Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States

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Abstract
This study investigates the long-term trends in precipitation, runoff and runoff coefficient in major urban watersheds in the United States. The seasonal Mann–Kendall trend test was performed on monthly precipitation, runoff and runoff coefficient data from 1950 to 2009 obtained from 62 urban watersheds covering 21 major urban centers in the United States. The results indicate that only five out of 21 urban centers in the United States showed an uptrend in precipitation. Twelve urban centers showed an uptrend in runoff coefficient. However, six urban centers did not show any trend in runoff coefficient, and three urban centers showed a significant downtrend. The highest rate of change in precipitation, runoff and runoff coefficient was observed in the Houston urban watershed. Based on the results obtained, we also attributed plausible causes for the trends. Our analysis indicated that while a human only influence is observed in most of the urban watersheds, a combined climate and human influence is observed in the central United States.

Keywords: precipitation, urban runoff, climate, human impact, Mann–Kendall

1. Introduction

Over the last century, humans and climate have significantly affected the hydrologic cycle and water availability [1]. Recently, several researchers have observed intensification of the hydrologic cycle at regional and continental scales [2, 3]. Urban areas around the world are rapidly growing and it is expected that more than 60% of the global population will live in urban watersheds by 2030 [4]. In the United States alone, around 80% of the population lives in urban areas (www.census.gov). Up to 20% of the land area in the United States contributes to the public water supply and 8% of this land is urban or semi-urban watersheds [5]. Furthermore, a large proportion of surface water flows through urban watersheds. Urban land cover disrupts the surface water balance and influences the partitioning of rainfall into surface runoff, evapotranspiration, soil moisture, and groundwater flow. Urbanization results in an increase in surface runoff and a decrease in evapotranspiration and groundwater flow [6, 7]. Moreover, water demand in urban areas for human consumption, industries, and irrigation directly affect water supply through water withdrawals and diversions. Because of these complex interactions, it becomes important to understand the changes in trends in rainfall and runoff in
the urban watersheds, especially for water availability and security.

Long-term trends in precipitation ($P$), runoff ($Q$) and temperature have been studied using station data [8–11]. However, information on nationwide trends in monthly $P$ and $Q$ especially in the major urban watersheds is limited. This study analyzed long-term trends in urban $P$, $Q$, and runoff coefficient ($Q/P$) over the period 1950–2009. This study is part of the US Department of the Interior’s WaterSMART (Sustain and Manage America’s Resources for Tomorrow) project, whose mandate is to ‘help water managers to plan for climate change and the other threats to our water supplies, and take action to secure our water resources for the communities, economies, and the ecosystems they support’. The objectives of this research are to (a) investigate the trends in $P$, $Q$, and $Q/P$ in urban watersheds, and (b) attribute plausible causes (climate or human) for the trends. The results from this study will help urban watershed managers understand the potential impacts of trends on water availability.

2. Data and methods

Mean precipitation for the major urban watersheds over the period 1950–2009 was extracted from 4 km monthly PRISM precipitation datasets [12, 13]. PRISM is the US Department of Agriculture’s official climatological data and is considered the highest quality spatial climate data over the United States [14]. Mean monthly 4 km gridded runoff data for each urban watershed was processed from hydrologic unit code (HUC) 8 runoff data by combining historical flow data from stream gauges, their drainage basins, and the boundaries of the HUCs. This data is obtained from US Geological Survey’s (USGS) Water Watch website [15]. Sixty-two HUC8 urban watersheds (each with an average area of 4000 km$^2$) covering 21 major urban centers in the United States were chosen for the analysis. Urban areas (figure 1) were derived by combining the National Land Cover Dataset (NLCD 2006) Developed classes 21 through 24 [16]. Two or more HUC8 watersheds were merged where the urban center was found to be larger than the HUC8 watershed. Monthly total precipitation ($P_\mu$) and runoff ($Q_\mu$) data for each combined urban center were derived. To understand if the trend in runoff ($Q_\mu$) is due to the change in precipitation ($P_\mu$) or due to other factors (land cover change), we derived runoff coefficient ($Q_\mu/P_\mu$). Finally, trends in $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$ were estimated using the Seasonal Mann–Kendall (SMK) trend test [17]. SMK statistic, variance, and 5% significance level ($p$-value ≤ 0.05) were estimated. Variance was corrected for ties and serial dependency [17].

The analysis of precipitation trends is important for monitoring the hydrologic response of urban watersheds to climate change. Similarly, the analysis of runoff trends is
important for understanding human influence on hydrology. While observed trends in \( P_\mu \) can be associated to the change in climate, the trends in \( Q_\mu/P_\mu \) cannot entirely be due to the change in the climatic variables but may be due to a combination of climatic and water management effects (human influence) [8, 18]. Hence, we attributed the causes for the trends in \( P_\mu \) and \( Q_\mu/P_\mu \) as climate and human influence on urban watersheds. Such attribution is important as changes in climate and land use have larger and more direct impacts on hydrology than the impact of rising CO\(_2\) levels [19]. Assuming no significant change in evaporative demand over the urban watersheds, (a) ± trend in \( P_\mu \) alone can be attributed to climate, (b) ± trend in \( Q_\mu/P_\mu \) alone indicates human influence, and (c) ± trend in both \( P_\mu \) and \( Q_\mu/P_\mu \) would indicate a combination of climate and human influence on the urban watershed. A list of plausible causes for the trends is given in table 1.

### 3. Results and discussion

#### 3.1. Mean and rate of change in \( P_\mu \), \( Q_\mu \), and \( Q_\mu/P_\mu \)

Long-term (1950–2009) mean \( P_\mu \), \( Q_\mu \), and \( Q_\mu/P_\mu \) are presented in table 2. Out of 21 major urban watersheds, the Las Vegas had the lowest mean annual \( P_\mu \) (184 mm yr\(^{-1}\)) and the Seattle had the highest annual \( P_\mu \) (1532 mm yr\(^{-1}\)). Urban watersheds for Phoenix and Portland generated the lowest and highest amount of runoff with 9 and 1237 mm yr\(^{-1}\) and runoff coefficients of 2% and 88%, respectively. The slope of regression fit obtained from the annual estimates of \( P_\mu \), \( Q_\mu \),
and $Q_\mu/P_\mu$ for each urban watershed was used to estimate rate of change (ROC) for each of the three parameters. The ROC for $P_\mu$ showed a decreasing rate in the Seattle, Portland, Atlanta, and Tampa urban watersheds; no-change in San Diego and Phoenix; and a positive change in the rest of the 15 urban centers. The ROC for $Q_\mu$ ranged from a decreasing rate of 8.1 mm yr$^{-1}$ for Portland to an increasing rate in runoff up to 5.6 mm yr$^{-1}$ for Houston. Water managers can convert these numbers to actual volume of runoff for example, Houston ROC in runoff (5.6 mm yr$^{-1}$) accounts for nearly 10 billion gallons yr$^{-1}$, which is equivalent to nearly 25 days of water supply for the City of Houston, estimated at the current average rate of 390 million gallons per day consumption (www.houstontx.gov). The ROC for $Q_\mu/P_\mu$ ranged from a $-4\%$ for the Portland watersheds to a $5\%$ for the Chicago urban watersheds.

3.2. Trends in monthly precipitation ($P_\mu$)

Seasonal Mann–Kendall trend test results for urban centers from the western and eastern United States (table 2) indicated that all the major watersheds showed no trends in $P_\mu$. The absence of trends in California and Nevada urban centers is consistent with the observations made by [20] over the period 1984–2006. A downturn was found in $P$ over the Pacific Northwest region during the 1948–1988 and 1916–2003 periods by [8, 21] respectively. Though we found similar downturns in the Seattle and Portland urban watersheds, these trends were not found to be statistically significant over 1950–2009. A lack of trends in $P_\mu$ in the eastern United States is in line with the findings from [22, 23]. A no-change in trend in the Precipitation data for the northeastern United States was found by [24]. In the central United States, our results indicate that all the major urban watersheds except for the Chicago urban center indicated an uptrend in $P_\mu$. These results further reinforce the findings of a general uptrend in precipitation in the Minnesota region [25]; an uptrend in precipitation during 1931–1996 over the central Great Plains and southern Great Lakes basins [22, 23]; and an uptrend in precipitation over the southern United States [26]. No-change in $P_\mu$ trend in the western and eastern United States and an uptrend in the central United States indicates that precipitation in the 20th century in general has increased in the United States. This result is consistent with the earlier findings [8, 27, 28]. It is to be noted that the $P_\mu$ trends in urban centers within a geographic region could be different from others in the same region due to differences in the weather systems that influence the precipitation. For example, the $P$ trends (negative) for Seattle and Portland are different from other urban centers in the western United States as they are influenced by Pacific Northwest weather systems and show more coherence with rainfall pattern of British Columbia region [29].

3.3. Trends in monthly runoff ($Q_\mu$) and runoff coefficient ($Q_\mu/P_\mu$)

Seasonal Mann–Kendall trend test results indicated that trends in $Q_\mu$ and $Q_\mu/P_\mu$ over most of the major urban centers were different from the observed $P_\mu$ trends (table 2). Twelve out of 21 urban centers showed a significant uptrend in $Q_\mu$ and $Q_\mu/P_\mu$. In the west, 3 out of 8 urban centers (Los Angeles, San Diego, and Las Vegas) showed a significant uptrend in both $Q_\mu$ and $Q_\mu/P_\mu$. This could be due to increase in urban land cover or due to water imported from other watersheds which is very common in the southwestern United States. Three urban watersheds (Seattle, San Francisco, and Phoenix) showed no-trend in $Q_\mu$ or $Q_\mu/P_\mu$ and two urban watersheds (Portland and Salt Lake City) showed significant downturn. Stream flow data for the period 1914−1993 was analyzed by [9] and observed downturns in runoff in the Pacific Northwest and northern California regions. Our results for 1950–2009 indicate significant downtrends in $Q_\mu$ for Seattle and Portland. However, for Seattle, although $Q_\mu$ was found to be significant, $Q_\mu/P_\mu$ was not statistically significant. While urban watersheds covering Seattle did not show any trend in $Q_\mu/P_\mu$, its sub-watershed, the Puget Sound watershed showed significant downturn in both $Q_\mu$ and $Q_\mu/P_\mu$. On the other hand, urban watersheds covering Portland and Salt Lake City urban centers showed significant downturn in $Q_\mu/P_\mu$. This result is in line with results obtained by [30] for urban basins in the Portland metro area. Our result of a downturn in $Q_\mu/P_\mu$ for Salt Lake City urban watershed can be explained by the findings of [31] who observed that much of the water in these watersheds is diverted for irrigation.

Three out of 7 urban centers in the eastern United States (Philadelphia, New York, and Boston) showed a significant uptrend in both $Q_\mu$ and $Q_\mu/P_\mu$. However, for Washington, DC, only $Q_\mu/P_\mu$ was found to be significant. These results are consistent with [9], who found a general uptrend in runoff in the New England and Mid-Atlantic regions. Urban centers in the southeastern United States showed varied trends. While Atlanta and Miami showed no-trend in $Q_\mu$ and $Q_\mu/P_\mu$, Tampa and St. Petersburg showed a decrease in both $Q_\mu$ and $Q_\mu/P_\mu$ trend. Urban centers in the central United States (Denver, Dallas, Houston, Detroit, and Chicago) except Minneapolis showed a significant uptrend in both $Q_\mu$ and $Q_\mu/P_\mu$. This result corroborates with the fact that stream flow has increased in the central United States [8, 9, 28].

Interestingly, while Chicago urban watersheds do not show any trend in $P_\mu$, these watersheds demonstrate a significant uptrend in both $Q_\mu$ and $Q_\mu/P_\mu$. In the Minneapolis urban watershed, $Q_\mu/P_\mu$ does not show any trend. This means that the trend in $Q_\mu$ is mainly due to increase in $P_\mu$. It was indicated by [32] that Minneapolis is one of the most successful cities to maintain a balance between urban development and natural ecosystems.

3.4. Climate and human influence on the urban watersheds

Results indicate that urban watersheds such as Seattle, San Francisco, Phoenix, Atlanta, and Miami showed no climate or human influence. However, a significant human influence was observed in majority of the other urban watersheds over western and eastern United States. Combined climate and human influence was seen on the urban watersheds in the central United States. However, Minneapolis showed $P_\mu$ only,
indicating climate influence. On the other hand, Chicago showed an uptrend in $Q_\mu/P_\mu$ and no $P_\mu$ trend indicating only human influence [33].

3.5. Limitations and further research

This study only analyzes the trends in monthly total precipitation and does not consider the changes in trends over shorter duration. While some of the increase in $P_\mu$ trends could be attributed to urban heat island [34], distinguishing climate impact and urban heat island on increasing rainfall is beyond the scope of this study. More detailed and focused studies across urban centers are needed to investigate these associations. The urban-to-watershed area fraction (UW AF) would also influence the overall trends in runoff in the urban watershed. The lack of a significant trend in $Q_\mu$, $Q_\mu/P_\mu$ in San Francisco, Phoenix, Atlanta, and Miami could be due to the small UW AF fraction. Caution must be taken while interpreting the importance of trends that are not significant.

A trend in $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$ may not be significant but could have important effects on water resources [18]. In spite of these limitations, the information generated in this study provides useful insights on (a) the changing trends in $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$ and (b) the plausible climate and human factors influencing $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$ trends in the major urban watersheds.

4. Conclusions

The results indicated that urban watersheds in the eastern and the western United States did not show any change in $P_\mu$ trend. However, 5 urban centers in the central United States indicated an uptrend in precipitation. Trends in $Q_\mu$ and $Q_\mu/P_\mu$ over the urban centers were found to be different from $P_\mu$ trends. Twelve out of 21 major centers showed an uptrend in $Q_\mu$ and $Q_\mu/P_\mu$. To understand climate and human influence on urban watersheds, we attributed plausible causes for the trends in $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$. Our analysis indicated that while a human only influence is noted in most of the urban watersheds, a combined climate (increase in $P_\mu$) and human influence (increase in $Q_\mu/P_\mu$) is observed in the most urban watersheds in the central United States. However, quantifying relative climate and human influence on each urban center requires further investigation. Given urban watersheds are changing at a rapid pace, the hydrologic characteristics of these watersheds will continue to change and influence water availability. This study contributes towards meeting WaterSMART project goals by understanding the impact of varying trends in $P_\mu$, $Q_\mu$, and $Q_\mu/P_\mu$ on water availability and management of urban water resources.

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