Journal of Hydrology: Regional Studies 41 (2022) 101071

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh

Spatiotemporal variation in runoff and baseflow in watersheds located across a regional precipitation gradient

Breanna Rivera Waterman[a,1,2], Gonzalo Alcantar[a], Samantha G. Thomas[b], Matthew F. Kirk[a,*,3]

[a] *Department of Geology, Kansas State University, Manhattan, KS 66506, USA*
[b] *Kansas Biological Survey, Lawrence, KS 66047, USA*

ARTICLE INFO

Keywords:
Streamflow components
Precipitation gradient
Groundwater
Climate change
Land use

ABSTRACT

Study region: Regional precipitation gradient across Kansas, USA.
Study focus: As precipitation increases, baseflow and surface runoff generally increase, but it is unclear whether they increase proportionally and how proportions respond to climate and land use changes. This study examined variation in streamflow components of perennial streams across the study region and its relationships with watershed properties. We evaluated streamflow components with hydrograph separation and used Spearman's rank correlation tests and principal component analysis (PCA) to assess spatial trends (28 sites) and Mann-Kendall and Sen's Slope tests to assess temporal relationships (9 sites, 1960–2018).
New hydrological insights for region: Runoff and baseflow both increase eastward with precipitation but the increase is greater for runoff. As such, baseflow index (BFI, baseflow/streamflow) decreases with increasing precipitation, potentially reflecting the limits of infiltration on recharge/runoff partitioning. Spatial patterns in variables that influence infiltration (land use and soil texture) also vary with precipitation, consistent with long-term influences of climate on landscapes. Since 1960, the watersheds included in our temporal analysis experienced small, mainly insignificant increases in precipitation and temperature and large, significant increases in irrigation. During this time, BFI increased significantly only in semi-arid, agriculture-dominated catchments overlaying higher permeability deposits. These findings underscore the importance of watershed characteristics as controls on current spatial patterns in streamflow and BFI and also the sensitivity of streamflow and BFI to climate and land use changes over time.

1. Introduction

The two major components of streamflow are runoff and baseflow. Runoff is water that runs over the land surface during precipitation and snowmelt events whereas baseflow is water added to streams from the subsurface. Baseflow sustains flow between precipitation events and helps regulate surface water quality and quantity (Price, 2011). The contribution of baseflow to streamflow is

* Correspondence to: Department of Geology, Kansas State University, 108 Thompson Hall, Manhattan, KS 66506, USA.
E-mail address: mfkirk@ksu.edu (M.F. Kirk).
[1] Current address: Department of Civil, Environmental, and Architectural Engineering, University of Kansas, Lawrence, KS 66045, USA.
[2] ORCID 000-001-6046-2555
[3] ORCID 000-0001-5562-7618

https://doi.org/10.1016/j.ejrh.2022.101071
Received 19 November 2021; Received in revised form 3 March 2022; Accepted 29 March 2022
Available online 6 April 2022
2214-5818/

known to be sensitive to catchment and regional characteristics, such as precipitation, temperature, topography, geology, and land use (defined here to include land use, cover, and management following Zipper et al., 2018) (Price, 2011; Carlier et al., 2018). However, how baseflow varies on large spatial and temporal scales is not well known for many regions (Miller et al., 2016; Ficklin et al., 2016; Cuthbert et al., 2019). Changes to baseflow can significantly impact water supplies and thus are important to understand for effective management and protection of water resources.

In this study, we consider variation in the contribution of baseflow to streams across the Kansas regional precipitation gradient (Fig. 1). The precipitation gradient across the state is one of the steepest in the US and may be changing in response to climate change. Mean annual precipitation is as low as 635 mm/yr (25 in/yr) at the western margin of the state to as high as 1145 mm/yr (45 in/yr) in the east. Previous research indicates that a warming climate increases atmospheric moisture and moisture demand over land (Held and Soden, 2006; IPCC, 2021). These changes can directly alter the occurrence and patterns in subsurface storage and streamflow, which can stress water resources and increase flooding and drought risks (Milly et al., 2005; Brikowski, 2008; Layzell and Evans, 2013; Seager et al., 2018; Cuthbert et al., 2019). Precipitation data collected since the 1890's indicates that total annual rainfall has generally increased across the state, particularly during the second half of the 20th century (Rahmani et al., 2015). However, over that same time span, average statewide warming of 0.06 °C per decade appears to be increasing dryness in western Kansas but not central and eastern Kansas, based on changes in the Palmer Drought Severity Index (Lin et al., 2017).

Alongside variation in precipitation, the contribution of baseflow to total streamflow may also vary across the study area in response to land use. Most of the study region is used for agriculture but urban land use is also present. In agricultural landscapes, irrigation pumping can decrease baseflow by lowering the water table (Earman and Dettinger, 2011; Barlow and Leake, 2012; Brikowski, 2008). However, it can also increase baseflow by adding irrigation return flow to streams (Blodgett et al., 1992). Either way, impacts of irrigation on baseflow may typically be greater in more arid regions, where rates of irrigation pumping are generally greater (Famiglietti et al., 2011; Voss et al., 2013). In urban areas, an increased abundance of impermeable surfaces increases runoff and thus decreases recharge and groundwater inputs to streams (Ku et al., 1992). However, 'leaky infrastructure' in urban settings can increase groundwater recharge and subsequent discharge to streams (Lerner, 2002; Bhaskar et al., 2015). Moreover, in both agricultural and urban settings, changes in plant growth can impact the contribution of baseflow to streamflow by altering soil permeability and evapotranspiration (ET) patterns (Zhang and Schilling, 2006; Price, 2011; Teutschbein et al., 2018). These examples illustrate that impacts of land use are variable. In general, however, land use changes that increase infiltration and recharge tend to increase baseflow to streams whereas those that increase evapotranspiration tend to decrease baseflow (Price, 2011).

The interaction of changes in land use and climate can have complex feedbacks for water resources. Changes in climate can cause changes in land use, which can in turn impact water resources and greenhouse gas budgets enough to drive further changes in climate at local and even regional scales (Foley et al., 2005; Brown and Pervez, 2014; Zabel et al., 2014; Bajželj and Richards, 2014). Although the coupled impacts of climate and land use have clear implications for water resources, our ability to analyze those impacts is made difficult by such feedback loops as well as the scales at which each occurs. Climate-groundwater response times can occur over thousands of years (Cuthbert et al., 2019), whereas impacts of land use change can manifest within years or decades (Zhang et al., 2016). Further, the coupled impacts of climate and land use can occur on different spatial scales, with local land use effects superimposed on regional climate controls (Wang and Hejazi, 2011; Martin et al., 2017; Wang and Stephenson, 2018; Zipper et al., 2018).

Regional scale studies may be critical to studying these relationships and their impact on baseflow (Ayers et al., 2018; Tan et al., 2020). Recently, a study examining relationships across the entire US found that runoff and baseflow generally increase with precipitation, yet the relationship between precipitation and the proportion of baseflow in streamflow was variable, suggesting that

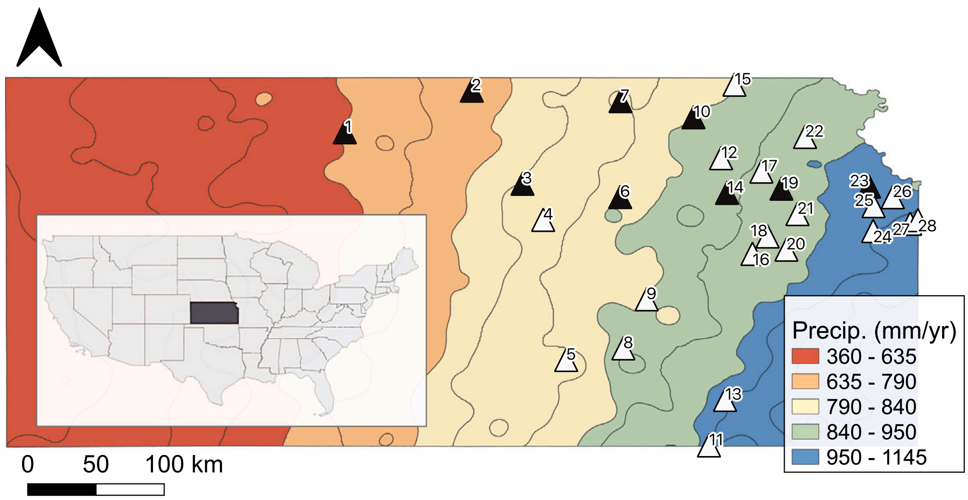

Fig. 1. Map of study sites across the Kansas precipitation gradient. Triangles identify locations of USGS gage sites used in this study. All of the sites were included in our spatial analysis. Sites indicated by black triangles had data extending at least as far back as the 1960s and were used in our temporal analysis.

regional factors were influential (Ficklin et al., 2016). Numerous physical catchment properties can impact streamflow components, making it difficult to determine spatiotemporal patterns and relationships (Santhi et al., 2008; Price, 2011; Gnann et al., 2019). Previous studies have investigated various watershed characteristics including topography, geology, soil, land use and climate, on baseflow and its proportion in streamflow within the Upper Colorado River Basin (Rumsey et al., 2015, 2020; Miller et al., 2016). However, these studies are specific to the study area, which differs considerably from Kansas. Studies that have included Kansas and the midwestern US (Brikowski, 2008; Ayers et al., 2018) were focused on impacts of climate and land use, and did not consider other factors known to drive baseflow generation and occurrence, including soil and bedrock composition, which can be among the most important controls (Richardson et al., 2020).

To help fill this knowledge gap, this study uses the Kansas regional precipitation gradient as a natural laboratory to examine how variation in precipitation rate, land use, and various watershed characteristics impact proportions of baseflow in streams. Results of our analysis are particularly relevant to the Central Great Plains of the US, along which the precipitation gradient occurs. However, the results may also shed light on potential future impacts of changes in the amount of precipitation in other regions.

For our analysis, we used streamflow records and watershed data to understand spatiotemporal patterns in the partitioning of streamflow components and their variation in response to changes in precipitation, land use, and other watershed properties. We first performed hydrograph separation calculations on stream discharge data from 28 watersheds across the precipitation gradient to analyze current spatial variation in streamflow components. The calculations evaluated runoff (RO), baseflow (BF), and baseflow index (BFI), which is the proportion of baseflow in total streamflow. We then used Spearman's Rank correlation tests to examine the relationship of these streamflow components to watershed characteristics across the precipitation gradient. Due to high covariance between some variables, we conducted a principal component analysis (PCA) to better understand relative significances of watershed and climate variables. Secondly, in nine watersheds with longer data records, we examined temporal trends (1960–2018) in hydrograph results, climate, and land use data using Mann-Kendall and Sen's Slope analyses.

2. Materials & methods

2.1. Site selection and study area

For our analysis, we selected USGS gage sites across Kansas that met requirements of hydrograph separation. Specifically, the analysis requires watersheds with drainage areas less than 1300 km^2 (500 mi^2) and streamflow contributions primarily from groundwater discharge and surface runoff (Barlow et al., 2014). None of the sites are downstream from dams or discharges from wastewater treatment facilities. Hydrograph separation analysis is most accurate when averaged over longer time periods, on the range of years (Barlow et al., 2014), so we required streams to have a minimum of 14 years of continuous discharge data to maximize accuracy and number of sites included. More details about this choice are provided in the next section below.

The resulting 28 sites span a steep precipitation gradient from eastern to west-central Kansas (Fig. 1). Annual precipitation varies from 635 mm/yr (25 in/yr) at the most western site up to 1145 mm (45 in/yr) at the furthest east site, giving a gradient of approximately 1.3 mm/km (0.1 in/mi) in average annual precipitation. Reflecting this precipitation gradient, soil moisture and vegetation change across the state with temperate deciduous forests and temperate tallgrass prairie in eastern Kansas to semi-arid grasslands in the west (Seager et al., 2018). Elevation also decreases eastward from 1231 to 207 m, with a gradient of 2.6 m/km (4038–679 ft; 13.7 ft/mi).

The sites include a range of sediments and sedimentary rocks deposited from the Paleozoic to the Cenozoic eras (KGS, 2008). From the western border extending into central Kansas, the predominant surficial rock and sediment type is unconsolidated silt and sand from loess and river valley deposits, Cretaceous shale, sandstone, and chalk deposits (KGS, 2008). In the eastern portion of the state, the lithology is predominantly flat lying, alternating limestone and mudstone of the Permian and Carboniferous systems (Stoeser et al., 2005). Similarly, Kansas aquifers shift from unconsolidated sand/gravel and sandstone aquifers of the larger Great Plains and High Plains Aquifers out west, to limestone aquifers of the Flint Hills and Osage Aquifers in the east, with glacial drift aquifers in the northeast corner (Macfarlane et al., 2000). Alluvial aquifers are scattered across the state and tend to dominate in eastern areas that experience high streamflow (Macfarlane et al., 2000). Dominant surficial rock type and aquifer maps can be found in Figs. S1 and S2 of the supporting information.

2.2. Hydrograph separation

We carried out the hydrograph separations using discharge data from each site with the USGS Groundwater (GW) Toolbox software (Barlow et al., 2017). The software requires daily discharge data which we acquired from the United States Geological Survey (USGS) National Water Information System (USGS, 2016). For all 28 sites, we collected daily streamflow data from 2004 to 2018 to calculate a 14-year average for runoff, baseflow and BFI, which we use as representative of current conditions. As stated in Section 2.1, graphical hydrograph separation analysis is more accurate when the hydrograph data span annual or longer time scales (Barlow et al., 2014). Considering that surface water and groundwater processes often occur over months to decades (Price, 2011; Jasechko, 2019), we sought to extend our time scale beyond a decade to analyze current conditions. Our choice of 14 years allowed us to achieve that goal and also maximize the number of sites included in our analysis of current relationships across the precipitation gradient.

For nine sites with long data records, we also carried out an analysis of changes in streamflow components over time. For those sites, we collected daily streamflow data from 1960 through 2018 to calculate annual and seasonal averages for runoff, baseflow and BFI. We averaged results from the cold and dry (Jan. - Feb., Oct. - Dec.) months and the warm and wet (April - Sept.) months for the

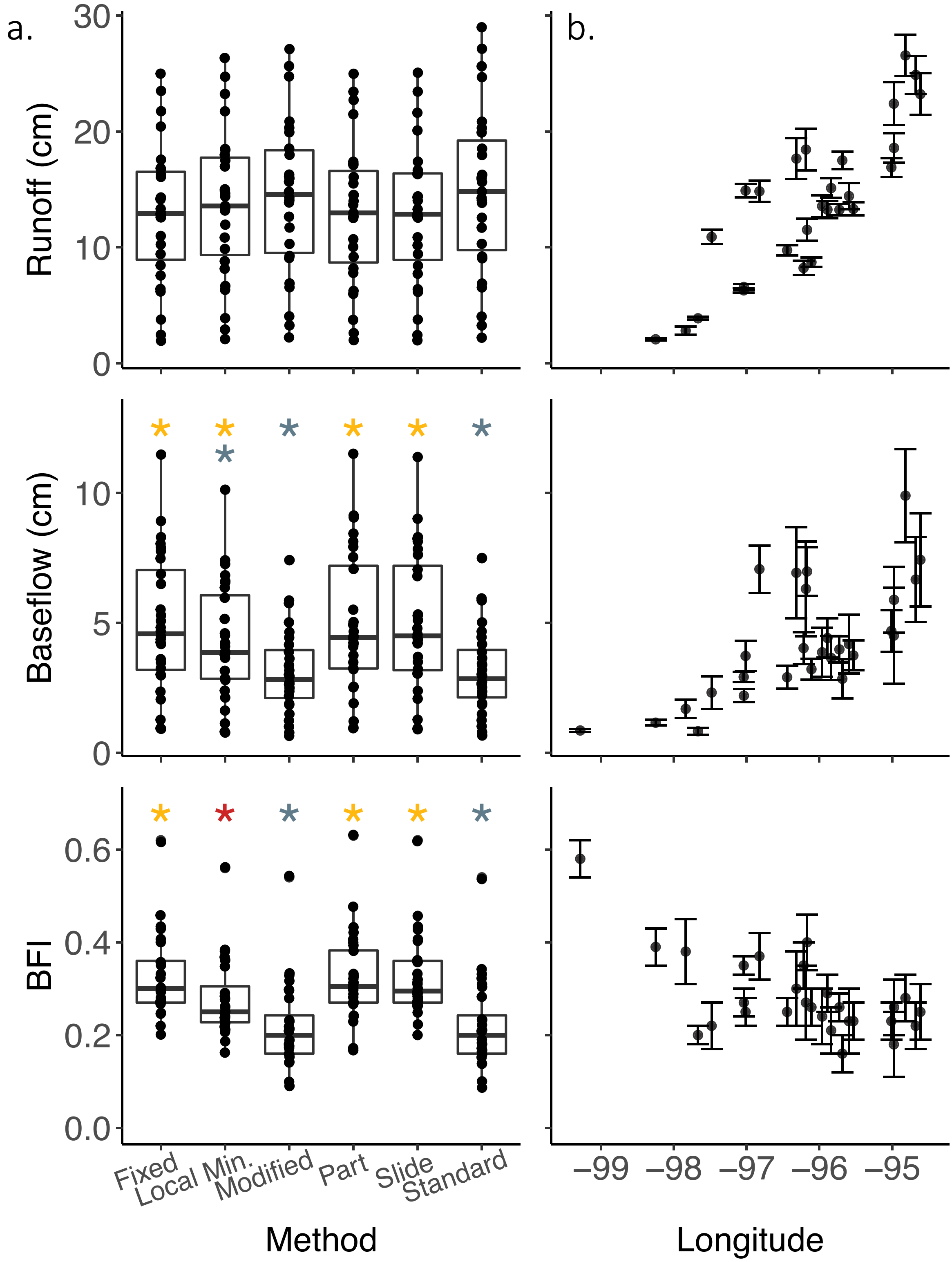

Fig. 2. Hydrograph separation results. Graphs on the left a) show the results of a Pair-wise Wilcox test between the hydrograph separation methods. Asterisks indicate whether differences between methods were significant. Results with asterisks of the same color were insignificantly different whereas those with asterisks of different colors were significantly different. Graphs on the right b) show hydrograph separation results versus longitude. Scatter points show mean values calculated by the different hydrograph separation methods and error bars show standard deviations. Runoff and baseflow units are centimeters (cm) and BFI is a unitless fraction.

seasonal analysis. We will refer to the two seasons as dry and wet seasons from this point forward.

GW Toolbox contains six different hydrograph separation methods to partition the discharge records into baseflow and runoff components: PART, BFI Standard and Modified, and HYSEP Fixed, Sliding, Interval, and Local Minimum. A detailed description for each method is available in the GW Toolbox user manual (Barlow et al., 2014). Briefly, the various separation analyses partition runoff from baseflow by determining the portions of the hydrograph that are not affected by runoff via various methods (turning point factor, recession index, algorithms to connect low points, and continuous recession). None of these methods appear to be more appropriate than the others for application to our study region. As such, we carried out both the spatial and temporal analyses using the average of all six methods.

We ran our analyses using the original settings in USGS GW Toolbox: Partition Length (N days) 5; Turning Point Test Factor (F) 0.9; Daily Recession Index (K) 0.97915. The watershed drainage area (mi^2) for each site is used to normalize the initial results of the hydrograph separation (given in cubic feet per second; cfs) to flow rate per unit area (cfs/mi^2). The software then converts values of streamflow components (runoff and baseflow) to units of inches. The BFI results are presented as unitless values between 0 (no baseflow component) and 1 (no runoff component). We then converted units for runoff and baseflow cm for our analyses.

2.3. Watershed, water usage and climate data

We gathered various watershed data from open-source, online databases. Kansas land cover patterns (percent forest, urban, agriculture and grassland) were gathered from raster data from the 2005 Kansas Land Cover Patterns Mapping Initiative (Peterson et al., 2009). Percent grassland includes grassland and pasture, and percent agriculture is defined as row crop agriculture. Geologic data was gathered from KGS and USGS (Stoeser et al., 2005; Falcone, 2011). Additional watershed data (elevation, potential evapotranspiration (PET), soil clay and sand content) was gathered from USGS GAGES II (Falcone, 2011).

Annual climate (mean precipitation and temperature) data were gathered from PRISM Climate Data at 4 km resolution for all 28 sites from the past 30 years, and monthly data from 1960 to 2018 were collected for the nine sites included in the temporal analysis (PRISM, 2020). We also gathered annual county-wide land (square km; acres irrigated) and groundwater usage (cubic meter; acre-feet diverted) data from KGS Water Information Management and Analysis System (WIMAS) for the web for nine sites used in the temporal analysis (Wilson et al., 2005). Land use, average annual climate and additional watershed data used for the spatial analysis can be found in Tables S1 and S2 of the SI. Annual and monthly climate data and annual land use data used for the temporal analysis can be found in Tables S10, S11 and S12 of the SI.

2.4. Statistical analyses

All statistical analyses were carried out using RStudio, version 1.2.5033 (RStudio Team, 2019). For all analyses, we considered probability values (p) less than 0.05 to be significant. We carried out nonparametric Kruskal-Wallis tests to determine if the results from the six hydrograph separation methods were significantly different. To identify specifically which method(s) were significantly different, we conducted a pairwise Wilcox test. Additionally, we assessed if BFI values were significantly different based on the dominant aquifer underlying each site with a one-way ANOVA. This approach is appropriate given that BFI values are normally distributed.

For all 28 sites, we tested the strength of relationships between the hydrograph results and climate and watershed parameters using Spearman's Rho rank order correlation test. We used a threshold for significance of correlation (rho) greater than the absolute value of 0.40. Due to the high covariance between variables within the dataset, we conducted a principal component analysis (PCA) using the FactoMineR package (Lê et al., 2008). Prior to or during the analysis, data with high absolute values were transformed and standardized (mean of zero and standard deviation of one). The results were extracted and visualized using the Factoextra package (Kassambara and Mundt, 2020). We used eigenvalue > 1 as a cutoff for which principal components (PC) are considered in the Results and Discussion as that threshold indicates variance within the component is greater than that of a single variable (Kaiser, 1961).

We tested the strength and significance of temporal relationships using Mann-Kendall and Sen's Slope analyses. The Mann-Kendall test determines the presence of trends in the time series data, where positive and negative values indicate increasing and decreasing trends, respectively. Sen's Slope determines the magnitude, or the slope, of that trend. The larger the number, the greater the slope and thus the greater the change over time. These analyses are common in studies that analyze climate and streamflow time series because they do not require the data to follow any specific distribution (Marques da Silva et al., 2015; Ficklin et al., 2016). The tests were used for annual trends in streamflow components (RO, BF, BFI), climate (temperature and precipitation), and groundwater usage and irrigated acreage and for seasonal trends in streamflow components and climate data.

3. Results

3.1. Variability between hydrograph separation methods

Differences in runoff estimates were insignificant for all hydrograph separation methods (Fig. 2 A). Average runoff across the gradient is 13.23 cm (4.80 in.). The difference in baseflow for Local Minimum, Modified, and Standard methods are insignificant from each other with an average value of 3.50 cm (1.29 in.; $p > 0.05$), but are significantly different from HySEP-Fixed and Part, which have an average of 4.97 cm (1.82 in.; $p < 0.05$). One method, HySEP-Slide, is insignificantly different from both groups and has an average of 5.03 cm (1.85 in.). Similarly, the difference in BFI for Local Minimum, Modified, and Standard methods are insignificantly different from each other with an average of 0.25, but again are significantly different from HySEP-Fixed and Part, which has an average of 0.33. However, for BFI, HySEP-Slide is significantly different from both groups and has an average of 0.34.

Standard deviations on the means calculated for each method are depicted by the error bars in Fig. 2B. Although there is some variability between methods, the trend with longitude is consistent for each method. Moving forward, we incorporate the differences in these estimates by using average values for runoff, baseflow, and BFI to compare the hydrograph separation results to climate and watershed data in both the spatial and temporal analyses. Detailed results of the hydrograph separation and the statistical test (Kruskal-Wallis and pairwise Wilcox test results) are located in Tables S3-S6 of the SI.

3.2. Spatial variation

Under current conditions, average runoff and baseflow in streams increases eastward across the study area ($p < 0.005$) (Fig. 2B). The increase in runoff (0.81–26.6 cm) is greater than that for baseflow (0.86–9.90 cm). As a result, the proportion of baseflow in total streamflow (BFI) generally decreased eastward from 0.6 to 0.26 ($p < 0.01$).

These streamflow components vary significantly with some of the climate, land use, and soil parameters in our dataset (Fig. 3). Among climate variables, streamflow components are more strongly related to precipitation than temperature or PET. Precipitation positively correlates with runoff and baseflow and negatively correlates with BFI, while temperature and PET only have weak but significant relationships with runoff and BFI, respectively. Precipitation co-varies with elevation and longitude across the precipitation gradient. Thus, it is not surprising that streamflow components are also significantly correlated with elevation and longitude. Among land use variables, streamflow components do not have significant relationships with the proportion of grassland in the watershed, which is the dominant land cover in most watersheds. However, runoff positively correlates with forest land cover and baseflow negatively correlates with agricultural land cover. BFI is significantly correlated to urban land cover. Lastly, the clay content of watershed soils is positively related to runoff and baseflow and sand is negatively related to runoff. Full results of the Spearman's Rank correlations can be found in Figs. S3 – S8 and Table S7 of the SI.

The PCA results show that approximately 86% of the total variance is explained by principal components (PC) 1–4 (Fig. S9; Table S17), which we focus on here and in the Discussion below. The PCA weightings and contribution of variance for watershed, climate and hydrograph variables are presented in Table 1. For interpreting PCA weightings, similar values (in magnitude) demonstrate highly correlated variables, with positive and negative values indicating positive and negative correlations, respectively. Precipitation, runoff, longitude, baseflow, and clay, are highly correlated with each other, as seen by similar (in magnitude and sign) weightings on PC1. Elevation is negatively correlated to the aforementioned variables shown by the equal but opposite (negative) weightings on PC1. Temperature and sand are positively correlated for PC2, while negatively correlated with latitude. For PC3, BFI and grassland are positively correlated to each other, and both are negatively correlated to agriculture and PET. Grassland and urban land use are negatively correlated on PC4.

The contribution of variables to the variance shows which variables best explain the variability within each PC (Fig. 4). In general,

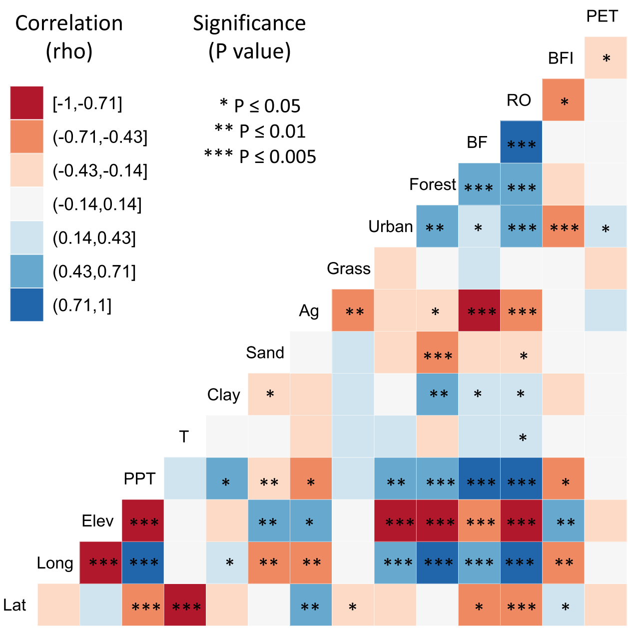

Fig. 3. Heatmap showing relationships between hydrograph separation results (14-year average for RO, BF, BFI), climate parameters (temperature (T), average annual precipitation (PPT), and potential for evapotranspiration (PET)), and other watershed characteristics (land use (Ag, Grass, Urban, Forest), soil sand and clay content, elevation (Elev), latitude (Lat), and longitude (Long). The significance of each relationship was tested using Spearman's Rank correlation tests. For land use, Ag refers to areas used for crops and Grass includes grassland and pasture.

Table 1
Results of the Principal Component Analysis for watershed variables as weightings and contribution to variance (percent) of principal components (PC) 1–4.

Watershed Variables	PCA weightings				Contribution to variance			
	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
Latitude	-0.14	-0.57	0.00	0.01	1.98	32.39	0.00	0.00
Longitude	0.36	-0.18	-0.08	0.06	12.63	3.09	0.62	0.37
Precipitation	0.37	0.08	-0.07	0.09	13.50	0.64	0.54	0.84
Temperature	0.15	0.53	0.04	-0.05	2.36	28.18	0.16	0.29
% Clay	0.31	-0.05	-0.04	0.29	9.61	0.21	0.20	8.57
% Sand	-0.16	0.41	-0.30	0.01	2.44	16.56	8.74	0.01
% Agriculture	-0.24	-0.21	-0.41	0.10	5.84	4.36	16.52	1.02
% Grassland	0.06	0.08	0.32	0.62	0.40	0.61	10.52	38.86
% Urban	0.19	-0.12	0.10	-0.62	3.58	1.40	1.00	38.34
% Forest	0.27	-0.32	0.00	0.10	7.31	10.07	0.00	1.00
Baseflow Index (BFI)	-0.23	-0.05	0.44	-0.17	5.35	0.23	19.17	2.76
Baseflow (BF)	0.32	0.06	0.28	-0.20	9.98	0.34	7.70	3.87
Runoff (RO)	0.36	0.03	0.02	-0.14	12.73	0.08	0.04	1.86
Elevation	-0.34	0.12	0.21	-0.06	11.71	1.49	4.47	0.41
Pot. Evapotranspiration (PET)	0.08	0.06	-0.55	-0.13	0.58	0.35	30.32	1.78

precipitation, runoff, longitude, elevation, baseflow and percent clay contribute similarly to the total variance of PC1, accounting for between 10% and 13% each, as observed by clustering of variables along axis 1 (Fig. 4 A). Latitude and temperature contribute roughly 30% to the total variance of PC2, followed by percent sand and forest cover (17% and 10%, respectively). PET accounts for 30% of variance captured in PC3, followed by BFI, percent agriculture and grassland (19, 17, 10% respectively.) Percent grassland and urban land cover each account for 38% of variance in PC4. The full results of the PCA (all biplots, eigenvalues and variable contributions) can be found in Fig. S9 and S10 and Tables S13 and S17 of the SI.

3.3. Variation over time

The results of the temporal analysis show that BFI has increased significantly at four sites (Bow, White Rock, Salt, and Mill at Washington) from 1960 through 2018 (Fig. 5). The change in BFI was small (slope < 0.01) for all sites, even at sites with significant trends. BFI increased at most sites, except at the three easternmost sites (Mill at Paxico, Soldier at Topeka, and Stranger). Similarly, baseflow increased at all sites except the three eastern sites. However, all trends were insignificant and small (slope ≤ 0.04 cm/year; Fig. 5). Runoff decreased at most sites, with Salt, Mill at Paxico and Soldier at Topeka as exceptions. Similar to baseflow, the trends in runoff were insignificant and small (slope ≤ 0.02 cm/year).

Annual average precipitation increased at all sites, with the trendline slopes ranging from 0.22 to 2.18, but the increase was significant only at the westernmost site (Bow). Temperature also increased slightly across all sites, with the trendline slopes ranging from 0.002 to 0.02 mm/year, with significant increases occurring at two sites (Chapman and Soldier at Topeka). Groundwater use and

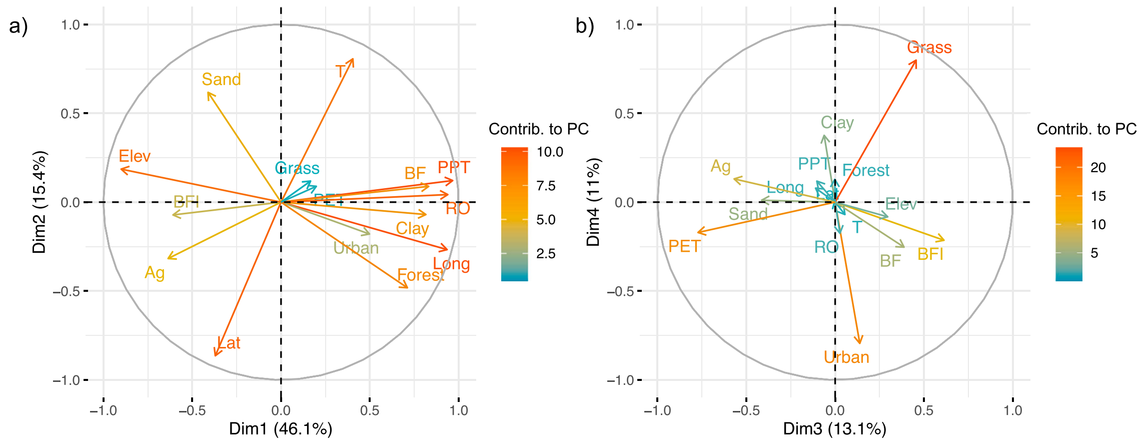

Fig. 4. Results of our principal component analysis (PCA). The plots show the contribution of each variable to variance within each principal component (PC). The left plot a) shows PC1 vs. PC2, which together account for 61.5% of the variance in our data, and the right plot b) shows PC3 vs. PC4, which explains 24% of the variance. Contributions of each variable are indicated by vector color, with the color gradient scaled to % contribution. Note differences in scale between plots. Vector length also indicates relative contribution. Longer vectors have greater contributions. Additionally, the proximity of variables to each other represents relationships among variables. Those near each other positively correlate whereas those far apart negatively correlate.

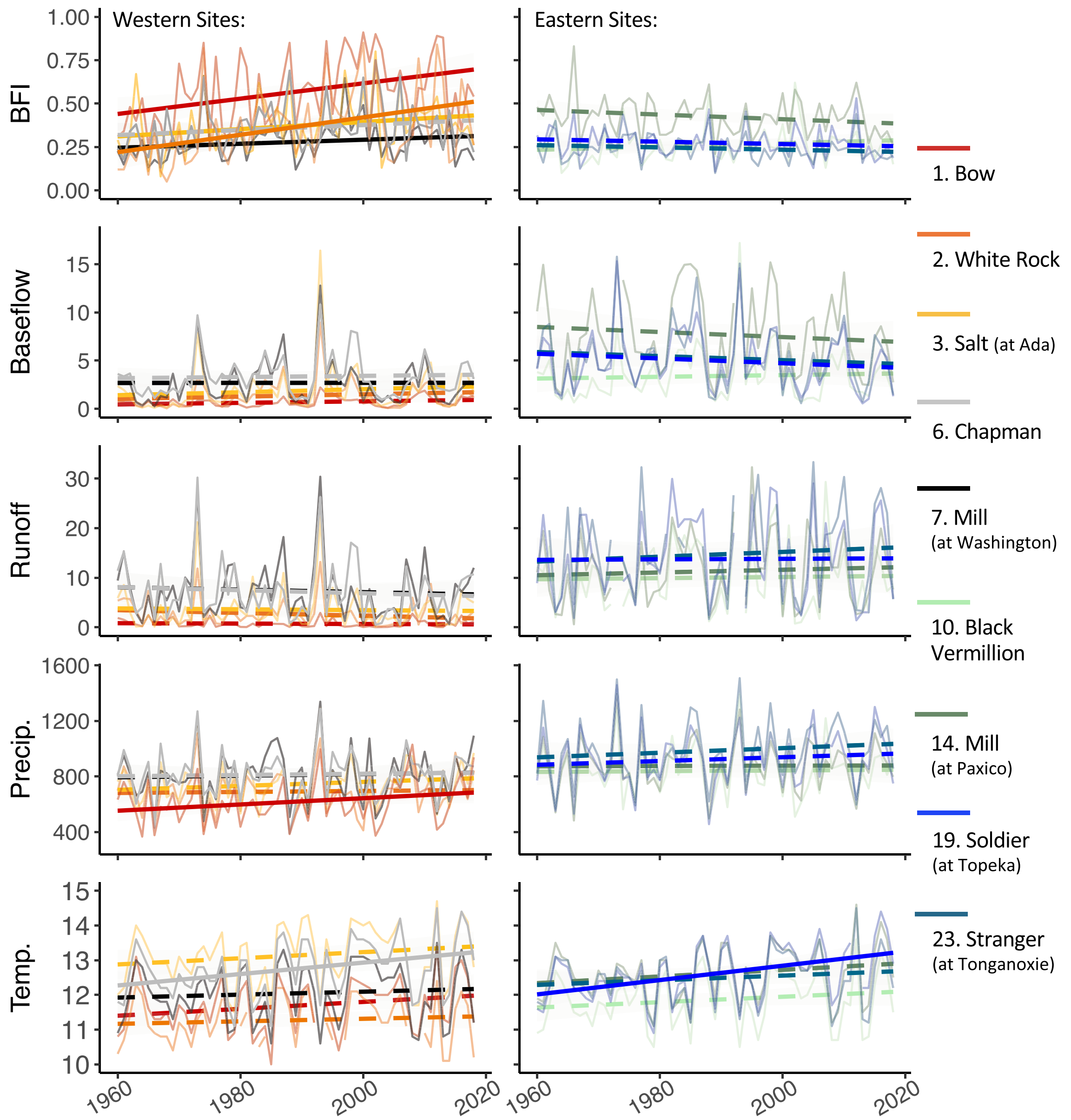

Fig. 5. Annual trends in BFI, baseflow, runoff, annual precipitation, and temperature from 1960 to 2018. The western sites (n = 5) are plotted on the left and the eastern sites (n = 4) on the right. The sites are divided into eastern and western groups for clarity. Individual sites are indicated by color and significant trends ($p < 0.05$) are indicated by solid lines. BFI is unitless. Units are centimeters (cm) for runoff and baseflow, millimeters (mm) for annual precipitation (precip.), and degrees Celsius (°C) for temperature (temp.).

irrigated acreage increased significantly at all sites (Fig. 6). The slopes for land use parameters were large, ranging from 32,003 (Bow) to 292,918 (Soldier) for groundwater use (m^3/year) and 85,410 (Black Vermillion) to 1,281,821 (Soldier) for irrigated area (km^2/year).

The results of the seasonal temporal analysis show that BFI significantly increased at five sites (Bow, White Rock, Salt, and both Mill at Washington and Paxico) for the dry season and at two sites (Bow and White Rock) for the wet season (Fig. 7). The slope of the trendlines were positive for both seasons at all sites except for the wet season at Mill at Paxico, Soldier at Topeka, and Stranger. Changes in baseflow were insignificant at all sites for both seasons except Bow in the dry season. The slope of the trendlines were positive at all sites but Mill (both seasons) and Stranger (dry season). Runoff significantly decreased at one site (White Rock) in the dry season. Changes in runoff for the wet season were insignificant at all sites. Trendline slopes were negative at all sites for the dry season sites and three sites for the wet season (Bow, White Rock and Chapman). Overall, the trendline slopes were small (less than 0.005) for

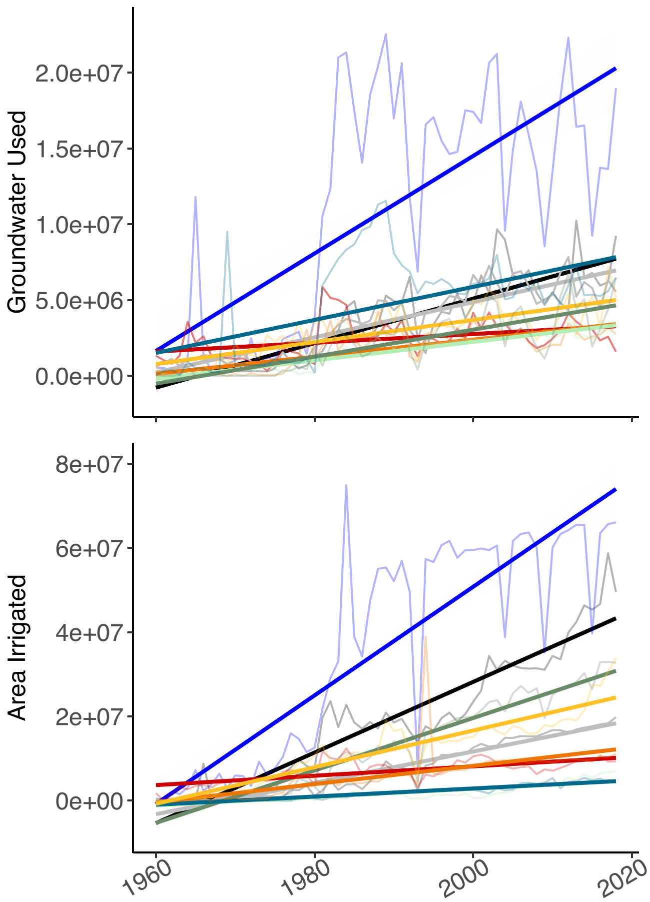

Fig. 6. Changes in annual averages for a) groundwater used (cubic meter/year) and b) area irrigated (square meter/year) from 1960 through 2018. All sites experienced significant increases for both parameters (indicated by solid lines).

BFI, baseflow and runoff.

Seasonal changes in precipitation were insignificant at all sites for both the wet and dry seasons. Temperature did not vary significantly during the wet season for all sites but increased significantly at two sites (Chapman and Soldier) for the dry season. Climate trends were generally positive, except for variation in precipitation at two sites (Mill at Paxico in wet season; Black Vermillion in dry season) and temperature at one site (White Rock in wet season). Full results of the annual and seasonal hydrograph results, climate and land use data can be found in Tables S8-S12 and results of the Mann-Kendall and Sen's Slope analyses can be found in Tables S14–15 of the SI.

4. Discussion

4.1. Influence of watershed characteristics on spatial patterns of streamflow and BFI

The spatial analysis of hydrograph separation results reveals significant and surprising relationships with precipitation. Baseflow and runoff are significantly correlated with increasing precipitation (Fig. 3, rho = 0.76 and 0.95, respectively; Fig. 4 A), consistent with other studies that have found strong relationships between streamflow components and climate (Ficklin et al., 2016; Ayers et al., 2018; Rumsey et al., 2020). We expected the average BFI in streamflow to also increase with precipitation. However, we observe that the calculated BFI values decrease significantly with increasing precipitation (Fig. 3, rho = −0.42) and negatively correlated with precipitation, runoff and baseflow on PC1 (Fig. 4 A).

We interpret the relationship between precipitation and BFI to reflect the influence of infiltration on the contribution of groundwater to streams. During precipitation events, some portion of the water infiltrates the surface, percolates downward, and ultimately recharges the underlying saturated zone. Thus, the amount of precipitation influences the absolute amount of groundwater discharge to streams by affecting recharge rates (Price, 2011). However, when the rate of precipitation exceeds the infiltration capacity of a soil, runoff is generated (Loague et al., 2010). Where infiltration capacity is exceeded, further increases in precipitation will increase the proportion of precipitation that flows over the land surface as runoff. We reason that the frequency with which this capacity is exceeded is likely higher in areas that receive more precipitation. Where that is the case, the relative contribution of

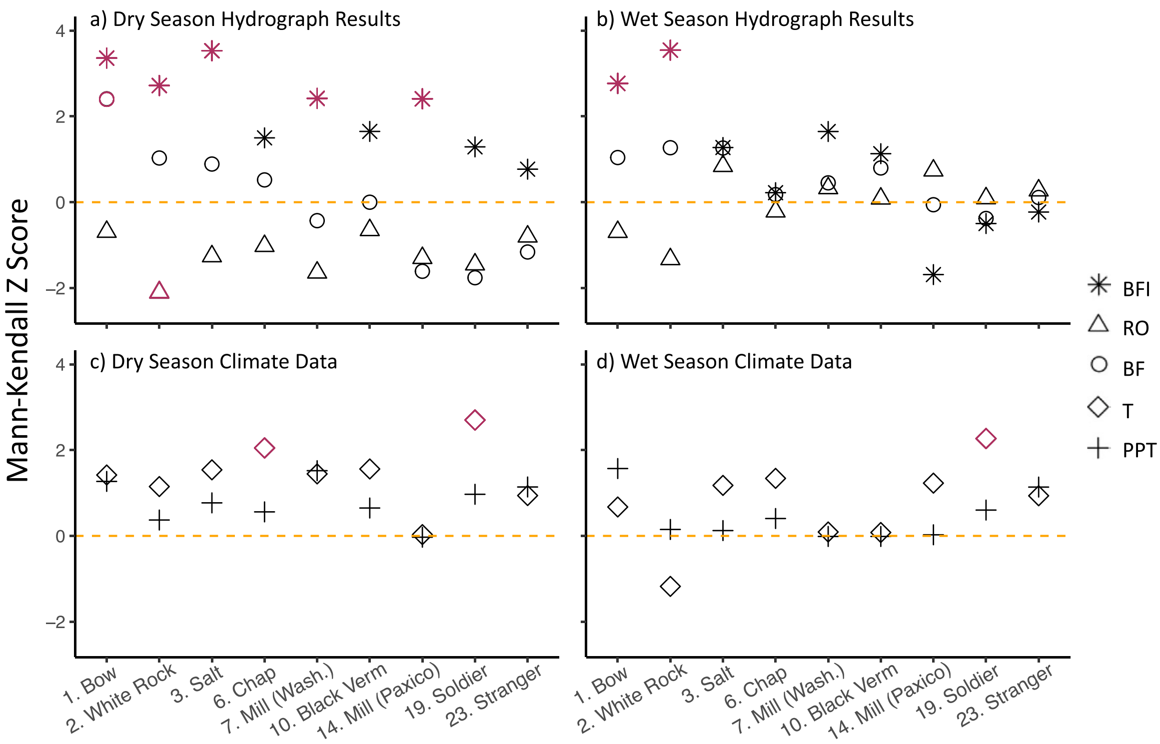

Fig. 7. The Mann-Kendall Z values for a) dry season (Jan. - Mar., Oct. - Dec.) hydrograph data (runoff, baseflow and BFI), b) wet season (April - Sept.) hydrograph data, c). dry season climate data (precipitation and temperature), and d) wet season climate data. Points plotting above the yellow lines have increasing trends and those below the line have decreasing trends over time. Significant trends are indicated with red scatter points.

groundwater to streamflow would decrease with increasing precipitation, consistent with our observations.

Partitioning between runoff and recharge across the precipitation gradient also varies in response to differences in natural watershed permeability. Increasing soil clay content is associated with decreased permeability and limited infiltration and groundwater recharge, which can ultimately impact groundwater discharge to streams (Hillel, 1982; Wolock et al., 2004; Rumsey et al., 2015). This relationship likely contributes to the high and positive correlation of soil clay content with precipitation, longitude, runoff, baseflow, and the weak negative association between soil clay content and BFI (Fig. 4 A). Similarly, surficial sediment and underlying bedrock type may also influence spatial trends in streamflow components, specifically BF and BFI. The western streams in our study area tend to be located on coarse sand and gravel deposits, sandstones, and chalks that have relatively high hydraulic conductivity (102 – 103, 3.1, and 30 m/day respectively; De Marsily, 1986) and are associated with high rates of infiltration, recharge and discharge (Wolock, 2004; Santhi et al., 2008). A shift in the relationships of precipitation with baseflow and BFI coincides with a change in bedrock composition (Fig. 8). The Flint Hills region consists of alternating limestone and mudstone bedrock in an early stage of karstification (Macpherson et al., 2008), which could support high infiltration rates that contribute to higher proportions of groundwater discharge. Indeed, the ANOVA results show that sites within the Flint Hills have significantly different BFI values compared to sites with streams flowing over strictly alluvial aquifers and overlying the Dakota aquifer (Fig. 8; Table S16).

Alongside variation in soil and bedrock composition, land use can also alter surface permeability and contribute to variation in streamflow components across the study area. The correlation between BFI and urban land use (Fig. 3; Table 1; Fig. 4B) potentially reflects the influence of impermeable surfaces in urban environments, which can limit infiltration into the subsurface (Ku et al., 1992; Price, 2011), as mentioned in the Introduction. Also as mentioned previously, changes to agricultural (crop), forest, and grassland coverage have the potential to impact streamflow and surface properties by altering plant compositions in ways that affect water fluxes into the subsurface (Sullivan et al., 2019). Compared to areas used for crops, grasslands can have lower evapotranspiration and higher infiltration rates, which work to increase baseflow and groundwater discharge (Nie et al., 2011). Although agricultural (crop) land use impacts to streamflow can vary, increased evapotranspiration as well as irrigation rates associated with crop areas have the potential to decrease groundwater discharge to streams (Wen and Chen, 2006; Price, 2011). Such interactions between vegetation and water resources may explain the relationships we observed between land use, BFI, and PET on PC3 (Table 1; Fig. 4B). The positive correlation between grassland and BFI coupled with negative correlation of BFI with agriculture and PET could indicate that such tradeoffs are occurring, however finer-scale data and analysis to unequivocally identify mechanisms.

These results illustrate the coupled nature of potential controls on streamflow components across broad regions. Our study area

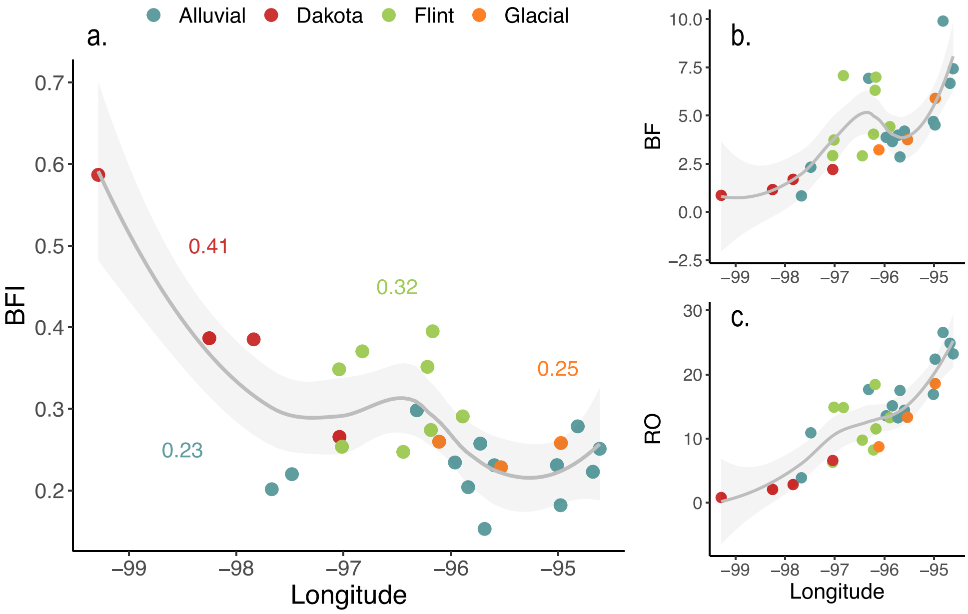

Fig. 8. Variation in a) BFI, b) BF, and c) RO with longitude grouped by bedrock aquifers underlying the watersheds ($R^2 = -0.64$, 0.70, 0.87, respectively). Numerical values indicated on (a) are average BFI values for the watersheds in each aquifer group. The one-way ANOVA results show that BFI values for watersheds underlain by Dakota, Alluvial and Flint Hills aquifers are all significantly different, while BFI values for watersheds with glacial aquifers were only significantly different from those underlain by Dakota aquifers. Full results of the ANOVA test are available in Table S16. The best fit line for each parameter is a polynomial calculated with R using local fitting. They are provided to help illustrate trends.

spans a steep precipitation gradient and as precipitation changes, it affects land use, land cover and other natural watershed properties. For example, the amount of urban and forested area in a watershed are positively correlated with precipitation while the amount of agriculture is negatively correlated with precipitation across the study area (significant Spearman rho $p < 0.005$; Fig. 4 A). These superimposed relationships suggest that the spatial patterns in streamflow components are driven by the precipitation gradient, both directly and indirectly by influencing to patterns in land use and physical watershed properties across the study area. Together, these findings add to the growing knowledge that the effects of local land use on hydrologic processes are often superimposed on larger climate trends (Wang and Hejazi, 2011; Martin et al., 2017; Wang and Stephenson, 2018; Zipper et al., 2018) and is important to take into consideration for future management of water resources.

4.2. *Impact of long-term trends in climate and land use on BFI*

Increases in average annual precipitation and temperature that we observe from 1960 are consistent with results Rahmani et al. (2015) and Lin et al. (2017). As mentioned in the Introduction, the general trends observed by those studies included an increase in annual precipitation and temperature across the state. Alongside these changes, irrigated acreage and groundwater use also increased for all watersheds. Although these changes in climate and land use all trend in the same direction, their influences on streamflow appear to be different for the three easternmost sites, where BFI decreased, compared to the five westernmost sites, where BFI increased (Fig. 5). We hypothesize that the differences between eastern and western sites reflect natural antecedent properties of each watershed. As discussed in the paragraphs below, watershed characteristics are not only important for determining hydrological processes under current climate but also their response to changing conditions (Teutschbein et al., 2018).

First, differences in soil and bedrock composition and land use likely impact the streamflow response to increasing precipitation over time, as they do across the precipitation gradient currently (Section 4.1). Specifically, soil and bedrock in the eastern watersheds generally has lower permeability than the western watersheds, reflecting differences in soil clay content, urbanization, and bedrock units. As precipitation and irrigation increases, soils and bedrock that are more permeable would be better able to accommodate an increase in infiltration than those with lower permeability (Yu et al., 2000; Wang et al., 2009; Vaezi et al., 2010). Thus, with increasing precipitation and irrigation, a greater proportion of the water may have infiltrated the subsurface in the western watersheds but not the eastern watersheds, causing their BFI values to increase and decrease over time, respectively. Consistent with this interpretation, more permeable lithologies such as sandstones have been found to provide a buffering effect that can sustain low flows during dry periods (Carlier et al., 2018). Their permeability is high enough to allow them to store large amounts of water during precipitation events but low enough to prevent a sharp decrease in storage after the event. Further, combined effects of higher clay content and urban land cover can also result in increased rates of sedimentation and siltation within stream channels, which intensifies the decoupling of surface-groundwater resources and negatively impacts water quality (Jones et al., 2015; Michalek et al., 2021).

Secondly, the different response between the eastern and western watersheds may reflect the greater aridity of the western sites.

Previous studies have also found that relatively arid catchments are more sensitive to impacts from climate and land use changes than humid catchments, where water is more abundant (Farmer et al., 2003; Wang and Hejazi, 2011).

Third, changes in seasonal patterns could also play a role in driving the trends over time. We observe that most watersheds have experienced increases in BFI over time. However, increases in BFI were significant in five watersheds for the dry season (Jan. - Mar. and Oct. - Dec.) compared to only two watersheds in the wet season (April - Sept.; Fig. 7). Precipitation and temperature also generally increased, although not significantly, in the dry season while the wet season does not appear to demonstrate consistent trends. Such changes in precipitation seasonality could be affecting the proportions of recharge and runoff and thus values of BFI over time (Jones and Banner, 2003; Zhang et al., 2020). Temperatures during the dry season are generally lower than those during the wet season. If a greater proportion of the annual precipitation falls while temperatures are cooler, lower evapotranspiration rates during that time may allow greater infiltration and recharge (Earman and Dettinger, 2011). Significant changes in BFI seasonality primarily occurred in western watersheds, which again support the notion that western watersheds appear to be more sensitive to changing conditions, both annually and seasonally, due to different watershed characteristics.

4.3. Limitations

There are important limitations to our analyses that should be considered when interpreting the results of our study. First, hydrograph separation techniques are relatively simple, widely used, and useful metric for understanding relationships between groundwater discharge and watershed characteristics (Eckhardt, 2008; Tesoriero et al., 2009; Price, 2011; Ficklin et al., 2016), but the results are estimates of streamflow components and BFI, with true values often unknown (Eckhardt, 2008; Barlow et al., 2014). The accuracy of the hydrograph separation method is dependent on local factors, such as watershed topography, channel geomorphology, and geology (Price, 2011). Alternative approaches have been used to validate results of hydrograph separation (e.g., chemical and isotopic tracers), however such validations and data required for them are geographically limited (Eckhardt, 2008) and these alternative methods have their own limitations. By comparing the results of multiple hydrograph separation techniques, we can help ensure accuracy (Barlow et al., 2014). For our study, we observed good agreement between methods (Fig. 2B).

Coupled with methodological uncertainty, there are also uncertainties that arise from our data sources. The groundwater usage and total irrigation acreage data are county-wide rather than watershed specific and are self-reported until 1980 (Wilson et al., 2005). Additionally, the climate data are not field-measured data, but rather the data are extrapolated/modeled from the PRISM Climate Group model. Although such climate data is frequently used in these types of analysis (e.g., Ficklin et al., 2016), the data could miss intensity and frequency of climate data that is crucial in understanding patterns in groundwater discharge over time. Similarly, we use average values for many watershed and streamflow properties which can result in lost information or over/underestimation of trends (Gnann et al., 2019).

In reality, interactions between numerous landscape variables are likely influencing streamflow generation and overall watershed hydrology to some extent at both spatial and temporal scales (Rumsey et al., 2015; Teutschbein et al., 2018). This work is exploratory in nature. The relationships we identified and our interpretation of them are based largely on statistical analysis. Future work is warranted that aims to assess finer scales of streamflow components in space and time, determine causal and functional relationships between watershed variables, streamflow components and BFI, and to and make water quantity/quality predictions. Regardless, our results add to the growing knowledge on the importance of understanding the complex relationships between watershed variables, climate and land use on regional water quantity and quality (Price, 2011; Zipper at al, 2018; Teutschbein et al., 2018).

5. Concluding remarks

This study examined spatial and temporal variation in streamflow components across the Kansas precipitation gradient to better understand how climate and land use variation impacts the contribution of baseflow to streamflow. The spatial analysis demonstrates that, under current conditions, both runoff and baseflow increase significantly in the direction of increasing precipitation. However, BFI decreases significantly with increasing precipitation because the increase in runoff with precipitation is greater than the increase in baseflow. We interpret this result to reflect the limits of infiltration on the proportion of precipitation that recharges the subsurface and can ultimately discharge into a stream. As precipitation increases, a greater proportion of water may be diverted over the land surface rather than through the subsurface. In addition, variation in the permeability of watershed soil and bedrock in response to natural lithologic variation and land use also appears to contribute variation in BFI across the study area. Spatial patterns in many watershed properties (e.g., land use, soil clay content) are driven by precipitation. Therefore, our results highlight the long-term importance of climate on landscape composition and water resources.

Our temporal analysis indicates that BFI significantly increased during 1960–2018 at sites in the western half of our study area. Precipitation, temperature, irrigated acreage, and groundwater pumping all increased over the same time interval and thus may have contributed to the observed increase in BFI. However, we hypothesize that the western watersheds were more sensitive to these changes than the eastern watersheds because the western watersheds have more permeable soils and bedrock and lower rates of annual precipitation. These characteristics not only influence streamflow under current climate but also its response to changing conditions (Teutschbein et al., 2018).

These findings have important implications for water quantity and quality across the Kansas precipitation gradient and beyond. First, the same properties that make the western watersheds more sensitive to variation in climate and land use likely make them more susceptible to groundwater contamination. Watersheds with high permeability soil and bedrock are considered high risk for groundwater contamination (USGS, 1999). Second, an increase in BFI coupled with widespread agricultural development may be causing an increase in the export of nutrients from groundwater to surface water over time. If so, this change would alter surface water composition and may promote algal growth (Johnson and Stets, 2020; Brookfield et al., 2021). Third, our work provides a strong foundation for understanding streamflow drivers and how they vary spatially and temporally (past 60 years) in our study region, but also in other moderate to low relief regions, where changes in precipitation rates will occur. Therefore, the results of this study are important to consider for future water management across the study area and other areas where precipitation rates are changing.

Author statement

BRW and MFK designed the study. BRW, GA, and SGT collected data and analyzed results. BRW led the manuscript development. All authors helped revise the manuscript and approved its submission.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This material is based upon work supported by the National Science Foundation under Award No. OIA-1656006 and matching support from the State of Kansas through the Kansas Board of Regents. We thank Walter Dodds and Jesse Nippert for helpful discussions and the USGS scientists who developed the software and generated the data used in this study. We also thank the Kansas EPSCoR office for their support. Datasets for this research are included in the figures and Supplementary information files for the purposes of peer review. The data is also available in the Kansas State University institutional repository (K-State Research Exchange (K-REx)). K-REx content is globally accessible by anyone with access to the internet.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ejrh.2022.101071.

References

Ayers, J.R., Villarini, G., Jones, C., Schilling, K., 2018. Changes in monthly baseflow across the U.S. Midwest. Hydrol. Process. 33, 748–758. https://doi.org/10.1002/hyp.13359.

Bajželj, B., Richards, K.S., 2014. The positive feedback loop between the impacts of climate change and agricultural expansion and relocation. Land 3 (3), 898–916. https://doi.org/10.3390/land3030898.

Barlow, P.M., Cunningham, W.L., Zhai, T., Gray, M., 2014. U.S. Geological Survey Groundwater Toolbox, a graphical and mapping interface for analysis of hydrologic data (version 1.0)—User guide for estimation of base flow, runoff, and groundwater recharge from streamflow data: U.S. Geological Survey Techniques and Methods, book 3, chap. B10, 27 p. ⟨https://doi.org/10.3133/tm3B10⟩.

Barlow, P.M., Cunningham, W.L., Zhai, T., Gray, M., 2017. U.S. Geological Survey Groundwater Toolbox version 1.3.1, a graphical and mapping interface for analysis of hydrologic data: U.S. Geological Survey Software Release, 26 May 2017. ⟨https://doi.org/10.5066/F7R78C9G⟩.

Barlow, P.M., Leake, S.A., 2012. Streamflow depletion by wells—understanding and managing the effects of groundwater pumping on streamflow: U.S. Geological Survey Circular 1376, 84 p. ⟨http://pubs.usgs.gov/circ/1376/⟩.

Bhaskar, A.S., Welty, C., Maxwell, R.M., Miller, A.J., 2015. Untangling the effects of urban development on subsurface storage in Baltimore. Water Resour. Res. 51 (2), 1158–1181. https://doi.org/10.1002/2014WR016039.

Blodgett, J.C., Walters, J.R., Borcers, J.W., 1992. Streamflow gains and losses and selected flow characteristics of Cottonwood Creek, north central California, 1982-1985. Water-Resources Investigation Report 92-4009. Reston, VA: US Geological Survey, 19 pp. DOI:⟨10.3133/WRI924009⟩.

Brikowski, T.H., 2008. Doomed reservoirs in Kansas, USA? Climate change and groundwater mining on the Great Plains lead to unsustainable surface water storage. J. Hydrol. 354 (1–4), 90–101. https://doi.org/10.1016/j.jhydrol.2008.02.020.

Brookfield, A.E., Hansen, A.T., Sullivan, P.L., Czuba, J.A., Kirk, M.F., Li, L., Newcomer, M.E., Wilkinson, G., 2021. Predicting algal blooms: are we overlooking groundwater? Sci. Total Environ. 769, 144442 https://doi.org/10.1016/j.scitotenv.2020.144442.

Brown, J.F., Pervez, M.S., 2014. "Merging remote sensing data and national agricultural statistics to model change in irrigated agriculture". USGS Staff – Published Research. 913. ⟨http://digitalcommons.unl.edu/usgsstaffpub/913⟩.

Carlier, C., Wirth, S.B., Cochand, F., Hunkeler, D., Brunner, P., 2018. Geology controls streamflow dynamics. J. Hydrol. 566 (2018), 756–769. https://doi.org/10.1016/j.jhydrol.2018.08.069.

Cuthbert, M.O., Gleeson, T., Moosdorf, N., Befus, K.M., Schneider, A., Hartmann, J., Lehner, B., 2019. Global patterns and dynamics of climate-groundwater interactions. Nat. Clim. Chang. 9, 137–141. https://doi.org/10.1038/s41558-018-0386-4.

De Marsily, G., 1986. Quantitative Hydrogeology. Academic Press, Paris, pp. 213–229. https://doi.org/10.2166/wcc.2011.034.

Earman, S., Dettinger, M., 2011. Potential impacts of climate change on groundwater resource. J. Water Clim. Chang. 2 (4), 213–229. https://doi.org/10.2166/wcc.2011.034.

Eckhardt, K., 2008. A comparison of baseflow indices, which were calculated with seven different baseflow separation methods. J. Hydrol. 352 (1–2), 168–173. https://doi.org/10.1016/j.jhydrol.2008.01.005.

Falcone, J.A., 2011. GAGES-II: Geospatial Attributes of Gages for Evaluating Streamflow (Report). Reston, VA. ⟨https://doi.org/10.3133/70046617⟩.

Famiglietti, J.S., Lo, M., Ho, S.L., Bethune, J., Anderson, K.J., Syed, T.H., Swenson, S.C., de Linage, C.R., Rodell, M., 2011. Satellites measure recent rates of groundwater depletion in California's Central Valley. Geophys. Res. Lett. 38, L03403 https://doi.org/10.1029/2010GL046442.

Farmer, D., Sivapalan, M., Jothityangkoon, C., 2003. Climate, soil, and vegetation controls upon the variability of water balance in temperate and semiarid landscapes: downward approach to water balance analysis. Water Resour. Res. 39 (2), 1035. https://doi.org/10.1029/2001WR000328.

Ficklin, D.L., Robeson, S.M., Knouft, J.H., 2016. Impacts of recent climate change on trends in baseflow and stormflow in United States watersheds. Geophys. Res. Lett. 43, 5079–5088. https://doi.org/10.1002/2016GL069121.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., 2005. Global consequences of land use. Science 309, 570–574. https://doi.org/10.1126/science.1111772.

Gnann, S.J., Woods, R.A., Howden, N.J.K., 2019. Is there a baseflowBudyko curve? Water Resour. Res. 55, 2838–2855. https://doi.org/10.1029/2018WR024464.

Held, I.M., Soden, B.J., 2006. Robust responses of the hydrological cycle to global warming. J. Clim. 19, 5686–5699. https://doi.org/10.1175/JCLI3990.1.

Hillel, D., 1982. Introduction to Environmental Soil Physics. Academic Press. ISBN 9780080918693.

IPCC, 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, B. Zhou (Eds.)]. Cambridge University Press. In Press.

Jasechko, S., 2019. Global isotope hydrogeology–review. Rev. Geophys. 57 (3), 835–965. https://doi.org/10.1029/2018RG000627.

Johnson, H.M., Stets, E.G., 2020. Nitrate in streams during winter low-flow conditions as an indicator of legacy nitrate. Water Resour. Res. 56 https://doi.org/10.1029/2019WR026996.

Jones, J., Growns, I., Arnold, A., McCall, S., Bowes, M., 2015. The effects of increased flow and fine sediment on hyporheic invertebrates and nutrients in stream mesocosms. Freshw. Biol. 1–36. https://doi.org/10.1111/fwb.12536.

Jones, I.C., Banner, J.L., 2003. Hydrogeologic and climatic influences on spatial and interannual variation of recharge to a tropical karst island aquifer. Water Resour. Res. 39 (9), 1253. https://doi.org/10.1029/2002WR001543, 2003.

Kaiser, Henry F., 1961. A note on Guttman's lower bound for the number of common factors. Br. J. Stat. Psychol. 14, 1–2.

Kansas Geological Survey (KGS), 2008. Surficial geology of Kansas: Kansas Geological Survey, Map M-118, scale 1:500,000.

Kassambara, A. and Mundt, F. (2020) Factoextra: Extract and Visualize the Results of Multivariate Data Analyses. R Package Version 1.0.7. https://CRAN.R-project.org/package=factoextra.

Ku, H.F.H., Hagelin, N.W., Buxton, H.T., 1992. Effects of urban storm-runoff control on ground-water recharge in Nassau County, New York. Ground Water 30 (4), 507–514. https://doi.org/10.1111/j.1745-6584.1992.tb01526.x.

Layzell, A.L., Evans, C.S., 2013. Kansas Droughts: Climatic Trends Over 1,000 Years. KGS Public Information Circular 35. https://www.kgs.ku.edu/Publications/PIC/PIC35r.pdf.

Loague, K., Heppner, C.S., Ebel, B.A., VanderKwaak, J.E., 2010. The quixotic search for a comprehensive understanding of hydrologic response at the surface: Horton, Dunne, Dunton, and the role of concept-development simulation: hydrological processes 24, 2499–2505. ⟨https://doi.org/10.1002/hyp.7834⟩.

Lê, S., Josse, J., Husson, F., 2008. FactoMineR: an R package for multivariate analysis. J. Stat. Softw. 25 (1), 1–18. https://doi.org/10.18637/jss.v025.i01.

Lerner, D.N., 2002. Identifying and quantifying urban recharge: a review. Hydrogeol. J. 10 (1), 143–152. https://doi.org/10.1007/s10040-001-0177-1.

Lin, X., Harrington, J., Ciampitti, I., Gowda, P., Brown, D., Kisekka, I., 2017. Kansas trends and changes in temperature, precipitation, drought, and frost-free days from the 1890s to 2015. J. Contemp. Water Res. Educ. 162 (1), 18–30. https://doi.org/10.1111/j.1936-704X.2017.03257.x.

Macfarlane, P.A., Misgna, G.M., Buddemeier, R.W., 2000. Atlas of Kansas High Plains Aquifer: Preliminary Analysis of Potential Ground-water Supplies. Kansas Geological Survey Educational Series 14. https://www.kgs.ku.edu/HighPlains/atlas/ataqhpr.htm.

Macpherson, G.L., Roberts, J.A., Blair, J.M., Townsend, M.A., Fowle, D.A., Beisner, K.R., 2008. Increasing shallow groundwater CO_2 and limestone weathering, Konza Prairie, USA. Geochim. Cosmochim. Acta 72 (2008), 5581–5599. https://doi.org/10.1016/j.gca.2008.09.004.

Marques da Silva, R., Santos, C.A.G., Moreira, M., Corte-Real, J., Silva, V.C.L., Medeiros, I.C., 2015. Rainfall and river flow trends using Mann–Kendall and Sen's slope estimator statistical tests in the Cobres River basin. Nat. Hazards 77, 1205–1221. https://doi.org/10.1007/s11069-015-1644-7.

Martin, K.L., Hwang, T., Vose, J.M., Coulston, J.W., Wear, D.N., Miles, B., Band, L.E., 2017. Watershed impacts of climate and land use changes depend on magnitude and land use context. Ecohydrology 10 (7), e1870. https://doi.org/10.1002/eco.1870.

Michalek, A., Zarnaghsh, A., Husic, A., 2021. Modeling linkages between erosion and connectivity in an urbanizing landscape. Sci. Total Environ. 764, 144255 https://doi.org/10.1016/j.scitotenv.2020.144255.

Milly, P., Dunne, K., Vecchia, A., 2005. Global pattern of trends in streamflow and water availability in a changing climate. Nature 438, 347–350. https://doi.org/10.1038/nature04312.

Miller, M.P., Buto, S.G., Susong, D.D., Rumsey, C.A., 2016. The importance of base flow in sustaining surface water flow in the Upper Colorado River Basin. Water Resour. Res. 52 https://doi.org/10.1002/2015WR017963.

Peterson, D.L., Whistler, J.L., Egbert, S.L., Martinko, E.A., 2009. 2005 Kansas Land Cover Patterns, Level IV, State of Kansas – Final Report. KBS Report #167.

Nie, W., Yuan, Y., Kepner, W., Nash, M.S., Jackson, M., Erickson, C., 2011. Assessing impacts of landuse and landcover changes on hydrology for the upper San Pedro watershed. J. Hydro. 407 (1), 105–114. https://doi.org/10.1016/j.jhydrol.2011.07.012.

Price, K., 2011. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: a review. Prog. Phys. Geogr. Earth Environ. 35 (4), 465–492. https://doi.org/10.1177/0309133311402714.

PRISM Climate Group, Oregon State University, ⟨http://prism.oregonstate.edu⟩, created January 2020.

RStudio Team, 2019. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA. ⟨http://www.rstudio.com/⟩.

Rahmani, V., Hutchinson Jr., S.L., J.A, H., Hutchinson, J.M.S., Anandhi, A., 2015. Analysis of temporal and spatial distribution and change-points for annual precipitation in Kansas, USA. Int. J. Climatol. 35 (13), 3879–3887. https://doi.org/10.1002/joc.4252.

Richardson, C.M., Zimmer, M.A., Fackrell, J.K., Paytan, A., 2020. Geologic controls on source water drive baseflow generation and carbon geochemistry: evidence of nonstationary baseflow sources across multiple subwatersheds. Water Resour. Res. 56 (7), e2019WR026577.

Rumsey, C.A., Miller, M.P., Susong, D.D., Tillman, F.D., Anning, D.W., 2015. Regional scale estimates of baseflow and factors influencing baseflow in the Upper Colorado River Basin. J. Hydrol. Reg. Stud. 4, 91–107. https://doi.org/10.1016/j.ejrh.2015.04.008, 2214-5818.

Rumsey, C.A., Miller, M.P., Sextone, G.A., 2020. Relating hydroclimatic change to streamflow, baseflow, and hydrologic partitioning in the Upper Rio Grande Basin, 1980 to 2015. J. Hydrol. 584, 124715 https://doi.org/10.1016/j.jhydrol.2020.124715.

Santhi, C., Allen, P.M., Muttiah, R.S., Arnold, J.G., Tuppad, P., 2008. Regional estimation of base flow for the conterminous United States by hydrologic landscape regions. J. Hydrol. 351 (1–2), 139–153. https://doi.org/10.1016/j.jhydrol.2007.12.018.

Seager, R., Lis, N., Feldman, J., Ting, M., Williams, A.P., Nakamura, J., Liu, H., Henderson, N., 2018. Whither the 100th Meridian? The once and future physical and human geography of America's arid-humid divide. Part 1: the story so far. Earth Interact. 22 (5), 1–22. https://doi.org/10.1175/EI-D-17-0011.1.

Stoeser, D., Green, G., Morath, J., Heran, W., Wilson, A., Moore, D., Van Gosen, B., 2005. Preliminary Integrated Geologic Map Databases for the United States Central States: Montana, Wyoming, Colorado, New Mexico, Kansas, Oklahoma, Texas, Missouri, Arkansas, and Louisiana, - The State of Kansas. Map. U.S. Geological Survey Open-File Report 2005–1351, Denver, CO. Using GIS software: QGIS.

Sullivan, P.L., Stops, M.W., Macpherson, G.L., Li, L., Hirmas, D.R., Dodds, W.K., 2019. How landscape heterogeneity governs stream water concentration-discharge behavior in carbonate terrains (Konza Prairie, USA). Chem. Geol. 527, 118989 https://doi.org/10.1016/j.chemgeo.2018.12.002.

Tan, X., Liu, B., Tan, X., 2020. Global changes in baseflow under the impacts of changing climate and vegetation. Water Resour. Res. 56 (9) https://doi.org/10.1029/2020WR027349.

Tesoriero, A.J., Duff, J.H., Wolock, D.M., Spahr, N.E., Almendinger, J.E., 2009. Identifying pathways and processes affecting nitrate and orthophosphate inputs to streams in agricultural watersheds. J. Environ. Qual. 38 (5), 1892–1900. https://doi.org/10.2134/jeq2008.0484.

Teutschbein, C., Grabs, T., Hjalmar, L., Karlsen, R.H., Bishop, K., 2018. Simulating streamflow in ungauged basins under a changing climate: the importance of landscape characteristics. J. Hydrol. 561 (2018), 160–178161. https://doi.org/10.1016/j.jhydrol.2018.03.060.

U.S. Geological Survey, 1999. The Quality of Our Nation's Waters—Nutrients and Pesticides: U.S. Geological Survey Circular 1225, 82 p. ⟨https://doi.org/10.3133/cir1225⟩.

U.S. Geological Survey, 2016. National Water Information System data available on the World Wide Web (USGS Water Data for the Nation). ⟨https://waterdata.usgs.gov/nwis⟩.

Vaezi, A.R., Bahrami, H.A., Sadeghi, S.H.R., Mahdian, M.H., 2010. Modeling relationship between runoff and soil properties in dry-farming lands, NW Iran. Hydrol. Earth Syst. Sci. Discuss. 7, 2577–2607. https://doi.org/10.5194/hessd-7-2577-2010.

Voss, K.A., Famiglietti, J.S., Lo, M., Linage, C., Rodell, M., Swenson, S.C., 2013. Groundwater depletion in the Middle East from GRACE with implications for transboundary water management in the Tigris-Euphrates-Western Iran region. Water Resour. Res. 49 (2), 904–914. https://doi.org/10.1002/wrcr.20078.

Wang, T., Istanbulluoglu, E., Lenters, J.D., Scott, D.T., 2009. On the role of groundwater and soil texture in the regional water balance: an investigation of the Nebraska Sand Hills, USA. Pap. Earth Atmos. Sci. 493 https://doi.org/10.1029/2009WR007733.

Wang, D., Hejazi, M., 2011. Quantifying the relative contribution of the climate and direct human impacts on mean annual streamflow in the contiguous United States. Water Resour. Res. 47 (10), W00J12. https://doi.org/10.1029/2010WR010283.

Wang, H., Stephenson, S.R., 2018. Quantifying the impacts of climate change and land use/cover change on runoff in the lower Connecticut River Basin. Hydrol. Process. https://doi.org/10.1002/hyp.11509.

Wilson, B., Bartley, J., Emmons, K., Bagley, J., Wason, J., Stankiewicz, S., 2005. Water Information Management and Analysis System, Version 5, for the Web. User Manual. Open-file Report No. 2005-30. Kansas Geological Survey. ⟨https://hercules.kgs.ku.edu/geohydro/ofr/2005_30/wimas_ofr2005_30.pdf⟩.

Wen, F., Chen, X., 2006. Evaluation of the Impact of Groundwater Irrigation on Streamflow in Nebraska. J. Hydro. 327 (3–4), 603–617. https://doi.org/10.1016/j.jhydrol.2005.12.016.

Wolock, D., Winter, T., Mcmahon, G., 2004. Delineation and Evaluation of hydrologic-landscape regions in the United States using geographic information system tools and multivariate statistical analyses. Environ. Manag. 34 (Suppl 1), S71–S88. https://doi.org/10.1007/s00267-003-5077-9.

Yu, Z., Gburek, W.J., Schwartz, F.W., 2000. Evaluating the spatial distribution of water balance in a small watershed, Pennsylvania. Hydrol. Process. 14 (5), 941–956. https://doi.org/10.1002/(SICI)1099-1085(20000415)14:5<941::AID-HYP2>3.0.CO;2-S.

Zabel, F., Putzenlechner, B., Mauser, W., 2014. Global agricultural land resources – a high resolution suitability evaluation and its perspectives until 2100 under climate change conditions. PLoS One 9 (9), e107522. https://doi.org/10.1371/journal.pone.0107522.

Zhang, Y.K., Schilling, K.E., 2006. Increasing streamflow and baseflow in Mississippi River since the 1940 s: effect of land use change. J. Hydrol. 324 (2006), 412–422. https://doi.org/10.1016/j.jhydrol.2005.09.033.

Zhang, Q., Liu, J., Singh, V.P., Gu, X., Chen, X., 2016. Evaluation of impacts of climate change and human activities on streamflow in the Poyang Lake basin, China. Hydrol. Process. 30 (14), 2562–2576. https://doi.org/10.3390/w13172404.

Zhang, Z., Li, Y., Barlage, M., Chen, F., Miguez-Macho, G., Ireson, A., Li, Z., 2020. Modeling groundwater responses to climate change in the Prairie Pothole Region. Hydrol. Earth Syst. Sci. 24, 655–672. https://doi.org/10.5194/hess-24-655-2020.

Zipper, S.C., Motew, M.M., Booth, E.G., Chen, X., Qiu, J., Kucharik, C.J., Carpenter, S.R., Loheide II, S.P., 2018. Continuous separation of land use and climate effects on the past and future water balance. J. Hydrol. https://doi.org/10.1016/j.jhydrol.2018.08.022.