# 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 $\mathrm{yr}^{-1}$, 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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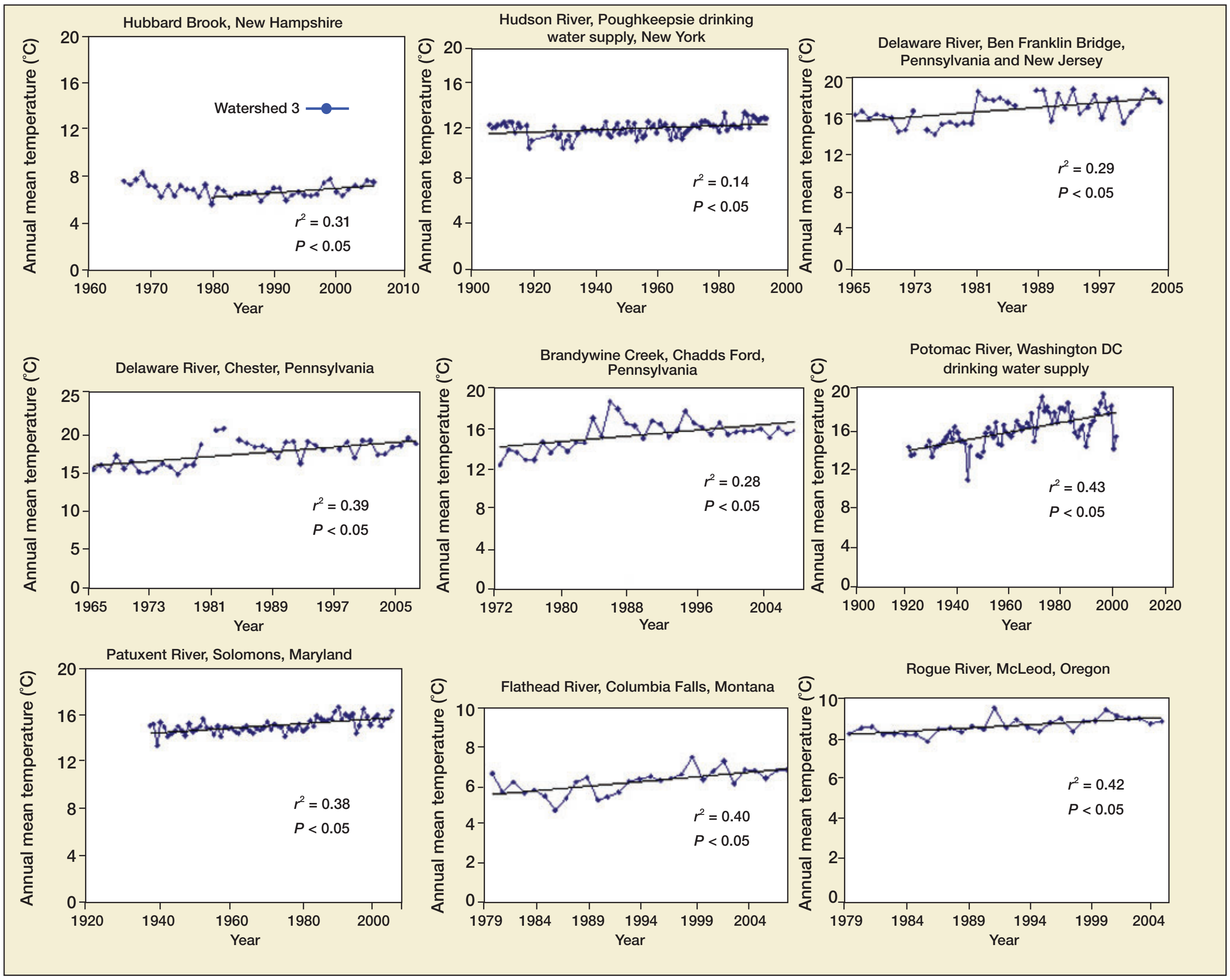

**Figure 1.** *Examples of long-term trends in historical water temperature in streams and rivers in the US (linear regression). Results from comparative analyses for all datasets using Mann-Kendall trend test and Sen's slope estimates are also found in WebTable 3.*

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 $yr^{-1}$

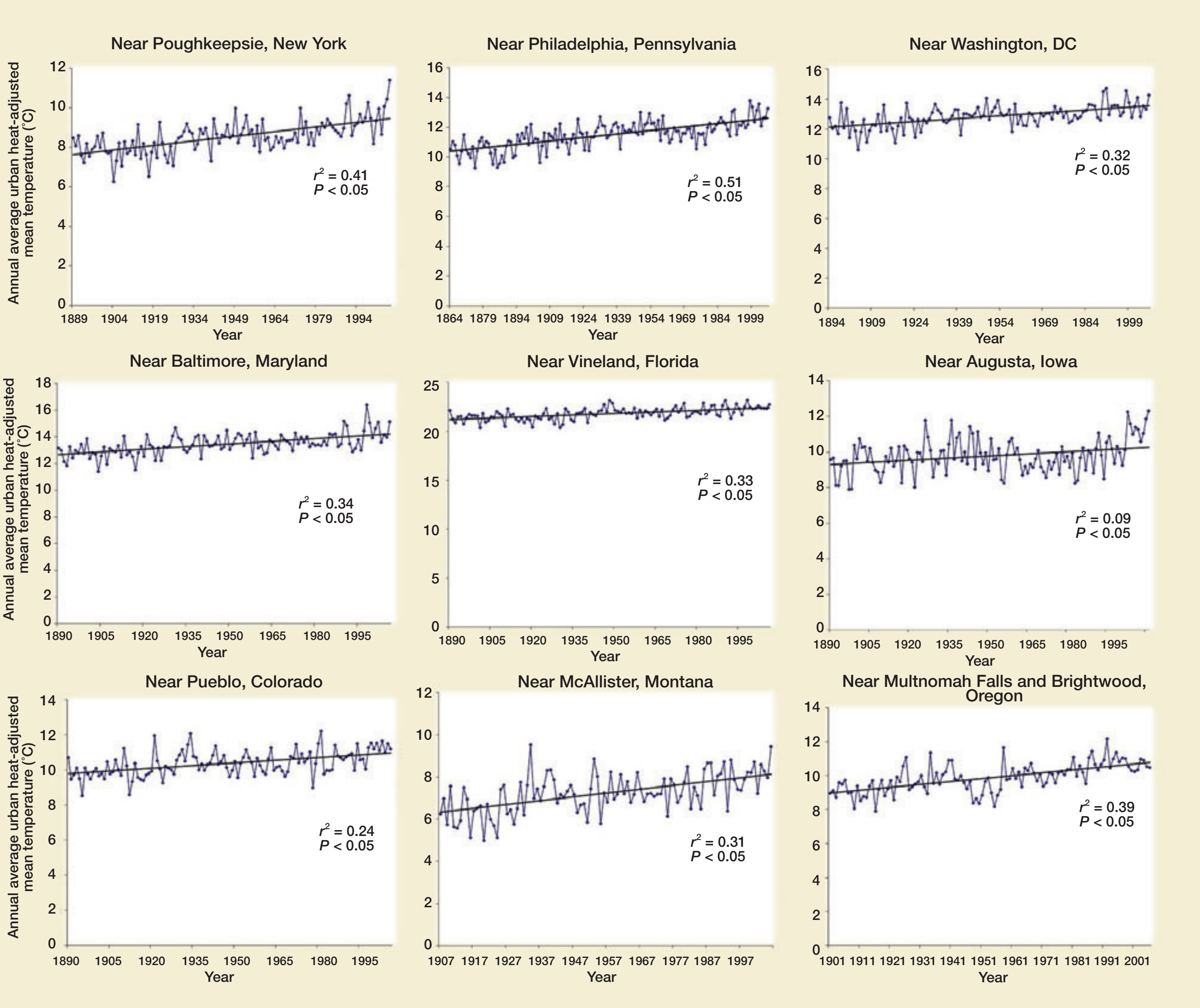

***Figure 2.*** *Examples of long-term trends in historical air temperatures provided by the US Historical Climatology Network (USHCN) near some of the stream and river monitoring sites (linear regression).*

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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## Supporting Information

### Other Temperature Trends in Streams and Rivers

We identified other examples of temperature trends reported for other streams and rivers located in different areas of the world. The objective was to identify other similar studies for comparative purposes. Our strategy involved searching the ISI Web of Science online database (http://isiknowledge.com/) for historical temperature trends in streams and rivers. Methods of measurement and statistical analyses across data sets sometimes differed, but typically involved long-term temperature records following sample withdrawal by thermometers (at least during the early 20th Century). There was a bias in our search with more published studies of trends from streams and rivers in North America and Europe. Some important historical records may have been omitted that were not cited on the ISI Web of Science. Other examples of published trends of long-term water temperature data sets ranged from 20-89 years; increasing temperature trends were typically in the same range and magnitude for different streams and rivers of the world as compared to those reported in the present study. Despite well-known increasing effects of urbanization and climate change on the temperature of the Earth's surface, there have been surprisingly few published historical temperature trends from streams and rivers in the United States, compared to other streams and rivers in the world.

| Streams and Rivers | Geographic Location | Record of Observation | Rate of Increase (°C/year) | Literature Reference |
|---|---|---|---|---|
| | *North America* | | | |
| Hudson River | New York, U.S.A. | 1920-1990 | 0.012 | Ashizawa and Cole (1994) |
| Streams in Minnesota | Minnesota, U.S.A. | 1977-2002 | 0.11 | Johnson and Stefan (2006) |
| Miramachi River | New Brunswick, Canada | 1970-1999 | 0.03 | Swansburg et al. (2004) |
| | *Europe* | | | |
| Llyn Brianne | United Kingdom | 1981-2005 | 0.058-0.071 | Durance and Omerod (2007) |
| River Itchen | United Kingdom | 1980-2006 | 0.104 (winter)<br>0.050 (summer) | Durance and Omerod (2008) |
| River Loire | France | 1976-2003 | 0.056-0.074 (spring and summer) | Moatar and Gailhard (2006) |
| 25 Streams/Rivers in Switzerland | Switzerland | 1978-2002 | 0.004 – 0.046 | Hari et al. (2006) |
| Gail River | Federaun, Austria | 1901-1990 | 0.00526 | Webb and Nobilis (1995) |
| Traun River | Wels, Austria | 1901-1990 | 0.01404 | |
| Danube River | Linz, Austria | 1901-1990 | 0.00893 | |
| Danube River | Ybbs, Austria | 1901-1990 | 0.01111 | |
| Inn River | Schärding, Austria | 1901-1990 | 0.00601 | |
| Lieser River | Spittal, Austria | 1901-1990 | 0.00968 | |
| Iron Mill Stream | Devon, United Kingdom | 1977-1990 | 0.073 | Webb and Walling (1992) |
| River Pulham | Devon, United Kingdom | 1977-1990 | 0.029 | |
| River Exeter | Devon, United Kingdom | 1977-1990 | 0.050 | |
| | *Asia* | | | |
| Ara River System | Tokyo, Japan | 1978-1998 | 0.11 - 0.21 (winter and spring) | Kinouchi et al. (2007) |
| Lena River Outlet During June | Siberia, Russia | 1950-1992 | ~ 0.02 | Yang et al. (2005) |

**Supporting Information Table 1.** Examples of other long-term water temperature trends reported for streams and rivers. Both linear regression analysis (e.g. Ashizawa and Cole 1994, Durance and Ormerod 2007) and nonparametric statistical approaches (e.g. Webb and Walling 1992, Webb and Nobilis 1995) have typically been used to analyze long-term trends.

## Methods: Sites for Long-term Temperature Trends in Streams and Rivers

We obtained long-term daily and monthly temperature data for 40 stream and rivers sites in the U.S. The data consisted of a variety of historical sources including records collected by researchers associated with the Hubbard Brook Ecosystem Study and University of Maryland Chesapeake Biological Laboratory. Archived records were analyzed from the Poughkeepsie Water Treatment Facility (Poughkeepsie, New York), Dalecarlia Water Treatement Plant (Washington D.C.), and Baltimore Department of Public Works (Baltimore, Maryland). Records were also analyzed from the long-term historic water quality data collected by the U.S. Geological Survey. The richest data sets were from the Delaware River, which included 6 long-term sites that ranged from upstream rural areas in New York to downstream urbanizing areas in Pennsylvania, New Jersey, and Delaware. Data sets from this study are biased towards larger streams and rivers draining the eastern U.S. Surrounding land uses where temperature was measured were quite diverse and were not consistent across all sites. Long-term monitoring of temperature at some study sites has been described previously in publications (e.g. Ritchie and Genys 1975, Likens and Bormann 1985, Ashizawa and Cole 1994, Jaworski et al. 2007)

The long-term records contain several imperfections that should be noted. Mercury thermometers were used where as present day technology also includes electronic digital thermometers and computer data loggers at some stream and river sites. In addition, sampling locations may have shifted during the period of 24-100 years when measurements were made at some sites. The sampling intensity and frequency varied for different sites (e.g. daily data were available for many sites whereas only monthly data were available for some sites). There were some gaps in the records for some sites where temperature measurements were not reported, although there were surprisingly many consistent records. Overall, the consistencies, length, and quality of long-term records from the diverse historical sources (academic researchers, drinking water treatment plants, and U.S. Geological Survey) would be very difficult to find elsewhere. In addition, these records represent a rare and valuable resource of empirical data based on long-term monitoring that indicate the effects of human accelerated environmental change on different streams and rivers in the U.S.

| **Stream and River** | **Geographic Location** | **Record of Observation** | **Latitude** | **Longitude** | **Drainage Area** | **Site Remarks** |
|---|---|---|---|---|---|---|
| **Northeastern U.S.** | | | | | | |
| Hubbard Brook Experimental Forest (Watershed 3) | Woodstock, New Hampshire | 1965-2006 | 43°57'17.54" | 71°43'22.14" | 0.424 km$^2$ | **Location:** Hubbard Brook Experimental Forest<br>**Operated By:** U. S. Forest Service<br>**Instrumentation:** Calibrated Thermometers and Thermistor-type thermometers<br>**Remarks:** All temperatures were measured at the collection site immediately upstream of the gauging weir (Buso et al. 2000). Temperature measurements were made with calibrated thermometers placed directly in the stream. Since January 18, 1994, thermistor-type thermometers, calibrated against NBS-calibrated thermometers, were used. |
| Hudson River | Poughkeepsie, New York | 1908-2006 | 41°43'25.81" | 73°56'10.66" | 30,406 km$^2$ (Wall et al. 2008) | **Location:** Hudson River at Poughkeepsie<br>**Operated By:** Poughkeepsie Water Treatment Facility<br>**Instrumentation:** Calibrated thermometers<br>**Remarks:** Drinking Water Supply. All water samples were collected from intake pipes located 4 meters below the low tide mark and measurements were made immediately upon sample withdrawal (Ashizawa and Cole 1994). Water collection methods varied somewhat over the 98 year period, but all temperature measurements at PWTF were made with calibrated thermometers soon after water withdrawal. |
| Delaware River | Harvard, New York | 1979-2007 | 42°01'28.5" | 75°07'09.4" | 1,186.2 km$^2$ | **Location:** On right bank 243.84 m downstream from Baxter Brook, and 335.28 m downstream from Harvard Road bridge at Harvard.<br>**Operated By:** This station is operated in cooperation with the NYS Department of Environmental Conservation**.** Record for this site is maintained by the USGS New York Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Subsequent to September 1954, entire flow from 960.9 km$^2$ of drainage area controlled by Pepacton Reservoir and part of flow diverted for New York City municipal supply. Remainder of flow (except for conservation releases and spill) impounded for release during periods of low flow in the lower Delaware River Basin |

| Stream and River | Geographic Location | Record of Observation | Latitude | Longitude | Drainage Area | Site Remarks |
|---|---|---|---|---|---|---|
| Delaware River | Hale Eddy, New York | 1986-2007 | 42°00'11" | 75°23'02" | 1,541.0 $km^2$ | **Location:** On left bank at downstream side of bridge on County Highway 56 in Hale Eddy, and 14.48 km upstream from confluence of East and West Branches near Hancock.<br>**Operated By:** This station is operated in cooperation with the New York City Department of Environmental Protection and NYS Department of Environmental Conservation. Record for this site is maintained by the USGS New York Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Subsequent to October 1963, entire flow from 1175.9 $km^2$ drainage area controlled by Cannonsville Reservoir. Part of flow diverted for New York City municipal supply. Remainder of flow (except for conservation releases and spill) impounded for release during periods of low flow in the lower Delaware River basin |
| Delaware River | Callicoon, New York | 1976-2007 | 41°45'24" | 75°03'28" | 4,713.8 $km^2$ | **Location:** On right bank 0.8 km downstream from Callicoon Creek, 0.8 km downstream from Interstate Bridge 7, and 1.29 km southeast of Callicoon.<br>**Operated By:** This station is operated in cooperation with the New York City Department of Environmental Protection and NYS Department of Environmental Conservation. Record for this site is maintained by the USGS New York Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Subsequent to September 1954, entire flow from 960.9 $km^2$ of drainage area controlled by Pepacton Reservoir, and subsequent to October 1963, entire flow from 1175.9 $km^2$ of drainage area controlled by Cannonsville Reservoir. |
| Delaware River above Lackawaxen River | Barryville, New York | 1976-2007 | 41°30'32" | 74°59'10" | 5,231.8 $km^2$ | **Location:** On left bank 2.57 km upstream from Lackawaxen River, and 7.4 km northwest of Barryville.<br>**Operated By:** This station is operated in cooperation with the National Weather Service, the New York City Department of Environmental Protection, and U.S. Geological Survey. Record for this site is maintained by the USGS New York Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Subsequent to September 1954, entire flow from 960.9 $km^2$ of drainage area controlled by Pepacton Reservoir, and subsequent to October 1963, entire flow from 1175.9 $km^2$of drainage area controlled by Cannonsville Reservoir. |

| **Stream and River** | **Geographic Location** | **Record of Observation** | **Latitude** | **Longitude** | **Drainage Area** | **Site Remarks** |
|---|---|---|---|---|---|---|
| Delaware River at Ben Franklin Bridge | Philadelphia, Pennsylvania | 1965-2007 | 39°57'14" | 75°08'16" | 20,701.8 $km^2$ | **Location:** On right bank at river end of pier 12, 45.72 m upstream from Ben Franklin bridge, and at Philadelphia.<br>**Operated By:** Funding for the operation of this station is provided by the Delaware River Basin Commission and the U.S. Geological Survey. This station managed by the Exton Field Office.<br>**Instrumentation:** Water-quality monitor interfaced with a data collection platform.<br>**Remarks:** Data collection discontinued during winter months. |
| Delaware River | Chester, Pennsylvania | 1965-2007 | 39°50'33" | 75°21'28" | 26,676.9 $km^2$ | **Location:** In the pumping house of Kimberly-Clark Paper Company at Chester.<br>**Operated By:** Funding for the operation of this station is provided by the Delaware River Basin Commission and the U.S. Geological Survey. This station managed by the Exton Field Office.<br>**Instrumentation:** Water-quality monitor since December 1961. Probes interfaced with a data collection platform since the 1986 water year.<br>**Remarks:** Prior to April 1981 sampling site located at auxiliary tidal-gaging station at the end of Reynolds Aluminum Company pier, 0.8 km downstream from Chester Creek in Chester (latitude 39°50'12", longitude 75°22'00"). Data collection discontinued during winter months. Other interruptions in the record were due to malfunctions of the instrumentation. |
| Delaware River | Reed Island Jetty, Delaware | 1970-2007 | 39°30'03" | 75°34'07" | 29,007.9 $km^2$ | **Location:** On dock on streamward side of jetty about 0.6 km downstream from Reedy Island near Port Penn.<br>**Instrumentation:** Water-quality monitor since February 1970. Probes interfaced with a data collection platform since the 1986 water year. Probes placed in situ since July 1998.<br>**Operated By:** Funding for the operation of this station is provided by the Delaware River Basin Commission and the U.S. Geological Survey. This station managed by the Exton Field Office. |
| Brandywine Creek | Chadds Ford, Pennsylvania | 1972-2007 | 39°52'11" | 75°35'37" | 743.3 $km^2$ | **Location:** On left bank 8.2 m upstream from Penn Central Railroad bridge at Chadds Ford, 45.72 m upstream from Harvey Run, and 365.76 m downstream from highway bridge on U.S. Highway 1.<br>**Instrumentation:** Water-stage recorder.<br>**Operated By:** Funding for the operation of this station is provided by the Pennsylvania Department of Environmental Protection, Chester County, and the U.S. Geological Survey.<br>**Remarks:** Data collection discontinued during winter months since the 1981 water year |

| **Stream and River** | **Geographic Location** | **Record of Observation** | **Latitude** | **Longitude** | **Drainage Area** | **Site Remarks** |
|---|---|---|---|---|---|---|
| Pohopoco Creek | Parryville, Pennsylvania | 1969-2004 | 40°50'44" | 75°38'46" | 249.7 km$^2$ | **Location:** On right bank 0.16 km upstream from Sawmill Run, 0.64 km downstream from Beltzville Dam, 2.09 km upstream from Bull Run, and 3.7 km northeast of Parryville.<br>**Operated By:** Funding for the operation of this station is provided by the U.S. Army Corps of Engineers, the Pennsylvania Department of Environmental Protection, and the U.S. Geological Survey.<br>**Instrumentation:** Water-stage recorder and concrete control. |
| Pohopoco Creek | Kresgeville, Pennsylvania | 1969-2003 | 40°53'51" | 75°30'10" | 129.2 km$^2$ | **Location:** On right bank 6.1 m downstream from bridge on U.S. Highway 209 at Kresgeville, 0.32 km downstream from Middle Creek, and 20.92 km northeast of Lehighton.<br>**Operated By:** Funding for the operation of this station is provided by the U.S. Army Corps of Engineers, the Pennsylvania Department of Environmental Protection, and the U.S. Geological Survey.<br>**Instrumentation:** Water-stage recorder. |
| Gunpowder River at Pretty Boy Reservoir | Near Baltimore, Maryland | 1983-2006 | 39°38'52.34" | 76°45'19.26" | 122.9 km$^2$ | **Location**: Pretty Boy Reservoir at Beckleysville Road Bridge<br>**Operated By:** Baltimore City Department of Public Works<br>**Instrumentation:** Thermometer<br>**Remarks:** Drinking Water Supply for Baltimore, Maryland |
| Patapsco River at Liberty Reservoir | Near Baltimore, Maryland | 1983-2006 | 39°26'56.60" | 76°52'40.35" | 233.2 km$^2$ | **Location:** Liberty Reservoir at Nicodemus/Deer Park Bridge<br>**Operated By:** Baltimore City Department of Public Works<br>**Instrumentation:** Thermometer<br>**Remarks:** Drinking Water Supply for Baltimore, Maryland |
| Potomac River | Washington, D.C. | 1923-2004 | ~ 38° 56' | ~ 77° 07' | ~29,785 km$^2$ | **Location:** Dalecarlia Water Treatment Plant<br>**Operated By:** Washington D.C. Water and Sewer Authority<br>**Instrumentation:** Thermometer<br>**Remarks:** Drinking Water Supply, Near Potomac River at Chain Bridge |
| Patuxent River | Solomons, Maryland | 1938-2006 | 76°27'12.92" | 38°19'1.05" | 2,352 km$^2$ (Voinov et al. 2007) | **Location:** Site was located at the mouth of the Patuxent River at the Chesapeake Biological Laboratory research pier.<br>**Operated By:** Chesapeake Biological Laboratory<br>**Instrumentation:** Thermometer<br>**Remarks:** Mesohaline salinity levels, mostly sand bottom with little to no vegetation. |

| **Stream and River** | **Geographic Location** | **Record of Observation** | **Latitude** | **Longitude** | **Drainage Area** | **Site Remarks** |
|---|---|---|---|---|---|---|
| **Southeastern U.S.** | | | | | | |
| Jackson River | Hot Springs, Virginia | 1979-2003 | 37°56'54" | 79°56'58" | 893.5 km$^2$ | **Location:** Jackson River at Hot Springs, Virginia<br>**Operated By:** Record for this site is maintained by the USGS Virginia Water Science Center<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 426.7 m above sea level |
| Hyco Creek | Leasburg, North Carolina | 1988-2007 | 36°23'52" | 79°11'48" | 118.9 km$^2$ | **Location:** Hyco Creek at Leasburg, North Carolina<br>**Operated By:** Record for this site is maintained by the USGS North Carolina Water Science Center<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 121.9 m above sea level |
| Reedy Creek | Vineland, Florida | 1978-2007 | 28°19'57" | 81°34'48" | 1,255.1 km$^2$ | **Location:** 30.5 m downstream of bridge on U.S. Highway 192, about 4.02 km upstream from bridge on Interstate Highway 4, 10.46 km southwest of Vineland, and 45.06 km upstream from mouth.<br>**Operated By:** This gage is monitored by USGS in cooperation with the Reedy Creek Improvement District.<br>**Instrumentation:** Water-stage recorder, water-quality monitor, and data-collection platform. |
| Coosa River | Stateline, Alabama and Georgia | 1977-2007 | 34°12'06" | 85°26'51" | 11,297.3 km$^2$ | **Operated By:** The USGS operation and maintenance of this real-time stream gage is funded in cooperation with the Alabama Department of Economic and Community Affairs (ADECA), and Alabama Power, under FERC licensing regulations. The USGS operation and maintenance of the real-time water-quality monitor is funded in cooperation with the Georgia Department of Natural Resources, Environmental Protection Division.<br>**Remarks:** Datum of gage is 169.2 m above sea level |
| Conasauga River | Tilton, Georgia | 1976-2006 | 34°40'00" | 84°55'42" | 1,779.3 km$^2$ | **Operated By:** The USGS operation and maintenance of this real-time stream gage is funded in cooperation with the U.S. Army Corps of Engineers, Mobile District.<br>**Instrumentation:** Gage<br>**Remarks:** Datum of gage is 189.7 m above sea level |

| Stream and River | Geographic Location | Record of Observation | Latitude | Longitude | Drainage Area | Site Remarks |
|---|---|---|---|---|---|---|
| **Midwestern U.S.** | | | | | | |
| White River | Centerton, Indiana | 1976-2007 | 39°29'51" | 86°24'02" | 6,329.9 km$^2$ | **Operated By:** Record for this site is maintained by the USGS Indiana Water Science Center. This gauging station is maintained in cooperation with The U.S. Army Corps of Engineers - Louisville District and The Ohio River Valley Water Sanitation Commision<br>**Instrumentation:** Gage<br>**Remarks:** Datum of gage is 181.5 m above sea level |
| Skunk River | Augusta, Iowa | 1976-2007 | 40°45'13" | 91°16'37.0" | 11,168.0 km$^2$ | **Operated By:** Record for this site is maintained by the USGS Iowa Water Science Center. Station operated in cooperation with Iowa DNR Geological Survey Bureau and the National Weather Service.<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 158.9 m above sea level |
| Des Moines River | Saylorville, Iowa | 1962-2004 | 41°40'50" | 93°40'05" | 15,128.1 km$^2$ | **Operated By:** Record for this site is maintained by the USGS Iowa Water Science Center. Station operated in cooperation with U.S. Army Corps of Engineers - Rock Island District.<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 240 m above sea level |
| **Western U.S.** | | | | | | |
| Arkansas River | Pueblo, Colorado | 1987-2007 | 38°16'18" | 104°43'03" | 12,095.2 km$^2$ | **Operated By:** This station managed by the Pueblo Southeast Colorado Office. Record for this site is maintained by the USGS Colorado Water Science Center.<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 1,444.8 m above sea level |
| Colorado River | Cisco, Utah | 1950-2004 | 38°48'38" | 109°17'34" | 62,418.7 km$^2$ | **Operated By:** Station operated by the U.S. Geological Survey as part of the National Streamflow Information Program in cooperation with the U.S. Bureau of Reclamation. Record for this site is maintained by the USGS Utah Water Science Center.<br>**Instrumentation:**<br>**Remarks:** Datum of gage is 1,246.6 m feet above sea level |
| Dolores River | Cisco, Utah | 1950-2003 | 38°47'50" | 109°11'40" | 11,862.1 km$^2$ | **Location:** On left bank 0.32 km downstream from Line Canyon, 14.65 km upstream from mouth, 21.73 km downstream from Colorado-Utah State line, and 22.37 km southeast of Cisco.<br>**Operated By:** Station operated by the U.S. Geological Survey as part of the National Streamflow Information Program in cooperation with the U.S. Bureau of Reclamation. Record for this site is maintained by the USGS Utah Water Science Center.<br>**Instrumentation:** Water-stage recorder. |
| Flathead River | Columbia Falls, Montana | 1979-2007 | 48°21'43" | 114°11'02" | 11,561.7 km$^2$ | **Operated By:** Record for this site is maintained by the USGS Montana Water Science Center. Station operated in cooperation with the Montana Department of Fish, Wildlife and Parks, Montana Department of Natural Resources and Conservation, PPL Montana, and the U.S. Bureau of Reclamation<br>**Remarks:** Datum of gage is 907.6 m above sea level |

| Stream and River | Geographic Location | Record of Observation | Latitude | Longitude | Drainage Area | Site Remarks |
|---|---|---|---|---|---|---|
| Madison River | McAllister, Montana | 1978-2007 | 45°29'25" | 111°38'00" | 5,661.7 km$^2$ | **Operated By:** Station operated in cooperation with the Montana Department of Fish, Wildlife and Parks and PPL Montana. Record for this site is maintained by the USGS Montana Water Science Center.<br>**Remarks:** Datum of gage is 1.429.2 m above sea level |
| Missouri River | Toston, Montana | 1978-2007 | 46°08'46" | 111°25'11" | 37,992.5 km$^2$ | **Operated By:** Record for this site is maintained by the USGS Montana Water Science Center. Station in cooperation with Montana Department of Fish Wildlife and Parks and the Montana Department of Natural Resources and Conservation.<br>**Instrumentation:** Gage<br>**Remarks:** Datum of gage is 1,190.5 m above sea level |
| Fir Creek | Brightwood, Oregon | 1978-2007 | 45°28'49" | 122°01'28" | 14.1 km$^2$ | **Location:** On right bank, 10.3 km north of Brightwood and 0.97 km above Bull Run Reservoir Number One.<br>**Operated By:** Station operated in cooperation with Portland Water Bureau. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Records provisional. No regulation or diversion upstream from station. |
| North Santiam River | Niagara, Oregon | 1979-2007 | 44°45'10" | 122°17'50" | 1,173.3 km$^2$ | **Location:** On left bank 0.16 km downstream from Little Sardine Creek, 1.29 km downstream from Big Cliff Dam, 3.38 km east of Niagara, and at kilometer 92.22.<br>**Operated By:** Station operated in cooperation with the U.S. Army Corps of Engineers and the city of Salem. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Flow regulated since 1953 by Detroit Lake and Big Cliff Reservoir. |
| Rogue River | McLeod, Oregon | 1979-2007 | 42°39'20" | 122°42'50" | 2,429.4 km$^2$ | **Location:** On left bank at Obstinate J Ranch, 2.09 km downstream from Big Butte Creek, 2.57 km southwest of McLeod, and at kilometer 247.84.<br>**Operated By:** Station operated in cooperation with the U.S. Army Corps of Engineers. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Flow regulated since February 1977 by Lost Creek Lake. Diversions for irrigation upstream from station; most of low flow of Big Butte Creek is diverted near Butte Falls. |
| Bull Run River | Multinomah Falls, Oregon | 1978-2007 | 45°29'50" | 122°00'50" | 124.1 km$^2$ | **Location:** In Mount Hood National Forest, on right bank 1.93 km upstream from North Fork, 11.27 km southeast of Multnomah Falls, and at kilometer 23.82.<br>**Operated By:** Station operated in cooperation with Portland Water Bureau. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Regulation at times since 1915 by Bull Run Lake, usable capacity, 15,134,910.03 m$^3$. |

| **Stream and River** | **Geographic Location** | **Record of Observation** | **Latitude** | **Longitude** | **Drainage Area** | **Site Remarks** |
|---|---|---|---|---|---|---|
| North Fork Bull Run River | Multinomah Falls, Oregon | 1979-2007 | 45°29'40" | 122°02'05" | 21.5 $km^2$ | **Location:** Mount Hood National Forest, on left bank 11.27 km southeast of Multnomah Falls and at mouth.<br>**Operated By:** Station operated in cooperation with Portland Water Bureau. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder. Site located 1.5 m upstream from bridge, on left bank wing wall.<br>**Remarks:** Regulation at times since 1958 by North Fork Reservoir, capacity, about 1,270,493.67 $m^3$. |
| South Fork Rull Run River | Multinomah Falls, Oregon | 1979-2007 | 45°26'38" | 122°06'20" | 39.9 $km^2$ | **Location:** In Mount Hood National Forest, on right bank 9.98 km northeast of Bull Run, and at kilometer 0.97.<br>**Operated By:** Station operated in cooperation with Portland Water Bureau. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** No regulation or diversion upstream from station. |
| Rogue River at Dodge Bridge | Eagle Point, Oregon | 1979-2007 | 42°31'30" | 122°50'30" | 3,146.8 $km^2$ | **Location:** On right bank 15.2 m upstream from Dodge Bridge, 1.13 km downstream from Reese Creek, 6.92 km northwest of Eagle Point, and at kilometer 223.06.<br>**Operated By:** Station operated in cooperation with the U.S. Army Corps of Engineers. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Flow regulated since February 1977 by Lost Creek Lake. Diversions for irrigation upstream from station; most of low flow of Big Butte Creek is diverted near Butte Falls. |
| Blue River | Blue River, Oregon | 1979-2007 | 44°09'45" | 122°19'55" | 227.1 $km^2$ | **Location:** On right bank 0.48 km upstream from Simmonds Creek, 1.13 km north of town of Blue River, 1.29 km downstream from Blue River Dam, and at kilometer 1.45.<br>**Operated By:** Station operated in cooperation with the U.S. Army Corps of Engineers. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Flow regulated since October 1968 by Blue River Lake. No diversion upstream from station. Discharge not adjusted for storage or release from Blue River Lake as losses from reservoir at times exceed natural flow. |

| Stream and River | Geographic Location | Record of Observation | Latitude | Longitude | Drainage Area | Site Remarks |
|---|---|---|---|---|---|---|
| South Santiam River | Foster, Oregon | 1979-2007 | 44°24'45" | 122°41'15" | 1,442.6 km$^2$ | **Location:** On left bank 0.97 km downstream from Wiley Creek and at kilometer 59.55.<br>**Operated By:** Station operated in cooperation with the U.S. Army Corps of Engineers. Record for this site is maintained by the USGS Oregon Water Science Center.<br>**Instrumentation:** Water-stage recorder.<br>**Remarks:** Flow regulated since October 1966 by Green Peter Lake and since December 1966 by Foster Lake. No diversion upstream from station. |
| Tuolumne River | Lagrange, California | 1971-2007 | 37°39'59" | 120°26'28" | 3,983.4 km$^2$ | **Location:** On left bank, 0.8 km downstream from La Grange Dam, and 1.77 km east of La Grange.<br>**Operated By:** This station managed by the Sacramento Field Office. Record for this site is maintained by the USGS California Water Science Center.<br>**Instrumentation:** Water-stage recorder and crest-stage gage.<br>**Remarks:** Flow diverted into Modesto Canal and Turlock Canal at La Grange Dam. Flow regulated by Don Pedro Powerplant, Don Pedro Reservoir, 7.2 km upstream, Hetch Hetchy Reservoir, Cherry Lake, and Lake Eleanor. Tuolumne Canal diverts water from the Stanislaus River Basin into the Tuolumne River Basin for power, irrigation, and domestic supply in the vicinity of Sonora, upstream from station. Diversion through Hetch Hetchy Aqueduct to San Francisco began Oct. 19, 1934. |

**Supporting Information Table 2.** Site characteristics and sampling locations for long-term temperature records in streams and rivers. Site information was obtained from U.S. Geological Survey for U.S. Geological Survey sites. Other information was provided from literature sources or investigators conducting research at specific sites. Watershed area may represent an approximate estimate for some long-term sampling sites.

## Methods: Analysis of Temperature Trends in Streams and Rivers

For each stream and river, the mean temperature over an annual period was computed. Daily data were averaged to calculate monthly means and these monthly means were then averaged to obtain annual means. Years with incomplete data for more than 3 months were omitted from the analysis. The annual mean was then plotted against time for each site to check for any anomalies or obvious steps in the data that would indicate differences due to forms of measurement at study sites. We analyzed long-term temperature trends using both simple linear regression and nonparametric Mann-Kendall test for trends and Sen's slope estimates for all sites (Supporting Information Table 2). Simple linear regression was performed using the SAS statistical software package and Mann-Kendall trend test was performed using the MAKESENS statistical software provided by the Finnish Meteorological Institute (Salmi et al. 2002). The significance of the simple linear regression analysis was typically similar to the Mann-Kendall trend test, but differed in only a few cases (6 out of 40 analyses); 5 of these cases showed significant trend results using Mann-Kendall. The data may have violated normality assumptions and general assumptions of simple linear regression, which would decrease power relative to that of the Mann-Kendall test. The Mann-Kendall statistic may not be powerful to detect trends with small sample sizes for some records, however. Both methods also have the independence assumption which is commonly violated in hydrologic time series. Previous work analyzing water temperature trends has widely used both linear regression and Mann-Kendall trend analysis approaches (e.g. Webb and Walling 1992, Ashizawa and Cole 1994, Hari et al. 2006, Durance and Omerod 2007).

| **Stream and River** | **Geographic Location** | **Record of Observation** | **N** | **Test Z** | | **Q** | **Qmin99** | **Qmax99** | **Qmin95** | **Qmax95** | **B** | **Bmin99** | **Bmax99** | **Bmin95** | **Bmax95** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Northeastern U.S.** | | | | | | | | | | | | | | | |
| Hubbard Brook-Watershed 3 | Woodstock, New Hampshire | 1966-2006 | 41 | -0.66 | | -0.008 | -0.029 | 0.017 | -0.025 | 0.012 | 6.69 | 7.08 | 6.19 | 7.00 | 6.28 |
| Hubbard Brook-Watershed 6 | Woodstock, New Hampshire | 1966-2006 | 41 | -0.55 | | -0.004 | -0.021 | 0.019 | -0.019 | 0.013 | 6.66 | 6.94 | 6.17 | 6.92 | 6.32 |
| Hudson River | Poughkeepsie, New York | 1908-2006 | 88 | 3.51 | *** | 0.010 | 0.002 | 0.017 | 0.004 | 0.015 | 11.93 | 12.34 | 11.59 | 12.22 | 11.72 |
| Delaware River | Harvard, New York | 1979-2007 | 29 | 0.39 | | 0.007 | -0.044 | 0.067 | -0.031 | 0.049 | 8.90 | 9.77 | 7.95 | 9.43 | 8.35 |
| Delaware River | Hale Eddy, New York | 1986-2007 | 22 | 1.47 | | 0.043 | -0.033 | 0.119 | -0.011 | 0.101 | 7.49 | 8.27 | 6.74 | 7.99 | 6.93 |
| Delaware River | Callicoon, New York | 1976-2007 | 29 | 2.31 | * | 0.024 | -0.011 | 0.056 | 0.005 | 0.047 | 10.08 | 10.57 | 9.42 | 10.42 | 9.67 |
| Delaware River above Lackawaxen River | Barryville, New York | 1976-2007 | 30 | 1.96 | * | 0.029 | -0.010 | 0.064 | -0.001 | 0.056 | 10.87 | 11.47 | 10.10 | 11.27 | 10.24 |
| Delaware River at Ben Franklin Bridge | Philadelphia, Pennsylvania | 1965-2007 | 40 | 3.09 | ** | 0.058 | 0.011 | 0.103 | 0.025 | 0.092 | 15.33 | 16.11 | 13.81 | 15.77 | 14.25 |
| Delaware River | Chester, Pennsylvania | 1965-2007 | 40 | 3.69 | *** | 0.077 | 0.027 | 0.115 | 0.038 | 0.105 | 14.94 | 16.47 | 14.39 | 16.13 | 14.58 |
| Delaware River | Reed Island Jetty, Delaware | 1972-2007 | 36 | 1.02 | | 0.015 | -0.023 | 0.045 | -0.011 | 0.036 | 14.41 | 15.21 | 13.81 | 14.97 | 14.01 |
| Brandywine Creek | Chadds Ford, Pennsylvania | 1972-2007 | 36 | 2.90 | ** | 0.063 | 0.019 | 0.112 | 0.036 | 0.098 | 13.40 | 14.47 | 12.84 | 14.02 | 12.97 |
| Pohopoco Creek | Perryville, Pennsylvania | 1969-2004 | 34 | -1.01 | | -0.014 | -0.050 | 0.018 | -0.038 | 0.008 | 9.93 | 10.60 | 9.18 | 10.41 | 9.33 |
| Pohopoco Creek | Kresgeville, Pennsylvania | 1969-2003 | 34 | 0.27 | | 0.003 | -0.026 | 0.037 | -0.020 | 0.029 | 9.93 | 1.41 | 9.50 | 10.26 | 9.63 |
| Gunpowder River at Pretty Boy Reservoir | Near Baltimore, Maryland | 1983-2007 | 23 | 2.75 | ** | 0.075 | 0.012 | 0.127 | 0.038 | 0.104 | 14.08 | 14.88 | 13.25 | 14.50 | 13.65 |
| Patapsco River at Liberty Reservoir | Near Baltimore, Maryland | 1983-2007 | 25 | -1.19 | | -0.031 | -0.100 | 0.054 | -0.079 | 0.024 | 16.32 | 16.87 | 15.27 | 16.71 | 15.54 |
| Potomac River | Washington, DC | 1923-2004 | 76 | 6.41 | *** | 0.050 | 0.034 | 0.066 | 0.039 | 0.061 | 13.35 | 13.98 | 12.91 | 13.85 | 13.00 |
| Patuxent River | Solomons, MD | 1938-2006 | 69 | 5.02 | *** | 0.022 | 0.011 | 0.031 | 0.014 | 0.028 | 14.47 | 14.76 | 14.17 | 14.66 | 14.28 |

| Stream and River | Geographic Location | Record of Observation | N | Test Z | Significance | Q | Qmin99 | Qmax99 | Qmin95 | Qmax95 | B | Bmin99 | Bmax99 | Bmin95 | Bmax95 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Southeastern U.S.** | | | | | | | | | | | | | | | |
| Jackson River | Hot Springs, Virginia | 1979-2003 | 25 | -3.25 | ** | -0.096 | -0.140 | -0.028 | -0.126 | -0.053 | 12.79 | 13.37 | 11.71 | 13.27 | 12.22 |
| Hyco Creek | Leasburg, North Carolina | 1988-2007 | 17 | 1.03 | | 0.043 | -0.074 | 0.129 | -0.052 | 0.091 | 13.94 | 15.63 | 13.15 | 15.29 | 13.48 |
| Reedy Creek | Vineland, Florida | 1978-2007 | 30 | 3.21 | ** | 0.043 | 0.008 | 0.073 | 0.016 | 0.061 | 20.91 | 21.43 | 20.45 | 21.29 | 20.52 |
| Coosa River | Stateline, Alabama and Georgia | 1977-2007 | 30 | 1.28 | | 0.027 | -0.032 | 0.104 | -0.021 | 0.079 | 18.45 | 19.21 | 17.37 | 19.01 | 17.79 |
| Conasauga River | Tilton, Georgia | 1976-2006 | 31 | 1.56 | | 0.020 | -0.013 | 0.053 | -0.006 | 0.042 | 16.63 | 16.95 | 16.07 | 16.88 | 16.27 |
| **Midwestern U.S.** | | | | | | | | | | | | | | | |
| White River | Centerton, Indiana | 1976-2007 | 24 | -0.07 | | -0.003 | -0.127 | 0.150 | -0.091 | 0.101 | 15.33 | 16.86 | 12.37 | 16.45 | 13.42 |
| Skunk River | Augusta, Iowa | 1976-2007 | 32 | 1.77 | + | 0.039 | -0.019 | 0.093 | -0.005 | 0.083 | 13.56 | 14.16 | 12.54 | 13.97 | 12.76 |
| Des Moine River | Saylorville, Iowa | 1962-2004 | 43 | 2.22 | * | 0.032 | -0.004 | 0.059 | 0.002 | 0.050 | 12.26 | 13.05 | 11.67 | 13.00 | 11.84 |
| **Western U.S.** | | | | | | | | | | | | | | | |
| Arkansas River | Pueblo, Colorado | 1988-2007 | 20 | 3.02 | ** | 0.040 | 0.006 | 0.066 | 0.016 | 0.057 | 10.79 | 11.11 | 10.51 | 10.99 | 10.64 |
| Colorado River | Cisco, Utah | 1950-2003 | 54 | 4.43 | *** | 0.033 | 0.016 | 0.052 | 0.019 | 0.047 | 11.23 | 11.64 | 10.56 | 11.53 | 10.73 |
| Dolores River | Cisco, Utah | 1950-2003 | 49 | 0.78 | | 0.007 | -0.018 | 0.032 | -0.011 | 0.026 | 12.24 | 12.82 | 11.38 | 12.57 | 11.59 |
| Flathead River | Columbia Falls, Montana | 1979-2007 | 29 | 3.62 | *** | 0.045 | 0.014 | 0.079 | 0.024 | 0.069 | 6.18 | 6.64 | 5.62 | 6.54 | 5.77 |
| Madison River | McAllister, Montana | 1978-2007 | 29 | 2.53 | * | 0.027 | -0.001 | 0.067 | 0.006 | 0.055 | 8.60 | 9.02 | 7.83 | 8.94 | 7.99 |
| Missouri River | Toston, Montana | 1978-2007 | 29 | 2.68 | ** | 0.034 | 0.001 | 0.068 | 0.007 | 0.055 | 8.94 | 9.40 | 8.34 | 9.26 | 8.55 |
| Fir Creek | Brightwood, Oregon | 1978-2007 | 30 | 2.46 | * | 0.021 | -0.001 | 0.043 | 0.004 | 0.036 | 6.73 | 7.06 | 6.40 | 6.99 | 6.45 |
| North Santiam River | Niagara, Oregon | 1979-2007 | 27 | 2.25 | * | 0.017 | -0.005 | 0.041 | 0.002 | 0.035 | 7.56 | 7.98 | 7.29 | 7.78 | 7.36 |
| Rogue River | McLeod, Oregon | 1979-2007 | 29 | 3.70 | *** | 0.028 | 0.012 | 0.044 | 0.017 | 0.040 | 7.96 | 8.15 | 7.68 | 8.07 | 7.72 |
| Bull Run River | Multinomah Falls, Oregon | 1978-2007 | 30 | 2.07 | * | 0.019 | -0.006 | 0.046 | 0.001 | 0.038 | 7.19 | 7.59 | 6.82 | 7.51 | 6.94 |
| North Fork Bull Run River | Multinomah Falls, Oregon | 1979-2007 | 29 | 1.14 | | 0.010 | -0.016 | 0.035 | -0.009 | 0.029 | 6.78 | 7.14 | 6.40 | 7.07 | 6.54 |
| South Fork Bull Run River | Multinomah Falls, Oregon | 1979-2007 | 29 | 2.19 | * | 0.017 | -0.004 | 0.043 | 0.002 | 0.033 | 7.53 | 7.84 | 7.24 | 7.77 | 7.30 |
| Rogue River at Dodge Bridge | Eagle Point, Oregon | 1979-2007 | 28 | 2.51 | * | 0.027 | -0.004 | 0.052 | 0.004 | 0.046 | 8.62 | 9.03 | 8.21 | 8.97 | 8.33 |
| Blue River | Blue River, OR | 1979-2007 | 27 | -2.42 | * | -0.036 | -0.080 | 0.001 | -0.070 | -0.010 | 8.94 | 9.59 | 8.38 | 9.42 | 8.57 |

| Stream and River | Geographic Location | Record of Observation | N | Test Z |  | Q | Qmin99 | Qmax99 | Qmin95 | Qmax95 | B | Bmin99 | Bmax99 | Bmin95 | Bmax95 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| South Santiam River | Foster, Oregon | 1979-2007 | 24 | -0.22 |  | -0.002 | -0.038 | 0.035 | -0.029 | 0.028 | 9.47 | 10.03 | 9.17 | 9.86 | 9.23 |
| Tuolumne River | Lagrange, California | 1973-2007 | 35 | -1.33 |  | -0.021 | -0.052 | 0.015 | -0.047 | 0.005 | 11.50 | 12.34 | 10.68 | 12.18 | 10.86 |

*** if trend at α = 0.001 level of significance
** if trend at α = 0.01 level of significance
* if trend at α = 0.05 level of significance
+ if trend at α = 0.1 level of significance

**Test Z**: The absolute value of Z is compared to the standard normal cumulative distribution to define if there is a trend or not at the selected level α of significance. A positive (negative) value of Z indicates an upward (downward) trend.

**Sen's slope estimate Q**: the Sen's estimator for the true slope of linear trend
**Qmin99**: the lower limit of the 99 % confidence interval of Q (α= 0.1)
**Qmax99**: the upper limit of the 99 % confidence interval of Q (α= 0.1)
**Qmin95**: the lower limit of the 95 % confidence interval of Q (α= 0.05)
**Qmax95**: the upper limit of the 95 % confidence interval of Q (α= 0.05)

**B**: estimate of the constant B in equation f(year)=Q*(year-firstYear)+B for a linear trend, the y-intercept
**Bmin99**: estimate of the constant Bmin99 in equation f(year)=Qmin99*(year-firstYear)+Bmin99 for 99% confidence level of linear trend
**Bmax99**: estimate of the constant Bmax99 in equation f(year)=Qmax99*(year-firstYear)+Bmax99 for 99% confidence level of linear trend
**Bmin95**: estimate of the constant Bmin95 in equation f(year)=Qmin95*(year-firstYear)+Bmin95 for 95% confidence level of a linear trend
**Bmax95**: estimate of the constant Bmax95 in equation f(year)=Qmax95*(year-firstYear)+Bmax95 for 95% confidence level of a linear trend

**Supporting Information Table 3.** Summary statistics for Mann-Kendall Rank time-series analyses. Each time series is considered independent of the others. No correction was put on the p values to keep the overall type I error <= 0.05

## Urban Heat Island Effects and Temperature

Many stream and river sites in urban areas of the mid-Atlantic U.S. showed the most rapid historical increases in temperature (e.g. the Delaware River, the Potomac River, Patapsco River, and Brandywine Creek). The Patuxent River site showed a statistically significant long-term increase in temperature, but it was lower than the other sites. The Patuxent River site is fully tidal and occurs as part of a shallow (<2 m) mesohaline portion of the Chesapeake Bay. The general attributes of shallow temperate estuaries should reflect efficient atmospheric forcing, and indeed during the 1960-2007 period, annual air and seawater temperatures showed tight coupling (r=0.61). Interestingly, levels of increase observed in the Patuxent River series were similar to those of surface air temperature (SATs) reconstructed at US and global scales: about 0.2 C per decade during past three decades (Hansen et al. 2001; http://data.giss.nasa.gov/gistemp/2005/).

In order to provide an example of interactive factors of land use change and urban "heat island" effects, continuous temperature data from August 2004 are also presented from streams draining the well-defined land use gradient at the Baltimore Ecosystem Study Long-term Ecological Research (LTER) site funded by the U.S. National Science Foundation in Baltimore, Maryland, U.S.A. Data represented continuous monitoring of stream temperature by data loggers at different stream locations within the greater metropolitan area of Baltimore, Maryland, U.S.A. Long-term monitoring of stream temperature has been conducted at the Baltimore (LTER) site in forest, suburban, and urban streams that spans a land-use gradient from the densely urban Baltimore City to rapidly urbanizing fringing areas in surrounding Baltimore County (Pouyat et al. 2007).

There were increases in water temperatures in suburban and urban streams that coincide with well-documented increases in air temperature in these geographic areas due to “urban heat island” effects (e.g. Brazel et al. 2000, Pouyat et al. 2007). In addition, there were periodic “surges” in stream temperatures due to runoff from warmed impervious surfaces during hot summer months, possibly due to heating effects of black pavement on storm runoff.

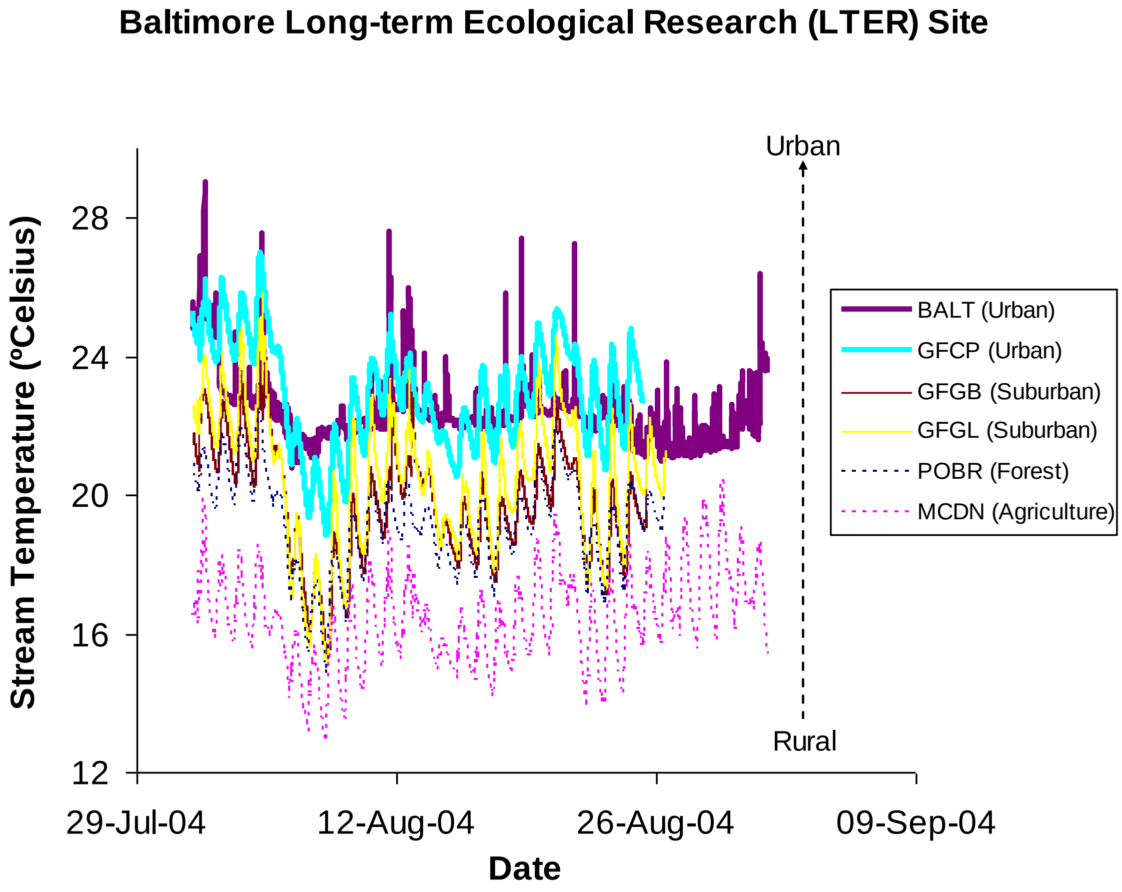

**Figure 2.** Patterns in continuous water temperature in streams draining watersheds of the Baltimore Long-term Ecological Research (LTER) site in Baltimore, Maryland, U.S.A. Sites represent a well-defined land use gradient from the urban core of Baltimore City, Maryland to rapidly developing rural fringes of Baltimore County, Maryland.

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