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Has urbanization changed ecological streamflow characteristics in Maine (USA)?

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Abstract This paper examines the potential effects of urbanization on streamflow in Maine, USA, from 1950 to 2000. The study contrasts nine watersheds in southern Maine, which has seen steady urban growth over the study period, with nine rural watersheds from northern Maine. Historical population data and current land cover data are used to develop an urbanization score for each watershed. Trends in watershed urbanization over the study period are compared to trends in ecologically relevant streamflow characteristics. The results indicate that trends in northern, rural watersheds are much more consistent than the trends in the southern watersheds. Additionally, trends in the southern watersheds are inconsistent with the hydrological characteristics observed in urban watersheds elsewhere, likely due to the comparatively low level of current urban development in Maine's urban watersheds. Our study suggests that urban areas in Maine have not yet reached an urbanization threshold where streamflow impacts become consistently detectable.

Key words urbanization; streamflow; land use; land cover; hydrology; Maine

L'urbanisation a-t-elle changé les caractéristiques des débits écologiques dans le Maine (USA)?

Résumé Cet article présente une étude des effets potentiels de l'urbanisation sur les écoulements dans le Maine, aux États-Unis, de 1950 à 2000. La comparaison concerne neuf bassins versants du sud du Maine, qui ont connu une urbanisation continue au cours de la période d'étude, et neuf bassins versants ruraux du nord de Maine. Des données démographiques historiques et des données actuelles d'occupation du sol ont été utilisées pour définir un indice d'urbanisation pour chaque bassin versant. Les tendances de l'urbanisation des bassins versants au cours de la période d'étude ont été comparées à l'évolution des caractéristiques des débits écologiquement pertinents. Les résultats indiquent que les tendances dans les bassins versants ruraux du Nord sont beaucoup plus cohérentes que les tendances dans les bassins versants du Sud. En outre, les tendances dans les bassins versants du Sud sont incompatibles avec les caractéristiques hydrologiques observées dans d'autres bassins versants urbains, probablement en raison du niveau relativement faible de développement urbain en cours dans les bassins versants urbains du Maine. Notre étude suggère que les zones urbaines dans le Maine n'ont pas encore atteint un seuil d'urbanisation où les impacts sur les débits deviennent significativement détectables.

Mots clefs urbanisation; débit; utilisation des terres; couverture du sol; hydrologie; Maine

INTRODUCTION

The USA is becoming increasingly urbanized (Konrad 2003, Meyer *et al*. 2005). Population growth is predicted to bring the total US population to 392 million by 2050, an increase of 50% from the 1990 population (US Census Bureau 2008). Consequently, urban areas across the United States are expanding to accommodate growing populations, with metropolitan areas adding urbanized land at a rate faster than population growth. Between 1982 and 1997 the US population grew by 17%, but the amount of urbanized land grew by 47% (Fulton *et al*. 2001). This trend of land-hungry growth is particularly

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evident in the Northeast and Midwest, where relatively small population growth between 1982 and 1997 (6.9% and 7.1%, respectively) has led to substantially more urbanization (39.1% and 32.2%) (Fulton *et al*. 2001).

The growing footprint of human activity has significant implications for hydrology (Wagener *et al.* 2010). Among the impacts of increased urbanization are changes to the hydrology, and subsequently ecology, within urbanized watersheds (Konrad and Booth 2005). Land-use changes correlated with urbanization include reduced vegetation, construction of storm drainage networks and increased impervious surfaces, all of which can result in decreased infiltration and increased runoff (Poff *et al*. 1997, Rose and Peters 2001, Konrad 2003, Sheng and Wilson 2009). Such land-use changes cause increases in peak discharge, volume and flood frequency in the downstream hydrology of developed areas (Konrad 2003). The term "urban stream syndrome", which describes streams with a flashier hydrograph, elevated concentrations of nutrients and contaminants, altered channel morphology and reduced biotic richness relative to less-disturbed streams (Meyer *et al*. 2005, Walsh *et al*. 2005), was developed to describe urban streams characterized by these changes. Urbanization effects on streamflow can also alter other facets of stream hydrology, such as bed geomorphology, as well as sediment, nutrient and pollutant loads (Gluck and McCuen 1975, Bledsoe and Watson 2001, Carle *et al*. 2005, Exum *et al*. 2005, Poff *et al*. 2006).

Changes to water pathways, storage and release from urbanization and other anthropogenic activities are predicted to have significant negative impacts on ecosystems (Wagener 2007). When combined with other urban effects, such as rising water temperatures, changes to streamflow may negatively impact fish assemblages (Marchetti *et al*. 2006) and macroinvertebrate species (Moore and Palmer 2005). Wang *et al.* (2003) found decreasing quality of fish assemblages with increasing urban land cover, resulting from increases in water temperature and decreases in baseflow, a low-flow metric that represents the main source of streamflow for many streams during summer months. Similarly, Roy *et al*. (2005) found that urbanization in Georgia, USA was associated with a shift in fish assemblages toward habitat generalists (tolerant of standing, lentic conditions) and a loss of stream dependant species. Kelleher *et al.* (2011) found that stream temperature's sensitivity to change was a function of baseflow contribution, indicating that urban areas with rising water temperatures and possibly decreasing baseflows may eventually no longer be habitable for cold water fish species. Many of these alterations can also have direct (e.g. property damage from increased flood frequency) and indirect economic impacts (e.g. reduced tourism from impaired recreational fisheries) (Aylward 2002).

Studies performed at different geographical and temporal scales show consistent alteration in urbanized watersheds relative to non-urbanized or less-urbanized watersheds across four categories of streamflow metrics: peak flows, low flows, flow durations and flow variability. A comprehensive review of different streamflow metrics that quantify hydrological alteration can be found in Richter *et al.* (1996). The conclusions of these studies, which compare urban streams to natural or rural streams, are summarized in Table 1. The impacts of urbanization on each of the flow metrics, and the subsequent impacts of changes to these metrics on hydrology and ecology, include (TNC 2009):

Peak flows: Peak flows are typically greater for urban *versus* more natural settings, due to decreased infiltration and storage associated with increased impervious surface coverage. Increases in peak flows will lead to flooding and erosion, as well as soil moisture stress for plants with inundated root systems, and changes to the volume of nutrient exchange.

Low flows: Low flows have been shown to decrease in urban watersheds. Ecological effects of reduced low flows can include low oxygen conditions, dehydration in animals, soil moisture stress in plants, and more concentrated chemicals in aquatic environments.

Flow duration: Flow durations have been shown to decrease in urban streams due to reduced infiltration and shorter flowpaths to streams. Ecological consequences of altered flow durations can include frequency and magnitude changes in soil moisture, anaerobic stress for plants, nutrient and organic matter exchange between stream and floodplain, and can also alter access for water birds to feeding, resting and reproduction sites.

Flow variability: Flow variability has been noted to increase in urban streams due to the presence of impervious surfaces and storm drain networks. Ecological effects of altered flow variability can include drought stress in plants, entrapment of organisms on islands, and desiccation stress in low-mobility stream-edge organisms.

Table 1 Conclusions of studies which compare urban streams to natural or rural streams. The table lists the study, the location(s) of analysis, the metrics investigated, and the study results and conclusions.

Study	Location	Metric	Result
Peak flows:			
Rose and Peters (2001)	Atlanta, Georgia	Peak daily flow	Higher peak flows for the urban stream
Poff *et al*. (2006)	Entire USA	Average annual 1-day maximum flow	Higher peak flows for urban streams in 2 of 4 hydrologic regions
			Lower peak flows in the arid southwest (low sample size)
Konrad and Booth (2002)	Washington State	Annual maximum flow	Statistically significant increases for all three urban streams
Low flows			
Poff *et al*. (2006)	Entire USA	3-day minimum flow	Generally decreased for urban streams relative to more natural streams
Konrad and Booth (2002)	Washington State	7-day minimum flow	Inconclusive results
			One urban stream had a positive correlation and two urban streams had a negative correlation between urbanization and low flows
Flow duration:			
Poff *et al*. (2006)	Entire USA	No. of days that average daily flow ≥ 1.5-year return-period maximum	Number of days was lower for urbanized streams
Flow variability:			
Poff *et al*. (2006)	Entire USA	Average daily change in flow divided by long-term mean flow (Sanborn and Bledsoe 2006)	Flow variability was greater for urban versus natural streams in all but one region
Konrad *et al*. (2005)	Washington State	Fraction of year that mean daily flow exceeds mean annual flow ($T_{Q,\,\mathrm{mean}}$)	Lower metric values for urban versus natural streams
Konrad and Booth (2002)	Washington State	$T_{Q,\,\mathrm{mean}}$	Lower metric values for urban versus natural streams
Chang (2007)	Portland, Oregon	$T_{Q,\,\mathrm{mean}}$	Lower metric values for urban versus natural streams

The state of Maine provides an interesting setting to study the phenomenon of urban impacts on streams for several reasons. Relative to much of the east coast of the USA, Maine has relatively few urbanized areas, so there is an opportunity to prevent or mitigate many of the problems associated with urban streams before they become too severe. The urban areas located in Maine are growing rapidly, a trend that the Maine State Planning Office has predicted to continue (MeSPO 2008). Between 1982 and 1997, the Portland, Maine metropolitan area was the ninth fastest urbanizing area in the country with a 108.4% increase in urbanized land (Fulton *et al*. 2001). The area of towns classified as "urban-suburban" is projected to exceed 10 000 km^2 by 2030, up from 4723 km^2 in 2000 and 2466 km^2 in 1970, as shown in Fig. 1. Within the relatively small extent of the state, there is a clear geographic distinction between rural areas and more urbanized areas, since most development in the past 50 years has occurred in southern and coastal portions of the state (Fig. 2). This distinction, as well as the relatively small extent of the state, allow for a comparison between urbanized and rural watersheds, while reducing confounding factors such as climate and geology. Maine also has a strong tradition of outdoor recreation, which includes a significant economic reliance on healthy waterways. Inland recreational fishing has a US$ 300 million impact on the state economy (MIFW 2010) which could be negatively influenced by altered hydrology and its associated effects (Wang *et al*. 2003).

The objective of this paper is to understand whether and, if so, to what extent, urbanization has altered streamflow in the expanding urbanized areas of southern and coastal Maine between 1950 and 2000. This is accomplished by first assigning a developed land cover score to each of the 18 watersheds, half in rural undeveloped portions of northern Maine and half in more urbanized portions of southern Maine, for each decade in the analysis time frame. Daily streamflow data are then analysed for the 18 watersheds for metrics which evaluate peak flow, low flow, flow variability and flow duration. Expected changes in urbanized watersheds, based on the research outlined above, include increased peak flows, reduced low flows, increased flow variability and reduced flow durations.

STUDY AREA

Hydrology and climate

Maine falls within a temperate climate. Based on a review of data from the period 1901–2000, obtained from the National Oceanic and Atmospheric Administration (NOAA), summers are warm with a mean temperature of 18°C, while winters are cold with a mean temperature of –8°C. The mean

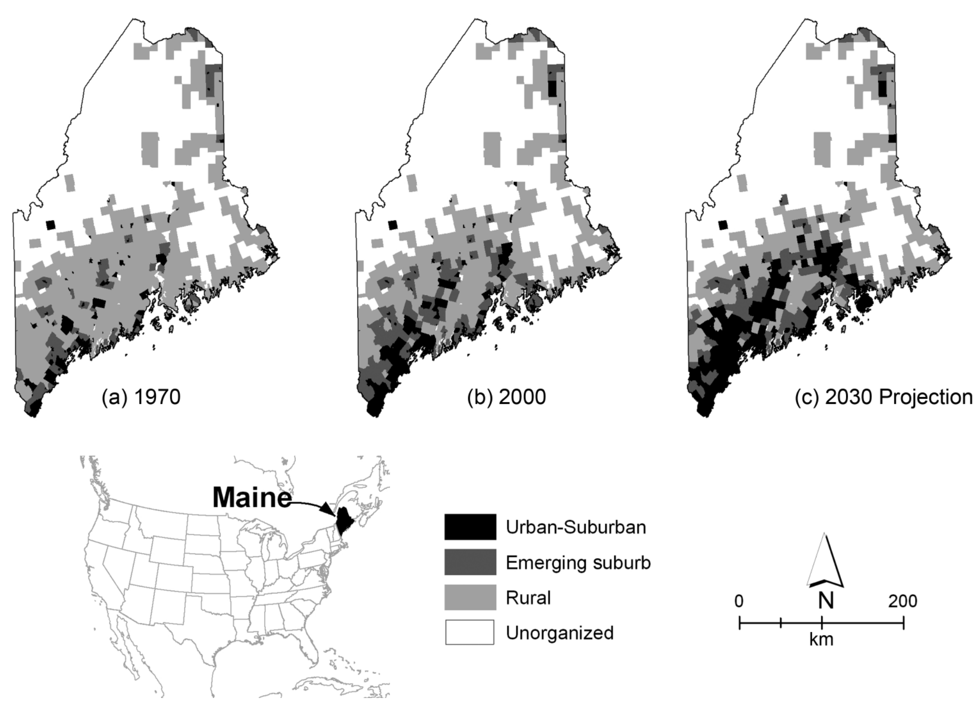

Fig. 1 Developed areas of Maine, showing (a) 1970 and (b) 2000 observations, as well as (c) 2030 projections (Data from: MeSPO 2008).

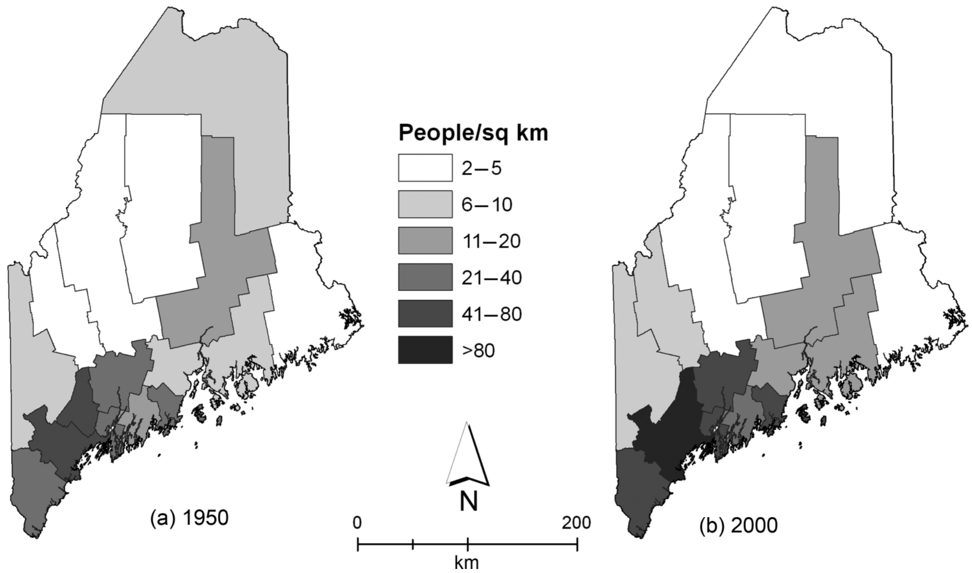

Fig. 2 Population density by Maine County: (a) 1950 and (b) 2000. (Data from: US Census Bureau 2008).

annual precipitation is 1070 mm, which is distributed relatively evenly throughout the year. Statewide variability in climate is low, though the southern coast is slightly warmer and wetter, and the north of the state is colder and drier by comparison (PRISM 2006). In winter, the moderating effect of the Atlantic coast creates a climatic gradient, with the warmest temperatures along the coast and the coldest temperatures in the western mountains (Hodgkins and Dudley 2006). Likewise, the Atlantic has a moderating effect in summer, with cooler temperatures near the coast and warmer temperatures inland. Between December and March, most precipitation falls as snow, which contributes to yearly maximum flows in Maine's rivers in March and April as snowmelt combines with spring rains. Maine is drained by almost 75 000 km of rivers and streams. Of these, 56% are classified as first-order streams, 23% are second-order, 12% are third-order and 9% are fourth-order or greater.

Topography and land cover

The topography of Maine ranges from coastal plains in the east to the heights of the Appalachian Mountains in the west. Mt Katahdin is the highest point in the state, reaching 1606 m. Maine has over 2200 lakes and ponds, which were scoured during the advance and retreat of the Laurentide Ice Sheet that ended some 12 500 years ago. This glacial period is also responsible for carving a convoluted mix of islands, peninsulas and bays that make up the Maine coast. Maine is part of the Appalachian Highlands physiographic province and includes portions of three eco-regions, the Northern Appalachians, the North Atlantic Coast and Lower New England. Approximately 90% of the state is forested (MDOC 1999), with much of the northern half of the state actively managed as commercial timber. Agriculture is a significant land use, accounting for over 500 000 ha of land cover (MDOA 2005). This is particularly the case in the northeastern part of the state, where potatoes are a major crop, and the eastern portion of the state, where there are extensive blueberry barrens.

Population

The population of Maine as of the 2000 census was 1 274 923. Most of the population is clustered in the southern and coastal parts of the state, while large portions of north and western Maine remain unorganized territory with few permanent residents. Increased population in southern and coastal Maine has led to increasing urbanization over the last 50 years, compared to a shrinking population in much of the agricultural areas of northeastern Maine. This trend is expected to continue into the foreseeable future (MeSPO 2008) (Fig. 1).

METHODOLOGY

A total of 18 watersheds with US Geological Survey (USGS) streamgauges were selected for inclusion in the analysis, half being located in northern Maine and half in southern Maine (Fig. 3). Availability of

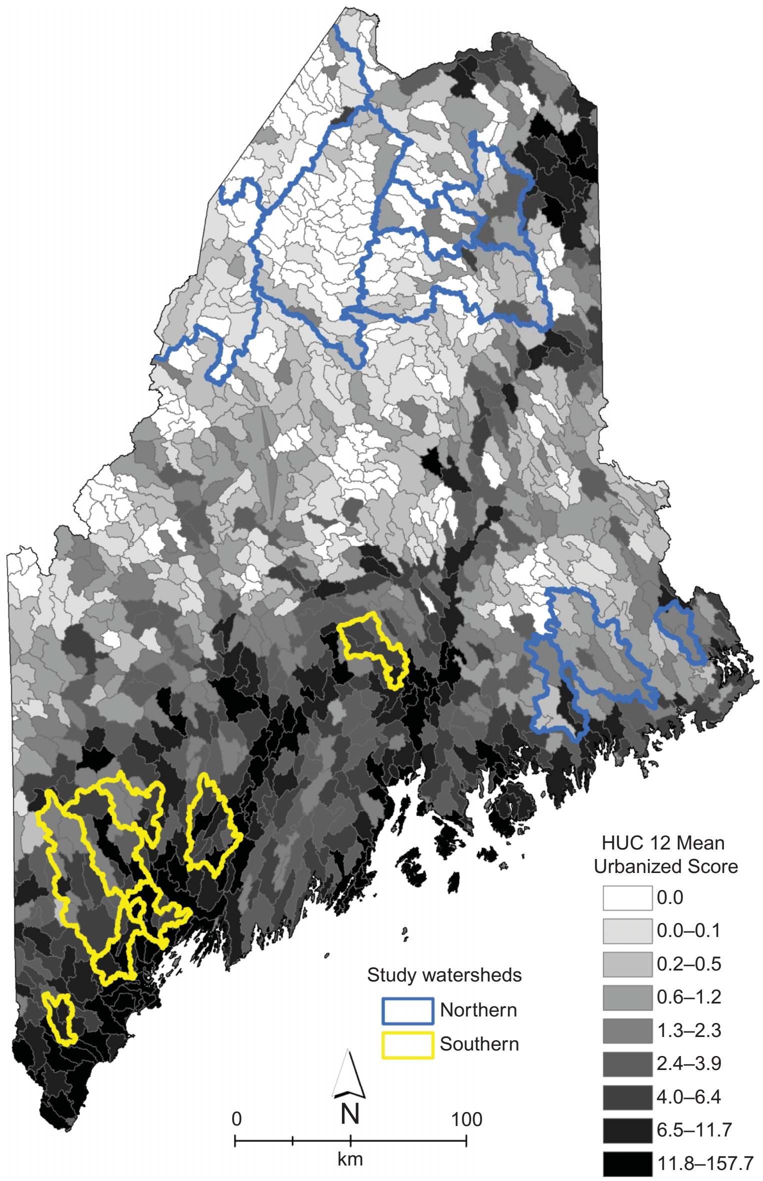

Fig. 3 Year 2000 urbanized land cover score for 1:24 000-scale watersheds (Hydrologic Unit Code 12). Urbanized score is calculated based on 2000 NOAA C-CAP (30-m grid cell) land cover data where High-Intensity Developed = 4, Medium-Intensity Developed = 3, Low-Intensity Developed = 2 and Developed Open Space = 1. Non-urban land cover is given a score of zero. Scores for individual grid cells were averaged across HUC-12 watersheds. Study watersheds in the north (blue) and south (yellow) of Maine are also outlined. Northern watersheds are typically less urbanized, whereas southern watersheds are more urbanized.

streamgauge data for the period of interest was a primary determining factor in watershed selection, with a goal of obtaining daily data from 1950–2000 (Table 1). In addition to available streamgauge data, watersheds were chosen based on the current percentage of developed land cover, as identified from the 2006 land-cover data collected by the National Oceanic and Atmospheric Administration Coastal Change Analysis Program (NOAA C-CAP; NOAA 1984). In southern Maine, watersheds with greater amounts of urban landscape were selected, while in northern Maine, watersheds with little urban cover were selected. The watersheds and their urbanization score are described in Table 2. Preference was given to smaller watersheds, due to the likely greater response of smaller watersheds to changes in land cover (Poff *et al*. 2006). However, the limited availability of streamgauge data required the inclusion of several larger watersheds, particularly in the less developed watersheds of northern Maine, where fewer gauges are present on small streams. In northern Maine, watershed size ranged from 241 to

Table 2 Summary of study watersheds and their urbanization scores. The table includes the USGS stream gauge number, the gauge station name, the contributing watershed area to the gauge, any missing years of streamflow, and the total and decadal watershed land cover scores.

USGS gauge number	Gauge station name	Watershed area (km^2)	Missing years		Average watershed land cover score					
			Period	Total	1950	1960	1970	1980	1990	2000
Northern watersheds:										
1010000	St. John River at Ninemile Bridge	3485	1950	1	0	0	0	0	0	0
1010500	St. John River at Dickey	6991	None	0	0.1	0.1	0.1	0.1	0.1	0.1
1011000	Allagash River near Allagash	3831	None	0	0	0	0	0	0	0
1015800	Aroostook River near Masardis	2322	1950–1956	7	0	0	0	0	0	0
1016500	Machias River near Ashland	829	1950, 1985–2000	17	0	0	0	0	0	0
1017000	Aroostook River at Washburn	4111	None	0	0.3	0.3	0.3	0.3	0.3	0.3
1021200	Dennys River at Dennysville	241	1950–1955	7	0.9	0.9	0.9	1.4	1.6	1.8
1021500	Machias River at Whitneyville	1205	1978–2000	23	0.9	0.9	0.9	0.9	0.9	0.9
1022500	Narraguagus River at Cherryfield	574	None	0	1.3	1.3	1.4	1.7	1.8	1.8
	Northern Maine mean	2621	–	–	0.4	0.4	0.4	0.5	0.5	0.6
Southern watersheds:										
1036500	Kenduskeag Stream near Kenduskeag	394	1980–2000	21	3.1	3.3	3.6	4.9	5.9	6.6
1049500	Cobbosseecontee Stream at Gardiner	574	1965–1976	12	4.2	4.7	5.4	7.3	8.2	9.1
1055500	Nezinscot River at Turner Center	430	1998–2000	3	2.1	2.3	2.6	3.7	4.4	5
1058500	Little Androscoggin River near Auburn	843	1984–2000	17	4.9	4.8	5.1	6.4	7.2	7.8
1059800	Collyer Brook near Gray	42	1950–1963	29	9.2	10.9	12.8	17.1	22.4	26.5
1060000	Royal River at Yarmouth	335	None	0	6.3	6.9	7.6	9.1	10.8	12.3
1064000	Presumpscot River at Outlet of Sebago Lake	1161	None	0	1.7	1.7	2.3	3.2	4.1	4.8
1064118	Presumpscot R. at Westbrook	1481	1950–1975	31	2.9	3.3	4.1	5.8	7.1	8.1
1069500	Mousam River near West Kennebunk	159	1985–2000	16	3.2	3.3	3.4	5.6	7.2	8.6
	Southern Maine Mean	602			4.2	4.6	5.2	7	8.6	9.9

6991 km^2, with a mean of 2621 km^2. In southern Maine, watershed size ranged from 42 to 1481 km^2 with a mean of 602 km^2 (Table 2).

Watersheds

Contributing watersheds were delineated using ArcGIS 9.3 Hydrology tools for the selected USGS streams based on 10-m resolution digital elevation models (DEM), obtained from the USGS's Seamless Server (http://seamless.usgs.gov/).

Land cover

State-wide land-cover data were obtained from the NOAA C-CAP. These data were derived from Landsat satellite imagery collected between 1999 and 2006. For the purpose of this analysis, this imagery was assumed to correspond to the year 2000, the year for which detailed population data were available. Each 30-m pixel is classified into one of 22 categories, including four urban or developed categories, three agricultural categories, three forest categories, 10 water or wetland categories, as well as scrub/shrub and bare land.

Because no state-wide land-cover data were available for the 1950s to the 1980s, we propose a new methodology to approximate the degree of urbanization for this period, while considering two alternative methods of estimating land cover. The first approach relies on a well-established connection between population and urban land cover (Stankowski 1972, Gluck and McCuen 1975, Lopez *et al.* 2001, Exum *et al.* 2005). As urban land cover is a direct result of human settlements, it follows that a measure of population should be a reasonable predictor of urban land cover (Exum *et al.* 2005). Several authors have developed methods for estimating urbanization, generally quantified as a percentage of impervious cover, using measures of population, measured as population density, in regions similar to the study area (Stankowski 1972, Graham *et al*. 1974). In these studies, the percentage impervious surface was found to increase and then level off asymptotically with increasing population densities. Although the relationships found by these studies can over- or under-predict at different levels of population density, the strong, positive relationship between population density and the percentage of impervious surfaces makes this approach particularly useful (Exum *et al.* 2005).

However, estimates for this approach are made solely from population data that are aggregated at a town (or other political district) level. Thus, the political district becomes the minimum mapping unit, as there is no spatially explicit detail within its boundaries. The limitation to this approach is that it assumes that population, and therefore urban land cover, is uniform throughout the town, which is not the case. Furthermore, town-level values present problems when estimates for urbanization are required for a spatial unit that crosses portions of many towns, such as a watershed.

An alternative approach, developed by Chabaeva *et al*. (2004), addresses this problem by representing urbanization via estimates of imperviousness, calculated as a function of land-cover class and population density, at the watershed level. Although this method produced a refined prediction of imperviousness (for many of the 236 watersheds for which empirical data were available the predicted values were within 1–2% of the actual values and the root mean squared error was less than 4%), it requires land-cover data for the analysis date. Therefore, for the purpose of a retrospective analysis, it also falls short.

A new methodology was therefore developed here that uses readily available census data and modern land-cover data to approximate the degree of urbanization for the time period for which land cover data are not available. For this approach, urbanized land cover was identified using four types of urban or developed land-cover classes from the NOAA C-CAP raster data (NOAA 1984):

– High-Intensity Developed land cover includes heavily built-up urban centres, large buildings, interstate highways and runways. Impervious surfaces account for 80–100% of the total cover within a given grid cell.
– Medium-Intensity Developed cover includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50–79% of the total cover.
– Low-Intensity Developed cover contains a mixture of constructed surfaces and vegetated surfaces. Impervious surfaces account for 21–49% of the total cover.
– Developed Open Space cover includes some amount of constructed land cover, but is largely composed of vegetation in the form of lawn grasses. Impervious cover is less than 20% of the total cover.

A simple numerical score was assigned to these four urban classes so that High-Intensity Developed grid cells received a score of 4; Medium-Intensity Developed grid cells: 3, Low-Intensity Developed grid cells: 2; and Developed Open Space grid cells: 1. Cells with a non-urban land-cover classification were given a value of 0. Although these scores roughly correspond to the percentages of impervious surfaces in each of the developed land-cover types (e.g. High-Intensity Developed land cover has approximately four times the amount of impervious surface as Developed Open Space), they are intended to provide relative measures of urbanization over space and time, as opposed to actual values of impervious surface on the ground.

Subsequently, a relationship between year 2000 population and urbanization, calculated as a function of year 2000 land cover, was established across all Maine towns for which population data were available. As can be seen in Fig. 4, when plotted against each other, a linear relationship describes the data relatively well, even with the large number of low-population towns in Maine, highlighted by the log-transformed axis. Additionally, when population is plotted against each of the four urban land-cover classes separately, the relationship between population and area corresponding to each urban score is not only linear, but increases in strength for urban scores 1 to 3 (Fig. 5), with R^2 values increasing from 0.70 for Developed Open Space to 0.86 for Medium-Intensity Developed. High-Intensity

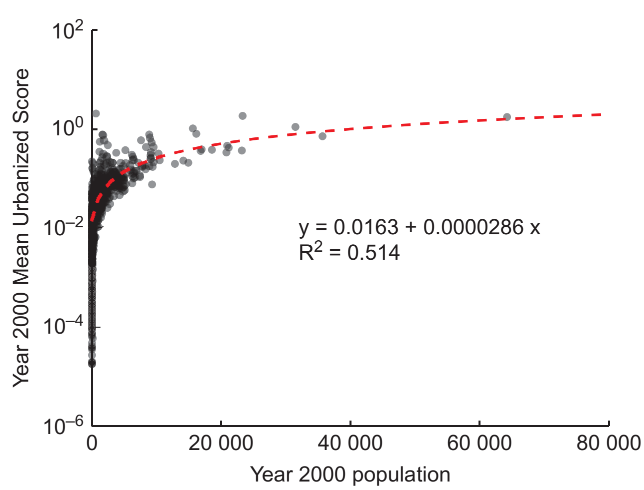

Fig. 4 Relationship between year 2000 population and urbanization, as measured by mean urbanized land cover score, for Maine towns. The relationship is strongly linear (r^2 = 0.514). Mean urbanized score is plotted on a log-axis to draw attention to the large number of small towns in Maine.

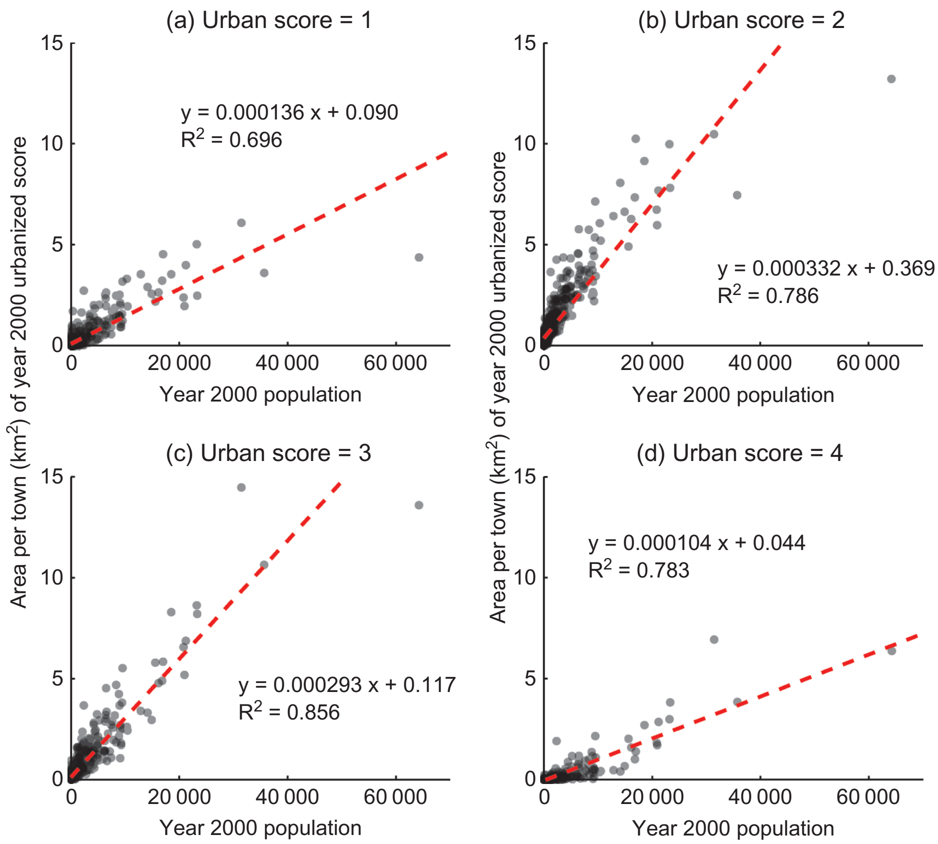

Fig. 5 Relationship between population and urbanized land cover score classes for (a) Developed Open Space (score = 1), (b) Low-Intensity Developed (score = 2), (c) Medium-Intensity Developed (score = 3), and (d) High-Intensity Developed (score = 4) land cover for Maine towns. Note that the relationship between urbanized score and population is stronger for high intensity developed areas than open space developed areas, as even a small town may have parks or golf courses, both of which are common features of the developed open space class.

Developed had a slightly lower R^2 value (0.78) than either Low or Medium-Intensity Developed land, but this relationship was still stronger than the relationship for Developed Open Space. This would indicate that, although small towns may have large areas of developed open space (e.g. town parks), only cities and towns with larger populations have high-intensity development.

The urbanized score for the historical decades (1950–1990) was calculated for each town across Maine based on the following proportion:

$$\frac{2000\ Population}{2000\ Mean\ Urbanized\ Score} = \frac{Decade \times Population}{Decade \times Mean\ Urbanized\ Score} \quad (1)$$

where X Decade refers to any decade between 1950 and 1990; 2000 Population, 2000 Mean Urbanized Score, and X Decade Population are all known based on the analysis described above, and X Decade Mean Urbanized Score is unknown.

In order to make this information spatially explicit on a cell-by-cell basis such that it can then be aggregated to the watershed scale, the percentage change in mean urbanized score was calculated between all decades without historical land cover data and the year 2000 data, derived from the population change by town obtained from equation (1). This percentage was then multiplied by the year 2000 land cover data on a cell-by-cell basis, as illustrated in Fig. 6, resulting in the creation of a new raster grid with urbanized score values modified to the decade that was compared to the year 2000 data. From this grid, summary statistics can be calculated for any watershed or other spatial unit.

For towns that lost population over time, as is the case for portions of northern Maine, the current

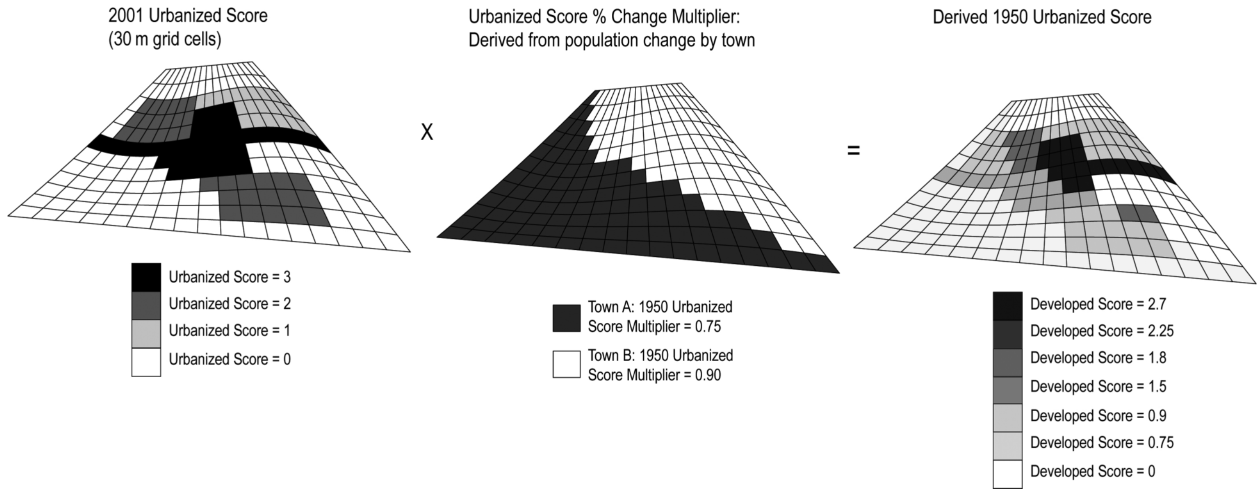

Fig. 6 Methodology used to estimate land cover scores for 1950, 1960, 1970, 1980 and 1990. The year 2000 developed land cover scores were multiplied by the developed score percentage change as calculated for each decade using population data. These data are not intended to predict actual on-the-ground conditions. Rather, when aggregated by watershed or other spatial unit, they can provide an estimate of development at the time in question.

land-cover score was retained for those prior years with larger populations. No decade was calculated to have more urbanization than is currently present. This decision was based on the assumption that re-vegetating impervious surfaces is an expensive undertaking that is done relatively infrequently in areas that still have ample open space for new developments, as northern Maine does. Therefore, it is unlikely any significant removal of impervious surface has occurred as populations have declined in northern Maine.

Once raster grids of urban score were developed for the entire state and for each decade in the study, mean scores were calculated for each study watershed. Values were aggregated both to town level and to watershed level by averaging across cell values corresponding to each town or watershed. Trends in scores for urban *versus* non-urban locations were further averaged across northern and southern watersheds (Table 2) and are plotted in Fig. 7. As Fig. 7 illustrates, while the mean urban score remains relatively unchanged between 1950 and 2000 in northern Maine, it almost triples in southern Maine. Similar studies often use percentage urban cover as a measure of watershed urbanization (e.g. Rose and Peters, 2001, Poff *et al*. 2006).

One weakness of this methodology is the simple assumption that there is a direct linear relationship between population and urbanization. Even though this relationship was found to be quite linear for Maine towns, as is illustrated in Figs 4 and 5, we posit that, unlike the more metropolitan areas studied by Stankowski (1972) and Graham *et al*. (1974), Maine towns have not yet reached the asymptotic stability in the urbanization–population relationship. Whereas a highly-urbanized area will retain some amount of open space as parks or other undevelopable features (e.g. steep hills or ravines), a region that still has ample developable terrain will continue to urbanize the landscape at a linear rate. Regardless, for the purpose of making a relative comparison between watersheds, this approximation is a useful tool.

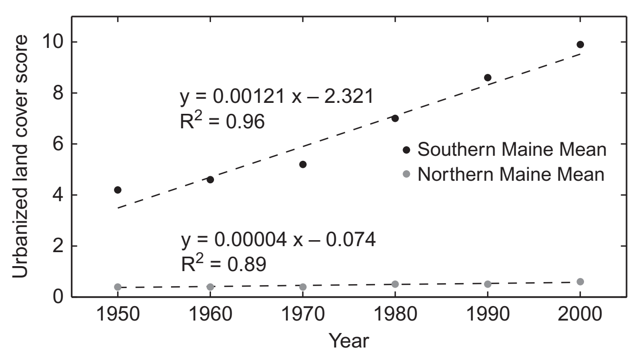

Fig. 7 Mean Developed Land Cover score for northern Maine and southern Maine watersheds, averaged across the nine study watersheds in each geographic class (Table 2). The mean score for the southern Maine watersheds roughly triples in the 50-year study period, while the northern Maine mean remains essentially flat. Both relationships are statistically significant ($p < 0.05$).

Another weakness of our methodology is that it does not produce actual estimates of urban land cover at any given location. That is to say, there is no way that population data can be used to unravel the lateral sprawl of an urban area. However, it is useful for

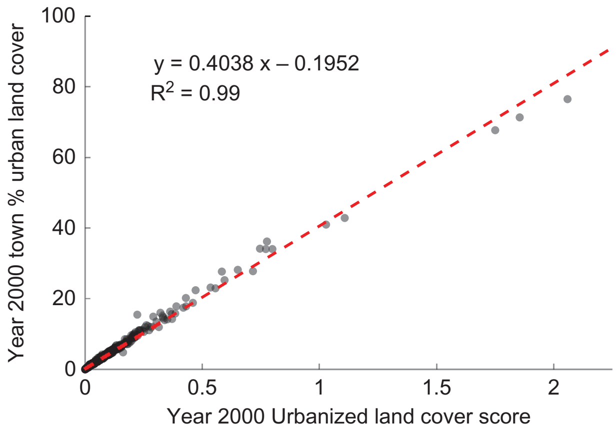

Fig. 8 Year 2000 urbanized land cover score, averaged for each town, *versus* the year 2000 percentage of each town classified as urban. Each point on the plot represents a different Maine town. The percentage urban land cover was measured as the summed area of all four urban land cover classes divided by the total area of the town.

analysing *relative* differences, when urbanized scores are aggregated by watershed or by another spatial unit. Additionally, our methodology has the advantage of relating the population growth in a given town to the degree of urbanization in that town. For example, the degree of urbanization that a predominantly residential town may experience from a given amount of population growth may be different than the degree of urbanization a largely industrial town may experience from the same amount of population growth. Further support of our approach is the strong relationship between this study's urbanization metric (urban land cover score), and the urbanized land cover percentage, which is often used by other studies (e.g. Rose and Peters 2001, Poff *et al.* 2006), across Maine towns (Fig. 8).

Indicators of Hydrologic Alteration

The Indicators of Hydrologic Alteration (IHA), version 7.1 toolkit, developed by The Nature Conservancy (TNC 2009), was used to analyse daily streamgauge records for changes of ecological significance due to urbanization. The number of potential metrics that can be used for assessing altered hydrology is considerable. The IHA software analyses 33 variables, which are indicators of altered hydrology. These are broken into five categories including: magnitude of monthly water condition, magnitude and duration of annual extreme water conditions, timing of annual extreme water conditions, frequency and duration of high and low pulses, and rate and frequency of water condition changes. Based on similar work performed in the previous studies described above and the suite of metrics available using the IHA software, the following metrics were chosen for analysis, grouped according to Poff *et al.*'s (2006) categories:

- Peak flows were assessed using the average annual 1-day maximum daily streamflow. Since urbanization can lead to decreased infiltration and increased runoff, the maximum flow from large storm events is expected to be higher in urbanized streams, as indicated by the review of previous studies in the Introduction section (Poff *et al.* 1997, Rose and Peters 2001, Konrad 2003, Sheng and Wilson 2009).
- Average annual 3-day minimum daily streamflow was used to assess low flows in this analysis. Urbanization results in less moisture retained in soil and vegetation, causing lower values for low flow metrics in urban *versus* natural settings. Under non-urban conditions, this moisture is slowly released following rain events to contribute to baseflow (Konrad 2003).
- Flow durations were measured using the number of "high pulse" days where flow is greater than the 75th streamflow percentile (Richter *et al.* 1996). The flow duration would be expected to be reduced due to reduced infiltration and subsequent retention of moisture.
- Two metrics were used to assess flow variability, the first being the mean fraction of time that daily mean streamflow exceeds the annual mean streamflow ($T_{Q,\mathrm{mean}}$). This is a temporal ratio of stormflow periods to baseflow periods, and was expected to decrease in urban streams as more flow occurs in storm events *versus* baseflow conditions (Konrad and Booth 2002). Flow variability was also assessed using rise rates, a measure of the rate of rising water levels over short time horizons. It is calculated as the mean of all positive differences between consecutive daily values (TNC 2009). Since urbanization can lead to decreased infiltration and increased runoff, particularly in the presence of storm drain networks, the rate at which flows increase would be expected to be higher in urbanized streams.

These metrics were calculated for each watershed for each year of the analysis and then averaged for the northern and southern regions. Streamflow data were not available for each watershed for each year. Values for 1-day maximum flows, 3-day minimum flows and rise rates were normalized based on the watershed area to allow for simple comparison across different watershed sizes. Trends were converted from changes in a flow metric value per year to a percentage change, normalized to the mean flow metric over the period of record for each gauge, per decade.

Climatic trends

Trends in air temperature and precipitation were computed for the study period to determine whether differences in climate exist. Average annual air temperature and total annual precipitation were downloaded from the US Historical Climatological Network (Easterling *et al.* 1996, Menne *et al.* 2009) for 1950–2000. Data for three northern sites (Presque Isle, Millinocket and Eastport) and three southern sites (Farmington, Gardiner and Portland) were used in the analysis. The trend (°C per year) was determined via linear regression for each station, and averaged across northern and southern stations.

RESULTS

Based on the work of the authors described above, we expected the analysis to reveal increased peak flows, decreased low flows, decreased durations and increased flow variability in the more urbanized streams of southern Maine. The following results are based on linear regressions using the IHA metrics discussed above. Graphs of the results are presented in Fig. 9.

Peak flows, measured as 1-day maxima, essentially showed no general trend in southern Maine over the period analysed. Five of the nine sites had decreasing peak flows, and four of them had increasing peak flows. The majority of southern sites did not have strong trends in peak flows. Of the sites with larger magnitude trends, two were strongly decreasing and only one was strongly increasing. In northern Maine, trends in 1-day maximum flows were all within 5% of the mean values. Five sites had slightly increasing trends for the period of record, and four sites had slightly decreasing trends. Overall, the watersheds in southern Maine have more variability in peak flows with some watersheds showing marked increases or decreases, whereas 1-day maximum flows in northern Maine do not appear to be changing.

Three-day minimum flows were more commonly increasing than decreasing for southern watersheds. Of the nine watersheds, three indicate no change (±3% per decade), three have strongly decreasing three-day minimum flows, and three have slightly increasing three-day minimum flows. Northern watershed three-day minimum flows were either primarily unchanged, with five of nine watersheds having trends of less than 3% per decade, or increasing, with four of nine watersheds showing changes in three-day minimum flows of between 9.7 and 37.7% per decade.

The number of high-flow pulses was primarily constant in southern Maine, with five of nine watersheds within 3% of the mean number of high-flow pulses. Of the remaining watersheds, two had an increasing number and two had a decreasing number of high-flow pulses. In comparison, watersheds in northern Maine primarily saw small increases in the number of high-flow pulses over the period of record. Only two of the nine northern watersheds had decreasing trends in high-flow pulses, and the values (–0.8 and –1.0% per decade) were both very small. Despite inconclusive results in trends, the mean number of high-flow pulse events is consistently greater in southern Maine, where the study period mean is 9.1, compared to 7.8 in northern Maine. This would indicate that watersheds in southern Maine behave more like urban streams, in that there are more frequent high pulse events. Changes in the northern watersheds may be a result of regional differences in rainfall intensities, or a possible effect of the timber industry.

Rise rates were slightly increasing for all but one site across northern Maine. For watersheds in southern Maine, trends in rise rates were increasing for four watersheds, strongly decreasing for two watersheds, and unchanging (within 3% of the mean) for three watersheds. As with the other metrics that evaluate flow *versus* time, there appears to be more variability in northern Maine than in southern Maine (Fig. 10). However, for the southern sites that show increasing variability, trends are much larger than for the northern watersheds, indicating that for watersheds where change is occurring, it is occurring to a much greater extent.

Trends in the fraction of days exceeding the mean annual flow ($T_{Q,\mathrm{mean}}$), a measure of flashiness, were all within 3% of the long-term mean, indicating that values were virtually unchanged. This was also true for seven of the nine of southern watersheds, though two watersheds did have increasing trends in flow variability. However, also important is that mean values differ between northern and southern watersheds; the southern watersheds have an average value of 0.32, while the northern watersheds have a value of 0.28. This is noteworthy, as Konrad *et al.*

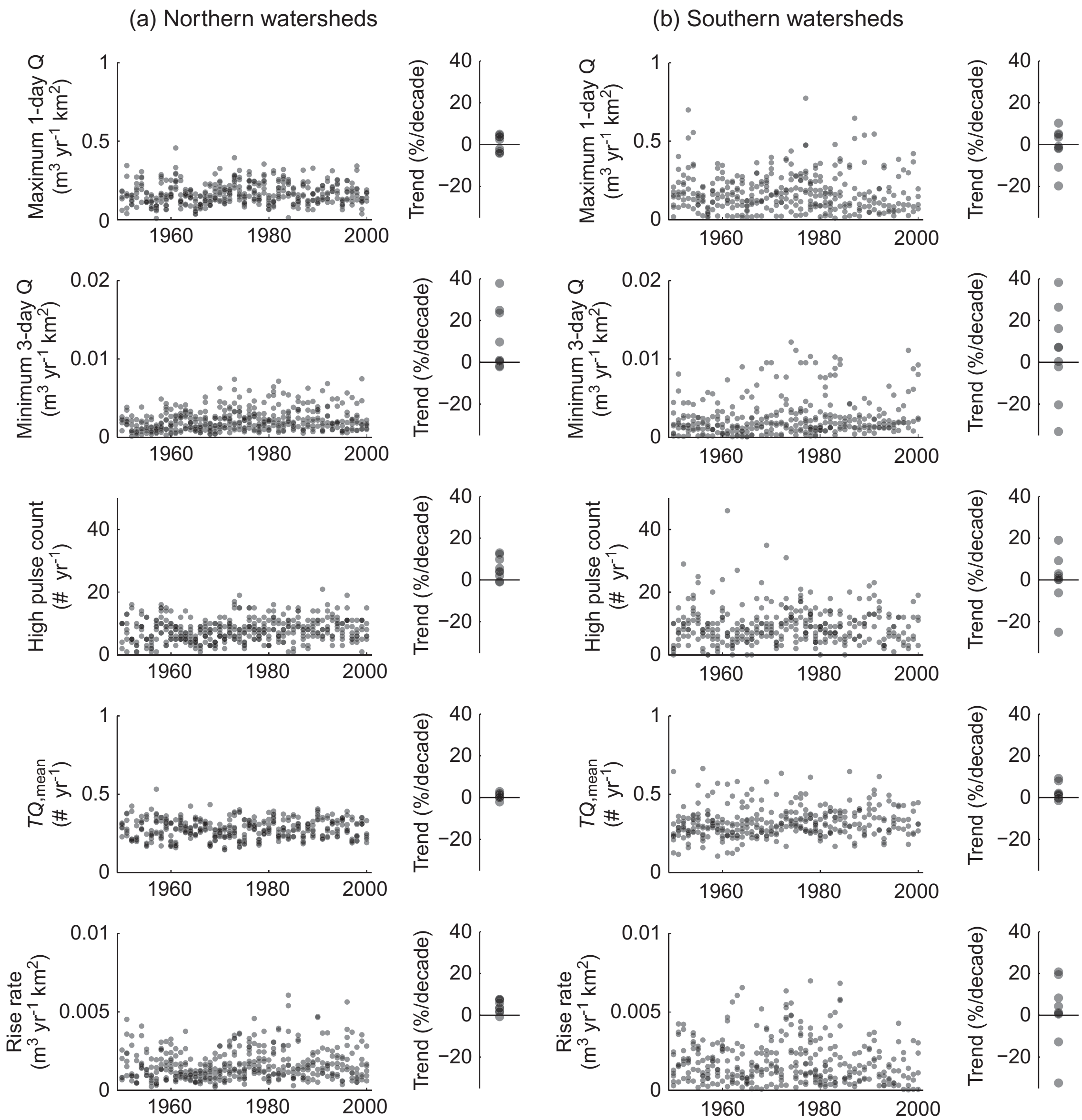

Fig. 9 Comparison of (a) northern and (b) southern Maine result metrics. Scatter plots include metrics for all watersheds for all years. Metrics are normalized to watershed area for maximum 1-day flow, minimum 3-day flow and rise rate. Trends, normalized by the mean metric value for each watershed, are plotted as a percentage change in each metric per decade.

(2005) found that a $T_{Q,\mathrm{mean}}$ of 0.3 provided a rough demarcation between urban and rural streams. Thus, in relation to Konrad *et al.*'s work, the southern Maine watersheds are behaving more like urbanized streams by this metric.

Climate trends for 1950–2000 indicate little change in cumulative annual precipitation and average annual air temperature. Furthermore, large differences did not exist between the northern and southern watersheds. The trend in cumulative annual precipitation for southern watersheds was 0.01 cm/year and for northern watersheds it was –0.02 cm/year. For air temperature, southern watershed values were increasing at 0.01°C/year and northern watershed values were increasing by 0.009°C/year. In general, the small trend values and little difference between southern and northern watersheds suggest that long-term trends in climate are not responsible for the differences in streamflow metric trends between northern and southern watersheds.

DISCUSSION

Despite the fact that trends in flow metrics were not of a common, predictable direction and strength, the large variability in trends across the southern

	USGS Gage ID	1-Day Max (%/decade)	3-Day Min (%/decade)	High pulse count (%/decade)	Fraction of days exceeding annual flow (%/decade)	Rise rate (%/decade)	Urbanized land cover score
Northern watersheds	01010000	3.7	0.6	5.6	2.0	7.5	0
	01015000	4.9	0.3	9.9	1.2	1.6	0
	01011000	4.5	9.7	3.9	1.9	7.7	0.0001
	01015800	3.7	-2.2	12.3	0.1	3.5	0
	01016500	-2.2	24.9	-0.8	0.4	3.4	0
	01017000	2.5	-1.8	13.0	3.0	1.8	0.0001
	01021200	-4.0	23.6	4.1	-2.0	7.2	0.0205
	01021500	-3.3	37.7	-1.0	0.5	-0.7	0.0007
	01022500	-4.2	1.0	2.0	-0.1	5.9	0.0144
Southern watersheds	01036500	4.8	26.3	0.1	1.7	20.8	0.0754
	01049500	-1.6	-33.2	19.1	9.2	-32.4	0.1046
	01055500	-2.0	7.1	0.3	1.1	4.3	0.0621
	01058500	-10.9	38.2	0.9	2.1	0.9	0.0670
	01059800	-0.9	7.2	2.9	-1.5	0.5	0.3574
	01060000	5.2	-2.1	1.9	-0.3	1.3	0.1225
	01064000	3.5	0.3	-25.0	-0.5	19.5	0.0676
	01064118	-19.8	16.1	9.2	8.0	-12.8	0.1114
	01069500	10.2	-20.4	-6.1	1.4	8.3	0.1177

Stronger positive trend
Milder positive trend
Milder negative trend
Stronger negative trend

Fig. 10 Trend values for streamflow and urbanization in northern and southern Maine watersheds, 1950–2000. Trends in the metrics for each watershed were normalized by the mean value of the metric to a percentage change and converted from per year to per decade. Milder trends correspond to values between 0 and 5%, and stronger trends are all values greater than 5%.

watersheds does suggest that the watersheds are being impacted on by urbanization, though not always in the way that would be expected. Four of the nine urbanized watersheds have at least two of five expected trends. More interestingly, the variability in trends is much greater across the southern Maine watersheds compared to the northern Maine watersheds. For the two sites in southern Maine illustrating either little change or the opposite change to what was expected, both watersheds are missing periods of data from the 1980s and 1990s, and this may be skewing resulting trends. Trends for streamflow metrics in northern Maine are all relatively homogeneous, with watersheds showing either no trend, or a similar trend for metrics, which also indicates that the more natural northern watersheds are all responding similarly to any land-use, climate, or other possible changes that can affect streamflow.

One potential explanation for the fact that the trends seen across the southern watersheds did not always follow expectations is that, relative to the locations of the similar studies described above, even the more urban areas of southern Maine remain largely undeveloped. The most urbanized watershed in this study, as measured by the summed percentages of the four urban cover types (high-intensity developed, medium-intensity developed, low-intensity developed and developed open space), was the watershed for the gauge at Collyer Brook near Gray, which was 12.2% urbanized. In contrast, urban land cover for watersheds in similar studies is much higher, of the order of 94% for a watershed studied by Rose and Peters (2001), and between 94 and 12.7% for those studied by Chang (2007). The most urbanized watershed in this study is roughly on the level of the least urbanized watersheds of Chang's (2007) study. Although most of the metrics used by Chang (2007) were different from those used in this study, the 12.7% urbanized watershed exhibited the highest $T_{Q,\mathrm{mean}}$ of the watersheds in the study, at approximately 0.32. This compares to 0.26 for Collyer Brook near Gray. By this metric, Collyer Brook actually exhibits a more urban characteristic than the watershed with similar levels of urbanization in Chang's study. Konrad (2002) used road densities greater than $9 km/km^2$ to identify urban watersheds in western Washington, with suburban watersheds characterized by road densities of 4–8 km/km^2 and rural watersheds characterized by road densities $<3 km/km^2$. By this measure, the most urban watershed in the study was again Collyer Brook near Gray, which had a road density of 2 km/km^2. This is still well within Konrad's rural classification.

Changes to land cover other than urbanization were not analysed in this study. Although urbanization tends to have a significant impact on hydrology, the loss or gain of forests, agriculture, or wetlands can also alter a watershed's hydrology (Poff *et al*. 2006). Throughout Maine, these other land cover changes include a continuation of the forest rebound from 19th century lows at the height of Maine's timber industry. The volume of timber currently in Maine's forests is almost double what it was in 1952 (Butler *et al*. 2005). An increase in forestland and concurrent loss of open land (agriculture) might offset hydrological changes resulting from urbanization. In a study examining historical changes in precipitation and streamflow in the US Great Lakes Basin, Hodgkins *et al*. (2007) describe increases in 7-day low flows for watersheds with larger amounts of agriculture. They suggested that these increased low flows may be an effect of changes in agricultural practices, such as contour ploughing and crop rotation, in addition to the reversion of crop and pasture to forest. These changes would all act to slow runoff, thus increasing low flows. Additionally, southern Maine was once far more agricultural than northern Maine. In the 1880s, counties in southern and coastal Maine were estimated to be between 35 and 50% forested, while, by the 1990s, they were between 70 and 81% forested (Irland 1998). Northern Maine counties, by contrast, were estimated to be between 60 and 90% forested in the 1880s and 89–97% forested in the 1990s (Irland 1998). Although these dates do not correspond to the 50-year study period examined herein, it does illustrate that the rebound in forest land was greater in the south than in the north, and would thus suggest that any hydrological effects caused by this change would be more pronounced in the south than in the north. This study also did not look at contiguous impervious surfaces; rather, it took aggregate totals within a watershed. That some studies, such as those conducted by Corbett *et al.* (1997) and Carle *et al.* (2005), examine contiguous impervious rather than all impervious surfaces suggests that the spatial orientation of impervious surfaces—those that are contiguous—may be an important factor to examine when assessing altered hydrology.

Two of the northern watersheds cross into the Canadian province of Quebec (USGS IDs: 01010000 and 01011000, both on the St John River). The Canadian portions of these watersheds were not included in this study. However, based on a qualitative review of roads and forested cover in historical (1962 and 1967) and current (2009) topographic maps of the region, increases in urbanization appear minimal. Unlike the virtually unbroken forest within these watersheds on the Maine side of the border, this portion of Quebec consists of a mix of forests, agriculture and small towns. Although the possibility that changes in land cover have altered the hydrology of the two watersheds in this area cannot be ruled out, it is unlikely that any strong response would result from these changes. In fact, the hydrological response in these watersheds did not exhibit alterations outside the realm of the other northern watersheds (Table 2).

In addition to other human modifications on the landscape that would affect flow metrics, also not considered with regards to low flows, the impact of water or wastewater treatment plants should be considered. As populations increase, the outflow to rivers from these plants will also generally increase, and is recognized to represent large contributions to baseflow for some streams (Paul and Meyer 2001). While the increasing trends for some southern streamflow sites may be caused by this outflow, the relatively low populations in Maine towns compared to areas where this change has been observed (Paul and Meyer 2001) probably indicate that this is not a major impact, though it is still an important consideration.

Dams are another major presence on Maine streams, on both main stems and small tributaries. There are over 780 impoundments in Maine (MEGIS 2006). Of these, the majority (78% of those for which data is available) were constructed before 1950. Although there are more dams present in southern Maine, they are also common in northern Maine. The impact of dams was not explicitly evaluated in this study, as key dam data, beyond the dates of construction, were not easily available. These missing data include how or whether management objectives may have changed over the years (e.g. loss or addition of active hydro-power plants, management for fish species, management for recreational boating) and the percentage of flow contributed by tributary streams that have dams. Any of these factors could have considerable impacts on the metrics evaluated in this study. In some cases where dams serve to substantially regulate flow, changes in streamflow could be wholly a result of management (Hodgkins personal communication October 2010).

Trends for two streamgauges evaluated in this study, both located along the Presumpscot River, corroborate this point. Metric trends are almost completely opposite one another for the two sites, one of which is immediately downstream of a large dam (01064000) and the other of which is located 15–20 miles (24–32 km) below the first site (01064118). For the site immediately below the dam, maximum and minimum flows are relatively unchanged, whereas the high pulse count strongly decreases and the rise rate strongly increases over the period of record. In contrast, the downstream site has strongly a decreasing trend in maximum flows and rise rates, and increasing trends in minimum flows, high pulse counts and $T_{Q,\mathrm{mean}}$. A number of low-head dams exist between the upper and lower sites that are probably resulting in the increasingly homogenized flow found at this location. Furthermore, it is clear that the site immediately downstream of the large dam exhibits less affected streamflow than that below the low-head dams. In either case, it is still unclear how changing management objectives at the larger dam may have influenced the metrics at the initial and lower sites, but it highlights how other human impacts result in very different effects on streamflow.

Changes in climate over the study period may also have obscured trends in streamflow caused by urbanization. Although the intent of the authors was to utilize the relatively similar climate in northern Maine as a point of comparison to southern Maine, Hodgkins *et al*. (2003) found that the timing of peak streamflows in northern Maine over a similar study period changed significantly, while those in southern and coastal Maine, and much of southern New England did not. Peak streamflows, measured as winter/spring centre of volume, were found to occur earlier in northern Maine and these changes were correlated with warmer temperatures and earlier snowmelt. This shift may be indicative of other climatic effects that have different impacts in the north and south, as well. Though trend analysis of cumulative annual precipitation and average annual air temperature did not show any large differences between northern and southern stations, seasonal changes could have a potentially large effect on many of the metrics discussed here.

Finally, despite efforts made at identifying watersheds with similar characteristics in the north and south, due to the limits of available streamgauge data, the mean size of northern study watersheds is several times larger than that of the southern study watersheds. This difference might add noise to the analysis, as different watershed sizes can have an impact on flow regimes (Booth 1991).

CONCLUSIONS AND OUTLOOK

This study sought to identify and measure changes in stream hydrology that were the result of increased urbanization in southern Maine, using watersheds from less-urbanized areas of northern Maine as a least-urbanized reference point. The results of this study indicate that no homogenous changes to stream hydrology have resulted thus far from the urbanization that has occurred in the study areas of southern Maine. Though many of the southern watersheds do exhibit one or two metric trends similar to what would be expected with urbanization, overall, there is no clear signal of urbanization's impact across all metrics. However, while the more natural northern watersheds all respond very similarly, trends in the southern watersheds were stronger and more variable, indicating that a variety of changes in this region are influencing streamflow in very different ways. This result is supported by similar studies, which consider watersheds with levels of urbanization comparable to the southern Maine watersheds to be "rural". Behaviourally, these types of watershed tend not to exhibit the altered hydrology that is associated with more urban streams.

Further study and analysis would nonetheless be valuable. In addition to the potential sources of error described above, which could be addressed in further analysis, several more steps could be taken to improve the results, or to seek occurrences of hydrological alteration in other urban areas in the state. For example, additional watersheds could be included in future studies. Although efforts were made in this study to select watersheds that were expected to exhibit urban stream characteristics, casting a wider net may reveal alterations in other watersheds. More detailed streamflow data may reveal trends that are not captured using daily streamflow data. For example, rise rates following a storm event may happen on a scale of hours, rather than days, particularly for smaller, urban watersheds. The USGS gauges with continuous monitoring report flow every 15 minutes, which may capture such an event. Examining a different time period or subsets of the 50-year period studied may reveal results that were absent or obscured in this analysis. In addition to the possibility that hydrological responses may be different over different time periods, selecting different or shorter temporal periods would change the number of candidate watersheds that have sufficient gauge data available for analysis.

The observed results might also simply reflect accurately the fact that Maine's urban areas are, for the time being, not sufficiently developed to cause hydrological alterations. Although the rate of urban growth in southern Maine is expected to continue rapidly (Fulton 2001, MeSPO 2008), relative to many metropolitan areas, southern Maine is still largely a land of small towns and scattered rural populations embedded in a matrix of temperate deciduous and coniferous forests. Population densities and contiguous sprawl present in the larger cities of the USA have not yet come to Maine at nearly the scale that they have in more populous areas. It follows that the extent of impervious surfaces and drainage networks has not yet reached the scale of the more urban areas considered in similar studies. Thus, reduced infiltration, increased runoff and other effects of urbanization may not have reached the level of severity that has been measured in other studies in more urbanized watersheds.

In any case, the results help illustrate that Maine is at a critical juncture, where the opportunity exists to minimize many of the problems associated with the "urban stream syndrome", as seen in more urbanized areas across the USA and beyond. Thoughtful planning can be used to help reduce the impacts of future urbanization. Examples of potential tools and techniques for reducing stormwater runoff and increasing infiltration include well-designed retention ponds (Booth and Jackson 1997), setting targets for tree cover (Pauleit and Duhme 2000), use of adequate vegetated riparian buffers (Castelle *et al*. 1994), and porous pavements (Bratteboro and Booth 2003). Successful implementation of these techniques could prevent or reduce the alteration of hydrological regimes and help prevent the degradation of natural habitats and the human uses of these habitats.

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