6-2013

Land Use and Socioeconomic Influences on a Vulnerable Freshwater Resource in Northern New England, United States

Firooza Pavri
University of Southern Maine

Anna Springsteen
University of Maine

Abraham Dailey
University of Southern Maine

Jean MacRae
University of Maine, jean.macrae@maine.edu

Land use and socioeconomic influences on a vulnerable freshwater resource in northern New England, United States

Firooza Pavri, Anna Springsteen, Abraham Dailey, Jean D. MacRae

F. Pavri, Department of Geography-Anthropology, University of Southern Maine, 300 Bailey Hall, Gorham, ME 04038, USA, e-mail: fpavri@usm.maine.edu

A. Springsteen, Department of Ecology and Environmental Science, University of Maine, Orono, ME 04469, USA

A. Dailey, Community Planning and Development, University of Southern Maine, Portland, ME 04104, USA

J. D. MacRae, Department of Civil and Environmental Engineering, University of Maine, 5711 Boardman Hall, Orono, ME 04469-5711, USA

Abstract

Land use and cover conversions as well as climatic factors drive current and future threats to freshwater systems. Research from the United States and across the globe has focused on already threatened and degraded freshwater systems, whose recovery requires significant investments. Attention must also be directed to monitoring freshwater systems that may appear robust, yet are likely to face enhanced vulnerabilities in the future due to climate and land use and cover changes. Such proactive monitoring can help identify problems early and provide potential solutions. In this study, we consider the case of Sebago Lake and its watershed in southern Maine; a region that has experienced significant population growth and development activity. Land use, socioeconomic change and water quality trends are monitored over a 20-year period using Landsat imagery, census, water quality and precipitation data. Our results indicate that Developed Land within the watershed has increased from 5.4 % of the total land area in 1987 to 8.9 % in 2009 with associated increases in population and housing activity. Sebago Lake's water quality indicators from 1990 to 2010 show a directional trend concomitant with this change. The increase in Developed Land is likely to place additional pressures on water quality in the future. The analysis also indicates that precipitation trends play an important role in water quality variability for Sebago Lake. Predicted changes to climatic factors including enhanced spring time precipitation or earlier ice-out conditions combined with further land use change may play an influential role in determining water quality. The analysis highlights emerging areas of concern and reiterates the essential role of proactively monitoring vulnerable systems to help mitigate future threats.

Keywords Freshwater systems, Land use change, Water quality, Remote sensing, Sustainability, New England, Sebago Lake

1 Introduction

Sustainability science has focused attention on monitoring human-induced changes to environmental systems and identifying the conditions that determine the vulnerability or resilience of systems to such changes (Kundzewicz et al. 2007; Levin and Clark 2009). Within this framework, the sustainability of freshwater resources in terms of their quality, quantity and allocation has been the focus of numerous recent studies (Alcamo et al. 2007; Bierwagen et al. 2010; Vörösmarty et al. 2000). Much of this research in the United States has focused on already threatened and degraded freshwater systems (Schelske et al. 2005; Schindler 2006). The recovery of freshwater systems after switching to less-desirable alternative states can be slow and require significant investments (Scheffer and Carpenter 2003). Even so, inadequate attention is directed to monitoring freshwater systems that appear robust and show few indications of water quality decline, yet are likely to face enhanced vulnerabilities in the future due to climate and land use and cover changes.

To that end, this study focuses on Sebago Lake in the northeastern United States. Sebago Lake and its watershed is located in the most developed and urbanized section of the state of Maine and is the direct source of freshwater for close to 200,000 people that live in neighboring towns and cities (Fig. 1). The watershed was recently identified as one of the top five most vulnerable watersheds of the northeastern United States to development pressures because of the amount of privately owned forested land in the watershed and its location in a rapidly changing region (Barnes et al. 2009). Future development and climate-related changes experienced across the region will have ramifications on the sustainability of this ecosystem and test its resilience to change.

This study is designed to assess the Sebago Lake watershed system from a coupled socio-ecological systems framework and provide a template for using readily available data to systematically monitor similar systems elsewhere. We assess key emerging threats and vulnerabilities to the system by examining land use and development changes across its drainage basin over the past 20 years. These changes are related to ecological observations of precipitation, lake water levels and water quality indicators for the lake. The analysis highlights emerging areas of concern and reiterates the essential role of proactively monitoring vulnerable systems to help mitigate future threats.

2 Threats to freshwater systems

Current and future threats to freshwater systems are driven by both ecological and social processes. Two of the most prominent processes are climate change and land use and cover conversions (Adrian et al. 2009). Temperature and precipitation are key climatic drivers. Predicted climate change influences in the upper latitudes including earlier spring thaws and ice-out dates are expected to affect regional water quality and the primary productivity of lakes (Murdoch et al. 2000; Hodgkins et al. 2002). Increases in the frequency of extreme precipitation events are also a potential outcome of climate change in areas such as the northeastern United States. Depending on their timing and watershed characteristics, heavy rainfall events can transport pollutants and additional nutrients to water bodies or dilute nutrients and alter lake stratification (Blenckner et al. 2007). With the latest Intergovernmental Panel on Climate Change (IPCC) report predicting such changes in precipitation patterns and temperature regimes globally, monitoring the capacity of freshwater systems to meet present and future human and ecosystem needs gains urgency (Kundzewicz et al. 2007; Meehl and Stocker 2007).

Non-climatic threats to water quality are equally, if not more, pressing in the near term and are subject to more immediate local factors (Carpenter et al. 1998; Murdoch et al. 2000). These factors include land use and cover change, population increases and development pressures within any given drainage basin (Atasoy et al. 2006; Kundzewicz et al. 2007). Change in water quality due to land use change, agriculture and urbanization is evident from paleolimnological studies of lake sediments (Leavitt et al. 2006; Pham et al. 2008) and other current assessments (Allan 2004; Coskun and Alparslan 2009; Fraterrigo and Downing 2008; Giardino et al. 2010). Conversions across urban areas affect storm water runoff and nutrient transport to lakes by increasing the impervious surface area in a watershed. Approximately 10 % impervious surface within a watershed is often reported as a threshold value beyond which the impact to streams and freshwater systems can be substantial (Brabec et al. 2002). However, depending on the configuration of land uses, these changes can also occur at lower levels of land cover conversion (Wickham et al. 2008).

The increased transport of watershed nutrients to water bodies leads to the cultural eutrophication of many lakes in regions dominated by agricultural land uses. This has encouraged the closer monitoring of phosphorus concentrations, chlorophyll *a* and water clarity in lakes as a measure of their quality (Vollenweider 1968; Reckhow and Simpson

1980). Total phosphorus is measured because it is often a constraining factor on lake productivity. Chlorophyll *a* is a measure of the amount of algae in a water column and is important for characterizing the productivity of a lake. Water clarity is measured using a Secchi disk to record how deeply light can penetrate the water column and is used to identify algal blooms (Secchi depths less than 2 m). Land use modifications can drive changes in nutrient export from catchments to streams and lakes therein, and concomitant increases in lake water column phosphorus are an indication of this. Further, phosphorus availability in the water column is often a limiting factor in algal abundance, which affects water clarity.

3 Study area

Sebago Lake is located within the larger Casco Bay watershed of Cumberland County, southern Maine (Fig. 1). Covering 120 km^2 with 170 km of shoreline, it is the deepest and second largest lake in Maine with an average depth of 32.60 m. The maximum depth is 96 m. The lake consists of three main bays; Big Bay, Jordan Bay and Lower Bay, and has a hydraulic residence time of 5.4 years. The Lake's watershed is 440 km^2, 16 % of which includes other lakes, ponds and rivers. Sebago Lake is connected to a chain of lakes in its upper watershed, but 70 % of its surface inflow is from the Songo/Crooked River (Hodgkins 2001). The region receives an annual precipitation of 1,126 mm (Dudley et al. 2001).

European settlers arrived in the region in the mid-1700s. Proximity to flowing water enabled small agricultural settlements to grow and prosper as mill towns. Transportation, trade and tourism improved with the introduction of rail lines in the 1870s. Population shifts mirroring shifts in economic activity were observed across the watershed since this early settlement period. The twentieth century saw a further consolidation of developmental changes. Shifts toward manufacturing and service sector industries concentrated along the coast and the city of Portland gained prominence. Meanwhile, patterns of sprawl became more evident mid-century as the automobile brought greater mobility and mortgage subsidies renewed interest in lake view property and vacation homes in towns across the watershed.

Sebago Lake has provided water to communities in southern Maine and to the Portland area since 1869, with services provided by the Portland Water District (PWD) since 1908. The outlet of Sebago Lake flows into the Presumpscot River and was first dammed in 1827. Water flow at the outlet has been regulated since 1875 with the Eel Weir dam constructed in 1890. The Eel Weir is currently one of 5 dams along the Presumpscot River managed for hydro-electric power generation by Sappi Fine Paper, originally the S.D. Warren Company started in Westbrook, Maine in 1854 (Dudley et al. 2001). The management of water outflow at the dam controls water levels in the lake. More recently, there is concern that changes to lake level management strategies since 1987 may be negatively affecting water quality through unnaturally high lake levels in late summer. Depending on dam management, precipitation and snow melt, lake levels typically range from 79.40 to 81.30 m above sea level (asl). In addition to Sappi Fine Paper, PWD and the population that relies on it for safe drinking water, Sebago Lake is also used for recreational boating and fishing and provides many public beaches.

4 Data and methodology

We use data from multiple sources to document land use and development changes across the Sebago watershed and monitor water quality indicators for the Lake over the past two decades. Studying historic and current trends enables us to comment on future threats to this watershed and recommend proactive management strategies to ensure sustainability. The study uses satellite data from the NASA's Landsat 5 Thematic Mapper (TM) multispectral sensor to conduct a land use change analysis for the Sebago Lake watershed over a 20-year period from 1987 through 2009. Population, housing and median income statistics from 1990, 2000 and 2009/2010 are used to track developmental changes for towns within the Sebago Lake watershed. Broad land use and development trends observed are then related to water quality measures including total phosphorus (µg/l), chlorophyll *a* (µg/l), Secchi depth (m) and lake level (m asl) data obtained from the Portland Water District (PWD).

4.1 Land use change

To assess changes in land use, three Landsat Thematic Mapper (TM) datasets (WRS: Path 12/Row 29/30) comprising six multispectral bands at 30-m spatial resolution each for September 16, 1987, September 6, 1995, and July 10, 2009 (Table 1), were obtained from the Earth Resources Observation and Science (EROS) Data Center (USGS EROS 2009). All image processing and analyses were conducted using specialized software including Acorn, ERDAS Imagine 9.3, Habitat Priority Planner and ESRI's ArcGIS. Original Landsat™ image files were cropped to the extent of the Sebago Lake watershed. Atmospheric correction algorithms were applied to each image set to remove effects due to variations in satellite-sun geometry and atmospheric conditions and allow cross-date comparisons. Acorn's multispectral correction module was used to run atmospheric correction algorithms on all three datasets using atmospheric visibility and water vapor parameters based on climatic conditions recorded for the image capture day (AIG 2002). The images were registered and processed with ERDAS Imagine. Cloud cover present in any of the images was masked out from each of the three dates.

An unsupervised classification using the Iterative Self Organizing Data Analysis (ISODATA) algorithm produced land use maps from the Landsat^{TM} datasets for each of the years of the study period. ISODATA groups pixels based on a minimum distance function (Lillesand et al. 2008). The classification algorithm reassigned the image pixel values into 30 initial classes. After some experimentation, the 30 classes were recoded into 4 broad land use classes that were of particular interest to our study. These included Water, Bare-ground, Green-space and Developed Land (Table 2). To assess landscape metrics, NOAA's Habitat Priority Planner was used to calculate the total number of patches or homogenous features and mean patch size for the land-based classes.

Accuracy assessments were performed on each of the images using a stratified random sample of 40 points per class for each of the classes. Using a sample of points, these assessments measure how well the classification method performed in spectrally distinguishing each of the land use classes (Lillesand et al. 2008). The error matrix produced for each of the images through this process enabled us to assess errors of omission and commission and calculate Kappa coefficients for individual land use classes (Congalton 1991). Digital Ortho Quarter Quadrangles (DOQQ) from 1998, National Agriculture Imagery Program (NAIP) data from 2009 obtained from the Maine Office of GIS and rapid field assessments were used to verify the accuracy of our classifications. The extent of land area within each of the land use classes was calculated from the results of the classification. A simple percent change function described in Eq. (1) below was used to calculate the change in land use class between 1987, 1995 and 2009.

$$\text{Percent change in land use class (PLUC)} = (LUC_{1995} - LUC_{1987}) / LUC_{1987} \qquad (1)$$

4.2 Population and housing change

Total population and housing unit data from the U.S. Census Bureau were retrieved for 1990, 2000 and 2010 for all towns within Maine (US Census Bureau 2011). Inflation adjusted median household income data were calculated for 1990, 2000, and since data for 2010 are not as yet available, sample survey data from the Census Bureau's 2009 American Community Survey were use instead (MSPO 2011). It is expected that these variables would each have a land use 'signal' as higher population, household units and median income growth would likely be represented by more construction and allied activities on the land and hence changes in land uses from Green-space to Developed Land. The variables were combined in a development index, which was derived by adding standardized *z*-scores of the percent change in population, housing units and median household income between 1990–2000, 2000–2009/10 and 1990–2009/10 to gauge the overall position of each town relative to the other. Z-scores enable comparison across the watershed. Finally, the development index for Sebago watershed towns was mapped in ArcGIS to analyze spatial variations. The sequence of steps to derive the development index was as follows:

First, the percent change in population (Eq. 2), housing units (Eq. 3) and median income (Eq. 4) between 1990–2000, 2000–2010 (2009 in the case of median income) and 1990–2010 (2009 in the case of median income) was calculated for each town from raw population, housing units and median income data obtained from the Census Bureau:

$$\text{Percent change in population}_i\ (\text{PPop}_i) = (\text{Pop}_{it2} - \text{Pop}_{it1}) / \text{Pop}_{it1} \quad (2)$$

$$\text{Percent change in housing units}_i\ (\text{PHou}_i) = (\text{Hou}_{it2} - \text{Hou}_{it1}) / \text{Hou}_{it1} \quad (3)$$

$$\text{Percent change in median income}_i\ (\text{PInc}_i) = (\text{Inc}_{it2} - \text{Inc}_{it1}) / \text{Inc}_{it1} \quad (4)$$

where $it1$ denotes town i at time t.

Second, to enable standardized comparisons across townships within the watershed, z-scores for the results from Eqs. 2, 3 and 4 above were calculated as:

$$z\text{ - score}_{\text{pop}i} = (\text{PPop}_i - \mu) / \sigma \quad (5)$$

$$z\text{ - score}_{\text{hou}i} = (\text{PHou}_i - \mu) / \sigma \quad (6)$$

$$z\text{ - score}_{\text{inc}i} = (\text{PInc}i - \mu) / \sigma \quad (7)$$

where $z\text{-score}_{\text{pop}i}$, $z\text{-score}_{\text{hou}i}$ and $z\text{-score}_{\text{inc}i}$ were the standardized scores for percent population change, percent housing unit change and percent median income change in town i, respectively, μ was the mean including all towns in Maine and σ was the standard deviation of the same. The same steps were conducted for all population and housing unit change data between 1990–2000, 2000–2010 and 1990–2010.

Finally, an index of development for each town was calculated by adding the z-scores for population and housing for each town as defined in Eq. 8 below. This aggregate index of development was mapped to allow for a comparative assessment across Sebago and surrounding watershed towns. A higher index number indicates more firmly entrenched development activities within that town as compared to others within the Sebago Lake watershed.

$$\text{Index of development}_i = z\text{ - score}_{\text{pop}i} + z\text{ - score}_{\text{hou}i} + z\text{ - score}_{\text{inc}i} \quad (8)$$

4.3 Water quality

Water quality data included in the analyses (total phosphorus, µg/l; chlorophyll *a*, µg/l; Secchi depth, m), and lake level data were obtained from PWD for Lower Bay. This bay has the longest record (1979 to present) and is nearest the intake area for the drinking water supply. Data were collected monthly when the lake was clear of ice, usually from April to November. Precipitation data were obtained from the PRISM Group (Parameter-elevation Regressions on Independent Slopes Model; http://prismmap.nacse.org/nn/) climate mapping system at grid point (43.78N, 70.51W). PRISM uses point measurements of precipitation and temperature to provide a time series of spatially distributed monthly, yearly and event-based climate parameters for a variety of watersheds (Gibson et al. 2002; Daly et al. 2004).

All of the water quality measurements since 1990 have been made at the current sampling location. Due to the sampling location change and some alterations in the analytical methods, some water quality data were adjusted for comparison to results obtained later (Whalen, 2010). The adjustment included adding 0.34 m to pre-1990 Secchi disk depths, which were collected closer to shore and had, on average, a shallower Secchi disk reading by 0.34 m than depths taken at the present, deeper site. Pre-1996 Secchi disk data were multiplied by 1.05 to account for the change in scopes at that time. For total phosphorus, the PWD determined there were no site differences via a Kruskal–Wallis test of the different sampling locations in Lower Bay. In 1996, there was also a reporting limit change for total phosphorus in 1996 from 1.0 to 0.1 ppb. The data prior to 1996 were not adjusted. Additionally, chlorophyll *a* samples were reported with phaeophyte correction post-1993, but without the correction in 1992 and before. Uncorrected chlorophyll *a* data for all dates were therefore used in the analyses presented here. No adjustments for sample site were made with chlorophyll *a* data.

To examine late-summer water quality, data were averaged between months July, August and September of each year, resulting in one data point per year. For this reason, we did not correct for seasonality when testing for trends. These months were chosen due to high data availability and a high correlation with total spring precipitation (May and June) and average spring lake levels (May and June). Analyses were completed using the seasonal means and totals listed above, as well as late-summer precipitation and lake levels, over two time periods: 1990–2010 and 1979–2010. The confidence in the data quality since 1990 is higher, and this shorter time period corresponds better with the land use data used in this study. However, in considering potential trends in hydrologic data, the complete record was also analyzed to gain perspective on longer-term trends and potential cycles.

To determine if there were temporal trends or step changes in water quality data, or relationships between water quality and lake water level or precipitation events, several approaches were used. Pettitt's test was used first to look for significant step changes in water quality (Siegel and Castellan 1988; Kundzewicz and Robson 2004). Spearman's Rank correlation was used on variables that had no significant step change to identify significant relationships between lake level, precipitation and water quality variables over time (Siegel and Castellan 1988). A partial correlation was used to determine the correlation between water quality variables and lake level while accounting for the variance explained by precipitation. A Wilcoxon *t* test was used to compare 1979–1990 and 1990–2010 spring precipitation and spring and summer lake levels to assess stationarity of potential explanatory variables. Analyses were performed in R (R Core Team 2012) and considered statistically significant at the 95 % confidence level ($p < 0.05$).

5 Results and discussion

5.1 Land use trends

The results of the ISODATA classification algorithm for the Sebago Lake watershed from 1987, 1995 and 2009 are displayed in Fig. 2. A visual analysis of Fig. 2 indicates a steady increase in the Developed Land class over the study period. As Table 2 reports, this class includes all urban, industrial, commercial, rural, suburban and other residential activity, transportation networks and other impervious surfaces. Development across the watershed displays a distinctive rural sprawl pattern typical of New England. In other words, it tends to concentrate along existing road networks and expand adjacent to areas that have historically already seen development. Despite the concentration of residential and commercial built-up areas within town centers, there remains significant farm and homestead development along transport routes mirroring a spatially distributed model of rural development. The Bare-ground class is a mixed class noticeable around lakes, dry river meanders and areas of exposed bare soil and beach across the watershed. The Water class includes all reservoirs, ponds, lakes and rivers within the study area. Finally, the Green-space class contains all other land uses including forest, pasture, agricultural fields and golf courses (Table 2).

The image data indicate an intensification of development activity over the study period, and the expansion of development is most distinct between 1995 and 2009. This correlates with southern Maine's development trajectory from census and housing data during the same period. Storm water runoff, septic tank leaks, the expansion and location of impervious surfaces, gravel pits, mining sites, soil compaction, rural land uses and inadequate riparian buffers or source water and shore-land protections can all enhance threats to water quality across the watershed.

The results of the accuracy assessments on each of the three images are included in Table 3. Typical of all accuracy assessments conducted with satellite data, the results of the accuracy assessment address only the random sample of points used for this process (Lillesand et al. 2008). High accuracy results for the sample used in this analysis suggest that the ISODATA algorithm performed well in spectrally separating different land use classes. The overall classification accuracy for the stratified random subset of points was reported at 90 % for 1987, 95 % for 1995 and 95.63 % for 2009 with the Kappa coefficients at 0.87, 0.93 and 0.94, respectively for 1987, 1995 and 2009. The overall high classification accuracy is not unexpected given the broad classification scheme used for the study (Table 3).

Using the area coverage statistics derived from this classification analysis, we are able to outline the total extent and percent change in the extent of land use classes between the dates of image capture (Table 4). The land cover analysis indicates that Developed Land accounted for 5.39 % of the total area of the Sebago watershed in 1987, 6.09 % in 1995 and 8.91 % in 2009 (Table 4). Green-space declined from 76.58 % of the watershed in 1987 to 72.41 % by 2009. Water and Bare-ground coverage across the watershed remained largely the same, with only a slight increase of approximately 0.51 % in the Bare-ground class between 1987 and 1995. The literature on impervious surfaces indicates that stream water quality is negatively influenced once impervious surfaces reach 10 % of a watershed's total area (Brabec et al. 2002). Our 20-plus year satellite image analysis indicates that the Sebago Lake watershed is gradually trending toward that threshold and is cause for concern.

Landscape metrics including the number of homogenous features or patches within a land use class and the mean patch size provide greater insight into each individual land use class (Table 5). The analysis indicates that between 1987 and 2009 the Developed Land class saw the greatest number of patches, while Green-space the fewest. Given the rural sprawl pattern of development observed across the watershed, the large number of patches as seen in the case of the Developed Land class is expected. The number of patches for Green-space increased between 1987 and 2009, while the mean patch size decreased from approximately 189 hectares to 108 hectares over the same time period (Table 5). This indicates a greater fragmentation of Green-space into smaller sized parcels over the past 20-plus years. These metrics provide a more detailed picture of the changes taking place within the two primary land use classes across the watershed.

5.2 Development changes

Demographic and socioeconomic conditions along with other variables influence how land and resources are used in any given region. The state of Maine has long been known for its natural capital and scenic splendor, yet changes in population and development have played an influential role in substantially modifying the landscape in recent decades. Over the 1990–2010 period, most towns across the Sebago Lake watershed and surrounding have experienced growth on a development index which includes population, housing unit and median income change. This is not unexpected, given that the watershed lies within southern Maine, which has seen the most rapid and expansive growth in the past few decades.

Standardized scores of percent change in population, housing units or median income generally fall within one standard deviation of the state average (Table 6). Standardizing scores enables an easy comparison across the watershed. The majority of towns indicate positive change across these variables over the 1990–2010 study period (Table 6). Towns located right along Sebago Lake including Windham, Casco, Naples, Raymond and Standish have experienced population growth at a rate greater than the state average. Similar trends were observed for housing unit expansion.

The index of development is derived from summing *z*-scores reported earlier (Table 7). A higher index number indicates a greater concentration of development-related activities within that town as compared to the others within the Sebago Lake watershed. Figure 3 provides a map of index scores for the watershed over the 1990–2010 study period. The spatial patterns observed in Fig. 3 indicate a high development index ranking for Sweden, Casco, Otisfield and Naples. All of these towns are located upstream from Sebago Lake, while the Songo/Crooked River, which is the primary source of freshwater inflow into Sebago Lake flows through Casco, Otisfield and Naples. Raymond, Bridgton and Waterford also indicate a development index higher than 1 and are likewise located upstream from the Lake. The spatial pattern borne out by the development index indicates that a majority of the watershed towns upstream from the Lake have seen significant development over the 1990–2010 period, and this is also supported out by the land use analysis.

5.3 Water quality

The Pettitt's test for a step change is used to detect a change (increase or decrease) in values that is maintained for the remainder of the record. This test showed a significant and sustained step increase in the late-summer total phosphorus concentration in 2005 when the analysis was restricted to the 1990–2010 time period. Spearman's rank showed declining water quality trends for both chorophyll *a* and Secchi disk depth over the same time period.

However, during the longer time frame (1979–2010), Pettitt's test and Spearman's rank correlation indicated no statistically significant step changes or trends over time for any of the three water quality variables in late summer (Table 8). These results agree with trend analyses conducted by the PWD (PWD 2008; Whalen 2010). They suggest that while present water quality may not be worse than measurements recorded in the 1980s, many of the bad water quality years over the most reliable period of measurement (1990–2010) have been toward the end of that period. Identical analyses performed on precipitation and lake level showed no trends or step changes in either time period. Moreover, the land use analysis indicates that the 1990–2010 timeframe is also one of significant development activity across the watershed. Taken together, these data indicate that the recent reductions in water quality may be linked to land use changes rather than changes in precipitation or lake level.

There were also differences between the two time periods in the correlations between environmental variables and water quality (Table 8). Late-summer chlorophyll was positively correlated with spring precipitation (rho = 0.43, $p = 0.05$) and spring lake levels (rho = 0.44, $p = 0.05$) during 1990–2010. During 1979–2010, Secchi disk depth was negatively correlated with spring precipitation (rho = -0.54, $p < 0.01$) as well as with spring lake level (rho = -0.44, $p = 0.01$). However, in both 1990–2010 and 1979–2010, spring lake level was also strongly correlated with precipitation (rho = 0.43, $p = 0.05$; rho = 0.62, $p < 0.01$, respectively). Additionally, Secchi disk depth was negatively correlated with summer lake levels (rho = -0.42, $p < 0.01$), which were also correlated with spring precipitation (rho = 0.55, $p < 0.01$) in the longer period of record. This suggests environmental drivers are linked to water quality declines but the effects may be exacerbated by land use changes.

The observed interaction between precipitation and lake level confounds interpretations of either as a primary driver of variations in water quality. However, non-significant results of partial correlations between lake level and water quality parameters while accounting for the effect of spring precipitation suggest the relationship between late-summer chlorophyll *a* and lake level is confounded by the underlying relationship of lake level with precipitation during 1990–2010. This is also true for late-summer water clarity over the longer time period in regard to both spring and late-summer lake level correlations. Additionally, average spring and summer lake levels have not significantly changed ($p = 0.29$; $p = 0.23$, respectively) between the most recent time period and the previous decade.

While we do see a trend in chlorophyll *a* during 1990–2010 and a correlation with spring precipitation, total spring precipitation amounts have not significantly changed during that time compared to the previous decade ($p = 0.43$). This suggests either the nature of the precipitation may have been different in more recent years or that precipitation is interacting with some other factor, such as land cover change as described above, to alter pollutant loading to the lake. Alternately, trophic interactions in Sebago Lake could explain recent changes in chlorophyll concentrations.

6 Conclusions and future directions

This study identifies emerging areas of concern for the sustainability of the Sebago Lake watershed. First, our findings indicate that Developed Land within the watershed has increased from 5.39 % of the total area in 1987 to 8.91 % in 2009, approaching a 10 % threshold value identified in the literature as indicative of stream degradation (Brabec et al. 2002). This is a concern, as degraded rivers and streams will likely increase inputs of nutrients to the lake. Meanwhile, poor water quality and nutrient loading associated with lakeshore development activities along Sebago Lake (Whalen 2009) and hyper-nutrient conditions reported for portions of the watershed's other lakes have already raised alarms (LEA 2010). These studies along with the results of our examination clearly point to the need for greater vigilance and quick action to protect against more sustained damage.

Second, along with the near doubling of Developed Land uses in the watershed, recent Sebago Lake water quality indicators from 1990 to 2010 show a directional trend concomitant with this change. Even though long-term records do not, these more recent changes highlight the need for continued monitoring and management of this lake. As the more recent record grows longer, it should show whether the current trends and step changes are part of a longer pattern of water quality variability in the lake or if they are more permanent. Moreover, there is concern that other factors may be obscuring water quality linkages with land use and cover trends. The large volume, depth and residence time of Sebago Lake may make it resistant to cultural eutrophication (Nõges 2009) and may increase its buffering capacity for nonpoint source nutrients (Liu et al. 2010). Importantly, this could induce a lag effect between the time of increased development and any changes in water quality indicators in the tributaries or the internal cycling of the lake itself as slow and fast state variables interact. Furthermore, climatic effects, such as the event-based nature of precipitation, may be a confounding factor to detecting relatively smaller drivers from current levels of land cover change.

The vigilant monitoring of Sebago Lake and similarly vulnerable systems using remotely sensed and other relevant socioeconomic and ecological data provide land managers and scientists with important information to support context-appropriate management strategies. These strategies can help mitigate land use changes that may have already been observed across the watershed, and can promote sustainable growth and development for the future. Regional and land use plans can champion smart growth and in-fill development strategies that balance development or urban revitalization with green-space protections. Subdivision regulations can encourage conservation designs with compact housing and mandatory green-space preservation for new developments. Other strategies at the household or commercial enterprise level may include adopting green building technology, replacing impervious surfaces with pervious pavers, promoting sustainable logging practices and monitoring dirt road construction on private lands.

Ecologically significant tracks can be secured through conservation easements or Land Trust purchases. Already, the Western Foothills Land Trust and other similar organizations have engaged in protecting sections of the Sebago basin. Similarly, the Portland Water District currently protects 2,500 acres of land around Sebago Lake's Lower Bay, but protection of forested land in the upper watershed may help preserve Sebago Lake's high quality of water into the future (Postel and Thompson 2005; Wickham et al. 2011). Likewise, minimizing the fragmentation of green-space through approaches such as greenway planning can strengthen existing riparian buffers and shore-land protections while also improving habitat connectivity. Many of the approaches outlined here are already being implemented across the Sebago Lake watershed. Such strategies would go some way toward securing the sustainability of this and similar vital resources elsewhere.

Acknowledgments

The authors wish to thank the Portland Water District for providing the water quality data. This research was funded by a National Science Foundation award EPS-0904155 to Maine EPSCoR at the University of Maine.

References

Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., et al. (2009). Lakes as sentinels of climate change. *Limnology and Oceanography*, *54*, 2283–2297.

Alcamo, J., Flörke, M., & Märker, M. (2007). Future long-term changes in global water resources driven by socio-economic and climatic change. *Journal of Hydrological Science*, *52*, 247–275.

Allan, J. D. (2004). Landscapes and riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*, 35, 257–284.

Analytic Imaging and Geophysics (AIG). (2002). Acorn 40 User's Guide. http://www.aigllc.com/pdf/acorn4_ume.pdf. Accessed August 24, 2011.

Atasoy, M., Palmquist, R. B., & Phaneuf, D. J. (2006). Estimating the effects of urban residential development on water quality using microdata. *Journal of Environmental Management*, *79*, 399–408.

Barnes, M., Todd, A., Whitney, L., Lilja, R., & Barten, P. (2009). *Forests, water and people: Drinking water supply and forest lands in the northeast and Midwest United States*.

Technical Report, NA-FR-01-08, United States Department of Agriculture Forest Service.

Bierwagen, B. G., Theobald, D. M., Pyke, C. R., Choate, A., Groth, P., Thomas, J. V., et al. (2010). National housing and impervious surface scenarios for integrated climate impact assessments. *Proceedings of the National academy of Sciences of the United States of America*, *107*, 20887–20892.

Blenckner, T., Adrian, R., Livingstone, D. M., Jennings, E., Weyhenmeyer, G. A., George, D. G., et al. (2007). Large-scale climatic signatures in lakes across Europe: A meta-analysis. *Global Change Biology*, *13*, 1314–1326.

Brabec, E., Schulte, S., & Richards, P. L. (2002). Impervious surfaces and water quality: A review of current literature and its implications for watershed planning. *Journal of Planning Literature*, *16*, 499–514.

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Ecological and economic analysis of lake eutrophication by nonpoint pollution. *Australian Journal of Ecology*, *8*, 559–568.

Congalton, R. (1991). A review of assessing the accuracy of classifications of remotely sensed data. Remote *Sensing of Environment*, *37*(1), 35–46.

Coskun, H., & Alparslan, E. (2009). Environmental modeling of Omerli catchment area in Istanbul, Turkey using remote sensing and GIS techniques. *Environmental Monitoring and Assessment*, *153*(1), 323–332.

Daly, C., Gibson, W. P., Doggett, M., Smith, J., & Taylor, G. (2004). Up-to-date monthly climate maps for the conterminous United States. In *Proceedings of the 14th American Meteorological Society conference on applied climatology (Paper P51 CD-ROM).*

Seattle, Washington: 84th American Meteorological Society annual meeting combined reprints American Meteorological Society, January 13–16, 2004.

Dudley, R. W., Hodgkins, G. A., & Nielsen, J. P. (2001). *Water budget for Sebago Lake, Maine*, 1996–99. USGS Water Resources Investigations Report 01-4235. http://mewater.usgs.gov/reports/ WRIR01-4235.pdf. Accessed November 29, 2011.

Fraterrigo, J. M., & Downing, J. A. (2008). The influence of land use on lake nutrients varies with watershed transport capacity. *Ecosystems*, *11*, 1021–1034.

Giardino, C., Bresciani, M., Villa, P., & Martinelli, A. (2010). Application of remote sensing in water resource management: The case study of Lake Trasimeno, Italy. *Water Resources Management*, *24*(11), 3885–3899.

Gibson, W. P., Daly, C., Kittel, T., Nychka, D., Johns, C., Rosenbloom, N., McNab, A., & Taylor, G. (2002). Development of a 103-year high-resolution climate data set for the conterminous United States. In *Proceedings of the 13th American Meteorological Society conference on applied climatology* (pp. 181–183). Portland, Oregon: American Meteorological Society, May 13–16.

Hodgkins, G. A. (2001). Total phosphorus loads for selected tributaries to Sebago Lake, Maine. *USGS Water Resources Investigations Report* 01-4003.

Hodgkins, G. A., James, I. C., & Huntington, T. G. (2002). Historical changes in lake ice-out dates as indicators of climate change in New England. *International Journal of Climatology*, *22*, 1819–1827.

Kundzewicz, Z. W., Mata, L. J., Arnell, N. W., Döll, P., Kabat, P., Jiménez, B., Miller, K. A., Oki, T., Sen, Z., & Shiklomanov, I. A. (2007). Freshwater resources and their management. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E.

Hanson (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability* (pp. 173–210). Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press.

Kundzewicz, Z. W., & Robson, A. J. (2004). Change detection in hydrological records—a review of the methodology. *Hydrological Sciences*, *49*, 7–19.

LEA (Lakes Environmental Association). (2010). Water testing report LEA, Bridgton, ME. http://www.mainelakes.org/documents/Water%20Testing%20summaries/2010%20LEA%20Water%20Testing%20Summaries.pdf. Accessed March 8, 2011.

Leavitt, P. R., Brock, C. S., Ebel, C., & Patoine, A. (2006). Landscape-scale effects of urban nitrogen on a chain of freshwater lakes in central North America. *Limnology and Oceanography*, *51*, 2262–2277.

Levin, S., & Clark, W. (2009). *Towards a science of sustainability*. Report from Toward a Science of Sustainability Conference (p. 109). Warrenton, Virginia: Airlie Center.

Lillesand, T. M., Kiefer, R. W., & Chipman, J. W. (2008). *Remote sensing and image interpretation*. New York, USA: Wiley.

Liu, W., Zhang, Q., & Liu, G. (2010). Lake eutrophication associated with geographic location, lake morphology and climate in China. *Hydrobiologia*, *644*, 289–299.

Meehl, G. A., & Stocker, T. F., et al. (2007). Global climate projections. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, & H. L. Miller (Eds.), *Climate change 2007: The physical science basis*. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (pp. 747–846). Cambridge: Cambridge University Press.

MSPO (Maine State Planning Office). (2011). Maine economics and demographics program. http://www.maine.gov/spo/economics/. Accessed October 30, 2011.

Murdoch, P. S., Baron, J. S., & Miller, T. L. (2000). Potential effects of climate change on surface-water quality in North America. *Journal of the American Water Resources Association*, *36*, 347–366.

Nõges, T. (2009). Relationships between morphometry, geographic location and water quality parameters of European lakes. *Hydrobiologia*, *633*, 33–43.

Pham, S. V., Leavitt, P. R., McGowan, S., & Peres-Neto, P. (2008). Spatial variability of climate and landuse effects on lakes of the northern Great Plains. *Limnology and Oceanography*, *53*, 728–742.

PWD (Portland Water District). (2008). State of the Lake Report, Sebago Lake, 2008 Portland Water District, Portland, ME. http://www.pwd.org/pdf/water_resources/ stateofthelake2009.pdf. Accessed November 22, 2010.

Postel, S. L., & Thompson, B. H. (2005). Watershed protection: Capturing the benefits of nature's water supply services. *Natural Resources Forum*, *29*, 98–108.

R Core Team. (2012). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org/.

Reckhow, K. H., & Simpson, J. T. (1980). A procedure using modeling and error analysis for the prediction of lake phosphorus concentration from land use information. *Canadian Journal of Fisheries and Aquatic Sciences*, *37*, 1439–1448.

Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology & Evolution*, *18*, 648–656.

Schelske, C. L., Lowe, E. F., Battoe, L. E., Brenner, M., Coveney, M. F., & Kenney, W. F. (2005). Abrupt biological response to hydrologic and land-use changes in Lake Apopka, Florida, USA. *Ambio*, *34*, 192–198.

Schindler, D. W. (2006). Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography*, *51*, 356–363.

Siegel, S., & Castellan, N. J. (1988). *Non-parametric statistics for the behavioural sciences*. New York: McGraw-Hill.

USCB (United States Census Bureau). (2011). http://www.census.gov. Accessed October 22, 2011.

USGS (United States Geological Survey). (2009). Maps, imagery, and publications. http://www.usgs.gov/pubprod/aerial.html. Accessed November 22, 2010.

Vollenweider, R. A. (1968). Scientific fundamentals of lake and stream eutrophication, with particular reference to phosphorus and nitrogen as eutrophication factors. Technical Report DAS/DSI/6827 Paris, France: OECD.

Vörösmarty, C. J., Green, P. J., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*, 284–288.

Whalen, N. (2009). Portland Water District Sebago Lake monitoring program lake monitoring presenting periphyton data from 1995-2009. Portland ME: Portland Water District. http://www.pwd.org/pdf/Reports/Periphyton%20Monitoring%20Results%20for%202009%20data.pdf. Accessed March 31, 2011.

Whalen, N. (2010). Characterization of Sebago Lake lower bay trophic state since 1976. Portland, ME: Portland Water District. http://www.pwd.org/pdf/water_resources/Pre_1990_Lower_Bay_Report.pdf. Accessed March 31, 2011.

Wickham, J. D., Wade, T. G., & Riitters, K. H. (2008). Detecting temporal change in watershed nutrient yields. *Environmental Management*, *42*, 223–231.

Wickham, J. D., Wade, T. G., & Riitters, K. H. (2011). An environmental assessment of United States drinking water watersheds. *Landscape Ecology*, *26*, 605–616.

Figures

Fig. 1 Sebago Lake watershed, Maine

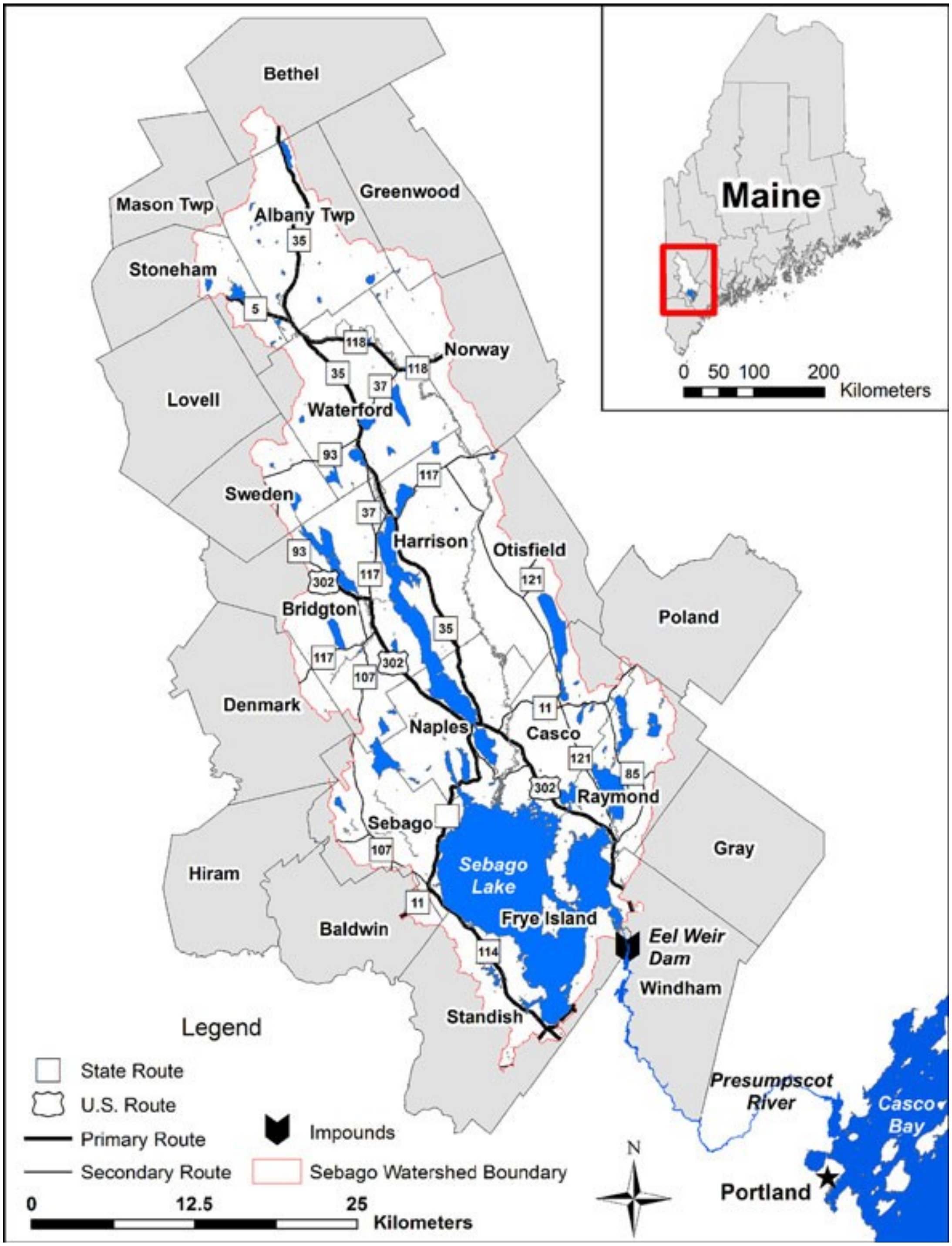

Table 1 Landsat thematic mapper spectral ranges

Band	Spectral range (μm)
Band 1	0.45–0.52
Band 2	0.52–0.60
Band 3	0.63–0.69
Band 4	0.76–0.90
Band 5	1.55–1.75
Band 7	2.08–2.35

Table 2 Land use/cover class descriptions

Class name	Class code	Class coverage
Water	WA	Freshwater features including lakes, creeks, rivers, pools
Bare-ground	BG	Bare soil surface, beach, dry creek and river beds and meanders, dry lake and pond edges, other recently cleared areas
Green-space	GS	A broadly defined land category that comprises all open and green space including forest, pasture, agricultural fields, herbaceous vegetation, areas regularly mowed or grazed such as golf courses and hay fields, scrub/shrub environments
Developed Land	DL	Rural, suburban, urban, and industrial built-up areas, impervious surfaces, infrastructure lines including roads, rails, power lines, gravel pits, open mines, un-vegetated rural spaces, compacted soils, recently cleared areas

Fig. 2 Land use classification using Landsat TM data

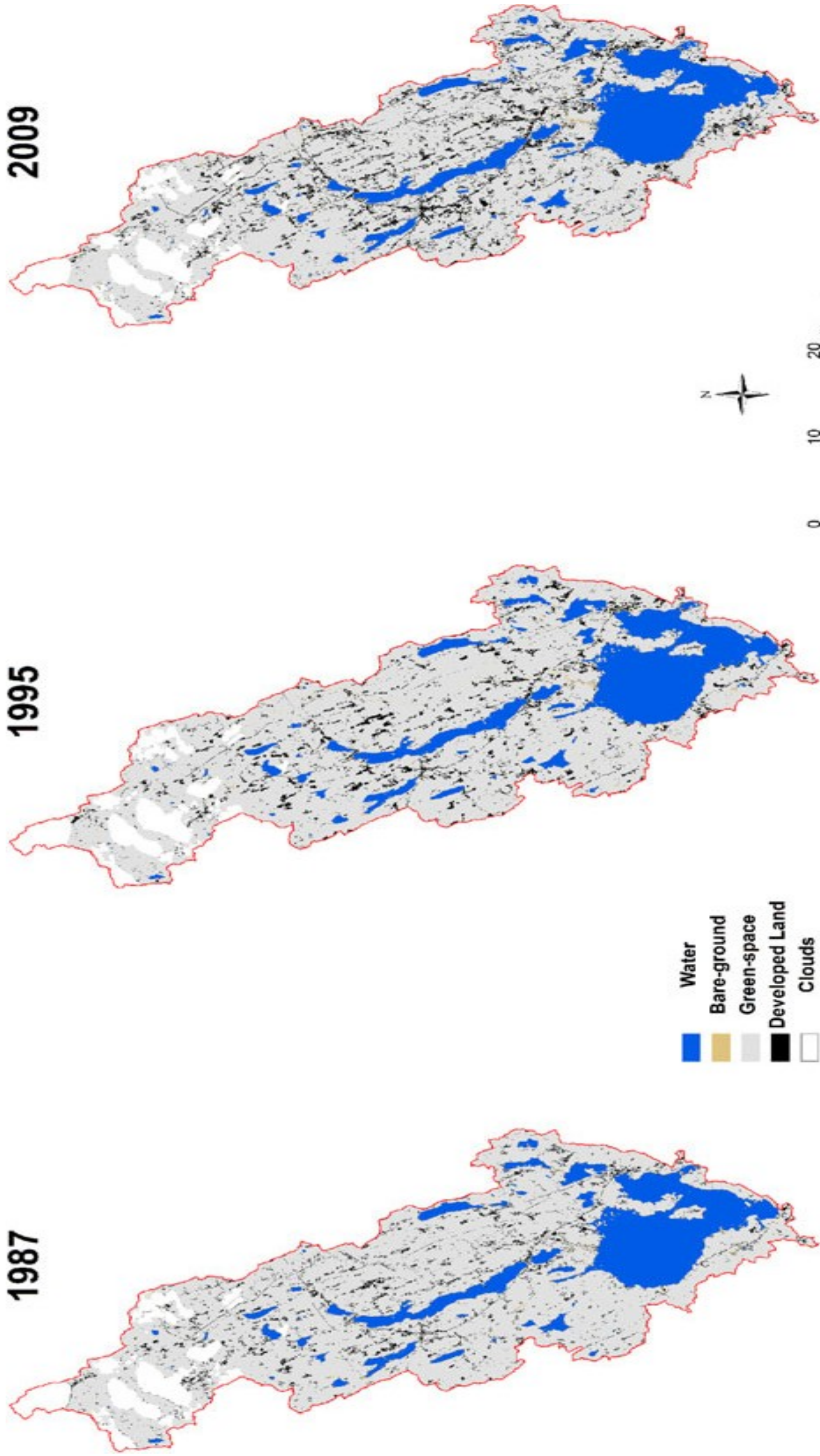

Table 3 Accuracy assessments for 1987, 1995, 2009 classification

Class code	WA	BG	GS	DL	Row total	PA (%)	UA (%)	Kappa
1987								
WA	40	0	0	0	40	85.11	100.00	1.00
BG	7	29	4	0	40	96.67	72.50	0.66
GS	0	1	37	2	40	86.05	92.50	0.90
DL	0	0	2	38	40	95.00	95.00	0.93
Total	47	30	43	40	160			
Overall accuracy 90.00 %, Kappa 0.87								
1995 classification								
WA	40	0	0	0	40	95.24	100.00	1.00
BG	2	34	2	2	40	100.00	85.00	0.81
GS	0	0	40	0	40	90.91	100.00	1.00
DL	0	0	2	38	40	95.00	95.00	0.93
Total	42	34	44	40	160			
Overall accuracy 95.00 %, Kappa 0.93								
2009 classification								
WA	40	0	0	0	40	97.56	100.00	1.00
BG	1	33	4	2	40	100.00	82.50	0.78
GS	0	0	40	0	40	90.91	100.00	1.00
DL	0	0	0	40	40	95.24	100.00	1.00
Total	41	33	44	42	160			
Overall accuracy 95.63 %, Kappa 0.94								

PA Producer's accuracy, *UA* user's accuracy

Table 4 Land use classes from Landsat TM data

Class code	1987 Area (hectare)	1987 % of total land area	1995 Area (hectare)	1995 % of total land area	2009 Area (hectare)	2009 % of total land area
WA	18,106	16.98	18,378	17.24	18,236	17.10
BG	1,101	1.03	1642	1.54	1,620	1.52
GS	81,648	76.58	80,100	75.13	77,207	72.41
DL	5,743	5.39	6,495	6.09	9,495	8.91

Table 5 Landscape metrics for land-based classes, 1987 and 2009

Class code	1987 Number of patches	1987 Mean patch size (hectare)	2009 Number of patches	2009 Mean patch size (hectare)
BG	2,261	0.49	2020	0.80
GS	429	189.18	729	108.23
DL	8,680	0.66	8612	1.09

Table 6 Z-scores of population, housing units and median income change

Table 6 *Z*-scores of population, housing units and median income change

Town	Population *z*-score			Housing *z*-score			Median income *z*-score		
	1990–2000	2000–2010	1990–2010	1990–2000	2000–2010	1990–2010	1990–2000	2000–2010	1990–2010
Baldwin	−0.06	0.86	0.38	−0.18	0.81	0.28	−0.66	1.16	−0.09
Bethel	−0.18	0.18	−0.05	−0.08	1.41	0.68	−0.32	0.26	−0.15
Bridgton	0.34	0.08	0.25	−0.62	1.72	0.36	0.22	−0.20	0.14
Casco	0.42	0.16	0.35	0.05	3.24	1.81	0.17	0.01	0.24
Denmark	0.56	0.60	0.69	−0.75	−0.07	−0.62	0.12	0.10	0.25
Gray	0.45	0.56	0.59	−0.17	0.69	0.23	−0.14	−0.24	−0.25
Greenwood	0.50	−0.13	0.23	−0.52	0.77	−0.02	0.10	0.26	0.33
Harrison	0.62	0.84	0.87	0.23	0.96	0.71	−0.36	−0.25	−0.49
Hiram	0.32	0.56	0.50	−0.28	0.50	0.04	−0.08	−0.16	−0.14
Lovell	0.14	0.78	0.49	1.07	−0.92	0.24	−0.14	0.32	0.09
Naples	0.40	0.86	0.72	0.37	1.21	0.97	−0.04	0.39	0.25
Norway	−0.53	0.22	−0.27	−0.64	−0.15	−0.57	−0.23	0.22	−0.07
Otisfield	1.62	0.54	1.40	0.46	0.33	0.54	0.43	0.11	0.60
Poland	0.27	0.34	0.34	0.36	0.33	0.46	0.38	−0.84	−0.17
Raymond	1.22	−0.15	0.68	0.44	0.07	0.38	−0.20	−0.31	−0.36
Sebago	0.36	0.97	0.76	−0.72	0.53	−0.30	−0.03	−0.38	−0.23
South Oxford UT	0.33	0.47	0.46	0.81	−0.93	0.05	−0.38	−0.05	−0.39
Standish	0.74	0.06	0.50	−0.23	−0.06	−0.22	0.13	−0.19	0.06
Stoneham	0.37	−0.87	−0.27	−0.96	−1.15	−1.28	0.87	−0.20	0.83
Sweden	2.08	1.02	2.07	−0.23	1.07	0.37	−0.52	1.39	0.23
Waterford	0.27	0.09	0.20	0.06	0.79	0.47	−0.60	0.59	−0.30
Windham	0.40	0.58	0.57	0.07	0.46	0.30	−0.30	−0.02	−0.30

Table 7 Index of development—Sebago watershed and surrounding (ranked by 1990–2010)

Town	1990–2000	2000–2010	1990–2010
Sweden	3.17	5.57	5.12
Casco	1.13	6.82	4.55
Otisfield	4.59	1.84	4.48
Naples	1.50	4.53	3.65
Harrison	1.35	3.34	2.68
Raymond	3.13	−0.48	1.75
Lovell	2.28	0.03	1.55
Poland	1.65	0.49	1.44
Windham	0.64	2.05	1.43
Gray	0.44	2.27	1.40
Bridgton	−0.34	3.41	1.35
Baldwin	−1.14	4.48	1.24
Bethel	−0.85	3.43	1.12
Waterford	0.05	2.34	1.04
Hiram	0.01	1.97	0.94
Greenwood	0.07	1.54	0.75
Sebago	−0.74	2.63	0.68
South Oxford UT	1.90	−0.97	0.62
Standish	1.15	−0.19	0.62
Denmark	−0.28	1.16	0.38
Norway	−2.57	0.36	−1.75
Stoneham	−0.33	−4.23	−2.28

Fig. 3 Index of development for Sebago towns 1990–2010

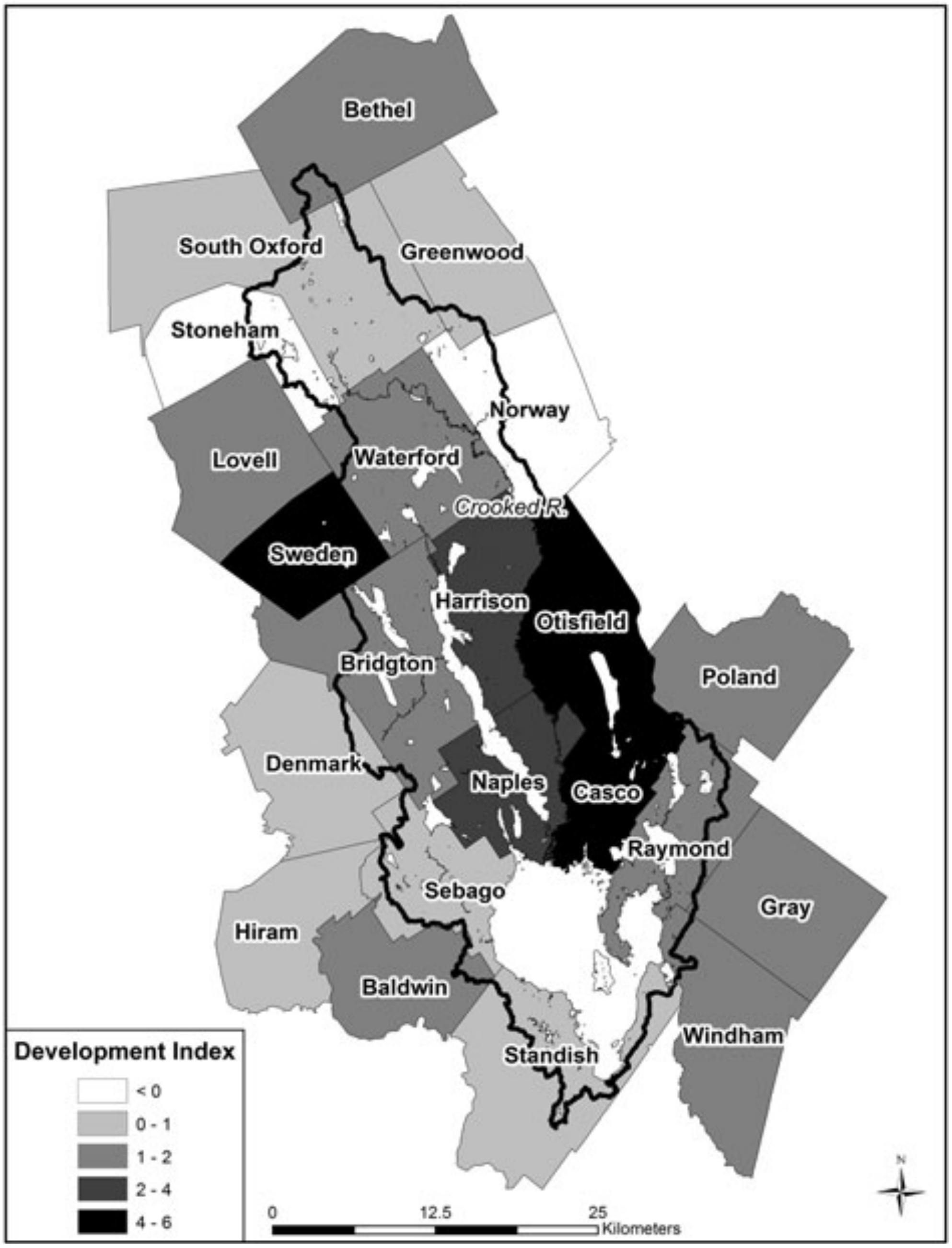

Table 8 Results for late-summer water quality means

	1990–2010		1979–2010	
	Year of change	*p* value	Year of change	*p* value
Pettitt's test for a step change				
Total phosphorus	**2005**	**0.03**	2005	0.12
Chlorophyll *a*	1998	0.16	1991	0.16
Secchi disk depth	1997	0.10	2005	0.39
	Rho	*p* value	Rho	*p* value
Water quality trends				
Total phosphorus	–	–	0.12	0.50
Chlorophyll *a*	**0.47**	**0.03**	0.03	0.86
Secchi disk depth	**−0.53**	**0.01**	−0.13	0.47
Water quality correlations				
Lake level				
Spring				
Total phosphorus	0.13	0.58	0.22	0.23
Chlorophyll *a*	**0.44**	**0.05**	0.30	0.11
Secchi disk depth	−0.30	0.18	**−0.44**	**0.01**
Summer				
Total phosphorus	0.11	0.64	0.18	0.33
Chlorophyll *a*	0.39	0.08	0.11	0.58
Secchi disk depth	−0.34	0.13	**−0.42**	**0.02**
Precipitation				
Spring				
Total phosphorus	0.14	0.56	0.23	0.21
Chlorophyll *a*	**0.43**	**0.05**	0.33	0.08
Secchi disk depth	−0.38	0.09	**−0.54**	**<0.01**
Lake level (spring)	**0.43**	**0.05**	**0.63**	**<0.01**
Lake level (summer)	0.38	0.08	**0.55**	**<0.01**
Summer				
Total phosphorus	0.20	0.39	0.12	0.50
Chlorophyll *a*	0.23	0.31	0.20	0.29
Secchi disk depth	−0.26	0.25	−0.14	0.46
Lake level (summer)	0.20	0.40	−0.10	0.58
Water quality partial correlations				
Precipitation (spring)				
And lake level (spring)				
Chlorophyll *a*	0.31	0.16	–	–
Secchi disk depth	–	–	−0.17	0.36
And lake level (summer)				
Secchi disk depth	–	–	−0.18	0.32

Partial correlations assess the relationship between lake level and water quality variables while accounting for the influence of spring precipitation

Values in bold are statistically significant at the 95 % confidence level