Rising stream and river temperatures in the United States

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Water temperatures are increasing in many streams and rivers throughout the US. We analyzed historical records from 40 sites and found that 20 major streams and rivers have shown statistically significant, long-term warming. Annual mean water temperatures increased by 0.009–0.077°C yr^{-1}, and rates of warming were most rapid in, but not confined to, urbanizing areas. Long-term increases in stream water temperatures were typically correlated with increases in air temperatures. If stream temperatures were to continue to increase at current rates, due to global warming and urbanization, this could have important effects on eutrophication, ecosystem processes such as biological productivity and stream metabolism, contaminant toxicity, and loss of aquatic biodiversity.

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The Intergovernmental Panel on Climate Change has concluded that the Earth's surface temperature increased by approximately 0.57–0.92°C over the past century, primarily due to emissions of greenhouse gases (IPCC 2007). The linear warming trend of the Earth's surface over the past 50 years – from 1956 to 2005 (0.10–0.16°C per decade) – is nearly double that for the previous 100 years, with record warm temperatures occurring between 1995 and 2006 (IPCC 2007). Simultaneously, atmospheric CO$_2$ concentrations have increased substantially from pre-industrial levels, with an expected warming of 0.2°C per decade based on future emissions scenarios (IPCC 2007). Although researchers have analyzed trends in historical ice cover on rivers and lakes (eg Magnuson *et al.* 2000), many temperature records for streams and rivers are discontinuous and have not been analyzed in the US as compared with those in other countries (WebTable 1; all Web-only material can be found at www.kaushallab.com/temperature). An understanding of the historical changes in the temperature of streams and rivers is critical to forecasting future changes in biodiversity and regulation of eutrophication, ecosystem processes such as metabolism and nutrient cycling, and contaminant toxicity in inland waters (Caissie 2006). Here, we analyze long-term trends in the temperature of 40 stream and river sites across the US. These systems represent critical supplies of human drinking water, sites for human recreation, and important ecological habitats.

Increases in global urbanization may also interact with climate change to influence runoff and water quality (eg Kaushal *et al.* 2005, 2008). Urbanization can increase stream and river temperatures through deforestation (Burton and Likens 1973), discharges from power plants and wastewater treatment facilities (Kinouchi 2007), runoff from impervious surfaces (Nelson and Palmer 2007), and warming behind river impoundments (Webb and Nobilis 2007). A synthesis of historical temperature trends can provide a context for forecasting future changes in water temperatures and will help inform strategies and goals for forest conservation, riparian buffers, and stream and watershed restoration efforts aimed at reducing temperature increases.

Methods

Historical time series of water temperatures were obtained from 40 different stream and river sites located throughout the US (WebTable 2). These records were compiled from long-term measurements made in major drinking water supplies; long-term monitoring by the Hubbard Brook Ecosystem Study; long-term monitoring programs by the University of Maryland Center for Environmental Science's Chesapeake Biological Laboratory; and historical water-quality data obtained from the US Geological Survey (records comprising at least 10 000 observations were chosen from the US Geological Survey). Although there were gaps in some records, we chose those with less than 6 years of consecutive missing data, and a period of monitoring that continued until at least the year 2000. The time series included in our analysis ranged between 24 years and almost 100 years in length. At all sites, samples were measured following sample withdrawal by calibrated thermometers (see Web-only material).

Daily temperature data were averaged to obtain monthly

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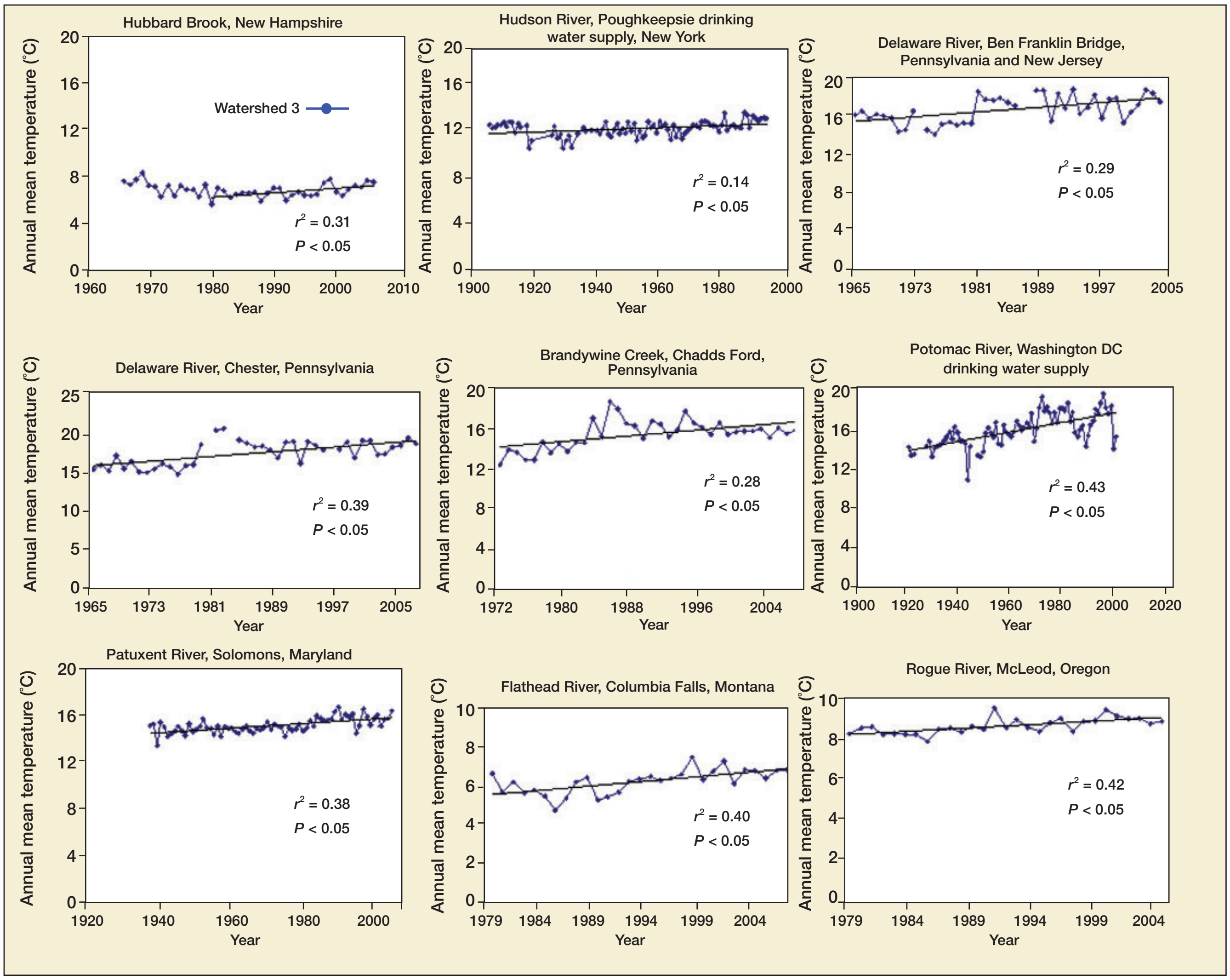

Figure 1. *Examples of long-term trends in historical water temperature in streams and rivers in the US (linear regression). Results from comparative analyses for all datasets using Mann-Kendall trend test and Sen's slope estimates are also found in WebTable 3.*

mean temperatures. Monthly mean temperatures were averaged over a 12-month annual period to obtain annual mean temperatures (see Web-only material). Long-term trends in annual mean temperatures were analyzed by both simple linear regression and non-parametric Mann-Kendall trend tests with Sen's slope estimates (WebTable 3). Linear regression was used because of its statistical power when normality assumptions are met, and non-parametric Mann-Kendall was used for comparison, because it is robust to outliers. Both statistical approaches have been reported for similar studies (eg Ashizawa and Cole 1994; Webb and Nobilis 1995; Durance and Ormerod 2007). A comparison showed there were very few differences regarding the significance of trends when comparing both methods (only six analyses out of 40 systems differed); in five of these cases, there was a significant trend ($P < 0.05$) observed using the Mann-Kendall test where the linear regression showed no significance at $P < 0.05$ (WebTable 3).

Historical air temperature records near stream and river monitoring sites were provided by the US Historical Climatology Network (USHCN). These data were selected because of the quality-control procedures used to adjust for changes in measurement techniques, time of observation bias, and variation due to station relocation (eg Brazel *et al.* 2000). Historical patterns were investigated for annual average urban heat-adjusted mean temperatures that were estimated and provided by USHCN. All measurements of air temperature were made available through 2005. The time series varied in length, but many of the historical air temperature records spanned over 100 years at many of the stream and river monitoring locations in the present study.

Further detailed description of datasets and methodology in trend analysis is available in the Web-only material.

Results

Significant linear increases in historical water temperatures were observed for 20 of the 40 streams and rivers analyzed ($P < 0.05$; Table 1; Figure 1). The longest record of increase (over 90 years) was observed for the Hudson River at Poughkeepsie, New York ($P < 0.05$). The most rapid rate of increase – of 0.077°C yr^{-1} – was recorded for the

Table 1. Results from linear regression analysis of long-term temperature trends in streams and rivers of the US

Stream and river	*Geographic location*	*Record of observation*	*Rate of increase ($^{\circ}C\ yr^{-1}$)*	P *value*
Northeastern US				
†Hubbard Brook Watershed 3 (hydrologic reference watershed)	Woodstock, NH	1966–2006	–0.005	0.5004
Hudson River	Poughkeepsie, NY	1908–2006	0.009	< 0.05*
Delaware River	Harvard, NY	1979–2007	0.021	0.2784
Delaware River	Hale Eddy, NY	1986–2007	0.040	0.1386
Delaware River	Callicoon, NY	1976–2007	0.017	0.1982
Delaware River above Lackawaxen River	Barryville, NY	1976–2007	0.024	0.0771
Delaware River at Ben Franklin Bridge	Philadelphia, PA	1965–2007	0.059	< 0.05*
Delaware River	Chester, PA	1965–2007	0.077	< 0.05*
Delaware River	Reed Island Jetty, DE	1972–2007	0.013	0.2958
Brandywine Creek	Chadds Ford, PA	1972–2007	0.070	< 0.05*
Pohopoco Creek	Perryville, PA	1969–2004	–0.020	0.0729
Pohopoco Creek	Kresgeville, PA	1969–2003	0.004	0.7039
Gunpowder River at Pretty Boy Reservoir	Near Baltimore, MD	1983–2007	0.059	< 0.05*
Patapsco River at Liberty Reservoir	Near Baltimore, MD	1983–2007	–0.018	0.4480
Potomac River	Washington, DC	1922–2006	0.046	< 0.05*
Patuxent River	Solomons, MD	1938–2006	0.022	< 0.05*
Southeastern US				
Jackson River	Hot Springs, VA	1979–2003	–0.103	< 0.05*
Hyco Creek	Leasburg, NC	1988–2007	0.021	0.5326
Reedy Creek	Vineland, FL	1978–2007	0.041	< 0.05*
Coosa River	State line, AL/GA	1977–2007	0.031	0.2483
Conasauga River	Tilton, GA	1976–2006	0.020	0.0932
Midwestern US				
White River	Centerton, IN	1976–2007	–0.121	0.7083
Skunk River	Augusta, IA	1976–2007	0.040	< 0.05*
Des Moines River	Saylorville, IA	1962–2004	0.027	< 0.05*
Western US				
Arkansas River	Pueblo, CO	1988–2007	0.037	< 0.05*
Colorado River	Cisco, UT	1950–2004	0.034	< 0.05*
Dolores River	Cisco, UT	1950–2003	0.007	0.4793
Flathead River	Columbia Falls, MT	1979–2007	0.046	< 0.05*
Madison River	McAllister, MT	1978–2007	0.025	< 0.05*
Missouri River	Toston, MT	1978–2007	0.032	< 0.05*
Fir Creek	Brightwood, OR	1978–2007	0.021	< 0.05*
North Santiam River	Niagara, OR	1979–2007	0.021	< 0.05*
Rogue River	McLeod, OR	1979–2007	0.030	< 0.05*
Bull Run River	Multnomah Falls, OR	1978–2007	0.019	0.0789
North Fork Bull Run River	Multnomah Falls, OR	1979–2007	0.009	0.3400
South Fork Bull Run River	Multnomah Falls, OR	1979–2007	0.019	0.0887
Rogue River at Dodge Bridge	Eagle Point, OR	1979–2007	0.021	< 0.05*
Blue River	Blue River, OR	1979–2007	–0.038	< 0.05*
South Santiam River	Foster, OR	1979–2007	0.000	0.9768
Tuolumne River	La Grange, CA	1973–2007	–0.019	0.1428

Notes: *denotes significance at $P < 0.05$. Results from comparative statistical analyses using non-parametric Mann-Kendall trend test and Sen's slope estimates for entire available long-term records are also found in WebTable 2. †Although we present statistical analyses for the entire long-term records here, there was a significant ($P < 0.05$) linear increase in stream temperature since 1980 at Hubbard Brook Experimental Forest and some other sites.

Delaware River near Chester, Pennsylvania, and there was also a significant increase ($P < 0.05$) for the Delaware River at the Ben Franklin Bridge near Philadelphia, Pennsylvania. Interestingly, not all sites along the Delaware River showed significant increases, and sites showing the most rapid rates of increase were located in downstream urban areas. Similarly, the Potomac River outside urban Washington, DC, (a major metropolitan area) showed a rapid rate of increase of 0.046°C yr^{-1} ($P < 0.05$). The nearby Patuxent River showed a lower, long-term increase of 0.022°C yr^{-1} at its rural confluence with the Chesapeake Bay ($P < 0.05$). There were also significant increases ($P < 0.05$) observed for streams and rivers in the southeastern, midwestern, and western regions of the US, although rates of increase were typically lower than those observed for the more urban areas of the mid-Atlantic US, including sites along the Delaware, Potomac, and Patapsco rivers, and Brandywine Creek. Hubbard Brook Experimental Forest did not show a statistically significant increase over its entire record ($P > 0.05$), but there was a significant increasing trend of 0.038°C yr^{-1}

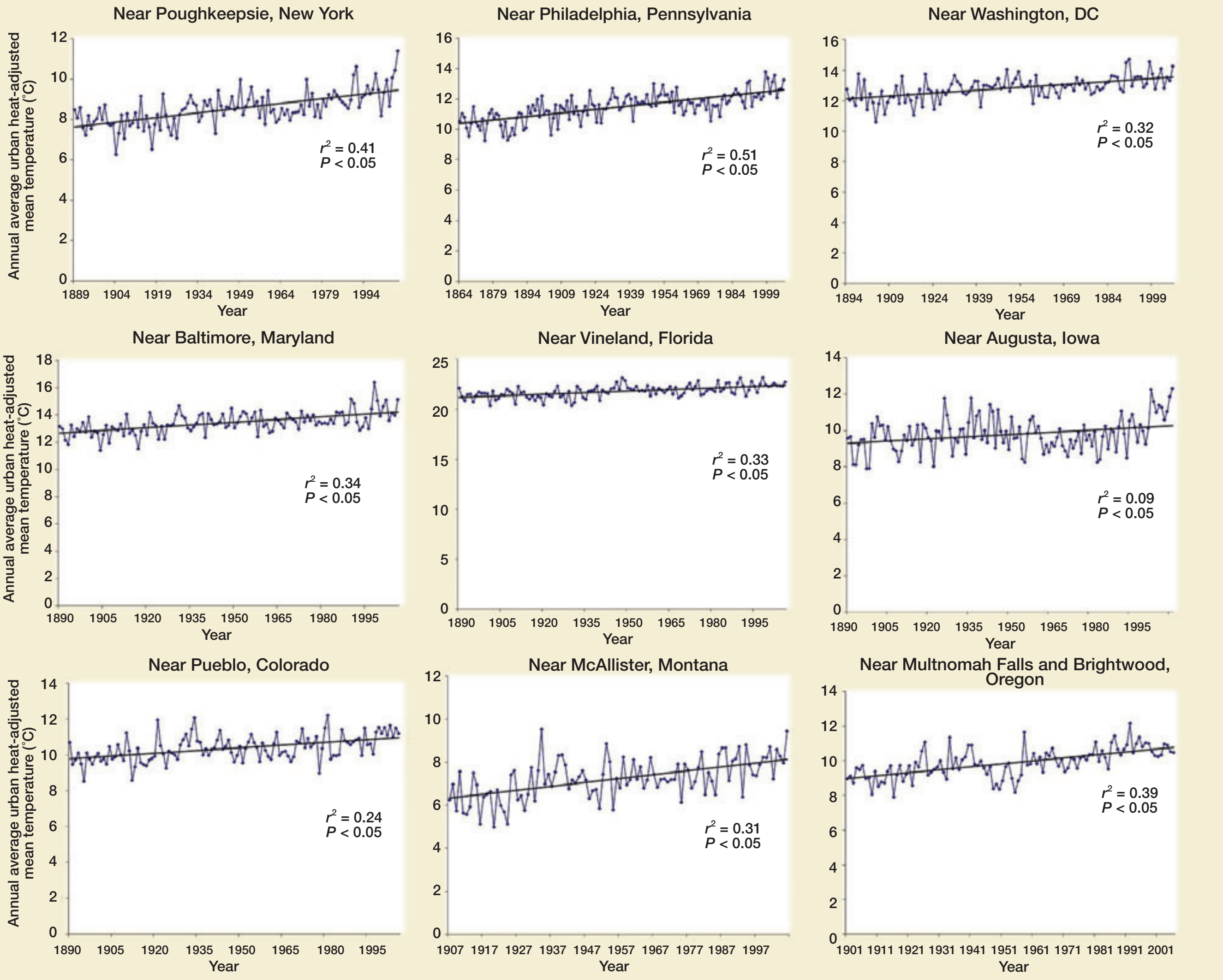

Figure 2. *Examples of long-term trends in historical air temperatures provided by the US Historical Climatology Network (USHCN) near some of the stream and river monitoring sites (linear regression).*

in water temperature from 1980 to 2007. Only two sites, the Jackson River, in Hot Springs, Virginia, and the Blue River, in Blue River, Oregon, showed a significant decrease ($P < 0.05$) in historical water temperatures. The Blue River site was downstream of a dam (WebTable 2).

Significant linear increases in historical annual mean air temperature were observed at many USHCN stations located near the long-term temperature monitoring locations for streams and rivers (Figure 2).

■ Discussion

Rising stream and river temperatures

Despite differences in environmental conditions across monitoring sites, there appeared to be consistent long-term warming trends in a considerable proportion of the streams and rivers that were analyzed; we observed only two significant long-term decreasing trends in historical temperatures. Stream temperature can be an integrator of multiple climatic, hydrologic, and land-use/land-cover factors in watersheds; these factors include groundwater inputs, geography, air temperature, and solar radiation (Webb and Nobilis 2007). Stream temperature can also be influenced by increasing human disturbances, such as global warming, deforestation, urbanization, damming, and thermal discharges (Kinouchi 2007; Nelson and Palmer 2007). Natural and human factors may have contributed to the presence of long-term trends and differences in rates of increase. Similar ranges in long-term warming trends have been reported from individual case studies in streams and rivers worldwide, but an analysis of multiple temperature trends in US streams and rivers is currently lacking (WebTable 1).

Ecological and environmental implications

Increasing water temperatures in streams and rivers may contribute to serious long-term ecological and environmental impacts. Warming of streams and rivers can alter community biodiversity, contribute to local species extinctions, and may facilitate the invasion of alien species (eg Peterson and Kwak 1999). Macroinvertebrate abundance has been projected to decline by 21% for every 1°C rise in water temperature in some areas of the UK, with the greatest risks experienced by sensitive taxa (Durance and Ormerod 2007). Increases in temperature can also disrupt seasonal timing of spawning and larval development (Schindler *et al.* 2005) and influence spatial distribution and abundance of species (Caissie 2006); for example, combined increases in water temperature and solar radiation have been shown to contribute to a decline in larval abundance of salamanders and increased algal blooms in a forest stream in New Hampshire (Burton and Likens 1973). Changes in water temperatures may also alter stream metabolism, rates of nutrient cycling, and reduce dissolved oxygen concentrations (Caissie 2006). In addition, increases in water temperature can amplify the toxicity of certain environmental contaminants (Rehwoldt *et al.* 1972). Analyses of empirical historical temperature data will be necessary to improve our ability to forecast future changes in temperature and the ecological effects on streams and rivers.

Effects of global warming on stream temperatures

The effects of global warming on increasing temperatures at the Earth's surface are unequivocal (IPCC 2007). For the next two decades, a warming trend of about 0.2°C per decade is projected for a range of projected emissions scenarios (IPCC 2007). Confidence in short-term warming predictions can be gained from previous predicted global average temperature increases of between 0.15 and 0.3°C per decade since the IPCC's first report in 1990, as compared with observed values of 0.2°C per decade from 1990–2005 (IPCC 2007).

At many sites, long-term increases in water temperatures of streams and rivers typically coincided with historical increases in annual mean air temperatures. Air temperature has been shown to be a very strong predictor of water temperature in streams and rivers (Webb and Nobilis 2007). Long-term shifts in large-scale climate oscillations (eg North Atlantic Oscillation) may also influence rates of stream and river warming in some regions (Durance and Ormerod 2007). There may have been some long-term oscillatory behavior in some of the time series, and it would be worth examining a constrained linear model to allow combination of disparate datasets and evaluate rates of long-term temperature increase. As discussed previously, many factors, including hydrology, land use/land cover, and climate change, can influence trends in historical water temperatures. A comprehensive analysis for all the factors that influence water temperatures is not possible at all sites; human-accelerated environmental changes may be co-occurring (Likens 1991) and the simultaneous effects of climate and land-use change on water temperatures need to be considered. For some rivers, such as the Hudson River, there has been no statistical change in stream flow, and no increase in urbanization (in fact, there has been an increase in forest cover), but there has been an increase in historical water temperatures coinciding with increases in historical air temperatures observed for this region (Burns *et al.* 2007). Other streams and rivers flowing through urban landscapes may have been influenced by the simultaneous heat effects of climate change and land-use change (Brazel *et al.* 2000; Kalnay and Cai 2003).

Interactive effects of global warming and urbanization

We observed the most rapid rates of increase in water temperatures in streams and rivers near urban areas of the mid-Atlantic US (eg the large metropolitan areas of Philadelphia, Pennsylvania; Baltimore, Maryland; and Washington, DC). An exception was the lower but significant rate of increase at the Patuxent River, a rural site located near the Chesapeake Bay (described in the Web-only material). Increasing urbanization and the spread of impervious surfaces can substantially impact runoff and water quality in streams and rivers (eg Kaushal *et al.* 2005, 2008). "Urban heat island" effects can also increase air temperatures (Brazel *et al.* 2000), and urbanization and other land-use changes account for an increase in mean air temperature of 0.27°C in the US over the previous century (Kalnay and Cai 2003). For example, there can be substantial differences in water temperatures in streams of similar sizes located across an urban-to-rural gradient at the National Science Foundation-supported Baltimore Ecosystem Study Long Term Ecological Research (LTER) site (WebFigure 1). These increases in stream temperatures correspond with local increases in surface temperature due to urbanization (Brazel *et al.* 2000).

Other interactive anthropogenic disturbances also probably contribute to increased water temperatures in urban areas. These include loss of riparian canopy cover and stream shading (Burton and Likens 1973), increased thermal discharges (Kinouchi 2007), stream and river impoundments (Webb and Nobilis 1995), and heated urban runoff from paved areas (Nelson and Palmer 2007). For example, large "surges" in stream temperatures are associated with urban runoff from hot pavements in watersheds of the Baltimore Ecosystem Study LTER site (WebFigure 1). This effect may contribute to the extreme variability in stream temperatures, in addition to the overall warming effects. In Europe, anthropogenic impacts at the watershed scale have played an important role in raising the temperature of rivers over the past 90 years; such impacts have included increases in effluent discharges and damming of streams and rivers, in addition to climate change (Webb and Nobilis 1995). In Japan, there has been a 34-year increase in the temperature of wastewater effluent as a result of domestic heating of water and energy use, in addition to the interactive effects of global warming (Kinouchi 2007). The expected worldwide increase in urbanization in many stream and river basins (eg Grimm *et al.* 2008 in conjunction with the interactive effects of climate change) will lead to a major increase in the amount of heat discharged into streams and rivers.

Reduced warming of streams and rivers

Ultimately, a substantial reduction in greenhouse-gas emissions is necessary to slow and reverse the effects that climate change will have on streams and rivers. Because it will be difficult to reverse warming trends within the next 100 years (IPCC 2007; Solomon *et al.* 2009), additional strategies are needed to mitigate the potentially harmful interactive effects of global warming and increasing urbanization.

A reduction in watershed coverage by impervious surfaces, an increase in urban tree canopy, shaded stormwater retention wetlands, and stream/riparian conservation and restoration strategies could have the potential to buffer harmful temperature surges in small streams draining urbanizing watersheds (eg Peterson and Kwak 1999). Increased conservation and restoration of riparian buffer width and trees can increase shading, cool the land's surface by evapotranspiration, and decrease conduction of heat from terrestrial environments to streams, rivers, and lakes (eg Burton and Likens 1973). Enhancing hyporheic exchange (subsurface mixing between surface water and adjacent shallow groundwater) and different wastewater treatment strategies may also be effective in reducing temperatures by stimulating heat exchange with the atmosphere, subsurface groundwater and substrate, and/or the ground surface. A decrease in water withdrawals as a result of improved conservation measures can reduce warming behind impoundments (Webb and Nobilis 1995) and the reuse of treated wastewater may reduce effluent volumes and temperature (Kinouchi 2007). Given that urbanization effects may be considerable in the future (Grimm *et al.* 2008), managing the interactive effects of climate change and land-use change on water quantity and quality will be critical (eg Nelson and Palmer 2007; Kaushal *et al.* 2008). More experimental and manipulative work is needed, to detail the empirical effects of climate change, land-use change, and watershed-restoration strategies on stream and river temperatures and ecosystem functions (such as stream metabolism, denitrification, and nutrient cycling). In addition, modeling and forecasting using available historical empirical data may help improve predictions of future interactive effects of global warming and urbanization on increases in stream and river temperatures and heat fluxes to downstream receiving waters.

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