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Hydrologic signals and surprises in U.S. streamflow records during urbanization

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Key Points:

- During urbanization, half of 53 urbanizing gages had increasing low streamflow.
- The largest urbanizing flow trends were in watersheds with changes in water supply and wastewater infrastructure, or in arid watersheds.
- Urbanization leads to widely-varying and substantial changes in streamflow across the flow duration curve.

ABSTRACT

Urban development has been observed to lead to variable magnitudes of change for stormflow volume and directions of baseflow change across cities. This work examines temporal streamflow trends across the flow duration curve in 53 watersheds during periods of peak urban development, which ranged from 1939 to 2016. We used U.S. Geological Survey streamgage records combined with pre-development and urbanization characteristics to identify 20 years for analysis in each urbanizing watershed. Each urbanizing gage was paired with a nearby reference gage representing climatic trends over the same time period. Results indicated that urbanization, as measured by housing density, did not homogeneously alter the flow duration curve. Urbanization led to widely variable trends in low flow, where half of the urbanizing gages had increasing flow at the 10th non-exceedance percentile, and the other half had declining low flow. High flows generally increased in streams as the area urbanized. The largest increases in high flows were in streams in semi-arid and arid areas. The largest urban flow changes had transformations in wastewater infrastructure, water supply infrastructure, and flood control facilities. Isolating flow changes due to urbanization from those of reference sites will serve to better identify and manage synergistic effects of urban development and climate change on flooding and water availability.

PLAIN LANGUAGE SUMMARY

We analyzed water flows in 53 U.S. streams that drain areas with housing density increases of at least 40% over 20 years. Streams had periods of low and high flows within that time frame. Low flows went up in about half the streams and went down in the other half. The largest decreases in low flows were seen where septic systems were converted to municipal sanitary sewer systems. High flows generally increased in streams as the area urbanized. The largest increases in high flows were in streams in semi-arid and arid areas. Using historical records of changes in stream flow can help predict future changes in flow with further urbanization and separate the effects of urban development on streamflow from those of reference conditions.

1 INTRODUCTION

Urban development can lead to shifts in streamflow across the full range of flow conditions, with stormflow shifts most well-documented. Urban streams receive a greater volume of flow after storms compared to non-urban streams (Beighley & Moglen, 2002; Jennings & Jarnagin, 2002; Leopold, 1968; Meierdiercks et al., 2010; Smith et al., 2005). While this pattern of increased stormflow volume has been found in many studies focused on single metropolitan areas, the few cross-city studies show urbanization metrics alone do not determine the magnitude of streamflow change with development (Hale et al., 2016). One of these cross-city studies found all 10 of the flashiest streams in the U.S. are urban, but stream flashiness is not ordered by imperviousness (Smith & Smith, 2015). Another study found maximum daily flow increases with road density, but the slope of the increase is variable across 9 cities (Hopkins, Morse, Bain, Bettez, Grimm, Morse, Palta, et al., 2015a). A third found high flow frequency is correlated to urban intensity in 6 of 9 cities, but not correlated in the other 3 cities (Brown et al., 2009). Lastly, previous work found high flows (flow that was greater than 95% of the flow record) generally rose with watershed imperviousness, but in some watersheds high flows declined while there was an increase in imperviousness (Oudin et al., 2018).

These studies indicate that for some flow metrics the effect of urbanization is mostly consistent where directly connected impervious surfaces, which quickly move rainfall as overland flow to streams, lead to higher stormflows. However, other factors, such as physiography, climate patterns, and stormwater management, may either diminish or magnify the effect of imperviousness. Understanding the relative importance of these mitigating or exacerbating factors would be a step towards being able to predict the magnitude of streamflow change in watersheds currently undergoing urbanization.

In contrast to increased stormflow volume, changes to baseflow volume with urban development are inconsistent (Dudley et al., 2020; Hopkins, Morse, Bain, Bettez, Grimm, Morse, Palta, et al., 2015; Walsh et al., 2005). Some studies attribute decreases in urban groundwater recharge and baseflow to the infiltration limitations of impervious surfaces (Ferguson & Suckling, 1990; Hardison et al., 2009; Konrad & Booth, 2005; Leopold, 1968; Rose & Peters, 2001). Other studies have found rising water tables or rising baseflow with urban development (Barron et al., 2013; Bhaskar, Hogan, et al., 2016; Harris & Rantz, 1964; Hollis, 1977; Jakovljev et al., 2002; Stephens et al., 2012; Townsend-Small et al., 2013). Changes to baseflow magnitude with urbanization are the combined result of diverse urban processes affecting baseflow, including impervious surfaces, but also changes to stormwater management, evapotranspiration, potable water supply and wastewater systems (e.g., septic tanks), infrastructure leakage, and channel morphology (Bhaskar, Beesley, et al., 2016). A framework was suggested for how urbanization processes combine with landscape vulnerability to alter baseflow magnitude as watersheds urbanize, but has not yet been widely tested (Bhaskar, Beesley, et al., 2016). For example, streams with low pre-urban baseflow may be more susceptible to baseflow increases than streams with high baseflow before urbanization.

Building on previous work that has largely employed spatial comparisons across watersheds with varying degrees of urban cover in single metropolitan areas, our work examines temporal trends across the full range of streamflow during urbanization in a diverse set of cities across the continental United States. Our research was guided by the question: How do low, high, and all the flows across the flow-duration curve change over time during urbanization across a range of U.S. watersheds? To answer this question, we combined recently released, national products of historical land use and housing density (Falcone, 2017) and other watershed characteristics (Falcone, 2011) with U.S. Geological Survey (USGS) daily mean streamflow data for temporal and spatial analyses. We use a paired watershed approach combined with a time trend analysis to separate changes from urbanization and climatic variation. Paired watershed approaches are commonly used to identify the effect of experimental treatments such as afforestation, deforestation, or management changes on hydrology (Bosch & Hewlett, 1982; Jones & Grant, 1996; Van Loon et al., 2019). These treatments are almost always rapid, step changes, whereas urbanization occurs more gradually over a period of years (Loftis et al., 2001). Therefore, we combine a time trend analysis with paired watersheds to identify the effect of hydrologic change during urbanization (Brown et al., 2005). We discuss drivers of flow change in individual urbanizing watersheds but focus more broadly on patterns across urbanizing watersheds.

2 METHODS

2.1 Urban metrics

The USGS GAGES-II (Geospatial Attributes of Gages for Evaluating Streamflow, version II) dataset has characteristics for 9,322 streamgages in the U.S. (Falcone, 2011). We used these compiled characteristics, along with the recently released historical time series of anthropogenic influences for these same gages (Falcone, 2017). We used housing density and impervious surface cover as metrics of urbanization. Housing density data were available for 1940, 1950, 1960, 1970, 1980, 1990, 2000, and 2010 (Falcone, 2017). Imperviousness was available from two sources (Falcone, 2017): the 30-m National Land Cover Database (NLCD) over 2001, 2006, and 2011 (Xian et al., 2011), and the 60-m U.S. conterminous wall-to-wall anthropogenic land use trends (NWALT) over 1974, 1982, 1992, 2002, and 2012 (Falcone, 2015). We did not use population density as a metric of urbanization as data pre-1990 are not spatially resolved enough to estimate population at the watershed scale (Falcone, 2017). Furthermore, housing density and population have been found to be directly related during times of increasing population and become decoupled during times of declining population when housing density and impervious surface cover remain stable (Hopkins, Morse, Bain, Bettez, Grimm, Morse, & Palta, 2015b). Our focus is explicitly on periods of urbanization growth, and we also expect that even during periods of declining population, the hydrologic response from urbanization will not reverse but rather will continue to be affected by the existing impervious surface cover.

2.2 Study gages

We created two subsets of study gages from GAGES-II: urbanizing gages and rural reference gages. Urbanizing watersheds were selected to be smaller than 200 km^2 in drainage area, to ensure at least 20 years of completely gap-free daily mean streamflow records, and to be unaffected by large-scale regulation or diversion. The drainage area limitation was used to constrain watershed land cover and climate heterogeneity. If there were two time periods of possible analysis (i.e., two separate time periods of gap-free daily streamflow longer than 20 years), the time period with a larger change in housing density was chosen. Regulation or diversion was indicated by two sources: a nonzero number of dams in the watershed from the enhanced 2009 National Inventory of Dams (created in December 2010; included in GAGES-II) and a start year during the period of analysis for a code indicating influence of regulation or diversion on streamflow as recorded by the USGS (Falcone, 2017).

To be characterized as urban in the most recent time period, watersheds were selected where imperviousness was at least 20% in 2012 NWALT and housing density was at least 200 housing units/km^2 in 2010. Housing density of 200 units/km^2 corresponds to 0.8 unit/acre, which falls within the range of low-density residential of 0.7 to 2 units/acre (NRC, 2009). Because we were focusing on urbanizing watersheds, watersheds that began the transition to urban development in our analysis period may be characterized by low-density residential in the most recent time period. On the other hand, currently high-density urban watersheds were likely to have been initially developed before our analysis period began in the 1940s. Therefore, our characterization of urban watersheds included those that were on the lower end of urban housing density.

To standardize analysis lengths between gages and focus on times of peak urbanization, we first identified the decade with the largest increase in housing density during the available gap-free record. Second, a portion of the daily streamflow record at each site was selected to produce a 20-year, gap-free streamflow record that centered on or around the decade during which the greatest rate of urbanization occurred. If the available flow record both started more than 10 years before and ended 10 years after the decade of peak housing density change, the start and end of the period of analysis was selected as 5 years before and after the decade of peak housing density change. If the start of the available flow record was more than 10 years before the start of the peak housing decade, the start for the period of analysis was shifted to be later to result in a 20-year period of analysis. Similarly, if the end of the available gap-free record was more than 10 years after the end of the decade with peak housing density change, the end of the period of analysis was shifted earlier to result in a 20-year period of analysis. In these cases, the record ended or started close to the decade of peak housing density change and a 20-year period of analysis was selected to include this time period. Overall, this time selection process resulted in periods of analysis that were in all cases 20 years long, included the time period of peak urbanization, and where possible were centered on this time period.

Urbanizing was defined as an increase in housing density during the period of analysis of greater than 40% compared to the start of the period of analysis, and a housing density of at least 200 units/km^2 at the end of the period of analysis. Because housing density was only available at decadal increments, and our periods of analysis, based on the period of record of streamflow data at each gage, may start or end mid-decade, we used a linear interpolation to estimate the period of analysis starting and ending housing density based on the decadal values. Imperviousness was not used as a criterion to define urbanizing gages, because the earliest available nationally consistent imperviousness was 1974 NWALT, which would limit our analysis to more recent start dates. A total of 53 urbanizing gages paired with periods of analysis were identified that met these criteria (Table A1).

Trends in rural reference gages were used to represent climatic trends that would also be affecting streamflow change in urbanizing regions. In the GAGES-II dataset, 2,057 gages are classified as reference gages. Reference gages are identified in GAGES-II as those least disturbed within each ecoregion and that have near-natural flow conditions (Falcone, 2011). A reference gage from the GAGES-II set of reference gages was paired with each urbanizing gage by selecting all reference gages that had a gap-free daily record of streamflow during the period of analysis for the urbanizing gage, and considering the following four factors:

1) the distance between the urbanizing and reference gage (*D*, km). Closer distances are preferable to minimize differences in climate, soils, vegetation, and geology.
2) the differences in average annual precipitation between the urbanizing (P_{urban}, cm) and reference (P_{ref}, cm) watersheds. Smaller differences in precipitation are preferable. This variable is reported in GAGES-II from 800 m PRISM data ("PRISM Climate Group, Oregon State U," n.d.) and based on a 30-year period of record 1971-2000.
3) the differences in drainage area between the urbanizing (A_{urban}, km^2) and reference (A_{ref}, km^2) watersheds. Differences in drainage area may affect how watersheds respond to urbanization, so smaller differences in drainage area are preferable.
4) dominant geologic type (Geo_{match}) at the urbanizing and reference watersheds, where a value of 0 indicates the dominant geologic types do match, and a value of 1 indicates they do not match. This variable is reported in GAGES-II as the dominant (highest percent of area) geology, derived from a simplified version of (Falcone, 2011; Reed & Bush, 2001)

These four factors may not be able to be optimized simultaneously. For example, selecting the closest reference gage may also lead to a selection of a reference drainage area that is very different from the urbanizing watershed drainage area. To combine these factors together, we created a reference suitability function to be minimized in order to select the paired reference gage:

$$Reference\ suitability = D + 10 * \frac{(P_{ref} - P_{urban})^2}{P_{urban}} + \frac{(A_{ref} - A_{urban})^2}{A_{urban}} + 100 * Geo_{match}.$$

Because of the difference in units, we weighted the precipitation differences (cm) by a larger amount than the area (km^2) and distance (km) values. We also weighed the binary value of the Geo_{match} by 100. These weights were selected based on comparison of multiple weighting schemes. There may be other confounding factors between urban and reference gages, such as slope, elevation, soils, timing of precipitation, and vegetation. However, there are a limited number of reference gages available, and the pairings are intended to find the best available representation of reference condition, rather than a perfect pairing.

2.3 Streamflow data

For this analysis, we used daily mean streamflow records from the USGS National Water Information System (NWIS) database (USGS, 2018). The long temporal scale of the analysis (the earliest urbanizing period of analysis started in 1939) precluded using instantaneous values. The R packages dataRetrieval and EGRET (Hirsch & DeCicco, 2015) were used to download and process all streamflow records. We examined trends across the entire flow duration curve using the Quantile-Kendall approach (https://owi.usgs.gov/blog/Quantile-Kendall/). The Quantile-Kendall approach sorts daily flow from smallest to largest for each year and assesses the trend on all 365 *n*-day flows, where *n* ranges from the smallest flow of the year (1-day min) to the largest flow of the year (1-day max). The Thiel-Sen slope estimator was applied to log-transformed streamflow to estimate the slope for flow trends in percent change in flow per year at 365 quantiles (Appendix B). These percent changes, representing the trends in flow (referred to hereafter as trend slopes), were then plotted with daily non-exceedance probability, which was calculated from the 365 quantiles using the Weibull plotting position (Helsel & Hirsch, 2002, p. 23). Climatic years, 1 April to 31 March, were used for analysis as they break up low flow periods less than using water years, particularly in arid regions (Riggs, 1985). At some gages, there were many days of the year that had no flow. EGRET added a small value (0.001 times the mean of all daily flow values) to all flow values, resulting in zero streamflow values becoming small and positive streamflow values. If flow was zero at a given quantile throughout the record, trend analysis resulted in a trend slope of zero for that quantile.

To isolate the effect of urbanization on the flow duration curve, we assumed that the percent change, or slope of the trend, at reference gages represented regional climate patterns. Therefore, percent change, or slope of the trend, at reference gages (corresponding to urbanizing gages over the same time period) were subtracted from percent change trend slopes at urbanizing gages (in which trends result from the combination of climatic trends and urbanization). This resulted in what we refer to as the urbanization-only trend slope, or the trend in flow from urbanization with the non-urban trend removed. The significance of these urbanization-only trend slopes was evaluated using a Mann-Kendall trend test on the difference between linear urban and reference streamflow, as the Mann-Kendall trend test is insensitive to logarithmic transformations (Appendix B).

3 RESULTS

3.1 Characteristics of study watersheds

First, we assessed our metrics of urbanization. The relationship between housing density and percent imperviousness was more linear at the lower end of urbanization (Figure 1). As we moved to more urban watersheds, housing density increased faster than imperviousness. Housing density does not have a theoretical upper limit and in ultra-urban areas housing expands upward rather than laterally, whereas imperviousness does have a theoretical upper limit (100%). Therefore, our criterion for a 40% increase in housing density would likely correspond to less than a 40% increase in imperviousness. There were no watersheds that had imperviousness greater than 70%, as GAGES-II represents watersheds that have gages on streams, and in ultra-urban areas streams are almost all buried in pipes rather than daylighted (Elmore & Kaushal, 2008). NLCD 2011 had higher maximum values of imperviousness compared to NWALT 2012 (Figure 1), which may be attributed to the finer spatial resolution of NLCD (30 m) compared to NWALT (60 m). There were some watersheds that had housing densities of less than 200 units/km^2 as well as imperviousness greater than 20%, which could represent watersheds dominated by commercial or industrial impervious surfaces, as opposed to the more commonly observed mixed residential urban area. Our approach of using lower boundaries on housing density eliminated these watersheds from analysis to focus on mixed residential urban areas (upper right quadrant of Figure 1).

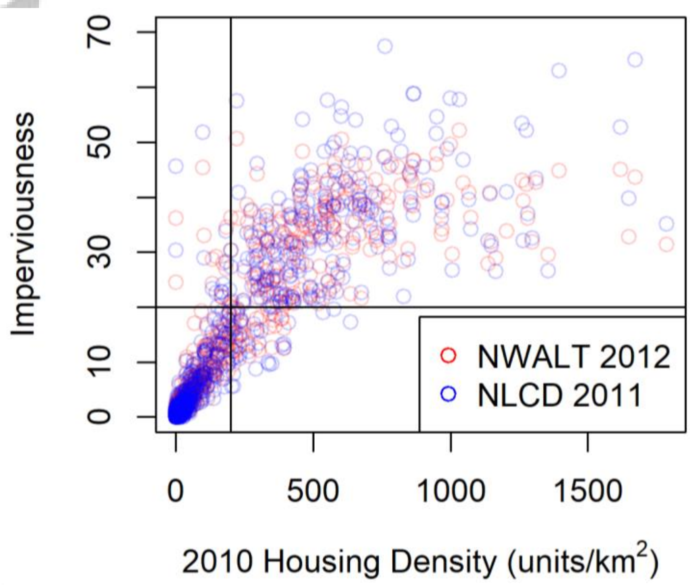


Figure 1. Housing density (2010) versus imperviousness (%) in NWALT 2012 and NLCD 2011 for all watersheds in GAGES-II < 1000 km^2. Lines are shown for 20% impervious and 200 units/km^2 housing density.

The study watersheds in New York generally urbanized the earliest (Figure 2; Table A1). The largest increase in housing density was at Bellmore Creek at Bellmore, NY (USGS station: 01310000), which went from an estimated 263 units/km^2 in 1945 to 812 units/km^2 in 1965, an increase of 549 units/km^2 over the period of analysis (Figure 2). The highest ending housing density as well as the largest single decade density increase was at Valley Stream at Valley Stream, NY (USGS station: 01311500) where housing density increased from an estimated 897 units/km^2 in 1954 to 1288 units/km^2 in 1974. The change in housing density at many urbanizing gages was well above our cutoff of 40% relative to the starting housing density. At 24 out of the 53 urbanizing gages, housing density more than doubled (increase of at least 100%) during the analysis period, and 13 gages had an increase of more than 200% relative to the starting housing density. Aliso Creek in El Toro, CA (USGS station: 11047500) had the largest increase in housing density relative to starting housing density, where there were 19 units/km^2 in 1960 and 309 units/km^2 in 1980, a more than 15-fold increase.

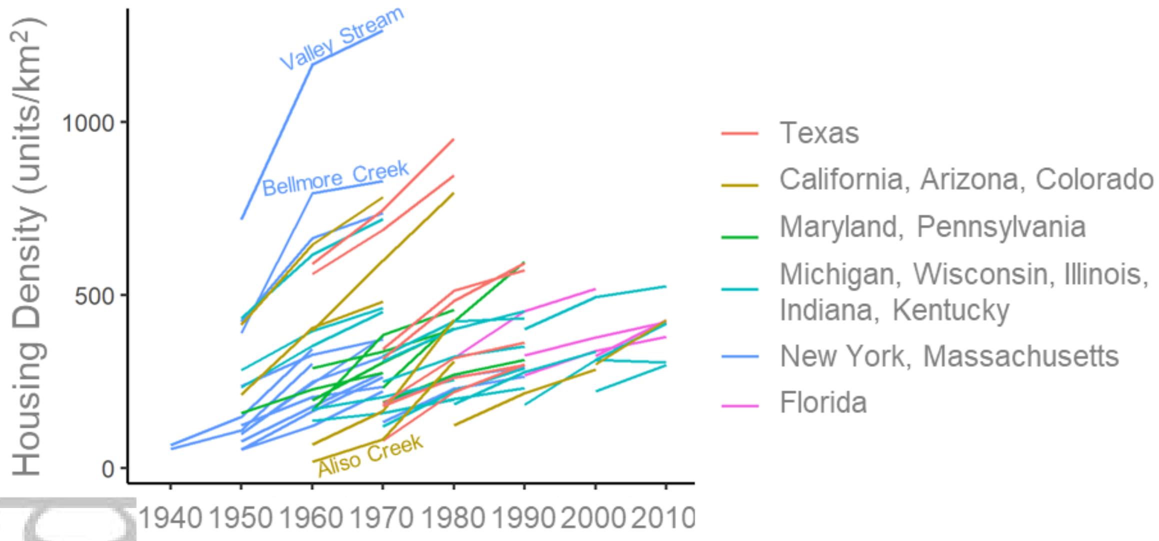
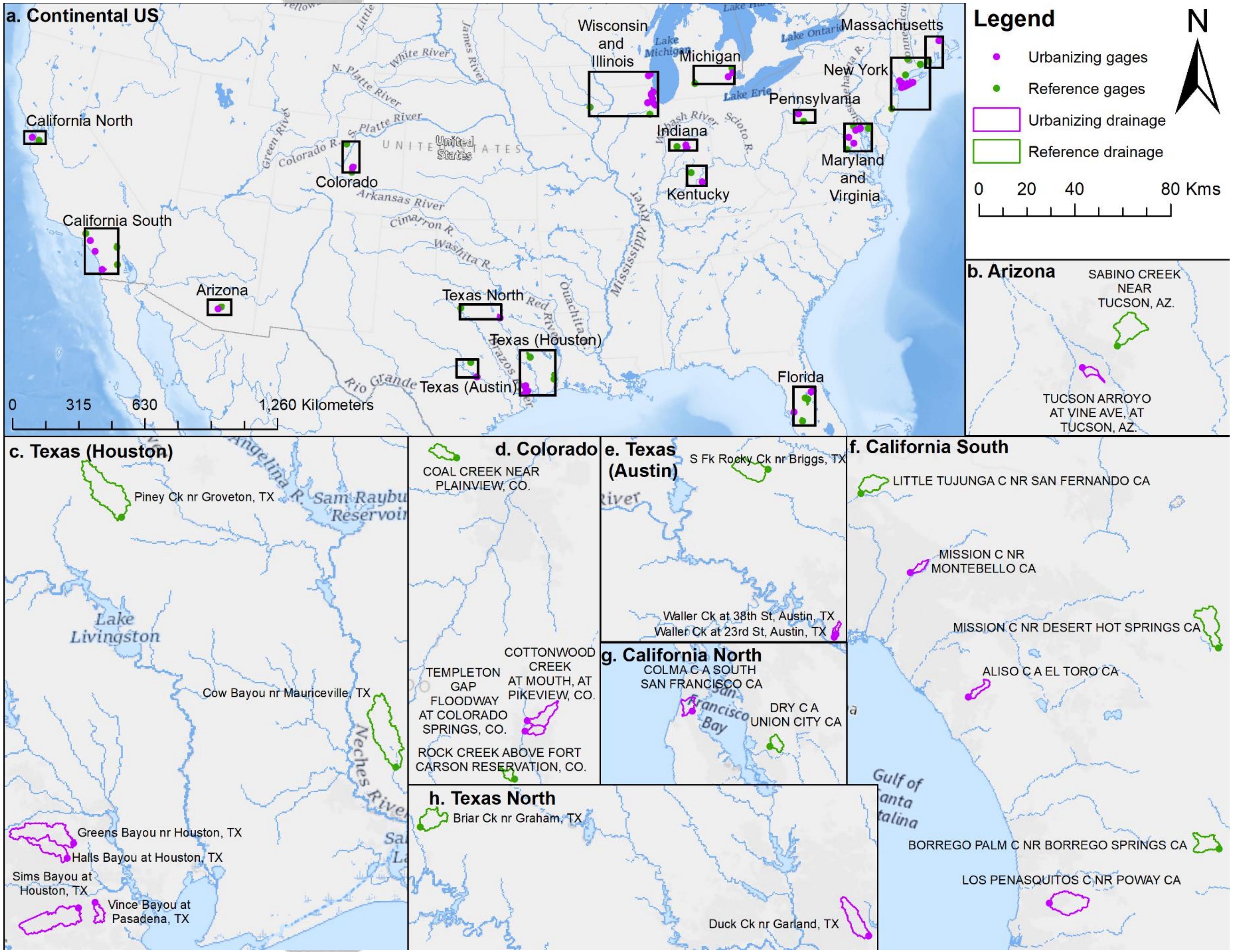
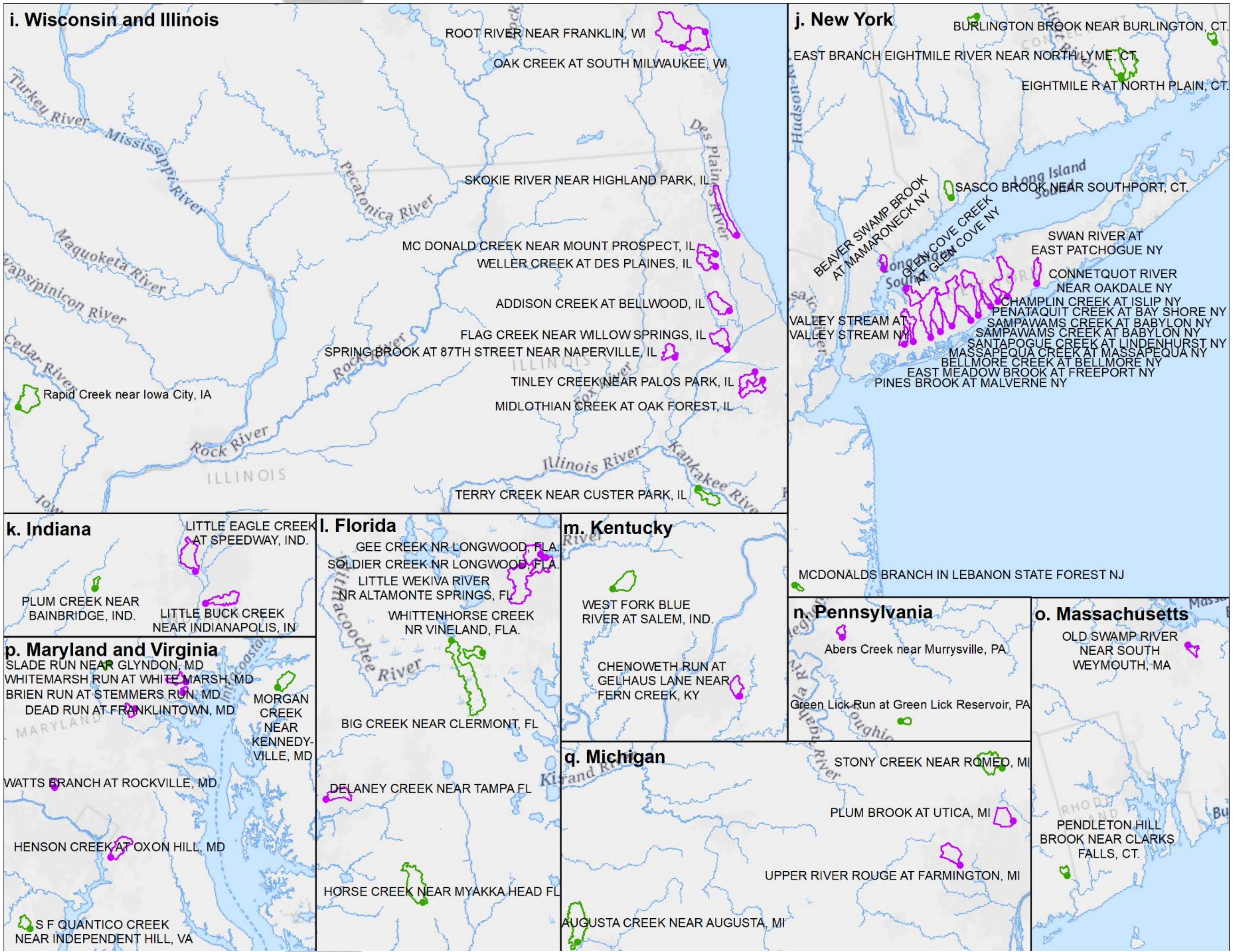


Figure 2. Each line shows an urbanizing gage's housing density over time, over its period of analysis, rounded to the nearest decade to match housing density data availability. The regional groupings used here are also used for Figures 5 and 7.

Urbanizing gages were paired with 30 reference gages, as some urbanizing gages in the same metropolitan area were paired with the same reference gage (Figure 3; Table A1).


a. Continental US
California North
California South
Arizona
Colorado
Texas North
Texas (Houston)
Texas (Austin)
Wisconsin and Illinois
Michigan
Indiana
Kentucky
Pennsylvania
New York
Massachusetts
Maryland and Virginia
Florida
0 315 630 1,260 Kilometers
Legend
Urbanizing gages
Reference gages
Urbanizing drainage
Reference drainage
0 20 40 80 Kms
N
b. Arizona
SABINO CREEK NEAR TUCSON, AZ.
TUCSON ARROYO AT VINE AVE, AT TUCSON, AZ.
c. Texas (Houston)
Piney Ck nr Groveton, TX
Cow Bayou nr Mauriceville, TX
Greens Bayou nr Houston, TX
Halls Bayou at Houston, TX
Sims Bayou at Houston, TX
Vince Bayou at Pasadena, TX
d. Colorado
COAL CREEK NEAR PLAINVIEW, CO.
COTTONWOOD CREEK AT MOUTH, AT PIKEVIEW, CO.
TEMPLETON GAP FLOODWAY AT COLORADO SPRINGS, CO.
ROCK CREEK ABOVE FORT CARSON RESERVATION, CO.
e. Texas (Austin)
S Fk Rocky Ck nr Briggs, TX
Waller Ck at 38th St, Austin, TX
Waller Ck at 23rd St, Austin, TX
f. California South
LITTLE TUJUNGA C NR SAN FERNANDO CA
MISSION C NR MONTEBELLO CA
MISSION C NR DESERT HOT SPRINGS CA
ALISO C A EL TORO CA
BORREGO PALM C NR BORREGO SPRINGS CA
LOS PENASQUITOS C NR POWAY CA
g. California North
COLMA C A SOUTH SAN FRANCISCO CA
DRY C A UNION CITY CA
h. Texas North
Briar Ck nr Graham, TX
Duck Ck nr Garland, TX



i. Wisconsin and Illinois
ROOT RIVER NEAR FRANKLIN, WI
OAK CREEK AT SOUTH MILWAUKEE, WI
SKOKIE RIVER NEAR HIGHLAND PARK, IL
MC DONALD CREEK NEAR MOUNT PROSPECT, IL
WELLER CREEK AT DES PLAINES, IL
ADDISON CREEK AT BELLWOOD, IL
FLAG CREEK NEAR WILLOW SPRINGS, IL
SPRING BROOK AT 87TH STREET NEAR NAPERVILLE, IL
TINLEY CREEK NEAR PALOS PARK, IL
MIDLOTHIAN CREEK AT OAK FOREST, IL
Rapid Creek near Iowa City, IA
TERRY CREEK NEAR CUSTER PARK, IL
j. New York
BURLINGTON BROOK NEAR BURLINGTON, CT.
EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME, CT.
EIGHTMILE R AT NORTH PLAIN, CT.
SASCO BROOK NEAR SOUTHPORT, CT.
BEAVER SWAMP BROOK AT MAMARONECK NY
GLEN COVE CREEK AT GLEN COVE NY
SWAN RIVER AT EAST PATCHOGUE NY
CONNETQUOT RIVER NEAR OAKDALE NY
CHAMPLIN CREEK AT ISLIP NY
PENATAQUIT CREEK AT BAY SHORE NY
SAMPAWAMS CREEK AT BABYLON NY
SAMPAWAMS CREEK AT BABYLON NY
SANTAPOGUE CREEK AT LINDENHURST NY
MASSAPEQUA CREEK AT MASSAPEQUA NY
BELLMORE CREEK AT BELLMORE NY
EAST MEADOW BROOK AT FREEPORT NY
PINES BROOK AT MALVERNE NY
VALLEY STREAM AT VALLEY STREAM NY
MCDONALDS BRANCH IN LEBANON STATE FOREST NJ
k. Indiana
LITTLE EAGLE CREEK AT SPEEDWAY, IND.
PLUM CREEK NEAR BAINBRIDGE, IND.
LITTLE BUCK CREEK NEAR INDIANAPOLIS, IN
l. Florida
GEE CREEK NR LONGWOOD, FLA.
SOLDIER CREEK NR LONGWOOD, FLA.
LITTLE WEKIVA RIVER NR ALTAMONTE SPRINGS, FL
WHITTENHORSE CREEK NR VINELAND, FLA.
BIG CREEK NEAR CLERMONT, FL
DELANEY CREEK NEAR TAMPA FL
HORSE CREEK NEAR MYAKKA HEAD FL
m. Kentucky
WEST FORK BLUE RIVER AT SALEM, IND.
CHENOWETH RUN AT GELHAUS LANE NEAR FERN CREEK, KY
n. Pennsylvania
Abers Creek near Murrysville, PA
Green Lick Run at Green Lick Reservoir, PA
o. Massachusetts
OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA
PENDLETON HILL BROOK NEAR CLARKS FALLS, CT.
p. Maryland and Virginia
SLADE RUN NEAR GLYNDON, MD
WHITEMARSH RUN AT WHITE MARSH, MD
BRIEN RUN AT STEMMERS RUN, MD
DEAD RUN AT FRANKLINTOWN, MD
MORGAN CREEK NEAR KENNEDY-VILLE, MD
WATTS BRANCH AT ROCKVILLE, MD
HENSON CREEK AT OXON HILL, MD
S F QUANTICO CREEK NEAR INDEPENDENT HILL, VA
q. Michigan
STONY CREEK NEAR ROMEO, MI
PLUM BROOK AT UTICA, MI
UPPER RIVER ROUGE AT FARMINGTON, MI
AUGUSTA CREEK NEAR AUGUSTA, MI

Figure 3. (a) Map of urbanizing (purple) and reference (green) gages analyzed in the continental U.S. All regional maps (b – q) showing gages and corresponding GAGES-II watershed boundaries have the same scale.

3.2 Observed flow trends

An example of how an urbanization-only trend slope was calculated is shown in Figure 4 for Valley Stream at Valley Stream, NY. This urbanizing stream had a larger magnitude urbanizing trend slope than the largest magnitude trend slope at the corresponding reference gage. In fact, most urbanizing watersheds (28 out of 53; 52%) had an urbanization-only trend slope that was larger than the largest magnitude trend slope at the corresponding reference gage, indicating that urbanization had a more profound influence compared to non-urbanizing conditions. The urbanization-only trend slopes across the flow duration curve were grouped into six regions for plotting purposes (the same six regions shown in Figure 2). In New York and Massachusetts, the trend slopes of urbanizing gages when reference gage trend slopes were subtracted (Figure 5a), were generally within 10% of zero. The largest excursions outside of 20% change were observed at Valley Stream at Valley Stream NY. Trends in maximum day flows were mostly upwards, and minimum day flows were evenly split between rising and falling. Valley Stream had falling trends throughout the entire flow duration curve, with the largest trends approaching -40% change in flow per year between the 25th and 50th percentile flows (Figure 4a). The reference site (McDonalds Branch) had little change across the flow duration curve (Figure 4b).

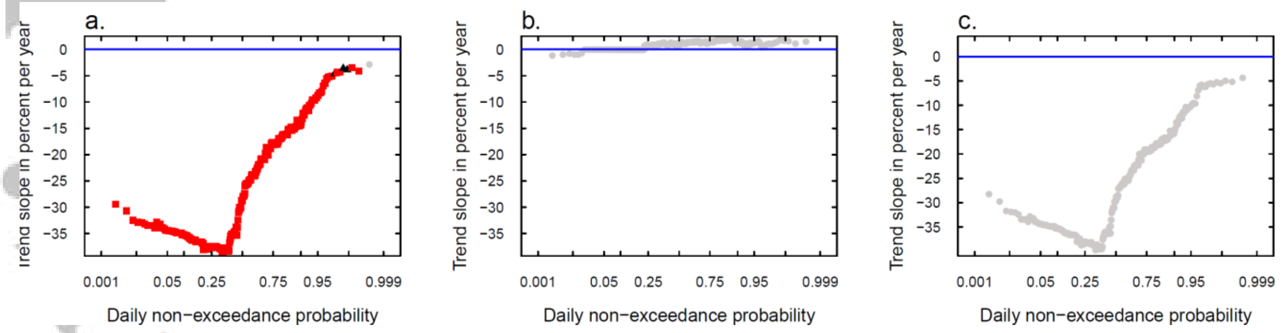
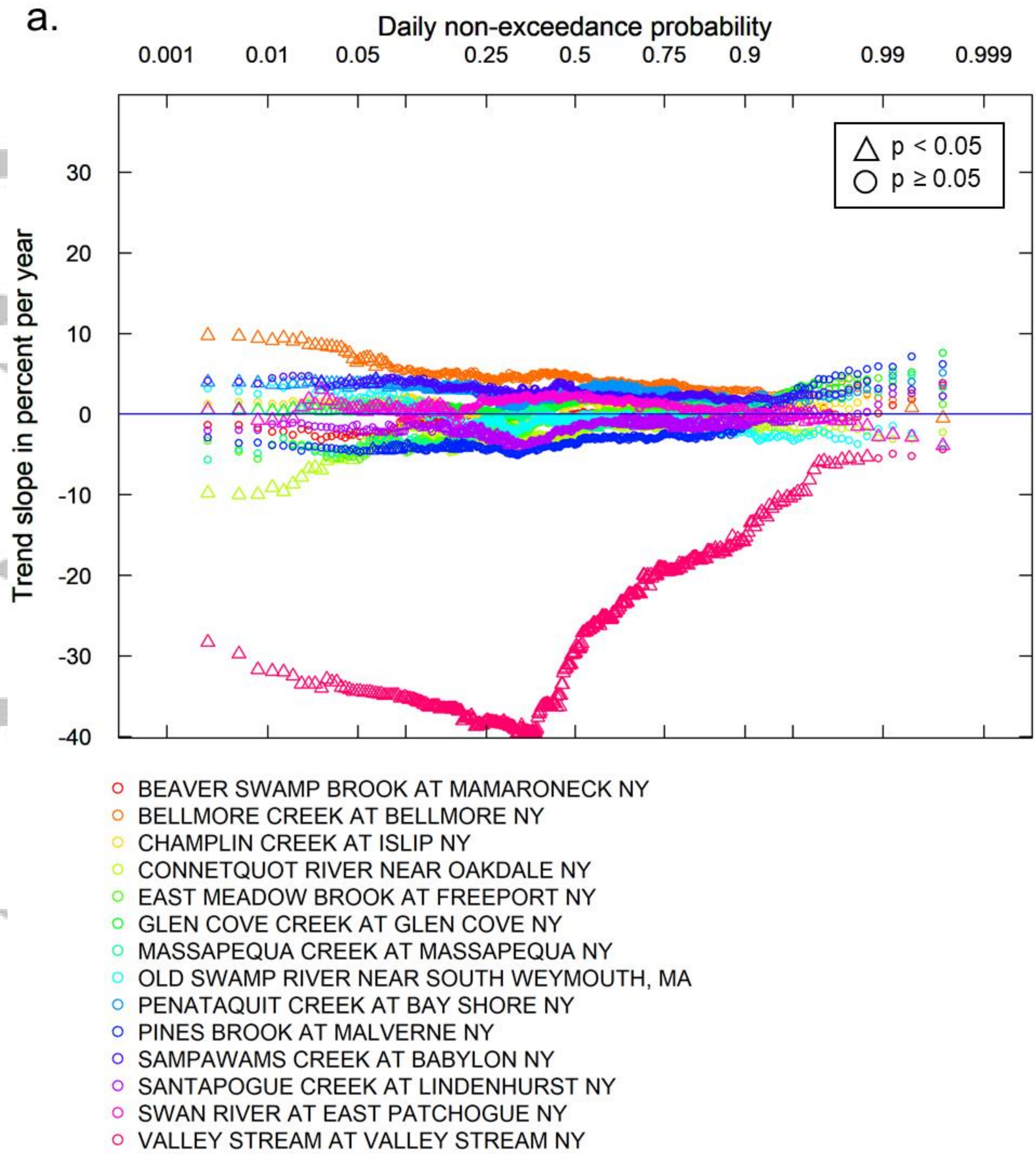
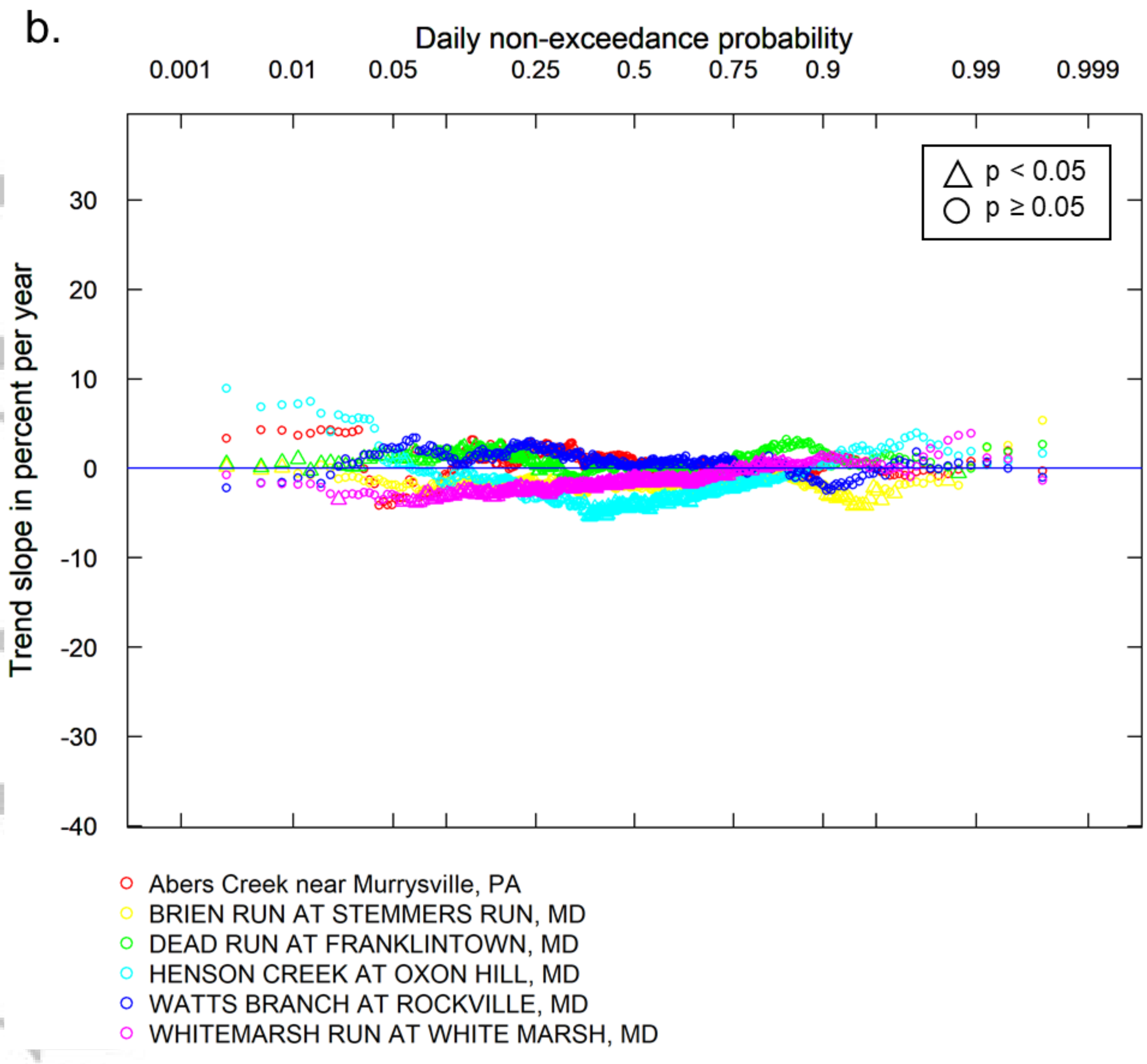
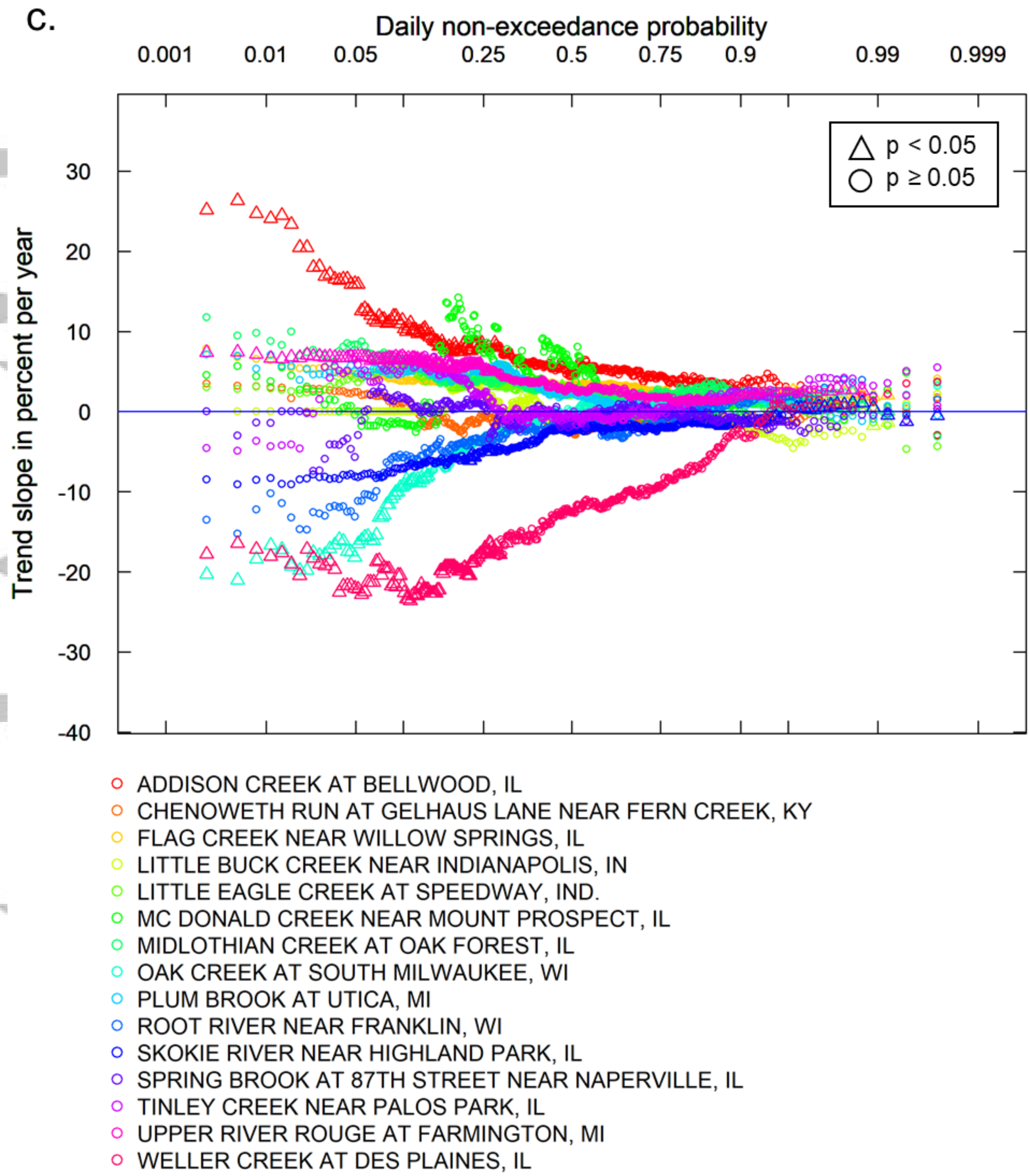


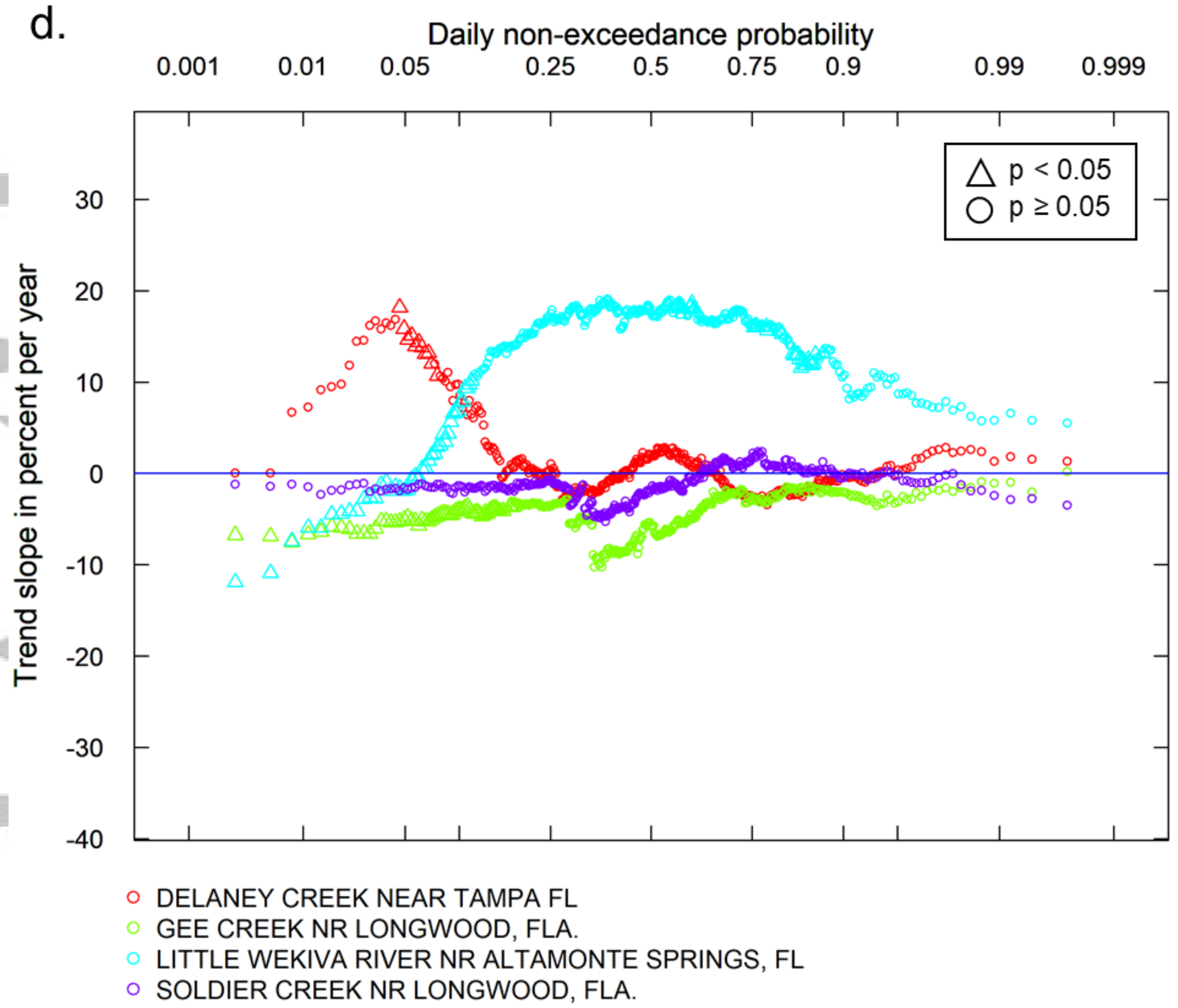
Figure 4. (a) Example quantile-Kendall plot of urbanizing gage: Valley Stream at Valley Stream, NY, (b) Quantile-Kendall plot of paired reference gage (McDonalds Branch in Byrne State Forest, NJ) during the same period of analysis (1954-07-01 to 1974-07-01), (c) The urbanizing trend slopes (shown in a) minus the reference trend slopes (shown in b), results in the urbanization-only trend slope (shown in c).

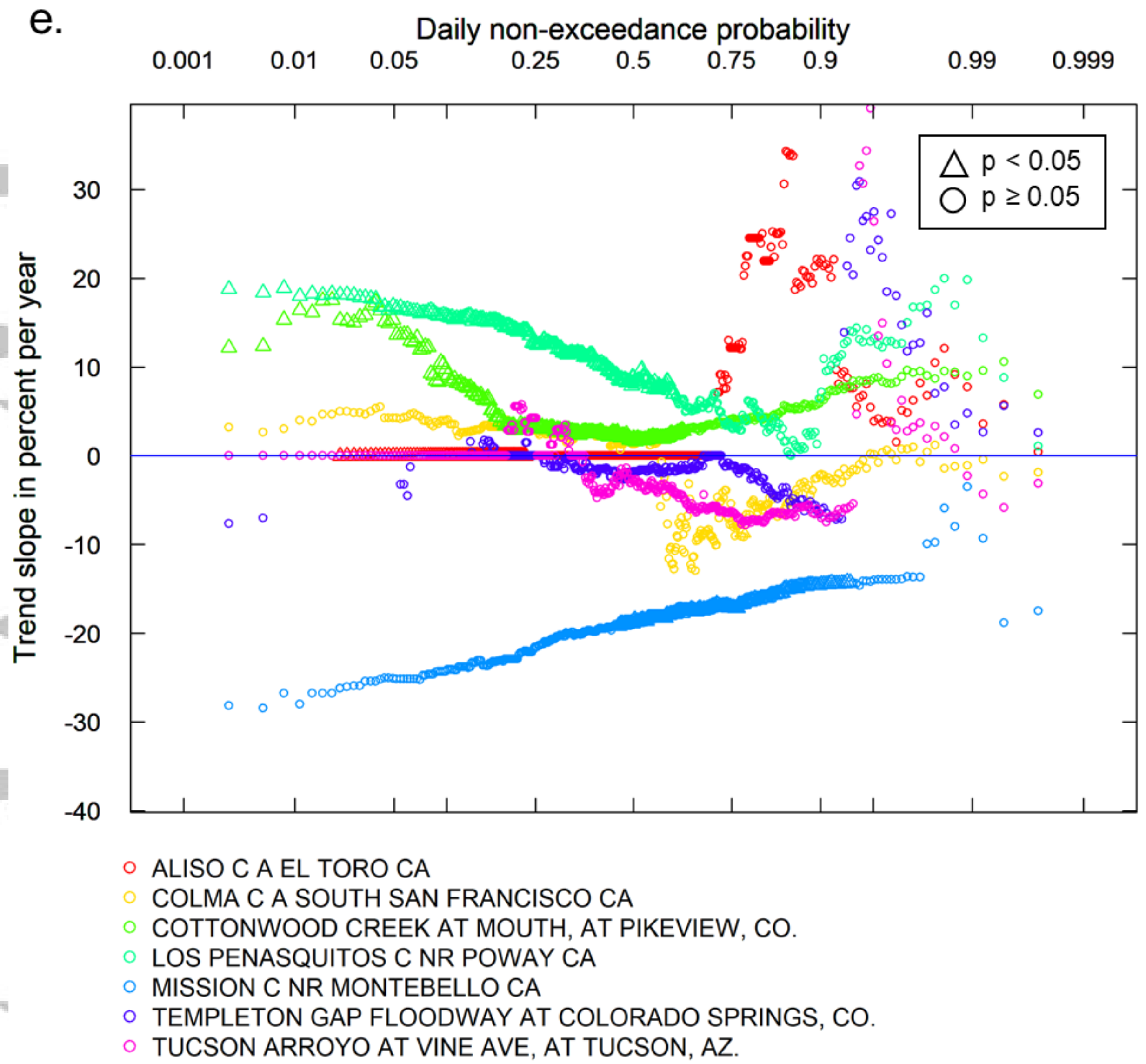

a.
Daily non-exceedance probability
0.001
0.01
0.05
0.25
0.5
0.75
0.9
0.99
0.999
p < 0.05
p ≥ 0.05
Trend slope in percent per year
30
20
10
0
-10
-20
-30
-40
BEAVER SWAMP BROOK AT MAMARONECK NY
BELLMORE CREEK AT BELLMORE NY
CHAMPLIN CREEK AT ISLIP NY
CONNETQUOT RIVER NEAR OAKDALE NY
EAST MEADOW BROOK AT FREEPORT NY
GLEN COVE CREEK AT GLEN COVE NY
MASSAPEQUA CREEK AT MASSAPEQUA NY
OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA
PENATAQUIT CREEK AT BAY SHORE NY
PINES BROOK AT MALVERNE NY
SAMPAWAMS CREEK AT BABYLON NY
SANTAPOGUE CREEK AT LINDENHURST NY
SWAN RIVER AT EAST PATCHOGUE NY
VALLEY STREAM AT VALLEY STREAM NY


b.
Daily non-exceedance probability
0.001
0.01
0.05
0.25
0.5
0.75
0.9
0.99
0.999
p < 0.05
p ≥ 0.05
Trend slope in percent per year
30
20
10
0
-10
-20
-30
-40
Abers Creek near Murrysville, PA
BRIEN RUN AT STEMMERS RUN, MD
DEAD RUN AT FRANKLINTOWN, MD
HENSON CREEK AT OXON HILL, MD
WATTS BRANCH AT ROCKVILLE, MD
WHITEMARSH RUN AT WHITE MARSH, MD



C.
Daily non-exceedance probability
0.001
0.01
0.05
0.25
0.5
0.75
0.9
0.99
0.999
Trend slope in percent per year
30
20
10
0
-10
-20
-30
-40
△ p < 0.05
○ p ≥ 0.05
ADDISON CREEK AT BELLWOOD, IL
CHENOWETH RUN AT GELHAUS LANE NEAR FERN CREEK, KY
FLAG CREEK NEAR WILLOW SPRINGS, IL
LITTLE BUCK CREEK NEAR INDIANAPOLIS, IN
LITTLE EAGLE CREEK AT SPEEDWAY, IND.
MC DONALD CREEK NEAR MOUNT PROSPECT, IL
MIDLOTHIAN CREEK AT OAK FOREST, IL
OAK CREEK AT SOUTH MILWAUKEE, WI
PLUM BROOK AT UTICA, MI
ROOT RIVER NEAR FRANKLIN, WI
SKOKIE RIVER NEAR HIGHLAND PARK, IL
SPRING BROOK AT 87TH STREET NEAR NAPERVILLE, IL
TINLEY CREEK NEAR PALOS PARK, IL
UPPER RIVER ROUGE AT FARMINGTON, MI
WELLER CREEK AT DES PLAINES, IL


d.
Daily non-exceedance probability
0.001
0.01
0.05
0.25
0.5
0.75
0.9
0.99
0.999
Trend slope in percent per year
30
20
10
0
-10
-20
-30
-40
△ p < 0.05
○ p ≥ 0.05
DELANEY CREEK NEAR TAMPA FL
GEE CREEK NR LONGWOOD, FLA.
LITTLE WEKIVA RIVER NR ALTAMONTE SPRINGS, FL
SOLDIER CREEK NR LONGWOOD, FLA.


e.
Daily non-exceedance probability
0.001
0.01
0.05
0.25
0.5
0.75
0.9
0.99
0.999
Trend slope in percent per year
30
20
10
0
-10
-20
-30
-40
p < 0.05
p ≥ 0.05
ALISO C A EL TORO CA
COLMA C A SOUTH SAN FRANCISCO CA
COTTONWOOD CREEK AT MOUTH, AT PIKEVIEW, CO.
LOS PENASQUITOS C NR POWAY CA
MISSION C NR MONTEBELLO CA
TEMPLETON GAP FLOODWAY AT COLORADO SPRINGS, CO.
TUCSON ARROYO AT VINE AVE, AT TUCSON, AZ.

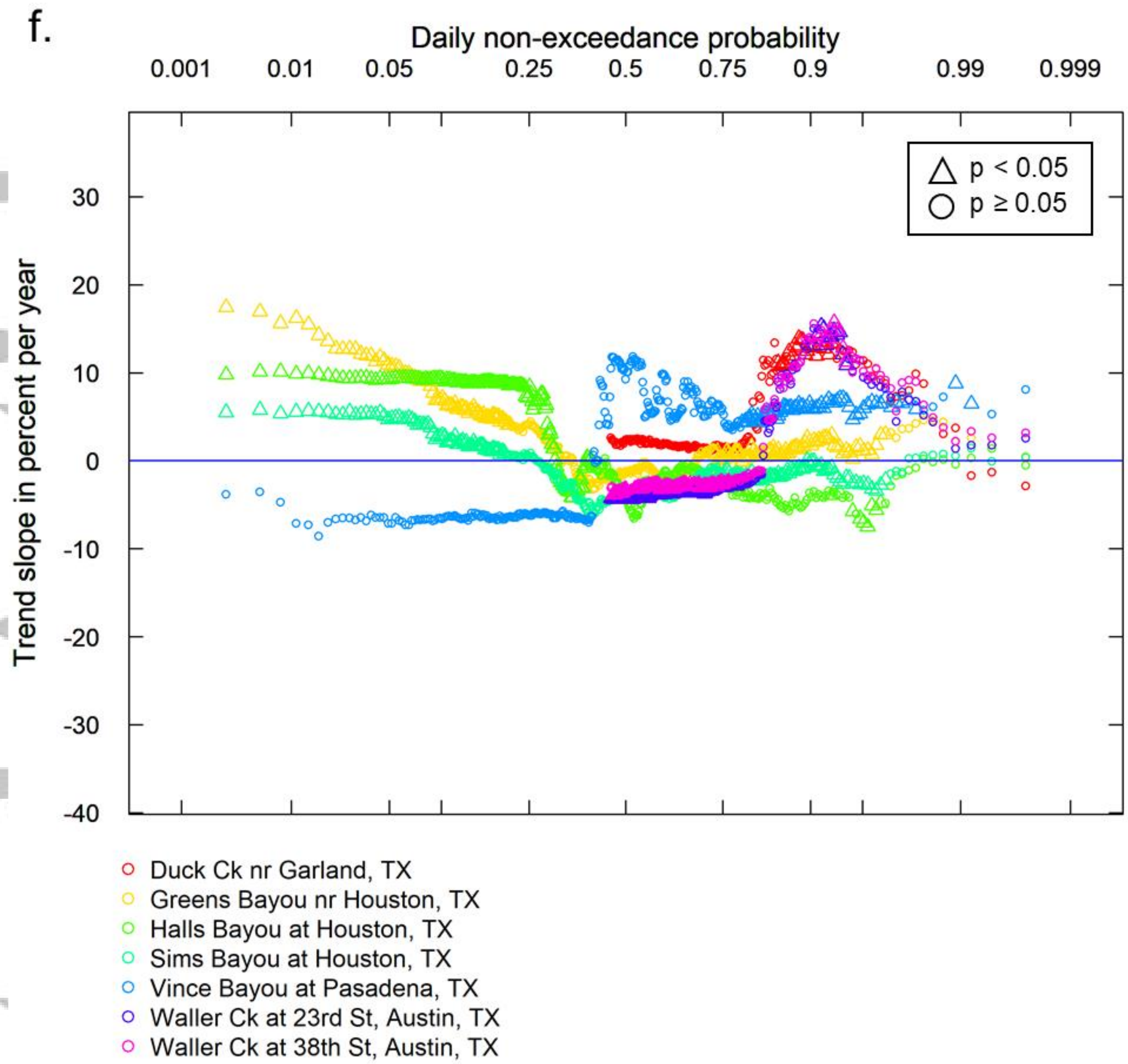


Figure 5. Quantile-Kendall plots with urbanizing gages trend slopes minus reference gage trend slopes for the corresponding period of analysis. Points above the blue line indicate an upward urbanization-only trend slope at the urbanizing gage relative to the reference gage and points below the blue line indicate a downward slope relative to the reference gage. Triangles indicate trends for which $p < 0.05$ and circles indicate $p \geq 0.05$. The plots are grouped into the following regions: (a) New York and Massachusetts, (b) Maryland and Pennsylvania, (c) Michigan, Wisconsin, Illinois, Indiana, and Kentucky, (d) Florida, (e) California, Colorado, and Arizona, and (f) Texas.

Urbanizing gages in New York and Massachusetts had trends that were largely within 10% of zero across the flow duration curve, except Valley Stream in NY (Figure 5a). Further discussion of the patterns in Valley Stream will be presented in the discussion section. The urbanizing gages in Maryland and Pennsylvania had trends that were all within 10% of zero (Figure 5b). Trends at the maximum daily flow were split between upwards and downwards urbanization-only trends. Flow trends across the flow duration curve were in some cases rising and in other cases falling. The patterns of flow change in Illinois, Michigan, Wisconsin, Indiana, and Kentucky that had the widest range of trend slopes were seen in minimum day flows (Figure 5c). The reference gage for Weller Creek (Terry Creek near Custer Park, IL) had trend slopes within 5% of zero, meaning that the strong downward trends observed for low flows at Weller Creek were not related to regional climate patterns. Addison Creek at Bellwood, IL was paired with the same reference gage for nearly the same time interval, but at Addison Creek low flows strongly increased during the period of analysis.

Urbanizing gages in Florida had stable or falling minimum day flows (Figure 5d). Maximum day flows were split between falling and rising. The reference gage paired with Little Wekiva River, near Altamonte Springs, FL had a downward trend over time for the entire flow duration curve. When this trend was subtracted from the downward trend across most of the flow duration curve for Little Wekiva River, the resulting urbanization-only trend was largely upward.

There were fewer gages that met our urbanizing criteria in the western U.S., which required a group for plotting that covered a large area (Figure 5e). Templeton Gap Floodway at Colorado Springs and Tucson Arroyo at Vine Ave had quantiles with no flow at both the urbanizing and reference gages, indicated by an urbanization-only trend slope of exactly zero at low flows (Figure 5e). These same two watersheds, along with Aliso Creek in Southern California, had large upward trends in high flows (85-95th percentiles) of greater than 30% increases in flow per year. Comparatively moderate trends, or sometimes falling, were seen for the maximum day flow. Los Penasquitos Creek in California, the largest watershed in this set, had increasing flow across the entire flow duration curve. Mission Creek in California, conversely, had consistently decreasing flow across the entire flow duration curve, with minimum day flow approaching 30% decreases per year. This pattern was not seen in the reference gage for Mission Creek, which had flow trends within 5% of zero.

The trends at urbanizing gages in Texas had patterns that can be grouped by metropolitan area (Figure 5f). Duck Creek (in the Dallas, TX area), and both urbanizing gages on Waller Creek in Austin, TX were increasing most strongly at the 90th percentile flow. In the Houston gages (Greens Bayou, Halls Bayou, Sims Bayou), there were increasing low flows and small trends at high flows. These three gages, although in close proximity, had two different reference gages as they had different urbanizing periods of analysis. The urbanization only trend pattern was different for Vince Bayou in Pasadena, TX, where there were decreasing low flows and increasing high flows.

3.3 Patterns in observed trends

To characterize patterns across all 53 urbanizing gages, we examined the distribution of trend slopes across the flow duration curve (Figure 6). For example, the interquartile range in trend slopes of urbanizing gages considered the spread across 53 urbanizing gages, whereas the median trend slope gives the midpoint across the 53 urbanizing gages. These measures of trend slope distribution were calculated for each of the 365 non-exceedance probabilities. The variability in trend slope (as measured by the interquartile range) in urbanizing gages (Figure 6a) was larger than that at reference gages (Figure 6b) for flows below the 25th percentile. This indicated that urbanization generated a wider range of low flow trends than non-urban effects (e.g., climate). In contrast, the variability of trend slopes above the 90th percentile was smaller for urbanizing gages than for reference gages, indicating that non-urban effects (e.g., climate) led to a range of high flow trends, but urbanization constrained that range to more consistent upward trends in high flows. High flow trends in urbanizing watersheds had a median above 1% per year above the 90th percentile flow (Figure 6a), although there are still urbanizing gages that even during peak urbanization had falling high flows. A trend slope of 1% flow change per year would lead to a 22% (1.01^{20}) increase (or decrease) in flow over 20 years compared to the start of the analysis period.

The median reference trend for the lowest urbanizing and reference flows was zero (Figures 6a and 6b). A median reference trend of zero indicates that although there were upwards and downwards trends at individual gages, the midpoint of the distribution of the 53 gages had trend slopes of zero at low flows. Gages with zero flow across the entire 20-year record will have a trend slope of zero, as no trend will be detected from constant zero values. Streamflow is recorded as constant either when changes in streamflow are below the detection resolution of the streamgage or if the stream is dry. Although the water table elevation may be varying substantially when the stream is dry, if these fluctuations are below the streambed elevation, they are not recorded by the streamgage.

The magnitude of urbanizing trends (Figure 6a) were reduced as the reference trends were removed (Figure 6b) to result in urbanization-only trend slopes (Figure 6c). Although trend slope magnitudes were reduced, other characteristics of urbanizing trends were preserved when the reference signal was removed. For example, the interquartile range below the 50^{th} percentile flow was larger compared to the 50^{th} percentile, and median trend slopes were upward for flows above the 95^{th} percentile and below the 30^{th} percentile. The largest median trend slopes observed were at the 99.5^{th} percentile flow at 1.7% increase in flow per year. This translates to the median change at these flows as an increase of 41% over a 20-year record.

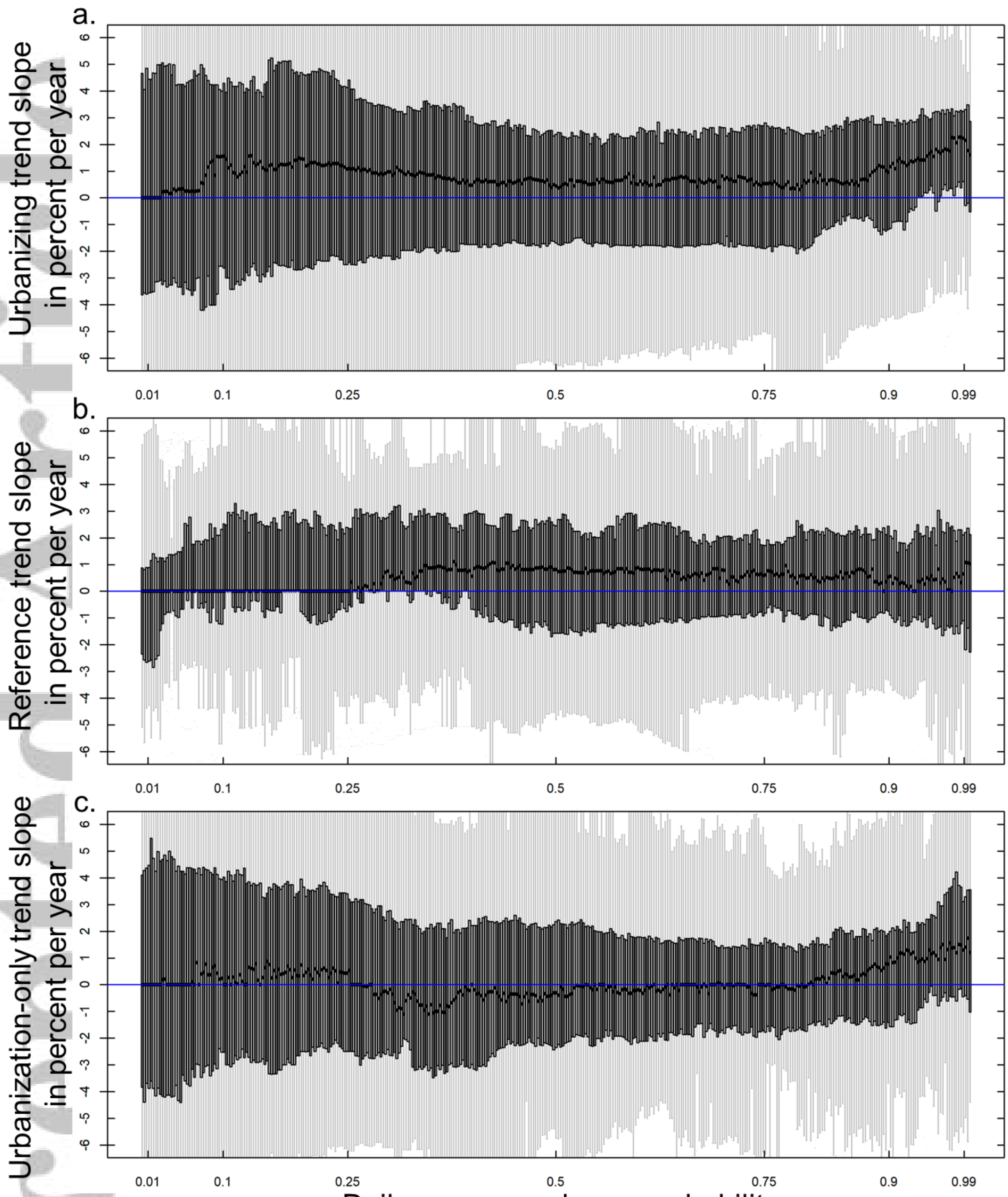

a.
b.
c.
Urbanizing trend slope in percent per year
Reference trend slope in percent per year
Urbanization-only trend slope in percent per year
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
0.01
0.1
0.25
0.5
0.75
0.9
0.99
Daily non-exceedance probability

Figure 6. (a) Boxplots of 53 urbanizing trend slopes vs. daily non-exceedance probability. (b) Boxplots of reference gage trend slopes for 30 reference gages over 53 periods of analysis to correspond to urbanizing gage periods of analysis, leading to n=53 to match (a), vs. daily non-exceedance probability. (c) Boxplots of urbanization-only trend slopes vs. daily non-exceedance probability. Boxplots are shown with a restricted y-axis where the median is shown by a thick black line, the range from the first to third quartile is shown as a black box, and the whiskers (extend to the data point that is no more than 1.5 times from the box) and outliers are shown in gray.

Characteristics of the distribution of trend slope across urbanizing and reference gages (Figure 6) obscure the association of trend slopes between high flows and low flows at individual gages. To present this, the distribution of trend slopes at individual gages, urbanization-only trend slopes at the 10th and 90th percentiles at each gage, were compared (Figure 7). Watersheds that had strongly falling low flows at the 10th percentile (Valley Stream, NY; Mission Creek, CA; and Addison Creek, IL) also had falling high flows at the 90th percentile. Except for Valley Stream, NY (lower left-most point in Figure 7), midwestern and northeastern states (Michigan, Wisconsin, Illinois, Indiana, Kentucky; New York, Massachusetts gages) were generally distributed more widely on the low flow trend slope axis than on the high flow trend slope axis. The magnitude of high flow trends in midwestern and northeastern states were lower compared to streams in southern and western states. Maryland and Pennsylvania trend slopes for high and low flows were generally small. Texas, California, Arizona, and Colorado had large high flow trend slopes that were not always associated with large trends in low flows. Increases and decreases in both high and low flows were observed in every region of the United States, indicating large variability in streamflow changes during urbanization.

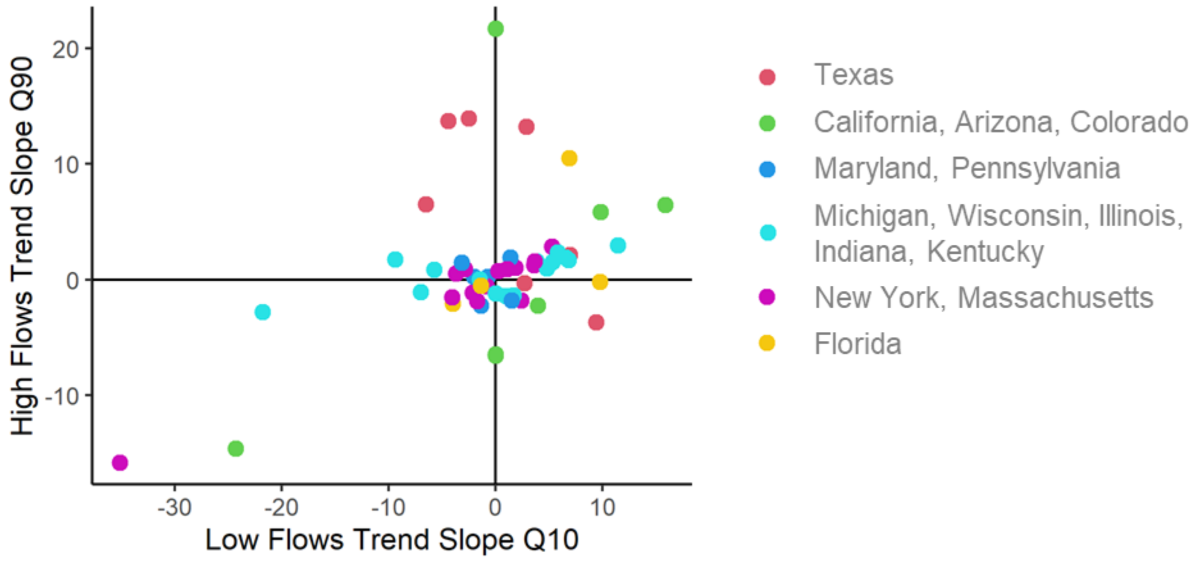


Figure 7. Urbanization only trend slopes at the 10th percentile (Q10, x-axis) and the 90th percentile (Q90, y-axis) summarized by the same regional groupings used in Figures 2 and 5.

4 DISCUSSION

Here we discuss the magnitude of trends observed across urbanizing and reference gages, and then watersheds with particularly notable trends.

4.1 Overall patterns

The largest magnitude trend in the urbanizing watershed across the flow duration curve (referred to as the most extreme trend) was in most cases (28 out of 53, 53%) larger than the most extreme trend at the associated reference gage. The largest differences in extreme trends observed between urbanizing-reference matches were 37% in Valley Stream, NY, 37% in Tucson Arroyo, AZ, 30% in Templeton Gap Floodway, CO, and 23% in Aliso Creek, CA (where urbanizing most extreme trend was always larger). In Valley Stream, the most extreme trend was at the 33rd percentile flow with a slope of -40% per year. Templeton Gap Floodway and Tucson Arroyo had the most extreme trends at the 94th and 95th percentile flows with slopes of 31% and 39% change in flow per year, respectively. Watersheds where the most extreme reference trend was larger than the most extreme urbanizing trend were Cottonwood Creek, CO (-17%), Root River, WI (-14%), and Oak Creek, WI (-13%).

There were 8 out of 53 urbanizing gages in which the magnitude of the urbanization-only trend slope exceeded 20% flow change per year at some point along the flow duration curve. These gages are Valley Stream, NY; Tucson Arroyo, AZ; Aliso Creek, CA; Templeton Gap Floodway, CO; Mission Creek, CA; Addison Creek, IL; Weller Creek, IL, and Oak Creek, WI. These flow trends translate to a uniform flow change of > 3000% (1.20^{20}) over 20 years. In contrast, urbanizing watersheds in New York, Maryland, and Pennsylvania typically had urbanization-only trend slopes less than 10% per year (Figure 5 ab).

4.2 Arid and semi-arid urbanization

There are few urban hydrologic investigations in arid or semi-arid settings in the literature to compare the generality of semi-arid and arid urbanizing watersheds having comparatively larger flow alterations relative to humid urban watersheds. In Phoenix, Arizona, naturally flashy streams, which have large and rapid rises and falls in streamflow after storms, were found to become less flashy after urbanization (Hale et al., 2015; McPhillips et al., 2019). In Tucson, urbanization was found to lead to increased runoff frequency and increased duration of runoff, but did not affect water yield, runoff depth, or time to peak since non-urban semi-arid monsoon response was already flashy with a short time to peak (Gallo et al., 2013). Our findings in contrast indicated that some urbanizing semi-arid or arid streams had over 20% increases in flow per year at specific flow quantiles that ranged from the 86^{th} to 95^{th} percentiles (Figure 5e). Characteristics of semi-arid areas that may lead to more extreme trend slopes are larger percent changes in flow in watersheds that have lower pre-development flow and particular forms of flood management that exacerbate the effect of urbanization at certain flow quantiles.

Templeton Gap Floodway is a levee constructed in 1949 in the Templeton Gap to divert floodwater away from central Colorado Springs, Colorado (Soule, Nathan et al., 2012). When the Templeton Gap Floodway levee was initially constructed, there was little urban development in the surrounding watershed, but housing density increased by almost 460% between 1961 to 1981. Flows between the 90^{th} and 99^{th} percentiles increased dramatically, in some cases over 30% flow change per year. In 2009, the Federal Emergency Management Agency did not extend accreditation to the levee because it did not have the requisite freeboard for large storm events, and this floodway is an ongoing flood control challenge for Colorado Springs (Tredway & Havlick, 2017).

Aliso Creek in California had a 1551% increase in housing density from 1960 to 1980, the largest percentage increase in this study. Both the reference gage paired with Aliso Creek, and Aliso Creek itself, had no trend at low flows. Flow trends are not detectible when streams are dry, as Aliso Creek was for 75% of the period of analysis. Both the reference gage (Borrego Palm Creek) and Aliso Creek had increasing trends in flow above the 75th percentile, although the reference gage had trends of a maximum of 15% increase in trend slope per year, whereas the trend slope in Aliso Creek was at some percentiles in excess of 35% per year.

Another nearby California watershed, Mission Creek, had very different trend slopes with consistently falling flow. Downward flow trends in Mission Creek near Montebello, CA may be explained by the water management history. During the period of analysis for Mission Creek (1945 to 1965), the Whittier Narrows Dam Complex, to which Mission Creek drains, was completed (1957). As part of this complex, water that previously would have entered Mission Creek was re-routed through North, Center, and Legg Lakes, and only overflow from these lakes reached Mission Creek (USEPA, 2012; G. Peacock, personal communication, 2018; USGS, 1957).

4.3 Sewerage and urbanizing streams

The only other urbanization-only trend slopes that exceeded 20% in magnitude at any quantile was Valley Stream in NY (Figure 5a). Valley Stream is the southwestern-most study watershed in Long Island, NY (Figure 3) and in the part of Nassau County that had the earliest sanitary sewer completion (hookups began in 1953 and were completed in 1964) (Simmons & Reynolds, 1982), which is during the period of analysis for Valley Stream. When these areas were converted to sanitary sewer service, they were predominantly using local confined groundwater for supply (Garber & Sulam, 1975), and had previously been discharging wastewater to septic systems recharging the unconfined aquifer. The transition to sanitary sewer service led to dramatic declines in flow during the analysis period for Valley Stream. Streams farther east on Long Island were not part of this first sewer district in Nassau County (Spinello & Simmons, 1992). Comparisons between urbanized sewered with urbanized unsewered areas indicated that the effect of impervious surfaces was small compared to the effect of sanitary sewer systems on baseflow (Simmons & Reynolds, 1982). Baseflow at East Meadow Brook had a decline in baseflow index after our analysis period ended (Pluhowski & Spinello, 1978).

Weller Creek in Illinois also had large and negative values in the urbanization-only trend slopes (Figure 5c). A previous inspection of aerial imagery indicated that there was a flood control reservoir in Weller Creek (Illinois Department of Transportation, 2009), although whether the date of construction was during our period of analysis was unclear. Weller Creek and Tinley Creek near Chicago, Illinois, had greatly expanded overlapping potable water distribution systems during the same time as urbanization (Meyer, 2005), which can be assumed to be occurring in other watersheds where this process was not directly documented.

In the same area as Weller Creek, Addison Creek had increasing low flow over a period of peak urbanization (Figure 5c). Addison Creek, upstream of Bellwood, Illinois, had four return flow facilities within 6 miles of the streamgage in 1988: two commercial stormwater runoff sites and two sewage treatment outfalls (LaTour, 1993). In 1988, the average annual return flow was 40% of the average annual streamflow, and during low flow months, the stream was nearly all wastewater effluent. The beginning of wastewater effluent discharge to Addison Creek during the urbanization time period (1951-1971) was associated with strong upward trends in the lowest flows.

4.5 Timescale of analysis

The time periods considered for paired watershed analyses range from 2 years to decades (Bishop et al., 2005; Jones & Grant, 1996; King et al., 2008). Trend analysis commonly considers longer periods (Prosdocimi et al., 2015), although trend analysis of 10-year periods have been used for annual minimums and maximums (Gotvald, 2016; McCabe & Wolock, 2002) and 10 years has been suggested as a minimum record length for trend analysis (Riggs, 1972).

Our combined paired watershed and time trend approach used an analysis period of 20 years. Even though longer periods of analysis would have yielded greater power in the trend tests (Yue et al., 2002), our focus was not on long-term trends in streamflow. The purpose of our work was to analyze changes in streamflow during periods of rapid urbanization. Longer trend analyses would mute the effect of urbanization, as it would include periods of rapid urban growth as well as periods of more constant land use.

Our focus on the period of peak urbanization was motivated in part by previous work in which the increase in high flow frequency was found to be proportional to changes in peak building density, rather than the change in building density during the entire flow record (Hopkins, Morse, Bain, Bettez, Grimm, Morse, & Palta, 2015b). Examining periods shorter than 20 years was precluded by the decadal resolution of housing density change available nationally. For a limited area, Hopkins et al. (2015b) reconstructed housing density from parcel-level parcel-tax assessments to obtain inter-decade (i.e., 1955, 1965, and 1975) values for housing density. If finer temporal resolutions of housing density were used, the peak housing density change per year would be larger than averaging over decadal changes.

4.6 Isolation of effects of urbanization

Our analysis focuses on identifying the trends in streamflow from urbanization. In urbanizing watersheds, streamflow may have trends over time due to urbanization, but also due to climatic trends, or other trends such as those from national changes in agricultural practices. Because we focused on periods of peak urbanization, precipitation and evapotranspiration records were not available to identify long-term climatic trends going back to the 1940s (Figure 2). Instead, we relied on reference watersheds as characterized by the GAGES-II dataset, the least disturbed watersheds with near-natural flow conditions. We assumed that temporal trends observed in rural reference watersheds were representative of the climate trends affecting urbanizing watersheds. These are the best available representatives for climatic trends in these urbanizing watersheds, but the trends in these reference watersheds still have limitations in the degree of similarity between urbanizing and reference watersheds. Because the reference and urbanizing watersheds are two different watersheds, they are going to be inherently different. However, our analysis does not require that the urbanizing and reference watersheds have the same streamflow characteristics. We are not directly taking the difference in flow duration curves and using this to represent the effect of urbanization. Rather, we assume that the differences in the trends in the flow duration curve represent the effect of urbanization on streamflow.

4.6 Other possible analyses

Our analysis focused on 1939 – 2016, with more records from the early part of that period. If this analysis was conducted using more recent records, it is possible that the effect of climate-change driven differences in rainfall may lead to larger flow changes in urban areas because of the tighter connection between rainfall and runoff generation in urban areas (Sharma et al., 2018). Furthermore, urbanization itself may affect rainfall intensity, particularly downwind of the rural-urban interface of eastern and midwestern cities (Niyogi et al., 2017). Another possible comparison would be analysis using gages draining watersheds with stable urban land cover with little land cover change over time, which would have urban-specific climate trends represented. However, there are far fewer stable urban gages as compared to rural reference gages, which makes them difficult to use as a positive control for an overlapping temporal trend analysis.

Urbanization involves a wide range of processes that affect streamflow: increasing impervious surface cover, stormwater drainage systems, stormwater control facilities, topographic alteration and re-routing of flow paths, water supply withdrawal, changes in wastewater disposal from septic to wastewater treatment facility, disposal of treated wastewater effluent, urban landscape irrigation, changes to urban vegetative cover area and type, urban soil alteration, inter-basin transfers of water, interactions with combined sewer infrastructure, and interactions with leaky water infrastructure. In our national-scale analysis, no attempt was made to isolate specific urbanization processes, other than eliminating regulation and diversion, but rather to describe trends found across the United States in watersheds broadly affected by urbanization processes.

This work would be complemented by studies carefully isolating specific mechanisms of flow change in urbanizing watersheds (e.g., Jefferson et al., 2017 discuss study design for isolation of stormwater management effects on flow).

Our focus was on long-term temporal trends in streamflow with increasing urban land use in watersheds, which necessitated using daily streamflow for our analysis. Although instantaneous discharge values have a comparatively short record, a fruitful avenue for future work would be an investigation of temporal and spatial (cross-city) trends in instantaneous values. Especially for small, urban watersheds, the 1-day maximum for daily streamflow obscures the magnitude of the flashy urban hydrograph response, in which storm responses may be on the order of minutes rather than days.

5 CONCLUSIONS

In this work, we examined 53 daily streamgage records in watersheds during 20 years of peak urbanization between 1939 and 2016, pairing USGS GAGES-II watershed characteristics with newly released historical housing density in each watershed. Trends across the entire flow duration curve in urbanizing watersheds were compared with trends over the same period of analysis for nearby reference gages. In summary:

1. Urbanization, as measured by increases in housing density, has a heterogeneous effect on the flow duration curve. In every region of the U.S., there are both increases and decreases observed for high flows and low flows (Figure 7).
2. Watersheds that were in semi-arid or arid areas of the U.S. had some of the largest observed flow trends for the gages analyzed. Near Tucson, AZ, and Colorado Springs, CO, during urbanization a watershed had a trend where flow increased more than 30 times over 20 years at flows between the 85^{th} and 95^{th} percentiles.
3. Other large trend slopes were associated with water supply infrastructure and wastewater infrastructure changes (e.g., Valley Stream, in Long Island, NY).

4. Processes of urbanization that affect urban streamflow go far beyond impervious surface cover. In fact, the most extreme changes in streamflow with urbanization were not associated with the largest increases in impervious surface cover during urbanization.
5. When reference trends were subtracted from urbanizing trends to yield urbanization-only trends, increasing trends in high flows were common (median of 1.2% flow increase per year over a 20-year peak urbanization period for maximum day flow), although not universal.
6. Trends in low flows in urbanizing watersheds varied more widely than for high flows, as low flows are sensitive to a wider range of urbanization processes than high flows. Flow at the 10th non-exceedance percentile had an upward urbanization-only trend at 27 of 53 gages (51%), whereas other watersheds had downward or no trends.
7. Directions for future work include examining spatial and temporal trends in instantaneous flow in urbanizing and stable urban watersheds, isolating specific urbanization processes and effects on flow changes over time, and investigating applicability of these findings to other urban areas.

ACKNOWLEDGEMENTS

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APPENDIX A

Table A1. Urbanizing and reference gages station numbers, station names, drainage areas, average annual precipitation, dominant geology type from the Reed Bush classification (where G is granitic, S is sedimentary, and Q is Quaternary), distance between urbanizing and reference gages, and start and end dates of periods of analysis. Drainage areas are based on information in the USGS GAGES-II dataset.

Urbanizing										**Reference**					
Station ID	Station name	Drainage area (sq km)	Average annual precipitation (cm)	Dominant geology	Starting housing density (units/km^2)	Ending housing density (units/km^2)	Analysis period start	Analysis period end	Distance between urbanizing and reference station (km)	Station ID	Station name	Drainage area (sq km)	Average annual precipitation (cm)	Dominant geology	Minimization function
01105600	OLD SWAMP RIVER NEAR SOUTH WEYMOUTH, MA	13	119	G	172	281	5/20/1966	5/20/1986	109	01118300	PENDLETON HILL BROOK NEAR CLARKS FALLS, CT.	10	127	G	115
01300500	BEAVER SWAMP BROOK AT MAMARONECK NY	12	125	S	223	350	3/31/1945	3/31/1965	112	01188000	BURLINGTON BROOK NEAR BURLINGTON, CT.	11	136	S	120
01302500	GLEN COVE CREEK AT GLEN COVE NY	30	125	Q	107	220	3/31/1945	3/31/1965	117	01188000	BURLINGTON BROOK NEAR	11	136	S	239

										BURLINGTON, CT.				
01305500	SWAN RIVER AT EAST PATCHOGUE NY	21	125	Q	100	247	3/31/1965	3/31/1985	50	01208950	SASCO BROOK NEAR SOUTHPORT, CT.	19	128	S	151
01306500	CONNETQUOT RIVER NEAR OAKDALE NY	72	123	Q	81	257	9/30/1954	9/30/1974	102	01194500	EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME, CT.	58	131	S	210
01307000	CHAMPLIN CREEK AT ISLIP NY	14	123	Q	73	257	6/29/1948	6/29/1968	118	01188000	BURLINGTON BROOK NEAR BURLINGTON, CT.	11	136	S	233
01307500	PENATAQUIT CREEK AT BAY SHORE NY	11	123	Q	80	312	8/22/1945	8/22/1965	120	01188000	BURLINGTON BROOK NEAR BURLINGTON, CT.	11	136	S	233
01308000	SAMPAWAMS CREEK AT BABYLON NY	58	123	Q	43	214	3/31/1945	3/31/1965	115	01194500	EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME, CT.	58	131	S	220
01309000	SANTAPOGUE CREEK AT LINDENHURST NY	10	124	Q	86	301	6/24/1947	6/24/1967	126	01188000	BURLINGTON BROOK NEAR BURLINGTON, CT.	11	136	S	238
01309500	MASSAPEQUA CREEK AT MASSAPEQUA NY	95	124	Q	57	282	11/30/1939	11/30/1959	125	01194500	EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME, CT.	58	131	S	243

01310000	BELLMORE CREEK AT BELLMORE NY	40	125	Q	263	812	3/31/1945	3/31/1965	131	01194000	EIGHTMILE R AT NORTH PLAIN, CT.	52	132	S	238
01310500	EAST MEADOW BROOK AT FREEPORT NY	78	125	Q	84	354	11/13/1942	11/13/1962	134	01194500	EAST BRANCH EIGHTMILE RIVER NEAR NORTH LYME, CT.	58	131	S	242
01311000	PINES BROOK AT MALVERNE NY	26	125	Q	333	700	3/31/1945	3/31/1965	138	01188000	BURLINGTON BROOK NEAR BURLINGTON, CT.	11	136	S	256
01311500	VALLEY STREAM AT VALLEY STREAM NY	18	124	Q	898	1288	7/1/1954	7/1/1974	110	01466500	MCDONALDS BRANCH IN LEBANON STATE FOREST NJ	5	118	S	222
01585100	WHITEMARSH RUN AT WHITE MARSH, MD	20	120	S	195	509	3/31/1965	3/31/1985	38	01493500	MORGAN CREEK NEAR KENNEDYVILLE, MD	33	114	S	51
01585400	BRIEN RUN AT STEMMERS RUN, MD	5	117	S	276	389	5/1/1958	5/1/1978	33	01583000	SLADE RUN NEAR GLYNDON, MD	5	114	S	34
01589330	DEAD RUN AT FRANKLINTOWN, MD	14	115	S	185	393	10/1/1959	10/1/1979	22	01583000	SLADE RUN NEAR GLYNDON, MD	5	114	S	27
01645200	WATTS BRANCH AT ROCKVILLE, MD	10	109	S	152	301	9/29/1967	9/29/1987	59	01658500	S F QUANTICO CREEK NEAR INDEPENDENT HILL, VA	19	110	S	69

01653500	HENSON CREEK AT OXON HILL, MD	45	109	S	124	421	3/31/1955	3/31/1975	45	01658500	S F QUANTICO CREEK NEAR INDEPENDENT HILL, VA	19	110	S	60
02234384	SOLDIER CREEK NR LONGWOOD, FLA.	46	133	S	216	363	10/1/1986	10/1/2006	48	02266200	WHITTENHORS E CREEK NR VINELAND, FLA.	26	129	S	57
02234400	GEE CREEK NR LONGWOOD, FLA.	43	132	S	264	400	8/12/1985	8/12/2005	48	02266200	WHITTENHORS E CREEK NR VINELAND, FLA.	26	129	S	55
02234990	LITTLE WEKIVA RIVER NR ALTAMONTE SPRINGS, FL	110	131	S	346	528	10/1/1982	10/1/2002	43	02236500	BIG CREEK NEAR CLERMONT, FL	14 7	129	S	55
02301750	DELANEY CREEK NEAR TAMPA FL	36	131	S	294	427	3/31/1995	3/31/2015	59	02297155	HORSE CREEK NEAR MYAKKA HEAD FL	94	134	S	154
03084000	Abers Creek near Murrysville, PA	11	104	S	152	267	10/1/1948	10/1/1968	43	03083000	Green Lick Run at Green Lick Reservoir, PA	8	117	S	62
03298150	CHENOWETH RUN AT GELHAUS LANE NEAR FERN CREEK, KY	30	120	S	208	299	1/23/1996	1/23/2016	69	03302680	WEST FORK BLUE RIVER AT SALEM, IND.	50	116	S	83
03353600	LITTLE EAGLE CREEK AT SPEEDWAY, IND.	64	101	S	359	511	3/31/1985	3/31/2005	43	03357350	PLUM CREEK NEAR BAINBRIDGE, IND.	8	107	S	95
03353637	LITTLE BUCK CREEK NEAR INDIANAPOLIS, IN	45	103	S	283	418	3/31/1995	3/31/2015	47	03357350	PLUM CREEK NEAR BAINBRIDGE, IND.	8	107	S	79

04087204	OAK CREEK AT SOUTH MILWAUKEE, WI	67	87	S	144	206	10/1/1963	10/1/1983	327	05454000	Rapid Creek near Iowa City, IA	65	92	S	330
04087220	ROOT RIVER NEAR FRANKLIN, WI	128	87	S	181	266	10/1/1963	10/1/1983	316	05454000	Rapid Creek near Iowa City, IA	65	92	S	349
04163400	PLUM BROOK AT UTICA, MI	47	82	S	98	257	7/1/1965	7/1/1985	22	04161580	STONY CREEK NEAR ROMEO, MI	64	80	S	29
04166300	UPPER RIVER ROUGE AT FARMINGTON, MI	46	81	S	143	308	3/31/1975	3/31/1995	44	04161580	STONY CREEK NEAR ROMEO, MI	64	80	S	52
05529500	MC DONALD CREEK NEAR MOUNT PROSPECT, IL	22	93	S	258	471	8/13/1952	8/13/1972	97	05526500	TERRY CREEK NEAR CUSTER PARK, IL	31	96	S	102
05530000	WELLER CREEK AT DES PLAINES, IL	33	93	S	433	721	10/1/1950	10/1/1970	92	05526500	TERRY CREEK NEAR CUSTER PARK, IL	31	96	S	93
05532000	ADDISON CREEK AT BELLWOOD, IL	47	94	S	295	470	10/1/1951	10/1/1971	75	05526500	TERRY CREEK NEAR CUSTER PARK, IL	31	96	S	80
05533000	FLAG CREEK NEAR WILLOW SPRINGS, IL	43	97	S	279	428	3/31/1965	3/31/1985	221	04105700	AUGUSTA CREEK NEAR AUGUSTA, MI	98	94	S	293
05535070	SKOKIE RIVER NEAR HIGHLAND PARK, IL	52	91	S	147	222	8/21/1967	8/21/1987	203	04105700	AUGUSTA CREEK NEAR AUGUSTA, MI	98	94	S	245
05536340	MIDLOTHIAN CREEK AT OAK FOREST, IL	33	97	S	289	428	3/31/1965	3/31/1985	213	04105700	AUGUSTA CREEK NEAR AUGUSTA, MI	98	94	S	342

05536500	TINLEY CREEK NEAR PALOS PARK, IL	29	97	S	218	337	3/31/1965	3/31/1985	309	05454000	Rapid Creek near Iowa City, IA	65	92	S	357
05540275	SPRING BROOK AT 87TH STREET NEAR NAPERVILLE, IL	25	96	S	156	308	10/1/1987	10/1/2007	250	03357350	PLUM CREEK NEAR BAINBRIDGE, IND.	8	107	S	275
07103990	COTTONWOOD CREEK AT MOUTH, AT PIKEVIEW, CO.	51	49	S	248	427	3/31/1995	3/31/2015	25	07105945	ROCK CREEK ABOVE FORT CARSON RESERVATION, CO.	17	57	G	159
07104500	TEMPLETON GAP FLOODWAY AT COLORADO SPRINGS, CO.	23	47	S	79	446	9/29/1961	9/29/1981	117	06730300	COAL CREEK NEAR PLAINVIEW, CO.	39	59	G	261
08061700	Duck Ck nr Garland, TX	82	102	S	256	538	3/31/1965	3/31/1985	193	08088300	Briar Ck nr Graham, TX	66	78	S	251
08075500	Sims Bayou at Houston, TX	162	130	Q	154	280	3/31/1965	3/31/1985	145	08031000	Cow Bayou nr Mauriceville, TX	231	149	Q	202
08075730	Vince Bayou at Pasadena, TX	24	135	Q	361	575	10/1/1971	10/1/1991	303	08103900	S Fk Rocky Ck nr Briggs, TX	86	81	S	779
08076000	Greens Bayou nr Houston, TX	154	127	Q	62	260	3/31/1965	3/31/1985	138	08031000	Cow Bayou nr Mauriceville, TX	231	149	Q	214
08076500	Halls Bayou at Houston, TX	75	128	Q	154	341	3/31/1965	3/31/1985	144	08033300	Piney Ck nr Groveton, TX	207	122	S	484
08157000	Waller Ck at 38th St, Austin, TX	6	87	S	561	847	10/23/1960	10/23/1980	335	08088300	Briar Ck nr Graham, TX	66	78	S	946
08157500	Waller Ck at 23rd St, Austin, TX	11	86	S	590	951	10/23/1960	10/23/1980	336	08088300	Briar Ck nr Graham, TX	66	78	S	629
09483000	TUCSON ARROYO AT VINE AVE, AT TUCSON, AZ.	20	31	Q	142	444	3/31/1945	3/31/1965	17	09484000	SABINO CREEK NEAR TUCSON, AZ.	104	76	G	1108

11023340	LOS PENASQUITOS C NR POWAY CA	110	39	G	88	251	3/31/1975	3/31/1995	127	10257600	MISSION C NR DESERT HOT SPRINGS CA	93	55	G	196
11047500	ALISO C A EL TORO CA	23	44	S	19	309	9/29/1960	9/29/1980	123	10255810	BORREGO PALM C NR BORREGO SPRINGS CA	56	43	S	172
11102000	MISSION C NR MONTEBELLO CA	16	40	Q	335	714	3/31/1945	3/31/1965	39	11096500	LITTLE TUJUNGA C NR SAN FERNANDO CA	55	56	G	298
11162720	COLMA C A SOUTH SAN FRANCISCO CA	29	67	S	459	825	10/1/1963	10/1/1983	36	11180500	DRY C A UNION CITY CA	24	67	S	37

APPENDIX B

To test whether the difference between the urbanizing and reference trends was significant, a Mann-Kendall trend test was used to test for slope coefficient $\beta_{1,i} = 0$ in

$$\frac{Q_{u,i}-\overline{Q_{u,i}}}{sd_{u,i}} - \frac{Q_{r,i}-\overline{Q_{r,i}}}{sd_{r,i}} = \beta_{0,i} + \beta_{1,i}\, t \quad \text{(A1)}$$

where Q_i indicates streamflow at quantile *i* (where *i* ranges from 1 to 365), subscript *u* indicates urban and *r* indicates reference, $\bar{Q}$ and sd indicate the mean and standard deviation of streamflow at a given quantile and urbanizing or reference gage, $\beta_{0,i}$ is the combined intercept and error term for quantile *i*, $\beta_{1,i}$ is the slope for quantile *i*, and *t* is time in years.

Equation A1 was used to test the significance of the difference in trends, but the magnitude of the slope value β_1 does not describe the slope in useful terms. So instead, we described the magnitude of the difference in slopes represented in percent terms. First, the Theil-Sen slope estimator was applied to natural logarithm-transformed streamflow,

$$\ln(Q_t) = \beta_0 + \beta_1\, t \quad \text{(A2)}$$

where Q_t is streamflow (Q) [cms] at time *t*, β_0 is a combined term for the intercept and the error and is not estimated here, β_1 is the slope estimated using the Theil-Sen slope estimator [1/year] (note that these coefficients are not the same values as those in Equation A1), and *t* is time in years. Equation (A2) can also be written, after exponentiation, as:

$$Q_t = e^{\beta_0}\, e^{\beta_1 t} \quad \text{(A3)}$$

For the year after *t*, *t* + 1, we have:

$$\ln(Q_{t+1}) = \beta_0 + \beta_1\,(t+1) \quad \text{(A4).}$$

By exponentiating Equation (A3), we get:

$$Q_{t+1} = e^{\beta_0}\, e^{\beta_1 t} e^{\beta_1} = Q_t e^{\beta_1} \quad \text{(A5).}$$

Therefore, the slope expressed in a percent change in *Q* per year, $100 * \left(\frac{Q_{t+1}-Q_t}{Q_t}\right)$, can be found as:

$$100 * \left(\frac{Q_{t+1}-Q_t}{Q_t}\right) = (e^{\beta_1} - 1) * 100 \quad \text{(A6).}$$

REFERENCES CITED

Barron, O. V., Froend, R., Hodgson, G., Ali, R., Dawes, W., Davies, P., & McFarlane, D. (2013). Projected risks to groundwater-dependent terrestrial vegetation caused by changing climate and groundwater abstraction in the Central Perth Basin, Western Australia. *Hydrological Processes*, 5513–5529. https://doi.org/10.1002/hyp.10014

Beighley, R. E., & Moglen, G. E. (2002). Trend Assessment in Rainfall-Runoff Behavior in Urbanizing Watersheds. *Journal of Hydrologic Engineering*, *7*(1), 27. https://doi.org/10.1061/(ASCE)1084-0699(2002)7:1(27)

Bhaskar, A. S., Hogan, D. M., & Archfield, S. A. (2016). Urban base flow with Low Impact Development. *Hydrological Processes*, *30*(18), 3156–3171. https://doi.org/10.1002/hyp.10808

Bhaskar, A. S., Beesley, L., Burns, M. J., Fletcher, T. D., Hamel, P., Oldham, C. E., & Roy, A. H. (2016). Will it rise or will it fall? Managing the complex effects of urbanization on base flow. *Freshwater Science*, *35*(1), 293–310. https://doi.org/10.1086/685084

Bhaskar, A. S. (2020). Analysis codes to conduct Quantile-Kendall trend analysis across flow duration curve of streamflow in urbanizing watersheds across U.S., HydroShare, https://doi.org/10.4211/hs.2279cac6748944d39035dacb6c2c8a85.

Bishop, P. L., Hively, W. D., Stedinger, J. R., Rafferty, M. R., Lojpersberger, J. L., & Bloomfield, J. A. (2005). Multivariate Analysis of Paired Watershed Data to Evaluate Agricultural Best Management Practice Effects on Stream Water Phosphorus. *Journal of Environmental Quality*, *34*(3), 1087–1101. https://doi.org/10.2134/jeq2004.0194

Bosch, J. M., & Hewlett, J. D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, *55*(1), 3–23. https://doi.org/10.1016/0022-1694(82)90117-2

Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., & Vertessy, R. A. (2005). A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. *Journal of Hydrology*, *310*(1–4), 28–61. https://doi.org/10.1016/j.jhydrol.2004.12.010

Brown, L. R., Cuffney, T. F., Coles, J. F., Fitzpatrick, F., McMahon, G., Steuer, J., et al. (2009). Urban streams across the USA: lessons learned from studies in 9 metropolitan areas. *Journal of the North American Benthological Society*, *28*(4), 1051–1069. https://doi.org/10.1899/08-153.1

Dudley, R. W., Hirsch, R. M., Archfield, S. A., Blum, A. G., & Renard, B. (2020). Low streamflow trends at human-impacted and reference basins in the United States. *Journal of Hydrology*, *580*, 124254. https://doi.org/10.1016/j.jhydrol.2019.124254

Elmore, A. J., & Kaushal, S. S. (2008). Disappearing headwaters: patterns of stream burial due to urbanization. *Frontiers in Ecology and the Environment*, *6*(6), 308–312. https://doi.org/10.1890/070101

Falcone, J. A. (2011). *GAGES-II: Geospatial attributes of gages for evaluating streamflow*. US Geological Survey. Retrieved from https://pubs.er.usgs.gov/publication/70046617

Falcone, J. A. (2015). U.S. Conterminous Wall-to-Wall Anthropogenic Land Use Trends (NWALT), 1974–2012. https://doi.org/10.3133/ds948

Falcone, J. A. (2017). U.S. Geological Survey GAGES-II time series data from consistent sources of land use, water use, agriculture, timber activities, dam removals, and other historical anthropogenic influences: U.S. Geological Survey data release. Retrieved from https://doi.org/10.5066/F7HQ3XS4

Ferguson, B. K., & Suckling, P. W. (1990). Changing rainfall-runoff relationships in the urbanizing Peachtree Creek watershed, Atlanta, Georgia. *Journal of the American Water Resources Association*, *26*(2), 313–322. https://doi.org/10.1111/j.1752-1688.1990.tb01374.x

Gallo, E. L., Brooks, P. D., Lohse, K. A., & McLain, J. E. T. (2013). Land cover controls on summer discharge and runoff solution chemistry of semi-arid urban catchments. *Journal of Hydrology*, *485*, 37–53. https://doi.org/10.1016/j.jhydrol.2012.11.054

Garber, M. S., & Sulam, D. J. (1975). *Factors affecting declining water levels in a sewered area of Nassau County, New York* (USGS Numbered Series No. 75–290). [s.n.],. Retrieved from http://pubs.er.usgs.gov/publication/ofr75290

Gotvald, A. J. (2016). *Selected low-flow frequency statistics for continuous-record streamgages in Georgia, 2013* (USGS Numbered Series No. 2016–5037). *Selected low-flow frequency statistics for continuous-record streamgages in Georgia, 2013* (Vol. 2016–5037). Reston, VA: U.S. Geological Survey. https://doi.org/10.3133/sir20165037

Hale, R. L., Turnbull, L., Earl, S. R., Childers, D. L., & Grimm, N. B. (2015). Stormwater Infrastructure Controls Runoff and Dissolved Material Export from Arid Urban Watersheds. *Ecosystems*, *18*(1), 62–75. https://doi.org/10.1007/s10021-014-9812-2

Hale, R. L., Scoggins, M., Smucker, N. J., & Suchy, A. (2016). Effects of climate on the expression of the urban stream syndrome. *Freshwater Science*, *35*(1), 421–428. https://doi.org/10.1086/684594

Hardison, E. C., O'Driscoll, M. A., DeLoatch, J. P., Howard, R. J., & Brinson, M. M. (2009). Urban Land Use, Channel Incision, and Water Table Decline Along Coastal Plain Streams, North Carolina1. *Journal of the American Water Resources Association*, *45*(4), 1032–1046. https://doi.org/10.1111/j.1752-1688.2009.00345.x

Harris, E. E., & Rantz, S. E. (1964). *Effect of urban growth on streamflow regimen of Permanente Creek, Santa Clara County, California* (No. WSP-1591-B). United States Geological Survey. Retrieved from http://pubs.er.usgs.gov/publication/wsp1591B

Helsel, D. R., & Hirsch, R. M. (2002). *Statistical methods in water resources* (Vol. 323). US Geological survey Reston, VA.

Hirsch, R. M., & DeCicco, L. A. (2015). User guide to Exploration and Graphics for RivEr Trends (EGRET) and dataRetrieval: R packages for hydrologic data. In *Techniques and Methods*. Reston, VA: U.S. Geological Survey. Retrieved from https://pubs.usgs.gov/tm/04/a10/

Hollis, G. E. (1977). Water Yield Changes After The Urbanization Of The Canon's Brook Catchment, Harlow, England. *Hydrological Sciences Journal*, *22*(1), 61–75.

Hopkins, K. G., Morse, N. B., Bain, D. J., Bettez, N. D., Grimm, N. B., Morse, J. L., Palta, M. M., et al. (2015). Assessment of Regional Variation in Streamflow Responses to Urbanization and the Persistence of Physiography. *Environmental Science & Technology*, *49*(5), 2724–2732. https://doi.org/10.1021/es505389y

Hopkins, K. G., Morse, N. B., Bain, D. J., Bettez, N. D., Grimm, N. B., Morse, J. L., & Palta, M. M. (2015). Type and timing of stream flow changes in urbanizing watersheds in the Eastern U.S. *Elem Sci Anth*, *3*(0). https://doi.org/10.12952/journal.elementa.000056

Illinois Department of Transportation. (2009). *Elgin O'Hare - West Bypass Study Cook and DuPage Counties, Illinois Tier One Draft Environmental Impact Statement* (No. Project Number: P-91-443-06) (p. 306). Illinois Department of Transportation. Retrieved from https://apps.dot.illinois.gov/eplan/desenv/environment/Elgin-Ohare%20Final%20EIS/Tier%20One/Tier%20One%20Draft%20EIS/EOWB_DEIS_Sept2009.pdf

Jakovljev, V. V., Svirenko, L. P., Chebanov, O. J., & Spirin, O. I. (2002). Rising Groundwater Levels in North-Eastern Ukraine: Hazardous Trends in Urban Areas. In K. W. F. Howard & R. G. Israfilov (Eds.), *Current Problems of Hydrogeology in Urban Areas, Urban Agglomerates and Industrial Centres* (pp. 221–241). Springer Netherlands. Retrieved from http://link.springer.com/chapter/10.1007/978-94-010-0409-1_12

Jefferson, A. J., Bhaskar, A. S., Hopkins, K. G., Fanelli, R., Avellaneda, P. M., & McMillan, S. K. (2017). Stormwater management network effectiveness and implications for urban watershed function: A critical review. *Hydrological Processes*, *31*(23), 4056–4080. https://doi.org/10.1002/hyp.11347

Jennings, D. B., & Jarnagin, S. T. (2002). Changes in anthropogenic impervious surfaces, precipitation and daily streamflow discharge: a historical perspective in a mid-atlantic subwatershed. *Landscape Ecology*, *17*(5), 471–489. https://doi.org/10.1023/A:1021211114125

Jones, J. A., & Grant, G. E. (1996). Peak Flow Responses to Clear-Cutting and Roads in Small and Large Basins, Western Cascades, Oregon. *Water Resources Research*, *32*(4), 959–974. https://doi.org/10.1029/95WR03493

King, K. W., Smiley, P. C., Baker, B. J., & Fausey, N. R. (2008). Validation of paired watersheds for assessing conservation practices in the Upper Big Walnut Creek watershed, Ohio. *Journal of Soil and Water Conservation*, *63*(6), 380–395. https://doi.org/10.2489/jswc.63.6.380

Konrad, C. P., & Booth, D. B. (2005). Hydrologic changes in urban streams and their ecological significance. *American Fisheries Society Symposium*, *47*, 157–177.

LaTour, J. K. (1993). *Contribution of return flows to streamflow in selected stream reaches in Illinois, 1988-89*. US Geological Survey; Earth Science Information Center, Open-File Reports ….

Leopold, L. B. (1968). *Hydrology for urban land planning--A guidebook on the hydrologic effects of urban land use* (Circular 554) (p. 18). Washington D.C.: U.S. Geological Survey.

Loftis, J. C., MacDonald, L. H., Streett, S., Iyer, H. K., & Bunte, K. (2001). Detecting cumulative watershed effects: the statistical power of pairing. *Journal of Hydrology*, *251*(1), 49–64. https://doi.org/10.1016/S0022-1694(01)00431-0

McCabe, G. J., & Wolock, D. M. (2002). A step increase in streamflow in the conterminous United States. *Geophysical Research Letters*, *29*(24), 38-1-38–4. https://doi.org/10.1029/2002GL015999

McPhillips, L. E., Earl, S. R., Hale, R. L., & Grimm, N. B. (2019). Urbanization in Arid Central Arizona Watersheds Results in Decreased Stream Flashiness. *Water Resources Research*. https://doi.org/10.1029/2019WR025835

Meierdiercks, K. L., Smith, J. A., Baeck, M. L., & Miller, A. J. (2010). Heterogeneity of Hydrologic Response in Urban Watersheds. *Journal of the American Water Resources Association*, *46*(6), 1221–1237. https://doi.org/10.1111/j.1752-1688.2010.00487.x

Meyer, S. C. (2005). Analysis of base flow trends in urban streams, northeastern Illinois, USA. *Hydrogeology Journal*, *13*(5–6), 871–885. https://doi.org/10.1007/s10040-004-0383-8

Niyogi, D., Lei, M., Kishtawal, C., Schmid, P., & Shepherd, M. (2017). Urbanization Impacts on the Summer Heavy Rainfall Climatology over the Eastern United States. *Earth Interactions*, *21*(5), 1–17. https://doi.org/10.1175/EI-D-15-0045.1

NRC. (2009). *Urban Stormwater Management in the United States*. Washington, D.C.: The National Academies Press.

Oudin, L., Salavati, B., Furusho-Percot, C., Ribstein, P., & Saadi, M. (2018). Hydrological impacts of urbanization at the catchment scale. *Journal of Hydrology*, *559*, 774–786. https://doi.org/10.1016/j.jhydrol.2018.02.064

Pluhowski, E. J., & Spinello, A. G. (1978). Impact of sewerage systems on stream base flow and ground-water recharge on Long Island, New York. *U.S. Geological Survey Journal of Research*, *6*(2), 263–271.

PRISM Climate Group, Oregon State U. (n.d.). Retrieved January 26, 2018, from http://www.prism.oregonstate.edu/FAQ/

Prosdocimi, I., Kjeldsen, T. R., & Miller, J. D. (2015). Detection and attribution of urbanization effect on flood extremes using nonstationary flood-frequency models. *Water Resources Research*, *51*(6), 4244–4262. https://doi.org/10.1002/2015WR017065

Reed, J. C., & Bush, C. A. (2001). Generalized geologic map of the conterminous United States The University of Chicago Press Denver. *Colorado (Available from: Http://Pubs. Usgs. Gov/Atlas/Geologic/48States/)*.

Riggs, H. C. (1972). *Low-flow investigations* (Techniques of Water-Resources of the United States Geological Investigations Survey). Washington, DC: U.S. Geological Survey.

Riggs, H. C. (Ed.). (1985). Chapter 9 Low-Flow Characteristics. In *Developments in Water Science* (Vol. 22, pp. 165–175). Elsevier. https://doi.org/10.1016/S0167-5648(08)70520-3

Rose, S., & Peters, N. E. (2001). Effects of urbanization on streamflow in the Atlanta area (Georgia, USA): a comparative hydrological approach. *Hydrological Processes*, *15*(8), 1441–1457. https://doi.org/10.1002/hyp.218

Sharma, A., Wasko, C., & Lettenmaier, D. P. (2018). If Precipitation Extremes Are Increasing, Why Aren't Floods? *Water Resources Research*. https://doi.org/10.1029/2018WR023749

Simmons, D. L., & Reynolds, R. J. (1982). Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. *Journal of the American Water Resources Association*, *18*(5), 797–805. https://doi.org/10.1111/j.1752-1688.1982.tb00075.x

Smith, B. K., & Smith, J. A. (2015). The Flashiest Watersheds in the Contiguous United States. *Journal of Hydrometeorology*, *16*(6), 2365–2381. https://doi.org/10.1175/JHM-D-14-0217.1

Smith, J. A., Baeck, M. L., Meierdiercks, K. L., Nelson, P. A., Miller, A. J., & Holland, E. J. (2005). Field studies of the storm event hydrologic response in an urbanizing watershed. *Water Resources Research*, *41*, 15 PP. https://doi.org/200510.1029/2004WR003712

Soule, Nathan, Parekh Minal L., Kuehr Steven, Amundson Al, Hanna Kanaan, Bare Dan, & Pauley Chris. (2012). Templeton Gap Floodway Levees, Investigation, and Mitigation of Mine Subsidence. *GeoChallenges*. https://doi.org/10.1061/9780784412633.0009

Spinello, A. G., & Simmons, D. L. (1992). *Base flow of 10 south-shore streams, Long Island, New York, 1976-85, and the effects of urbanization on base flow and flow duration* (USGS Numbered Series No. 90–4205). U.S. Geological Survey ; Open-File Reports-ESIC [distributor],. Retrieved from http://pubs.er.usgs.gov/publication/wri904205

Stephens, D. B., Miller, M., Moore, S. J., Umstot, T., & Salvato, D. J. (2012). Decentralized Groundwater Recharge Systems Using Roofwater and Stormwater Runoff. *Journal of the American Water Resources Association*, *48*(1), 134–144. https://doi.org/10.1111/j.1752-1688.2011.00600.x

Townsend-Small, A., Pataki, D. E., Liu, H., Li, Z., Wu, Q., & Thomas, B. (2013). Increasing summer river discharge in southern California, USA linked to urbanization. *Geophysical Research Letters*. https://doi.org/10.1002/grl.50921

Tredway, J. C., & Havlick, D. G. (2017). Assessing the Potential of Low-Impact Development Techniques on Runoff and Streamflow in the Templeton Gap Watershed, Colorado. *The Professional Geographer*, *69*(3), 372–382. https://doi.org/10.1080/00330124.2016.1252272

USEPA. (2012). Los Angeles Area Lakes TMDLs March 2012: Section 9 North, Center and Legg Lakes TMDLs, 29.

USGS. (1957). *Survey Water Supply of the United States 1957. Part 10. The Great Basin.* U.S. Government Printing Office.

USGS. (2018). USGS Water Data for the Nation. https://doi.org/10.5066/F7P55KJN

Van Loon, A. F., Rangecroft, S., Coxon, G., Breña Naranjo, J. A., Van Ogtrop, F., & Van Lanen, H. A. J. (2019). Using paired catchments to quantify the human influence on hydrological droughts. *Hydrology and Earth System Sciences*, *23*(3), 1725–1739. https://doi.org/10.5194/hess-23-1725-2019

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan II, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*(3), 706–723.

Xian, G. Z., Homer, C. G., Dewitz, J., Fry, J., Hossain, N., & Wickham, J. (2011). Change of impervious surface area between 2001 and 2006 in the conterminous United States. *Photogrammetric Engineering and Remote Sensing*, *77*(8), 758–762.

Yue, S., Pilon, P., & Cavadias, G. (2002). Power of the Mann–Kendall and Spearman's rho tests for detecting monotonic trends in hydrological series. *Journal of Hydrology*, *259*(1), 254–271. https://doi.org/10.1016/S0022-1694(01)00594-7