Impacts of recent climate change on trends in baseflow and stormflow in United States watersheds

Darren L. Ficklin¹,², Scott M. Robeson¹, and Jason H. Knouft³

¹Department of Geography, Indiana University, Bloomington, Indiana, USA, ²Center for Geospatial Data Analysis, Indiana Geological Survey, Bloomington, Indiana, USA, ³Department of Biology, Saint Louis University, St. Louis, Missouri, USA

Abstract Characterizing the impacts of climatic change on hydrologic processes is critical for managing freshwater systems. Specifically, there is a need to evaluate how the two major components of streamflow, baseflow and stormflow, have responded to recent trends in climate. We derive baseflow and stormflow for 674 sites throughout the United States from 1980 to 2010 to examine their associations with precipitation, potential evapotranspiration, and maximum/minimum temperature. The northeastern (NE) and southwestern (SW) United States display consistent trends in baseflow and stormflow: increasing during fall and winter in the NE and decreasing during all seasons in the SW. Trends elsewhere and at other times of the year are more variable but still associated with changes in climate. Counter to expectations, baseflow and stormflow trends throughout the United States tend to change concurrently. These trends are primarily associated with precipitation trends, but increases in PET are influential and likely to become important in the future.

1. Introduction

The quantity and quality of water circulating through riverine systems is fundamentally important to humans and the ecosystems that are dependent on these resources. While analyses of total streamflow have documented meaningful trends in the United States [Kumar et al., 2009; Lins and Slack, 1999; Zhang and Schilling, 2006] and throughout the world [Birsan et al., 2005; Milly et al., 2005; Stahl et al., 2010; Zhang et al., 2001], trends in the constituents of total streamflow—baseflow and stormflow—and their interaction have yet to be examined in detail across large spatial scales. Baseflow is the slowly varying component of streamflow that originates from saturated soil or groundwater flow and is influenced by a combination of climate and basin characteristics. Several studies have examined changes in baseflow due to urbanization [King et al., 2016; Simmons and Reynolds, 1982], land use change [Harr et al., 1982; Price, 2011], and changes in agricultural management changes [Bledgett et al., 1992; Dow, 2007]. Stormflow is typically at higher volume over a short period of time following major precipitation events. Baseflow and stormflow, and their mixing, are essential for proper hyporheic exchange [Cardenas and Wilson, 2007], water quality (i.e., contaminant dilution and sediment flushing [Barnes and Kalita, 2001; Gomez-Velez et al., 2015]), ecosystem structure and function (i.e., water temperature and species diversity [Boulton, 2003; Poff et al., 1997]), and water supply [Hornbeck et al., 1993]. The importance and impacts of baseflow are fully reviewed in Price [2011].

Globally, land-surface air temperature has increased by at least 0.2°C/decade over the past 30 years [Hartmann et al., 2013]. These increases in air temperature have led to a more energized hydrological cycle, which is generally associated with higher saturation water vapor pressures, higher water vapor pressures, and higher precipitation amounts [Hartmann et al., 2013; Karl et al., 2009; Trenberth, 2011]. Also associated with these changes are increases in potential evapotranspiration (PET) in some locations [Ficklin et al., 2015; McCabe and Wolock, 2015; Sheffield et al., 2012], which integrates the evaporative demand from the atmosphere.

While there is an expectation for ongoing climatic change to increase precipitation and PET at large spatial scales, there will be regionally varying expressions of this expectation, with changes in the relative magnitude of precipitation and PET largely determining the regional streamflow response. Given that extreme precipitation events are increasing for some regions in the United States [Kunkel et al., 2003; Prein et al., 2016], increases in stormflow are also expected for those regions. Previous work indicates that baseflow
will change with increases in PET and vegetation, but the sign of this change is unclear due to differences in infiltration rates [Price, 2011]. The relationships between recent PET trends and baseflow and stormflow, however, are unclear.

Using streamflow data across the United States, we estimate the spatial variation in baseflow and stormflow trends from 1980 to 2010. We then associate baseflow and stormflow trends with precipitation, PET, and temperature trends over the same period. Trends in these climate variables can have dramatic effects on streamflow responses. Knowledge of the partitioning of streamflow into baseflow and stormflow, and its change with time, is particularly important for evaluating the impacts of climatic change on water quantity, water quality, and freshwater ecosystems.

2. Materials and Methods
2.1. Streamflow Data
Baseflow and stormflow were estimated using daily streamflow from 1980 to 2010 for 674 United States Geological Survey (USGS) HydroClimatic Data Network-2009 (HCDN) [Lins, 2012; http://water.usgs.gov/osw/hcdn-2009/] gauges throughout the United States. Daily baseflow, stormflow, total streamflow, and the baseflow index (BFI; baseflow divided by total streamflow) were then averaged at the monthly time step for comparison with monthly climate data. HCDN gauges represent natural streamflows that are not under significant human influence (i.e., damming or major land use changes) and are preferred for assessing the relationship between climate and streamflow. Recent streamflow data (2011 to present) have not been screened by the USGS for human influence and are not used. Additionally, streamflow data before 1979 are excluded to match the availability of the PET record (see section 2.3). HCDN watersheds used in this study range in area from 4 to 25,800 km², with 87% of the gauges having no missing data, 9% of the gauges having <10% missing data, and 2% of the gauges having <25% missing data. Newman et al. [2015] include additional climatological and hydrological characteristics of a large portion of this data set.

2.2. Separating Streamflow Into Baseflow and Stormflow
The USGS automated baseflow-separation method HYSEP (hydrograph-separation) [Sloto and Crouse, 1996] was used to separate total streamflow into baseflow and stormflow. The local minimum HYSEP method was used, whereby each daily streamflow value is evaluated to determine if that value is lower than the previous and next day [Sloto and Crouse, 1996]. If so, then that local streamflow minimum is connected by a straight line to other local streamflow minima in the time series. This interpolation procedure is used to estimate a baseflow time series. Stormflow is then estimated by subtracting baseflow from total streamflow.

2.3. Climate Data
Climate data including minimum/maximum air temperature, precipitation, downward solar radiation, wind speed, and specific humidity for the years 1980–2010 were extracted from the University of Idaho Gridded Surface Meteorological Data set (METDATA) [Abatzoglou, 2013] available at a 4 km resolution. Monthly PET was calculated using the Penman-Monteith method using the approach of Allen et al. [1998]. Climatic inputs for estimating Penman-Monteith PET at the 4 km spatial scale are available starting in 1979, but only data starting in 1980 were used so that a full winter season was represented by the first year of data.

2.4. Statistical Analyses
Statistical analyses were performed on hydroclimatological variables averaged over individual seasons (winter: December-January-February, DJF; spring: March-April-May, MAM; summer: June-July-August, JJA; fall: September-October-November, SON). The Mann-Kendall nonparametric trend test [Kendall, 1975; Mann, 1945] was used to determine trends and trend significance from 1980 to 2010. The Mann-Kendall statistic, $Z$, has the same interpretation as other trend-analysis statistics (positive value indicates an increase over time, and negative value indicates a decrease), but because $Z$ is standardized, it is particularly useful for comparing locations where the variable has different magnitudes of variability. While $Z$ does not give the trend rate, the magnitude of $Z$ indicates the consistency of the trend while significance is evaluated by comparing $Z$ to the critical $Z$ value from the standard normal cumulative distribution function [Modarres and de Paulo Rodrigues da Silva, 2007]. Trends with $p$ values $\leq 0.05$ are considered significant.
The climate data were averaged over the upstream watershed area for each gauge to match the streamflow record, resulting in a spatially averaged climate time series for each gauge. For watersheds smaller than the 4 km resolution of the climate data, a spatial buffer was used to incorporate nearby climate data.

3. Results

Trends in total streamflow are not discussed here but are shown in Figure S1 in the supporting information. Our results point to some similarities in the previous work despite different time periods [Groisman et al., 2001; McCabe and Wolock, 2002].

3.1. Trends in Baseflow

Regional clustering of significant baseflow trends from 1980 to 2010 occurs for a number of seasons (Figure 1). While most regions have a mix of positive and negative trends among seasons, the southwestern U.S. consistently exhibits negative trends in baseflow. For the winter season, there are a large number of significant baseflow increases in the northeastern United States and the central/upper Great Plains, while significant baseflow decreases are largely concentrated in the upper Midwest (Michigan and Wisconsin) and the arid/semiarid regions of the western United States. These patterns continue into the spring season; however, many of the trends are no longer significant, though the upper Midwest and southwestern United States continue to show significant decreases in baseflow. Significant baseflow decreases continue into the spring in the southwestern United States and expand into the southern United States. The decrease in baseflow in the southern United States persists into the summer season when significant increases in baseflow arise again in the northern United States, creating spatially opposing signs of baseflow trends. In the upper Great Plains, the significantly increasing summer baseflows are much larger than those in the spring season. Lastly, for the fall season, the significant decreases that were found for the upper Midwest and southwestern United States during the winter season are still apparent and also larger, while significant baseflow increases in the northeastern United States and upper Great Plains are also apparent.

3.2. Trends in Stormflow

While baseflow exhibits positive trends for the winter season in much of the northeastern United States, stormflow trends are not as large or significant. In some cases (mid-Appalachia region), there are significant decreases in stormflow associated with significant increases in baseflow, suggesting an overall shift in their contribution to streamflow. For the upper and central Great Plains, stormflow decreases significantly for the winter season compared to increases in baseflow for the same season, potentially indicating a change...
in streamflow contribution. Trends in stormflow are similar to trends in baseflow for the spring, summer, and fall seasons, but the trends tend to be less significant.

### 3.3. Trends in the Baseflow Index

The regional trends of BFI are not as large as those for baseflow and stormflow, though BFI is significantly decreasing in the northeastern United States during the summer and fall seasons (Figure 1). For the winter, BFI is increasing for a large portion of the central United States and Ohio River Valley, demonstrating that baseflow became a larger component of streamflow than stormflow over this time period. The only region where BFI is significantly decreasing in winter is the higher-elevation HCDN gauges in Colorado, Utah, and Wyoming and the upper Midwest (Michigan and Wisconsin). No clear clustering is found for the spring, but there are significant decreases in BFI for the central Midwest (Illinois and Indiana) during the spring. BFI is significantly increasing in a large portion of the upper Midwest and significantly decreasing in a large portion of the northeastern United States for the summer and fall time periods. For the fall time period, this significant decrease in BFI stretches from the entire Appalachian region into the northeastern United States.

### 3.4. Trends in Climatic Components

Similar to the trends in baseflow and stormflow, the trends in climatic components are regional, and thus, for brevity, we focus primarily on significant trends. Trends in precipitation for the HCDN watersheds exhibit regional associations (Figure 2) that follow spatial patterns described by Prein et al. [2016]. For the winter season, there is a relatively consistent increase in precipitation for a large portion of the United States that is largest in the northeastern United States and upper Midwest (most but not all increases are significant). The spring, summer, and fall seasons display more regional clustering of precipitation trends, with the eastern United States exhibiting positive trends, while decreases in seasonal precipitation are largely clustered in the southwestern/western United States.

For the spring, summer, and fall seasons, significant increases in PET are found throughout the United States. The largest increases in PET are clustered in the western United States and upper Midwest (summer and fall). Winter and spring are the only seasons that have a large number of watersheds exhibiting significant decreases in PET, with these concentrated in the Pacific Northwest for the winter season and the upper Great Plains for the spring season (but neither season has particularly large PET values in these locations).
Recent trends in maximum and minimum air temperatures, and their influence on vapor pressure deficits, are largely responsible for recent trends in PET [Ficklin et al., 2015; Seager et al., 2015]. The trends in maximum and minimum air temperature for the HCDN watersheds (Figure 2) show generally similar spatial patterns as found in the 2014 National Climate Assessment Report [Melillo et al., 2014], with the spring, summer, and fall seasons showing widespread increases of minimum air temperature throughout the United States. The summer season has the largest number of significant increases in minimum temperature and no significant decreases in the summer and fall seasons. Compared to minimum air temperature, trends in maximum air temperature are much less significant for all seasons and surprisingly show some negative values during all seasons (although many are not significant). It is worth noting that some of the “trends” in the gridded climate data, including the negative trends in maximum air temperature, may be an artifact of the methods used to generate the gridded fields. When producing a grid of absolute temperature or precipitation (rather than anomalies), this can cause spurious trends when stations with differing statistical distributions go online or offline throughout the time period of data generation [Maurer et al., 2002; Hamlet and Lettenmaier, 2005; Livneh et al., 2013]. The fall season has the largest number of watersheds with significant increases in maximum air temperature. It is important to note that some snowmelt-dependent areas, such as the intermountain western United States, display increases in both maximum and minimum temperature (though not always significant) for the spring, summer, and fall seasons.

4. Discussion

We first note that the linkage between baseflow and stormflow trends is particularly strong in summer and fall (Figure 3), which is likely due to the more direct influence (with fewer temporal lags) of precipitation and PET on local hydrology during these seasons. For these seasons, when precipitation occurs, the baseflow/stormflow recession rate is modulated by evapotranspiration [Tallaksen, 1995]. The balancing effect of PET and precipitation on baseflow and stormflow may become decoupled during seasons (winter and spring) where PET is much less than precipitation (and vice versa). Previous work has shown that this coupling/decoupling is particularly noticeable in areas with shallow groundwater tables and extensive vegetation, where a drying of the upper soil layer can be succeeded by slow capillary transport from the groundwater [Brown et al., 2005; Price, 2011].

As expected, precipitation trends consistently have the same sign as those of baseflow and stormflow (Figure 3 and supporting information Table S1). The only season when this does not occur is winter, suggesting that the accumulation of snow or ice (and not direct precipitation) may be having a large effect on local hydrology, perhaps delaying the response. Additionally, precipitation and PET during the winter time period are decoupled for many parts of the United States, further adding to the increased scatter during the winter season. Trends in temperature may also be having a larger impact on hydrology during the winter season by potentially altering snowmelt regimes. While weaker than the other seasons, the positive correlation between trends in precipitation and baseflow/stormflow for the winter season is still significantly different from zero (supporting information Table S1).

There also is a clear connection between increases and decreases in baseflow and stormflow and trends in PET (Figure 3 and supporting information Table S1). This relationship does not appear to be as large as the relationships between precipitation and baseflow or stormflow (average seasonal correlation between trends in PET and baseflow/stormflow is −0.30 and −0.27, respectively), in part because nearly all locations and seasons are experiencing an increase in PET (albeit differential in magnitude). During the spring, summer, and fall seasons, baseflow and stormflow have negative trends that coincide with large positive PET trends, suggesting that increases in PET within the HCDN watersheds are having a diminishing effect on baseflow and stormflow volumes. This result is consistent with other studies that show ET or PET increases [Federer, 1973; Shaw et al., 2013; Szilagyi et al., 2007]; however, Shaw et al. [2013] suggest that the direct linkage between ET and baseflow is negligible and entirely dependent on the effect of ET on soil moisture storage (which can then percolate into groundwater) within the watershed.

The changes in minimum and maximum air temperature are primarily manifested through changes in PET via increases in vapor pressure deficit (see negative correlations in supporting information Table S1). Conversely, for the summer season, decreases in maximum air temperature may have contributed to increases in baseflow and stormflow in the central and southeastern U.S. (Figures 1 and 2). Increases in minimum air temperature and vapor pressure deficit are most significant in the spring season, where PET is much less than precipitation (and vice versa). Previous work has shown that this coupling/decoupling is particularly noticeable in areas with shallow groundwater tables and extensive vegetation, where a drying of the upper soil layer can be succeeded by slow capillary transport from the groundwater [Brown et al., 2005; Price, 2011].

5. Summary

The significant increases in minimum air temperature and PET throughout the United States, and the large number of significant increases in minimum air temperature during the summer seasons, suggest that the increasing vapor pressure deficit has a strong influence on baseflow and stormflow trends. The increasing vapor pressure deficit is expected to lead to higher ET rates and lower soil moisture storage, which may have implications for future hydrological regimes. However, the associated increase in PET may also have a direct impact on hydrology, potentially altering snowmelt regimes and affecting the timing and magnitude of baseflow and stormflow. Further research is needed to fully understand the complex interactions between climate, hydrology, and vegetation dynamics in the context of changing climate conditions.
temperature occur during all seasons and are associated with both positive and negative trends in baseflow and stormflow, so there are confounding influences. As a result, while temperature is an important driver of integrated hydrologic controls such as PET, temperature alone is not a primary control on observed baseflow or stormflow trends.

Spatially, Figure 4 further corroborates the results found in Figure 1. Figure 4 shows that watersheds with high aridity indices (precipitation/PET) have increases in baseflow and decreases in stormflow for the winter and summer time periods, but there is no clear relationship between aridity and baseflow/stormflow trends during the spring and fall seasons. Watersheds with low aridity indices tend to cluster in the decreasing baseflow and decreasing stormflow quadrant for the summer and fall seasons, while no clear clustering occurs for the winter and spring seasons.

Changes in baseflow and stormflow—and their interaction—can have significant effects on the structure and function of aquatic ecosystems. Water temperature is a primary predictor of ecosystem function and species diversity among habitats [Ficke et al., 2007; Hynes, 2001]. Several studies have used stream temperature to

Figure 3. Scatterplots of Mann-Kendall trends in baseflow and stormflow. The colors represent Mann-Kendall Z trends for climate components (potential evapotranspiration (PET), maximum temperature (Max T), minimum temperature (Min T), and precipitation) as shown by the color bar. Significant trends at $p \leq 0.05$ for the Mann-Kendall Z values are $\pm 1.96$. \cite{Ficke2007, Hynes2001}
 estimate the amount of incoming baseflow to a river [Becker et al., 2004; Hatch et al., 2006], indicating the role that baseflow has in regulating stream temperature. As shown in Figure 3 (and validated in supporting information Figure S2), values above the 1:1 line indicate that baseflow is increasing relative to stormflow while values below the 1:1 line indicate that baseflow is decreasing relative to stormflow. Stratifying by trends in BFI clearly shows these differential trends (supporting information Figure S2). However, we find that BFI is not consistently related to changes in precipitation or PET (supporting information Figure S3). This differential mixing of source water to streamflow can have a large effect on water temperature. For the summer and fall, and potentially spring, a decrease in baseflow with an increase in stormflow can lead to an increase in water temperature owing to the fact that baseflow is a source of cool water, providing a thermal buffer [Constantz, 1998; Ficklin et al., 2014; Isaak et al., 2010; Kurylyk et al., 2013; Rice and Jastram, 2015]. Considering the direct effects of predicted increases in air temperature on surface water temperature in the coming century [Ficklin et al., 2013, 2014; van Vliet et al., 2011], the buffering effects of baseflow on increases in water temperature are critical to ecosystem structure and function.

In addition to water temperature, flow volume and variability are the primary determinants of variation in biodiversity in flowing freshwater systems [Lytle and Poff, 2004; Niu et al., 2012; Poff et al., 1997], and the effects of baseflow and stormflow on this variation is becoming more apparent [Knouft and Chu, 2015]. Generally, freshwater biodiversity tends to increase with increasing flow volume and variability, although particular taxonomic responses can vary [Knouft and Chu, 2015; Niu et al., 2012]. Importantly, freshwater species are not distributed evenly across watersheds, with headwater streams tending to support different assemblages of taxa compared to larger downstream areas [Vannote et al., 1980]. This differentiated distribution of biodiversity within a watershed results in differential ecological responses to changes in baseflow and stormflow. For example, decreases in baseflow tend to have a relatively larger effect in headwaters (compared to downstream areas) due to the stronger flow and temperature dependencies on baseflow in these smaller streams [Knouft and Chu, 2015]. Conversely, increases in baseflow and stormflow will have relatively greater impacts on downstream areas by increasing flow volume and variability at these sites. Knouft and Chu [2015] demonstrated that increases in stormflow, albeit due to urbanization, created more habitats for downstream species, while decreasing habitat for upstream species presumably due to decreases in baseflow.
Because trends in baseflow, particularly decreasing trends in the southwestern United States, appear to be more consistent and larger in magnitude than stormflow trends, headwater species may be at greater risk as climate changes.

5. Summary and Conclusions

Overall, trends in baseflow and stormflow tend to occur in tandem for the United States; however, regional differences are apparent during particular seasons. The northeastern (NE) and southwestern (SW) United States exhibit consistent trends in baseflow and stormflow from 1980 to 2010: increasing during fall and winter in the NE and decreasing during all seasons in the SW. Trends elsewhere and at other times of year are more variable and less homogeneous. Even within regions that have large trends in baseflow and stormflow, there are instances of watersheds that are responding differently from the entire region. This suggests that inferring trends in streamflow and its components from trends in climate is a complex challenge.

Using the baseflow index (baseflow/total streamflow), a decrease in baseflow contributions to streamflow is found in the northeastern United States during the summer and fall seasons. During the winter, baseflow contributions to streamflow are increasing for the central United States. These results suggest that there are regions where baseflow and stormflow are not increasing in tandem. Additionally, we linked trends in baseflow and stormflow to recent climate change by identifying concurrent directional trends among these variables. As expected, results indicate that an increase in precipitation leads to an increase in baseflow or stormflow (and vice versa). There is also a clear connection between recent increases and decreases in baseflow/stormflow and trends in PET. During the spring, summer, and fall seasons, baseflow and stormflow each exhibit negative trends that coincide with positive PET trends, suggesting that increases in PET within the HCDN watersheds are having a negative effect on baseflow and stormflow volumes.

The results presented here indicate that spatial variation in trends in natural baseflow and stormflow are largely the result of recent trends in climate. The response of baseflow and stormflow to altered climate patterns can result in spatially varying streamflow responses that are environmentally and ecologically important. These results provide insights into the complexity of water resources and aquatic ecosystem management within and among watersheds, as well as the increasing need for management decisions at the local scale.

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