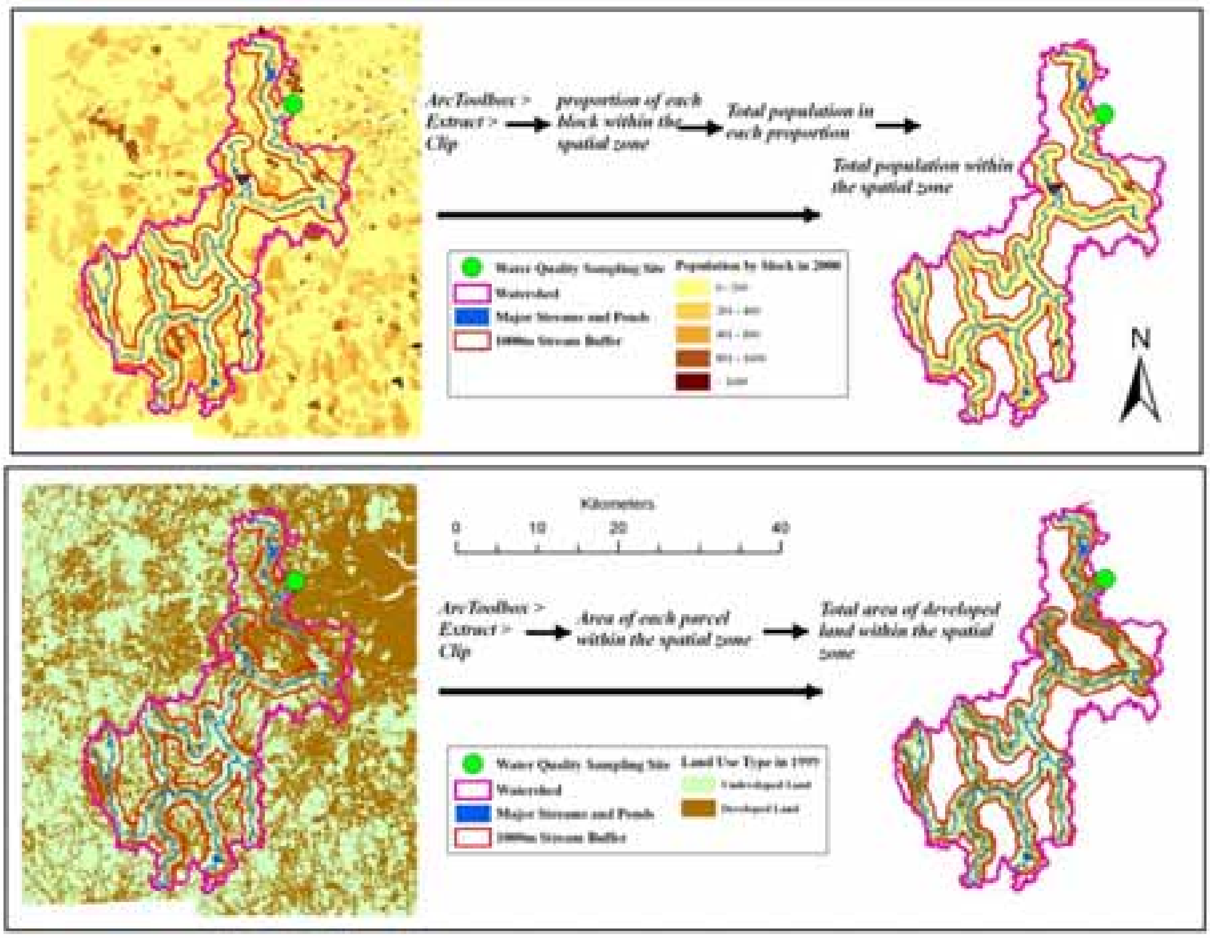

Figure 5 Procedure of population and developed land data calculation for a spatial zone of a water quality sampling site

Through these steps, a linkage of water quality for point locations to suburbanization indicators for areas was established.

Identical statistical analyses were employed in SPSS software for all the spatial scales to quantify the relationship between suburbanization variables and water quality variable over space and time. The Kolmogorov-Smirnov test, histogram plot, and Q-Q plot were used to examine the normality of distribution of the variables. After appropriate transformations such as natural log were performed on the variables that were not normally distributed in order to meet the condition of normal distribution, simple linear bivariate regression was used to analyze the relation of suburbanization variables with water quality variable at different spatial scales. For each combination of variables, coefficients of determination (r^2) and significant level (p) values were compared to determine the relative importance of suburbanization indicators influencing water quality and the relative significance of different scales for the impacts. When r^2 and P were similar for the combination of the same variable at different scales, the regression slopes were further compared, and higher slopes indicate stronger relationships.

4 Results and Discussion
4.1 General Spatial Patterns of Suburbanization and Its Impact
4.1.1 Spatial Relationship between Suburbanization and Water quality

In this study, the spatial relationship refers to how water quality changes with the spatial variation in suburbanization indicators. The spatial relationship between population density (PD) and specific conductance (SC), and between developed land use and SC are shown in Figure 6 and Figure 7, respectively. The time period of SC data was the 1990s and after. The corresponding PD data was for 2000 by census block, and the corresponding developed land use data was interpreted from 1999 aerial photographs, which can show the relationship between suburbanization indicators and SC change over space in the same time period.

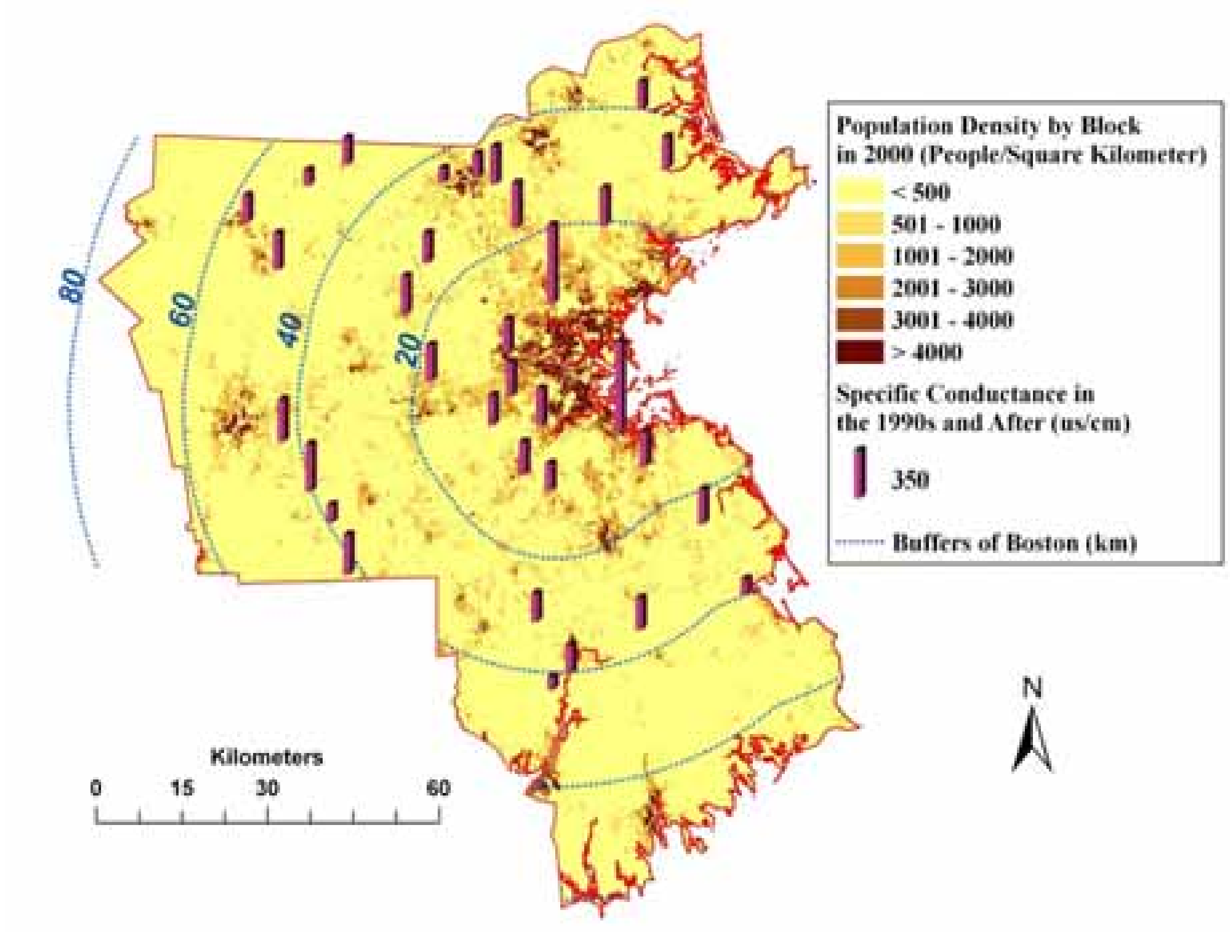

Figure 6 Spatial relationship between PD and SC

The area within the 20 km buffer of Boston had high PD. Most blocks with PD higher than 4000 people/km^2 were concentrated in the Metropolitan Boston area. PD decreased as the distances increased from the City of Boston, except several municipalities such as Worcester, Lowell, and Lawrence. Most of the areas outside of the 20 km buffer of Boston had PD lower than 1000 people/ km^2 (Figure 6).

In general, the concentration of SC also had a similar spatial pattern. The two sites with highest SC concentrations (>400 μs/cm) were within the Metropolitan Boston area, which had high PD, while all the sites with lowest SC concentrations (<100 μs/cm) were within low PD areas outside of the 20 km buffer (Figure 6). This result indicates that high PD areas, representing highly urbanized areas, tend to be related to high SC concentrations.

Another suburbanization indicator, developed land use, also showed the same pattern to that of population distribution (Figure 7). Almost all the land in the Metropolitan Boston area was developed. Developed land use decreased as the distance increased from Boston. Except Worcester, most of the land outside of 40 km buffer was undeveloped. Like PD, densely developed land use areas tend to be related to high SC concentrations.

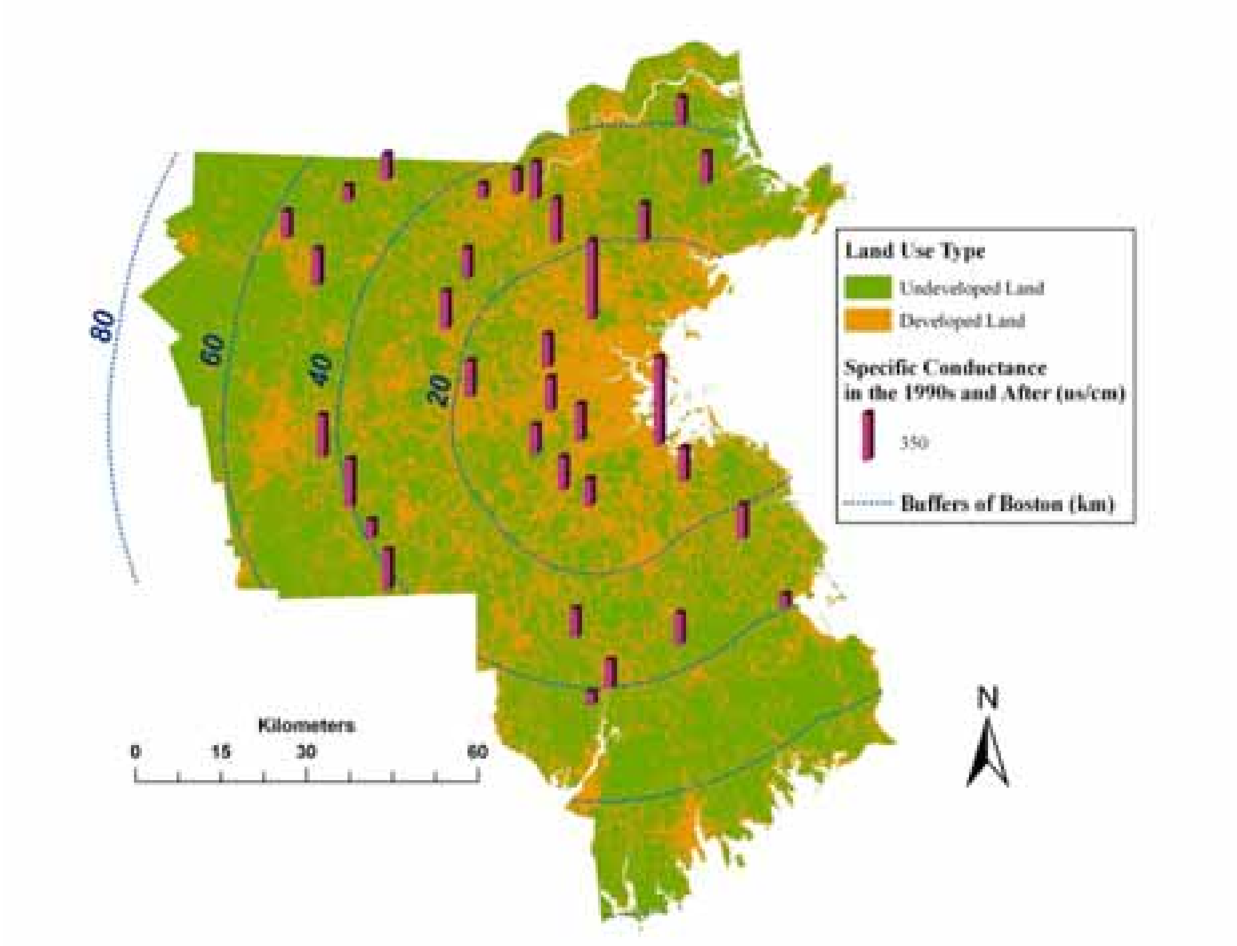

Figure 7 Spatial relationship between developed land use and SC

4.1.2 Temporal Relationship between Suburbanization and Water quality

In this study, temporal relationship refers to how the water quality changes as the suburbanization indicators change over time. The spatial pattern of the temporal relationship between PD and SC, and between percentage of developed land use (PDLU) and SC are shown in Figure 8 and Figure 9, respectively. PD change by municipality from 1970 to 2000, PDLU by municipality from 1971 to 1999, and SC change from the 1970s to the 1990s and after were mapped.

The majority of the municipalities outside 20 km buffer of Boston experienced significant population growth from 1970 to 2000, while considerable population decline happened in most municipalities within the 20 km buffer (Figure 8). This result shows one of the typical patterns of urban sprawl: the outward movement of population from central cities to suburban areas.

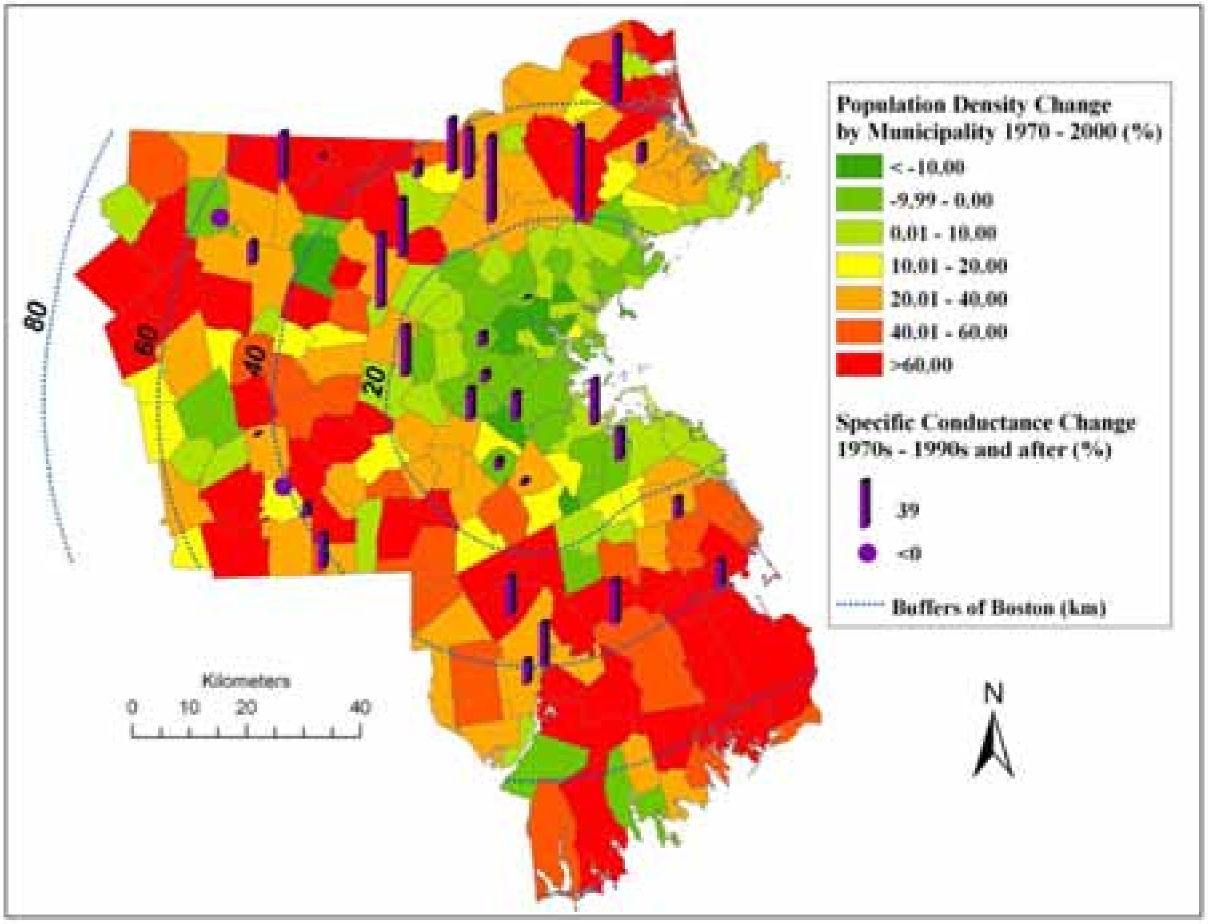

Figure 8 Spatial pattern of temporal relationship between PD and SC

SC concentrations in most sites increased from the 1970s to the 1990s and after; however, a significant difference between inside and outside of the 20 km buffer also existed. SC concentration in most sites inside of the 20 km buffer increased by less than 30%, while that in most of the sites between the 20 km and 40 km increased by more than 30%. This result indicates that the SC concentration increase over time at a site is related to the population growth in its surrounding area. The only two sites with decreased SC concentrations were outside of the 40 km buffer. However, one of these two sites was within a municipality with population density decrease more than 10%, and another site is close to Worcester, which also experienced population decline.

PDLU change also showed significant impact of suburbanization on water quality change over time. A clear pattern of the expansion of developed land use from the Metropolitan Boston area to suburban areas during 1971-1999 was shown in Figure 9. The areas outside of the Metropolitan Boston area experienced fast land development over the 30 years period. The most significant land development happened in the area between the 20 km and 40 km buffers. In this area, PDLU of some municipalities increased by more than 20 percentage points, and correspondingly the SC concentrations had the most significant increase. In contrast, most of the sites with low SC increase were within or close to the municipalities that experienced low PDLU increase or even decrease, most of which were in the Metropolitan Boston area. This result indicates that the change of SC concentration over time at a site was also related to land development in its surrounding area.

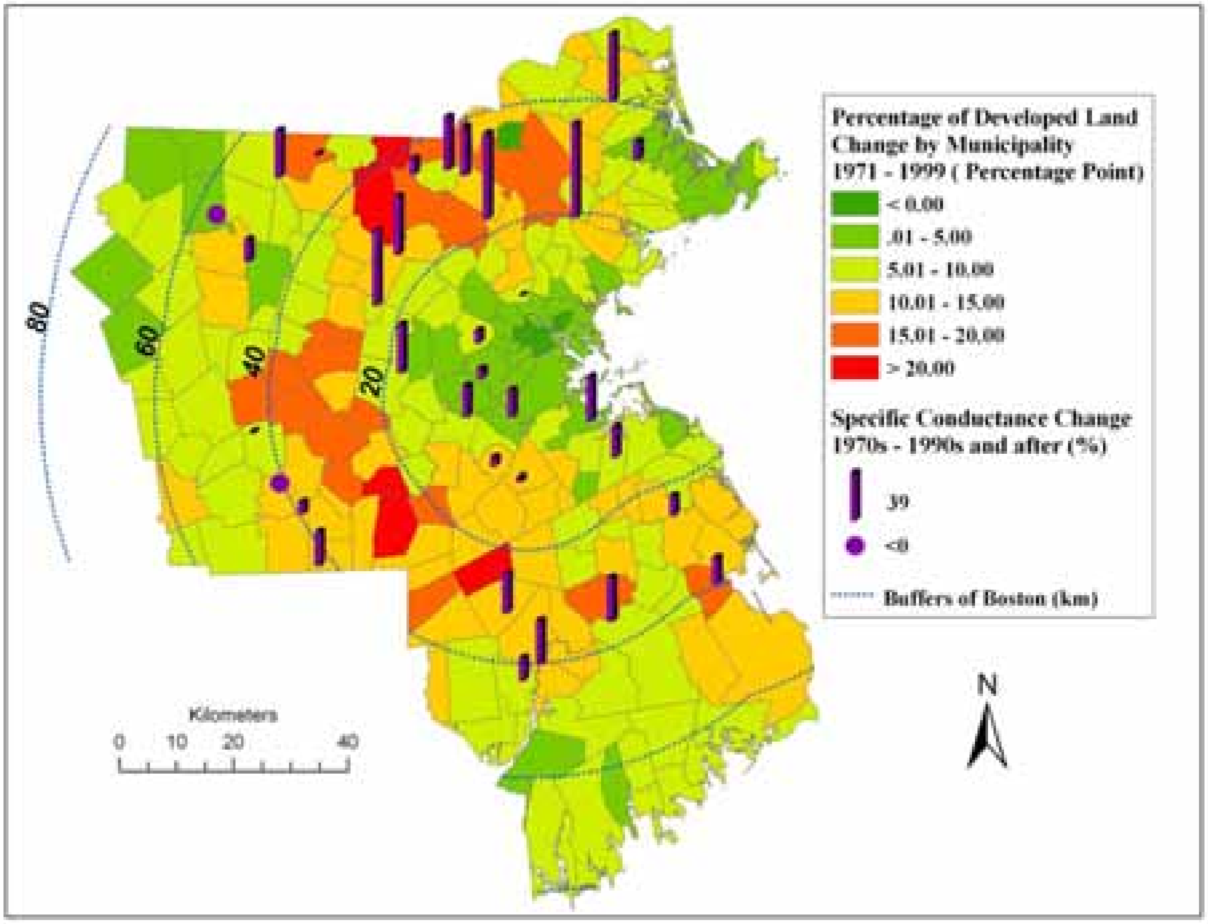

Figure 9 Spatial pattern of temporal relationship between PDLU and SC

The PD and the PDLU temporal change maps show that the northern part of the area between the 20 km and 40 km buffers, which could be classified as suburban areas, had high increase in both PD and PDLU, and the sampling sites in the area also had the highest increase in SC (Figure 8 and Figure 9). In contrast, the Metropolitan Boston area had low increase or even decline in both PD and PDLU, and most of sites there had low increase in SC. Furthermore, the area outside of 40 km buffer and the southern part of the area between the 20 km and 40 km, which could be classified as rural area because of low population density and developed land use (Figure 6 and Figure 7), experienced high increase in PD but low increase in PDLU, and almost no significant increase in SC was found. Therefore, a general spatial pattern of SC concentration change over time was identified: High, medium, and low SC concentration increase occurred in suburban areas, rural areas, and central cities, respectively. This result also indicates that the impact of suburbanization on water quality comes from the combined effect of population growth and land development.

4.2 Statistical Relationship between Suburbanization and Water Quality at Multiple Spatial Scales

4.2.1 Statistical spatial relationship between suburbanization indicators and water quality

PD for 2000 and PDLU for 1999 in the 18 delineated sub-watersheds ranged from 103 to 1209 persons/km^2 and 18.0% to 74.9%, respectively, which represented different extents of suburbanization over space. In order to quantify the impact of varying suburbanization indicators over space on specific conductance concentration, a simple linear bivariate regression was carried out using SC concentration in the 1990s and after versus PD in 2000 and PDLU in 1999 for the sub-watershed scale and the 6 buffer scales. The results are shown in Table 1.

Table 1. Simple linear regression results for SC and suburbanization indicators over space

Scale	Population Density			Percentage of Developed Land Use		
	r^2	Slope	r	r^2	Slope	r
Sub-watershed	***0.70*** [a]	***0.32***	***0.84***	***0.61***	***5.40***	***0.78***
1000 m stream buffer	***0.72***	***0.37***	***0.85***	***0.68***	***6.32***	***0.83***
500 m stream buffer	***0.71***	***0.38***	***0.84***	***0.65***	***6.39***	***0.81***
250 m stream buffer	***0.69***	***0.43***	***0.83***	***0.65***	***7.11***	***0.81***
4000 m site buffer	**0.33** [b]	**0.13**	**0.57**	**0.30**	**2.59**	**0.55**
2000 m site buffer (Ln)	**0.25**	**38.9**	**0.50**	**0.26**	**2.00**	**0.51**
1000 m site buffer (Ln)	0.19	31.3	0.44	**0.24**	**1.62**	**0.49**

[a] Bold and italic number indicates values significant at P < 0.01 (n=18)
[b] Bold number indicates values significant at P < 0.05 (n=18)
Ln indicates that population density was natural log transformed

For the sub-watershed scale and all the stream buffer scales, significant positive correlations were found between SC concentration and PD ($r = 0.83$-0.85, $p < 0.01$), and between SC concentration and PDLU ($r = 0.78$-0.83, $p < 0.01$). This result indicates that the more urbanized drainage areas with higher population density and higher percentage of developed land use tend to have higher specific conductance concentration.

PD had a slightly more significant correlation with SC than PDLU did. For example, in sub-watershed scale PD explained 70% of the variation in SC, while PDLU explained 61%. The r values for sub-watershed scale and the stream buffer scales were very close. However, the slope increased steadily from larger scale to smaller scale (the sub-watershed scale to the 250 m stream buffer), indicating that the correlations got stronger at smaller scale. This result suggests that the population and developed land adjacent to streams had stronger influence on water quality. To control urbanization of riparian buffer strips along streams is very important for water environment conservation.

Significant correlations were also found for 4000 m and 2000 m site buffer scales. Nevertheless, they were much weaker than those for the sub-watershed scale and the stream buffer scales. For instance, PD only explained 33% of the variation in SC at 4000 m site buffer scale. Among the site buffer scales, the correlations decreased consistently from larger scale to smaller scale, and no significant correlation was found for PD with SC at 1000 m site scale. This result indicates that water quality in one sampling site was more strongly influenced by the urbanization of the whole sub-watershed and the riparian zone upstream instead of the proximate upstream surrounding area.

4.2.2 Statistical temporal relationship between suburbanization indicators and water quality

The increases in PD from 1970 to 2000 and PDLU from 1971 to 1999 in the 18 delineated watersheds ranged from 0.3% to 80.4% and 16.9% to 147%, respectively, which represented different rates of suburbanization over time. In order to quantify the impact of suburbanization indicators change on specific conductance temporal change, a simple linear bivariate regression was used to do regression of SC concentration change from the 1970s to the 1990s and after on each of the population and developed land variables for the seven spatial scales. Another suburbanization indicator, per capita developed land use (PCDLU), was also included to reflect the combined effect of population growth and land development. The results are shown in Table 2.

Table 2. Simple linear regression results for SC temporal change and suburbanization indicators*

		Sub-watershed	1000 m stream buffer	500 m stream buffer	250 m stream buffer	4000 m site buffer	2000 m site buffer	1000 m site buffer
PD	1970	-0.40	-0.43	-0.37 Ln	-0.37 Ln	-0.29	-0.14 Ln	0.04 Ln
	1980	-0.39	-0.42	-0.40	-0.34 Ln	-0.26	-0.10 Ln	-0.14 Ln
	1990	-0.40	-0.40	-0.36 Ln	-0.36 Ln	-0.26	-0.11 Ln	-0.10 Ln
	2000	-0.40	-0.42	-0.42	-0.40	-0.30	-0.07 Ln	-0.11 Ln
PDLU	1971	-0.20	-0.18	-0.39	-0.25	-0.24	-0.37 Ln	-0.06
	1985	-0.19	-0.16	-0.37	-0.20	-0.20	-0.10	0.01
	1999	-0.18	-0.16	-0.39	-0.20	-0.18	-0.04	0.08
PCDLU	1971	**0.51**	**0.49**	0.32	0.33	0.03	0.13	-0.24 Ln
	1985	**0.53**	**0.52**	0.38	0.33	0.02	0.13	-0.27 Ln
	1999	**0.55**	**0.53**	0.37	0.36	0.08	0.20	-0.30 Ln
PD change 1970-2000		0.28	0.27	0.27	0.27	0.24	0.22	0.26
PDLU change 1971-1999		0.26	0.22	0.30 Ln	0.29 Ln	0.18 Ln	-0.11	0.16
PCDLU change 1971-1999		0.04	0.02	0.13	0.08	-0.08	-0.19 Nr	0.05

* Only correlation coefficient (r) is shown here. Bold number indicates value significant at $P < 0.05$ (n=18)
Ln indicates the suburbanization indicator is natural log transformed
Nr indicates the suburbanization indicator is negative reciprocal transformed

Positive correlations were found between SC concentration temporal change and both PD and PDLU change over time, suggesting that population growth and land development caused water quality degradation. However, the correlations were not significant, indicating that water quality temporal change did not have consistent response to the rate of suburbanizaition since some other factors such as policy and climate change may also have some impact on water quality.

Non-significant negative correlations were found between SC temporal change and PD or PDLU change over space, but significant positive correlations were found between SC temporal change and PCDLU change over space in each time period at the sub-watershed and 1000 m stream buffer ($r = 0.49\text{-}0.55$, $p < 0.05$). In other words, high PD and PDLU, low PCDLU sub-watersheds, mainly within central cities, tended to have low SC concentration increase, while low PD and PDLU, high PCDLU sub-watersheds, mainly within suburban areas, tended to have high SC increase. Furthermore, the correlation at the sub-watershed scale was stronger than that at 1000 m stream buffer scale. Therefore, to assess the impact of suburbanization on water quality temporal change, per capita developed land use at the sub-watershed scale is a more appropriate indicator than the other two, which also confirms that the suburbanization is a combined effect of population and land use change.

5 Conclusions

Over the past three decades, suburbanization had a significant impact on water quality in eastern Massachusetts, which was identified by analyzing the relationships between urban sprawl indicators and specific conductance through GIS analyses and statistical analyses.

Both GIS analyses and statistical analyses found that high correlations existed between specific conductance concentration and population density and developed land use change over space. Specific conductance concentration had significant positive correlations with both population density and percentage of developed land use. The urbanized sub-watersheds with high population density and high percentage of developed land use tended to have high specific conductance concentration.

In assessing the spatial relationship between suburbanization and water quality, both population density and percentage of developed land use were good predicators of water quality change influenced by suburbanization, but population density was slightly better than developed land use. The impact was also scale dependent. The correlations between water quality and suburbanization indicators were stronger at the sub-watershed scale and stream buffer scales than site buffer scales, suggesting that water quality in one sampling site was more strongly influenced by the urbanization of the whole sub-watershed and the riparian zone upstream instead of the proximate upstream surrounding area. Among the sub-watershed scale and stream buffer scales, the smaller scales (500 m and 250 stream buffer) had stronger correlations. This result indicates that the population and developed land adjacent to streams had stronger influence on water quality. To control urbanization of riparian buffer strips along streams is very important for water environment conservation.

Specific conductance concentration has increased in most of the watersheds in eastern Massachusetts since the 1970s. However, differences in the impact of suburbanization on specific concentration between suburban areas and central cities were clear. The results of GIS analyses showed that the central cities with higher population density and percentage of developed land use experienced lower increase in specific conductance concentration, while suburban areas and rural areas with lower population density and percentage of developed land use, especially the municipalities between 20 km and 40 km from Boston, experienced higher increase in specific conductance concentration. These results were also verified by the significant positive correlation between specific conductance concentration temporal change and per capita developed land use change over space for each time period, and by the negative correlations between specific conductance concentration temporal change and both population density and percentage of developed land use change over space through statistical analyses. However, the negative correlations for both population density and percentage of developed land use were not significant. This result suggests that specific conductance temporal change was more sensitive to per capita developed land use change, and the negative impact of suburbanization over time on water quality was due to the combined effect of population and land use change. The faster rate of land use development than that of population growth in suburban areas was one major reason for water quality degradation in terms of specific conductance concentration increase. Per capita developed land use is a more appropriate indicator to study the impact of suburbanization over time on water quality than population density and percentage of developed land use. The correlation between specific conductance temporal change and per capita developed land use change over space was also scale dependent. The correlation was stronger at larger scales (sub-watershed and 1000 m stream buffer scale) than the other scales, indicating that watershed management is important to control the impact of suburbanization over a long term period on stream water quality.

No significant correlation was found between specific conductance temporal change and suburbanization indicators change over time, indicating that water quality temporal change did not have consistent response to the rate of suburbanization since some other factors such as policy and climate change may also have some impact on water quality.

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