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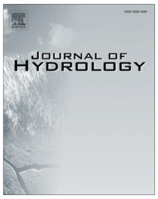

Fundamental spatial and temporal disconnections in the hydrology of an intermittent prairie headwater network

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SUMMARY

We characterize the hydrology of intermittent prairie headwater streams of the Konza Prairie Biological Station (Konza) located in northeastern Kansas, USA. Flow records from four gaging stations were used to quantify flow intermittence and mean and peak annual discharges. Gage sites used in this analysis are classified as harshly intermittent with all sites having over 90 days of zero-flow annually. The largest basin had the fewest zero-flow days and the shortest durations of zero-flow while the smallest basin had the most zero-flow days and the highest frequency zero-flow durations. There were strong correlations between total annual precipitation and the total number of zero-flow days and the number of zero-flow periods. Correlations were less strong between the Palmer Drought Severity Index (PDSI) and the number of zero-flow days and between PDSI and the number of zero-flow periods. Basin-averaged total annual precipitation poorly predicted mean annual and peak annual discharges. Double mass plots of streamflow to precipitation and streamflow in the headwaters to the receiving stream demonstrate many instances of flow desynchronization. Results of this study suggest that local watershed-scale processes, such as groundwater storage in limestone and alluvial strata, dynamic infiltration flow paths, and soil moisture conditions, produce a threshold-driven hydrologic response, decoupling the headwater hydrologic regimes from sub-annual weather patterns.

1. Introduction

Headwater streams form where channelized flow originates and are tightly hydrologically, geomorphically, and biologically linked to hillslope processes (e.g. Horton, 1945; Hack and Goodlett, 1960; Hewlett and Hibbert, 1967; Likens et al., 1977; Dietrich and Dunne, 1993; Gomi et al., 2002; MacDonald and Coe, 2007). Headwaters are also important for longitudinal linkages with larger streams and are major contributors of energy and matter to those larger streams (Gomi et al., 2002; MacDonald and Coe, 2007; Banner et al., 2009). Due to their comparatively small size and connectivity to hillslopes, headwater streams are particularly responsive to perturbations within the watershed relative to larger streams (e.g. Benda et al., 2005). Headwater streams, generally, have a stream order of less than three (Vannote et al., 1980) and comprise between 66% (Leopold et al., 1964) and 80% (Naiman et al., 2005) of the total stream length of watersheds worldwide. Intermittent streams account for more than 60% of the total river length in the contiguous United States (Nadeau and Rains, 2007). Grasslands and wooded grasslands with intermittent streamflow are responsible for approximately 28% of global runoff (Dodds, 1997).

Native tallgrass prairie once covered 160 million hectares within the United States but is now one of the most endangered biomes with 95% of tallgrass prairie lost (Samson and Knopf, 1994). Within remaining fragments of prairie, many streams are not large enough to support a fully functional watershed (Dodds et al., 2004). In the Great Plains (USA) streams have harsh intermittent or perennial discharge regimes with distinct periods of flooding and drying (Dodds et al., 2004), high flood frequency, and low predictability (Samson and Knopf, 1994). Although intermittent prairie streams may have substantial portions of a year with zero-flow, these systems can still strongly influence downstream water quality (Dodds and Oakes, 2006, 2008).

Patterns of ecosystem expansion and contraction, as seen in intermittent streams, have strong implications for ecological communities. The extremely variable hydrologic regimes and prolonged periods of zero-flow create a mosaic of aquatic and terrestrial habitats that control ecological dynamics and regulate the transfer and transformation of energy and materials in a

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system. Intermittent streams and their riparian zones are hot spots for biogeochemical processes in arid to semi-arid regions (McIntyre et al., 2009). Unsaturated riparian soils are a source of nitrogen (Bernal et al., 2007), which is rapidly mobilized after periods of zero-flow as groundwater levels rise (Butturini et al., 2003). The extreme variation in hydrology and associated abiotic habitat elements structure the biotic assemblages of intermittent streams (e.g. Lake, 2000; Dodds et al., 2004; Fritz and Dodds, 2005; Schriever et al., 2014). The dry periods are key extrinsic drivers on responses of functional and taxonomic richness in intermittent streams (Schriever et al., 2014). Despite the frequent and often severe hydrologic variations, intermittent headwater stream biological communities are highly resilient with microbes, invertebrates, and vertebrates recolonizing within days of a resumption of flow (Murdock et al., 2010, 2011).

Within the last several decades, drought severity and duration in the Great Plains have increased (Andreadis and Lettenmaier, 2006; Perkin et al., 2014) with up to 20% decreases in mean annual precipitation (Gamble et al., 2008). General circulation models predict more frequent, intense precipitation events with longer intervening dry periods in the coming decades for the Great Plains region (Knapp et al., 2002; Milly et al., 2005). Climate projections imply that global climate change will change precipitation regimes dramatically, which may increase the prevalence and extremes of intermittency (Larned et al., 2010b; Jaeger et al., 2014). Yet, there is a general lack of knowledge of the characteristics of intermittent streamflow because hydrologic records from small prairie streams are typically scarce, short, and rarely complete (Shook and Pomeroy, 2012) and few intermittent streams are intensively studied regardless of biome. While some attention has been devoted to large river floods, which are generally independent of decadal precipitation trends (Schumm and Lichty, 1963; Julian et al., 2012), we know of no systematic analysis of hydrologic regimes on smaller, intermittent headwater systems in the Central Great Plains region, USA. Confounding this data limitation is a general lack of knowledge of the applicability of standard hydrologic indices developed for perennial streams when applied to intermittent streams (Olden and Poff, 2003). While these hydrologic models and indices (e.g. the Indicators of Hydrologic Alteration; Richter et al., 1996) have been frequently used to quantify the flow regime of perennially flowing rivers (e.g. Magilligan and Nislow, 2005; Costigan and Daniels, 2012), intermittent streams have received scant attention.

Intermittent streams are particularly endangered ecosystems worldwide because they lack adequate management practices and protective policies or legislation (Datry et al., 2014). We cannot properly evaluate ecological responses or provide management and protective policies without a baseline understanding of the abiotic characteristics and mechanisms that drive intermittent flow regimes (e.g. Acuna et al., 2014). The overall objective of this study was to characterize the flow regime of intermittent prairie headwater streams in the central Great Plains, USA. We expected that hydrologic regimes would demonstrate little correlation with large scale atmospheric patterns and instead be correlated with local precipitation. We examine 25-years of hydrologic records from four gages within an intermittent headwater stream network to explore relationships between streamflow and precipitation as well as hydrologic relationships spatially within the network.

2. Material and methods

2.1. Study site

This study was conducted within the Konza Prairie Biological Station (herein Konza). Konza is owned by The Nature Conservancy and Kansas State University (KSU) that is operated as a field research station by the KSU Division of Biology and as an NSF-funded Long Term Ecological Research (LTER) facility. Konza comprises 3487 ha of native tallgrass prairie in the Flint Hills region of northeastern Kansas, USA (Fig. 1). We used flow records from three intermittent, third order headwater streams (N01B, N02B, and N04D) and the receiving fifth order, main trunk stream (Kings Creek) to characterize discharge regimes. Distances that the headwaters gages are from Kings Creek are: N01B is 3.51 km, N02B is 2.70 km, and N04D is 2.75 km (Table 1). All watersheds are completely within the boundary of Konza. Kings Creek has been monitored by a U.S. Geologic Survey (USGS) stream gage (06879650) since 1979 as a Hydrologic Benchmark. Gaging of the headwater streams began when KSU installed trapezoidal concrete weirs in 1987, which monitor less than half the total drainage area above the Kings Creek gage. All of the headwater sub-basins used in this study have been grazed by *Bos bison* (American bison) since 1992 and have burn rotations ranging from 1 to 4 years (Table 1). The streams used in this analysis are intermittent with complete seasonal channel drying common in all but spring-fed reaches.

Konza is located within a temperate climate and the mean annual precipitation for the study period (1987–2011) was 780 mm year^{-1} with 75% falling in the April through September growing season (Fig. 2A). Approximately 52 mm year^{-1} of total precipitation falls as snow (Hayden, 1998). Headwater floods typically occur in the summer months (Fig. 2B and C) and are tied to antecedent moisture conditions (Gray et al., 1998). Precipitation recharges the aquifers within a few hours through preferential flow and stream-groundwater interactions (Tsypin and Macpherson, 2013). The vegetation at the site is mesic native tallgrass prairie dominated by perennial warm-season grasses. The Flint Hills region contains the largest areas of unplowed native tallgrass prairie remaining in North America (Samson and Knopf, 1994). Woody plants dominate the valley bottoms, with recent expansion up tributary networks (Veach et al., 2014), while grasses dominate the hillslopes (Briggs et al., 2005).

The Flint Hills physiographic province is underlain by flat to slightly dipping 0–0.19° Permian-aged sedimentary rocks (Oviatt, 1998; MacPherson and Sophocleous, 2004). Stream networks dissect the landscape, exposing alternating layers of 1–2 m thick chert-bearing limestones and 2–4 m thick mudstone shales (Fig. 3) (Macpherson, 1996; Oviatt, 1998). The more resistant limestone layers form benches on hillslopes and knickpoints in stream channels, while less resistant mudstones erode to more gradual slopes, producing a terraced topography. Within the Kings Creek drainage system, the Florence Limestone is the highest and youngest layer and the Neva Limestone is the lowest and oldest layer (Oviatt, 1998). Many seasonal freshwater springs emerge from limestone exposures and can maintain isolated pools of water in otherwise dry channels. Konza soils are developed from loess, limestone, and shale, and are typically less than a meter thick on hillslopes. Soils are thickest at the base of slopes and in the stream valley bottoms (Ransom et al., 1998). There are numerous fractures in the underlying limestones and shales, and during prolonged dry periods soils form large (>3 cm) surface macropores (Tsypin and Macpherson, 2013).

Mean annual precipitation at Konza has been partitioned into 14% direct runoff, 2% lateral flow through soils, 9% groundwater recharge, and 75% evaporation (Steward et al., 2011). However, annual water yield varies substantially as the long-term precipitation mean is close to potential evapotranspiration (Dodds et al., 1996). Soil moisture is greatest after frequent precipitation events in the spring and early summer and lowest in the late summer and fall (Tsypin and Macpherson, 2013). Rain gage measurements in each sub-basin demonstrate that event specific precipitation is heterogeneously distributed across the site.

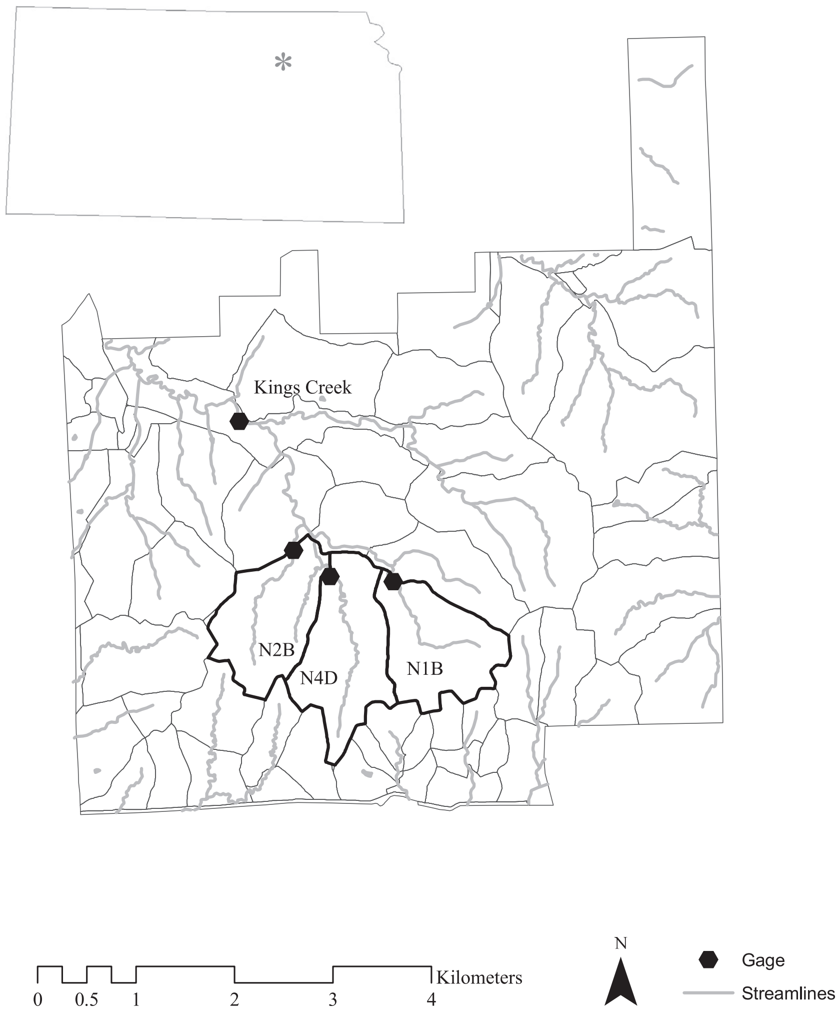

Fig. 1. Study site locations within the Konza Prairie Biologic Station, Kansas.

Table 1
Konza watershed descriptions.

Gage	Area (ha)	Distance from Kings Creek (km)	Burn frequency
Kings Creek	1060	–	–
N01B	118.8	3.51	Annual
N02B	120.7	2.70	Biannually
N04D	135.5	2.75	4-years

2.2. Data

Stream gages on N01B, N02B, and N04D are maintained by the KSU Division of Biology, and data are available for a 25 year period (1987–2011). These gages record discharge at five-minute intervals during stormflow and are calibrated weekly when streams are flowing. Discharge for Kings Creek is recorded in 15-minute intervals. Total daily precipitation data is recorded at the Konza weir sites during the growing season (April 1 through October 31) and at Konza headquarter's (~2 km from the weirs) during the entire year. The Konza headquarter's precipitation gage was used to as a proxy for precipitation in the headwaters when large precipitation events occurred outside of the growing season. Individual streamflow and precipitation gages, or headquarters precipitation gage during the non-growing season, were used to assess the relationship between precipitation and streamflow. Peak discharges were extracted from the record and matched with floods at the other basins following Perkins and Jones (2008). Event precipitations were extracted from total daily precipitation and were well-defined increase in total daily precipitation to which there is a progressive rise from or near zero and after which there is a progressive return to or near zero. Only distinct floods were included in the analysis. The analysis used peak discharges and precipitation measurements for the period of overlapping records for all basins. Snow water storage was assumed to have minimal influence on hydrologic regimes because less than 6% of the precipitation that falls at Konza is in the form of snow.

Over the 25-year period of record, the discharge records from 2006–2011 for N04D were of questionable quality due to a gage malfunction. Multi-linear regressions ($r^2 = 0.82$) were completed to estimate mean daily discharge for N04D as a function of mean daily discharge at N01B, N02B, and Kings Creek. No extrapolated mean daily discharge data were used for estimation for peak discharges and analysis where peak discharge was used were truncated for a period of record form 1987–2006 for the N04D gage. Only days with complete and quality data were used for analyses purposes for all gages.

The Palmer Drought Severity Index (PDSI) is one of the original drought indices developed for the US (Palmer, 1965). The PDSI is a cumulative drought index that measures deviations in moisture conditions that is calculated based off of precipitation,

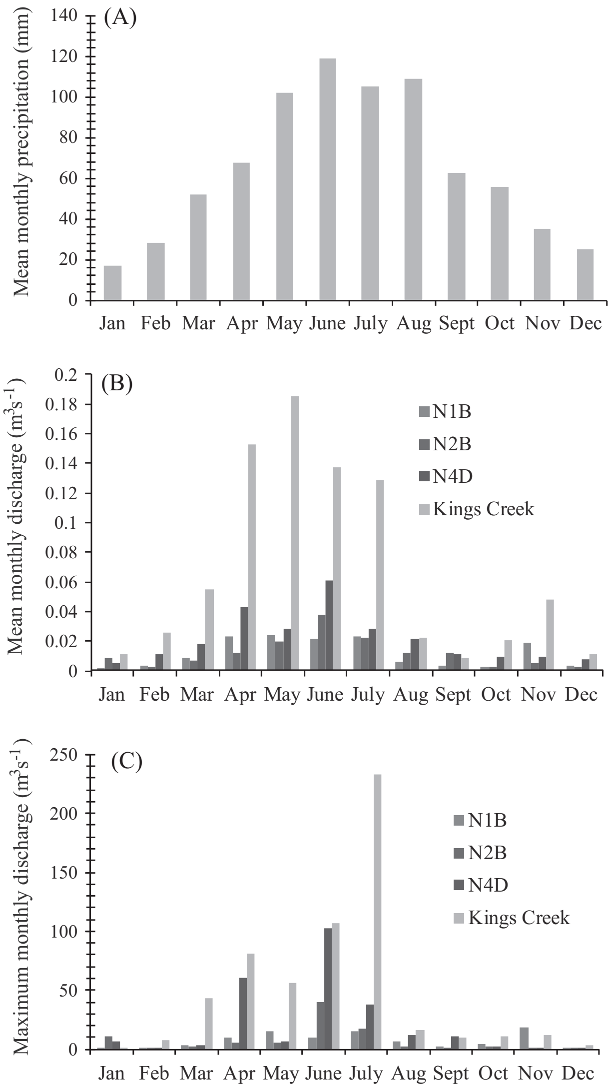

Fig. 2. Konza Prairie Biological Station's (A) mean monthly precipitation (1987–2011), (B) mean monthly discharge (1987–2011), and (C) maximum monthly discharge (1987–2011).

temperature, and local available water content that are reported at regional scales. Annual PDSI data for the Northeast region of Kansas (1987–2011) were obtained from the National Climatic Data Center (http://www.ncdc.noaa.gov).

2.3. Data analysis

Hydrologic characterizations employ a wide range of indices, but only two are commonly used to describe flow intermittency: the frequency and duration of zero-flow periods (e.g. Poff, 1996; Knighton and Nanson, 2001). Zero-flow frequency and duration are fundamental characteristics of intermittent streams and are increasingly being reported in ecologic studies of intermittent streams because of the direct translation to habitat availability and persistence (e.g. Jaeger et al., 2014; Schriever et al., 2014). Our analyses focused on the relations between discharge, precipitation, and PDSI within the Konza dataset. Following Daniels (2007), simple linear regressions were completed for correlations between maximum annual and mean annual discharge to total annual precipitation. Peak discharges and associated precipitation were log-transformed prior to model fitting and linear regressions and correlations were used (Jones and Perkins, 2010).

Double mass curves are a simple visual method widely used to study consistency and long-term trends in hydro-meteorological data sets. Double mass plots (Searcy and Hardison, 1960) are the plots of the cumulative amount of a quantity of interest at a station under consideration against the cumulative amount of a neighboring station. If the variables plot as a straight line on a double mass plot, they are consistently proportional over time and the slope of this line is the ratio between the two variables. Changes in the slope of a double mass curve are indicative of changes in the original relationship between variables that can include a change in the gaging station and or rating curve, errors in the data, changes in the catchment conditions, and/or changes to climate that affect the relationships between the variables of interest.

Temporal changes in annual streamflow statistics for the period of record were evaluated with standardized departure analyses of annual streamflow statistics. Departure analyses are useful for determining how daily flow magnitudes change over time (McCabe and Wolock, 2002). Departure analyses were conducted for mean, median, and maximum flows as determined by

$$\frac{\bar{Q} - Q_i}{\sigma_Q}$$

where $\bar{Q}$ is the long-term mean discharge, Q_i is the discharge for the ith time period, and σ_Q is the standard deviation of the long-term record of streamflow data of each gage.

3. Results

3.1. Flow intermittency

Discharge regimes at Konza were characterized as intermittent with all gages experiencing periods of prolonged zero-flow annually. No gaging station had zero-flow recorded exclusively in the winter, indicating that freezing was not the sole cause of intermittence at any station. The year in which the highest zero-flow frequencies or longest zero-flow duration occurred at each station was variable across stations (Table 2). Streams at Konza can be flowing or dry during any month throughout the record. In some years, the channels were almost completely dry and others they flowed for almost the entire year.

Kings Creek experienced the least amount of zero-flow days with an average duration of 179 days per year of zero-flow recorded at the gage site (Table 2). N02B had the most zero-flow days with an average duration of 248 days per year of zero-flow. Kings Creek had the lowest amount of zero-flow days recorded in 1998 with only 28 days that year experiencing zero-flow. N02B had the most zero-flow days recorded in 2006 with 356 days that year experiencing zero-flow. Trends in the number of zero-flow days followed the size of watershed with the largest watershed having the least number of zero-flow days and the smallest watersheds having the most zero-flow days. There were significant negative correlations between the number of zero-flow days and mean annual precipitation. The relationship was the strongest for N02B but Kings Creek, N01B, and N04D were also strong.

The frequency of zero-flow periods varied among watersheds. Kings Creek had an average frequency of zero-flow periods of three per year while N02B had seven per year (Table 2). Kings Creek had the least amount of zero-flow day frequencies in 1998 and 2010 where there was only one period of drying. N02B had the highest frequency of zero-flow days (19 periods in 2009). As with the number of zero-flow days, the frequency of zero-flow days also indicated the largest watershed has the most infrequent periods and the smallest watershed had the most frequent periods of zero-flow. The frequencies for zero-flow periods were highly correlated with mean annual precipitation for the headwater gages.

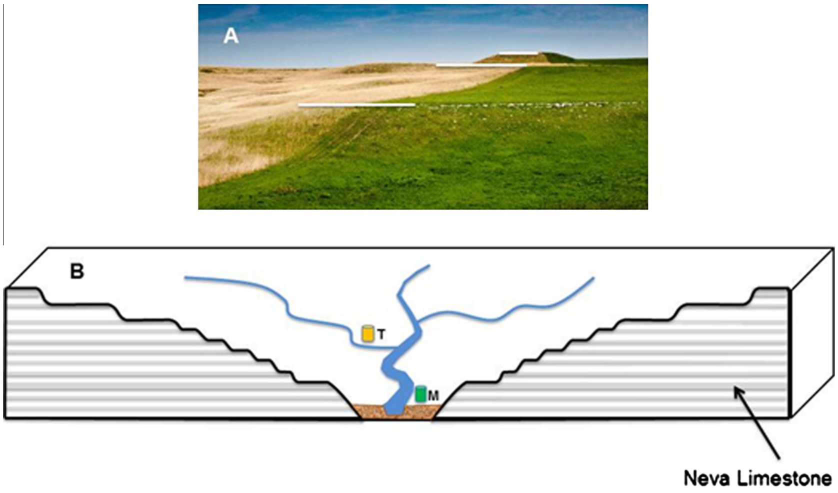

Fig. 3. (A) Photograph of the upper hillslopes of the Kings Creek study watershed. The green right-hand portion of the image is a recently burned sub-basin, revealing the limestone outcroppings as lines of white boulders corresponding to bench levels in the topography, highlighted by white bars. The uppermost bench pictured here is the Florence Limestone, the highest elevation surface in the study watershed. (B) Cross sectional diagram of local geology within the Kings Creek network. Shaded layers represent limestone alternating with mudstone shales, indicated by un-shaded layers. Relative landscape elevation position of the main stem Kings Creek gage (cylinder M) and the higher tributary gages (cylinder T) are placed within the geological framework. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Average (standard deviation), maximum, and minimum duration of zero-flow days and periods for the period of record (1987–2011).

	N01B	N02B	N04D	Kings Creek
Zero-flow days				
Average	231 (76)	248 (76)	217 (75)	179 (95)
Maximum	351	356	326	318
Minimum	56	50	57	28
Zero-flow periods				
Average	6 (3)	7 (5)	5 (3)	3 (2)
Maximum	12	19	14	7
Minimum	2	2	1	1

The frequency and duration of zero-flow days were poorly correlated for all the watersheds except N02B. Regressions of number of zero-flow days with PDSI and total annual precipitation revealed negative slopes between the number of zero-flow days with PDSI and total annual precipitation (Table 3). These negative correlations were significant for all watersheds but were more strongly negatively correlated for total annual precipitation than they were for PDSI. Correlations for the frequency of zero-flow periods were not as significant or strong for precipitation or PDSI as correlations for total number of zero-flow days (Table 4). The correlation of frequency of zero-flow days were significant for N04D and N02B against PDSI, while N01B and Kings Creek were insignificant. With the exception of Kings Creek, correlations between the frequencies of zero-flow days for each of the watersheds were significant and positive against total annual precipitation.

3.2. Annual flows

Mean annual discharge of the four watersheds used in this analysis were dominated by discharge that occurred between April and July (Fig. 2B). Correlations of mean annual discharge and total annual precipitation revealed that the relationship for the smaller watersheds of this study was stronger and more significant (N01B 0.53, $p = 0.006$; N02B 0.57, $p = 0.003$) than that of the larger watersheds (N04D 0.06, $p = 0.78$; Kings Creek 0.03, $p = 0.88$). Linear regressions of mean annual discharge and total annual precipitation overall did not have strong relationships (Fig. 4A; Table 5). The linear regressions for the smallest watershed (N02B: $F_{2,28} = 11.00$, $r^2 = 0.32$, $p = 0.0003$; N01B: $F_{2,28} = 9.04$, $r^2 = 0.28$, $p = 0.006$) were much stronger than those for the larger watersheds (N04D: $F_{2,28} = 0.08$, $r^2 = <0.01$, $p = 0.78$; Kings Creek: $F_{2,28} = 0.02$, $r^2 = <0.01$, $p = 0.88$). Peak annual discharge events occurred in the same time period that mean annual discharge events occured, in April through July (Fig. 2C). Overall, the linear regressions for peak

Table 3
Correlation matrix of the duration of zero-flow periods (i.e., the number of days of each dry period) in each watershed with total annual precipitation and the Palmer Drought Severity Index (PDSI) for the period of record (1987–2011). The first line is the strength of the correlation and the second line is the *p* value of the correlation.

	Precipitation	Kings Creek	N01B	N02B	N04D	PDSI
Precipitation	1	−0.66 <0.005	−0.55 0.01	−0.75 <0.003	−0.45 0.03	0.51 0.01
Kings Creek		1	0.7 <0.001	0.83 <0.001	0.54 0.006	−0.65 0.001
N01B			1	0.76 <0.002	0.83 0	−0.52 0.01
N02B				1	0.62 0.001	−0.69 <0.002
N04D					1	−0.43 0.03
PDSI						1

Table 4
Correlation matrix of the frequency of zero-flow periods in each watershed with total annual precipitation and the Palmer Drought Severity Index (PDSI) for the period of record (1987–2011). The first line is the strength of the correlation and the second line is the p value of the correlation.

	Precipitation	Kings Creek	N01B	N02B	N04D	PDSI
Precipitation	1	−0.11	0.52	0.45	0.57	0.51
		0.62	0.009	0.03	0.004	0.01
Kings Creek			0.16	−0.02	0.10	−0.27
			0.46	0.93	0.63	0.20
N01B				0.24	0.60	0.19
				0.27	0.002	0.37
N02B					0.17	0.41
					0.42	0.05
N04D						0.43
						0.04
PDSI						1

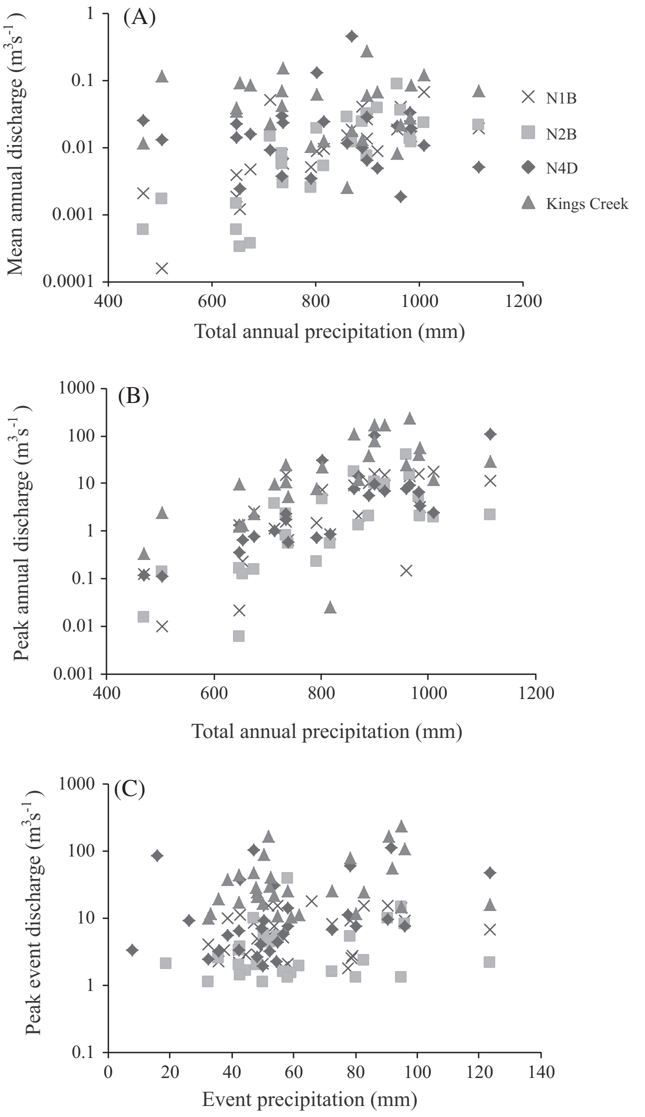

Fig. 4. Konza Prairie Biologic Station's (A) mean annual discharge (1987–2011) and (B) peak annual discharge (1987–2011) as a function of total annual precipitation and (C) peak event discharge (1987–2011) as a function of the event's discharge.

annual discharge were more significant than those for mean annual discharge (Fig. 4B; Table 6). N01B had the strongest relationship ($F_{2,28} = 15.04$, $r^2 = 0.4$, $p < 0.001$).

Table 5
Parameter estimates for simple linear regression analysis between mean annual discharge and total annual precipitation.

	a	b	SE_b	r^2	F	p
N01B	−0.03	5.69E−05	1.89E−05	0.28	9.04	0.006
N02B	−0.04	6.83E−05	2.06E−05	0.32	11.00	<0.003
N04D	0.01	3.36E−05	1.00E−04	3.50E−04	0.08	0.78
Kings	0.05	1.20E−05	7.88E−05	1.00E−03	0.02	0.88

Here a and b are parameters in the relation $y = a + bx$. SE_b is the standard error of the coefficient b; r^2 is the coefficient of determination; F is the value of the F distribution; p is the significance probability.

Table 6
Parameter estimates for simple linear regression analysis between peak annual discharge and total annual precipitation.

	a	b	SE_b	r^2	F	p
N01B	−14.23	0.03	0.01	0.40	15.04	<0.001
N02B	−12.88	0.02	0.01	0.17	4.63	0.04
N04D	−52.65	0.08	0.03	0.20	5.69	0.03
Kings	−101.75	0.18	0.07	0.21	6.12	0.02

Here a and b are parameters in the relation $y = a + bx$. SE_b is the standard error of the coefficient b; r^2 is the coefficient of determination; F is the value of the F distribution; p is the significance probability.

3.3. Flood flows

The majority of peak discharges matched a large precipitation event within 12-h but were occasionally up to 36-h apart in the larger watersheds (Table 7). The most extreme floods were the product of strong convective thunderstorms that occurred in summer (Fig. 5). All gages had at least one peak flood outside of the summer months. Extreme peak discharges of record were 232.8 and 168.5 m^3 s^{-1} (17 July 1993 and 22 July 1992), both at the Kings Creek gage where 26 of the top 30 floods occured between April and July. The floods that occurred outside of the summer were not associated with rain-on-snow events. N01B was the only watershed that had a peak discharge of record outside of spring or summer (3 November, 1998), which corresponded with the 25th largest Kings Creek flood (Table 7). The two largest peak floods at Kings Creek were ranked among the top six for N01B and N02B. The timings and magnitude of peak floods were not consistent between gages used in this analysis and were, for the most part, associated with unique precipitation events (Table 7). Although the record for N04D is truncated, trends in peak discharges were similar to other gages in that summer floods dominate (Fig. 5). While rankings of peak floods were not completed due to data quality issues for a small portion of the period of record, four of the five top floods at N04D were coincident with those at the Kings Creek gage (Table 7).

Correlations of floods rankings reveal that N01B and N02B were highly correlated to Kings Creek. Correlations between headwaters, excluding Kings Creek, demonstrated that the smallest watershed gages were strongly correlated. Peak flood discharges and event precipitation correlations in these basins were not significant. Linear regressions of the peak flood discharge and event precipitation demonstrated that the relationships for all the watersheds used in this analysis were not significant (Fig. 4C; Table 8).

3.4. Trends and change points for hydro-climatic series

The temporally dynamic relationship between annual rainfall and annual streamflow at all gages was evaluated using double mass plots (Fig. 6A and B). Breaks in the slope of these double mass curves indicated inconsistent relationships between annual

Table 7
Rankings of the top 30 peak discharge events at the headwater gages with respect to Kings Creek where PPT is the total event precipitation and PQ is the peak discharge seen at the gage. * indicates peak discharges not experienced at Kings Creek.

N01B				N02B				N04D				Kings Creek			
Date	PPT (mm)	PQ (m^3/s)	Rank	Date	PPT (mm)	PQ (m^3/s)	Rank	Date	PPT (mm)	PQ (m^3/s)	Rank	Date	PPT (mm)	PQ (m^3/s)	Rank
11/3/1998	66	18.2	25	6/19/2001	58	39.8	15	7/24/1993	52	9.2		7/17/1993	95	232.8	1
5/13/1995	55	15.6	10	7/17/1993	95	15	1	7/22/1992	113	9.1		7/22/1992	91	168.5	2
7/22/1992	91	15.6	2	7/22/1992	91	10.2	2	6/19/2001	56	7.6		7/2/2004	52	165.9	3
5/26/1996	83	15.4	17	6/20/2009	47	10.1	8	6/4/2005	96	7.4		6/4/2005	96	106.8	4
7/2/2004	52	15.3	3	6/4/2005	96	8.4	4	7/2/2004	69	7.1		7/25/1993	51	89.2	5
7/17/1993	95	14.1	1	7/24/1993	51	5.9	5	5/23/1995	69	6.7		4/26/2009	78	80.7	6
7/8/2008	43	11.1	*	4/26/2009	78	5.4	6	5/17/1995	49	6.5		5/6/2007	92	55.8	7
6/28/1999	39	10.1	11	5/13/1995	55	5.3	10	6/28/1999	37	5.6		6/21/2009	47	48.1	8
4/26/2009	78	9.3	6	6/2/2011	54	4.7	18	5/12/1995	58	4		3/30/2007	43	43.3	9
6/4/2005	96	9.1	4	7/2/2004	52	4.6	3	6/11/2005	49	3.3		5/12/1995	53	41.6	10
6/20/2009	47	8.5	8	6/10/2005	52	4.4	12	5/27/1995	32	3.3		6/28/1999	39	37.7	11
5/23/1995	72	8.4	14	5/5/2002	43	3.8	31	4/13/1999	55	2.7		6/10/2005	52	30.3	12
6/2/2011	54	7.5	18	5/17/1995	42	3.4	21	10/5/1998	32	2.4		6/2/2008	48	29.2	13
8/9/2008	124	6.8	23	5/27/1995	36	2.5	20	6/29/2003	56	2.3		5/23/1995	72	25.3	14
6/10/2005	52	5.8	12	5/26/1996	83	2.3	17	5/10/1993	61	1.9		6/20/2001	58	25.2	15
6/2/2008	57	5.1	13	8/9/2008	124	2.2	23	6/6/1996	15	1.8		4/13/1999	48	24.9	16
4/13/1999	48	4.9	16	4/21/2001	19	2.1	46	2/24/2001	35	1.6		5/26/1996	83	24.6	17
10/5/1998	33	4.1	79	3/30/2007	43	2.1	9	11/2/1998	63	1.6		6/2/2011	54	21.7	18
4/5/1999	38	3.3	42	4/13/1999	48	2	16	10/18/1998	53	1.5		6/25/1995	48	21.2	19
3/30/2007	43	3.3	9	10/18/1998	62	1.9	27	4/5/1999	37	1.4		5/27/1995	36	19.4	20
6/16/2009	44	2.9	34	6/16/2009	44	1.7	34	7/1/1993	36	1.4		5/17/1995	42	17.2	21
6/25/1995	48	2.8	19	5/23/1995	72	1.6	14	11/16/1996	48	1.3		5/10/1993	50	16.9	22
7/4/1992	79	2.8	54	6/2/2008	57	1.6	13	9/8/1989	43	1.3		8/9/2008	124	15.9	23
8/14/2006	79	2.5	85	7/31/1998	59	1.6	29	4/27/1999	27	1.1		7/4/1993	95	14.6	24
5/27/1995	36	2.3	20	7/8/2008	43	1.4	*	5/5/2002	49	1		11/1/1998	33	11.8	25
8/25/2006	42	2.2	64	6/13/2010	58	1.3	52	6/25/1995	77	1		4/22/2010	80	11.8	26
5/10/1993	50	2.1	22	7/4/1993	95	1.3	24	5/3/1993	24	1		10/17/1998	62	11.4	27
6/13/2010	58	2.1	52	4/22/2010	80	1.3	26	7/4/1992	87	1		6/29/2003	55	10.7	28
7/18/2008	57	1.9	47	5/10/1993	50	1.1	22	8/12/1987	81	0.9		7/30/1998	59.4	10.5	29
9/12/2008	78	1.8	36	10/5/1998	33	1.1	79	4/13/1987	43	0.8		9/8/1989	32.5	9.9	30

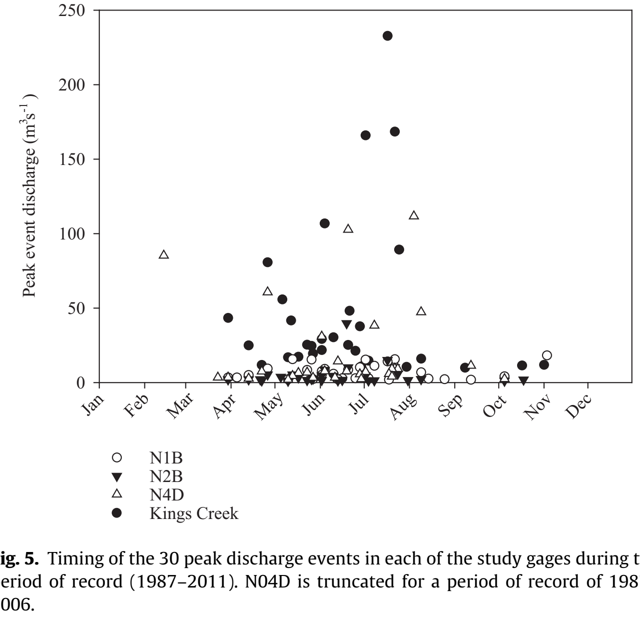

Fig. 5. Timing of the 30 peak discharge events in each of the study gages during the period of record (1987–2011). N04D is truncated for a period of record of 1987–2006.

Table 8
Parameter estimates for simple linear regression analysis between peak event discharges and their associated event precipitation.

	a	b	SE_b	r^2	F	p
N01B	−0.52	0.72	0.04	0.10	3.10	0.89
N02B	−0.35	0.48	0.42	0.05	1.32	0.26
N04D	8.07	0.22	0.32	0.03	0.92	0.35
Kings	0.09	0.79	0.46	0.10	3.01	0.09

Here a and b are parameters in the relation $y = a + bx$. SE_b is the standard error of the coefficient b; r^2 is the coefficient of determination; F is the value of the F distribution; p is the significance probability.

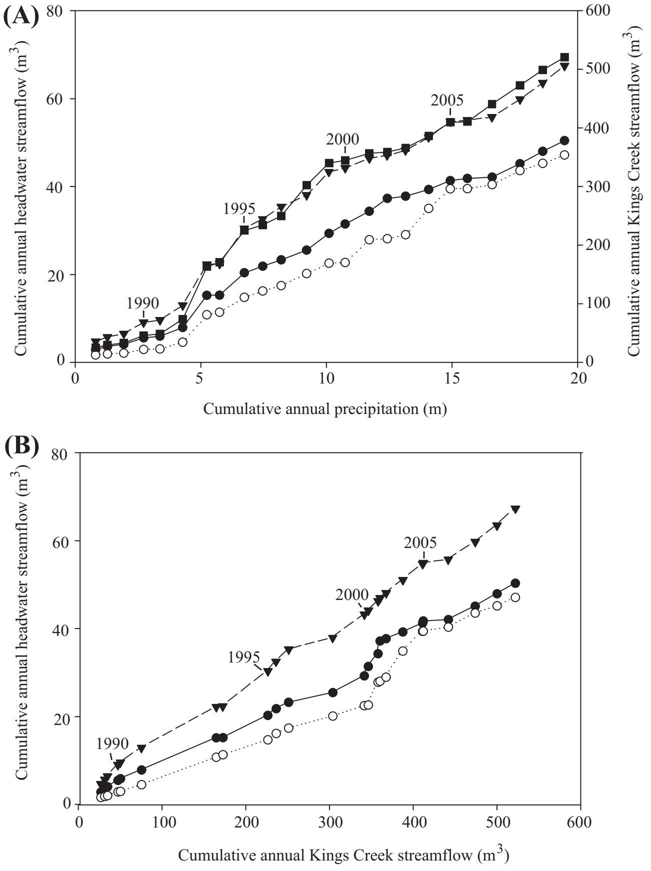

Fig. 6. Double mass curves for total annual (A) streamflow and precipitation at Konza and (B) streamflow in the headwaters and Kings Creek. Each data point represents one year of record.

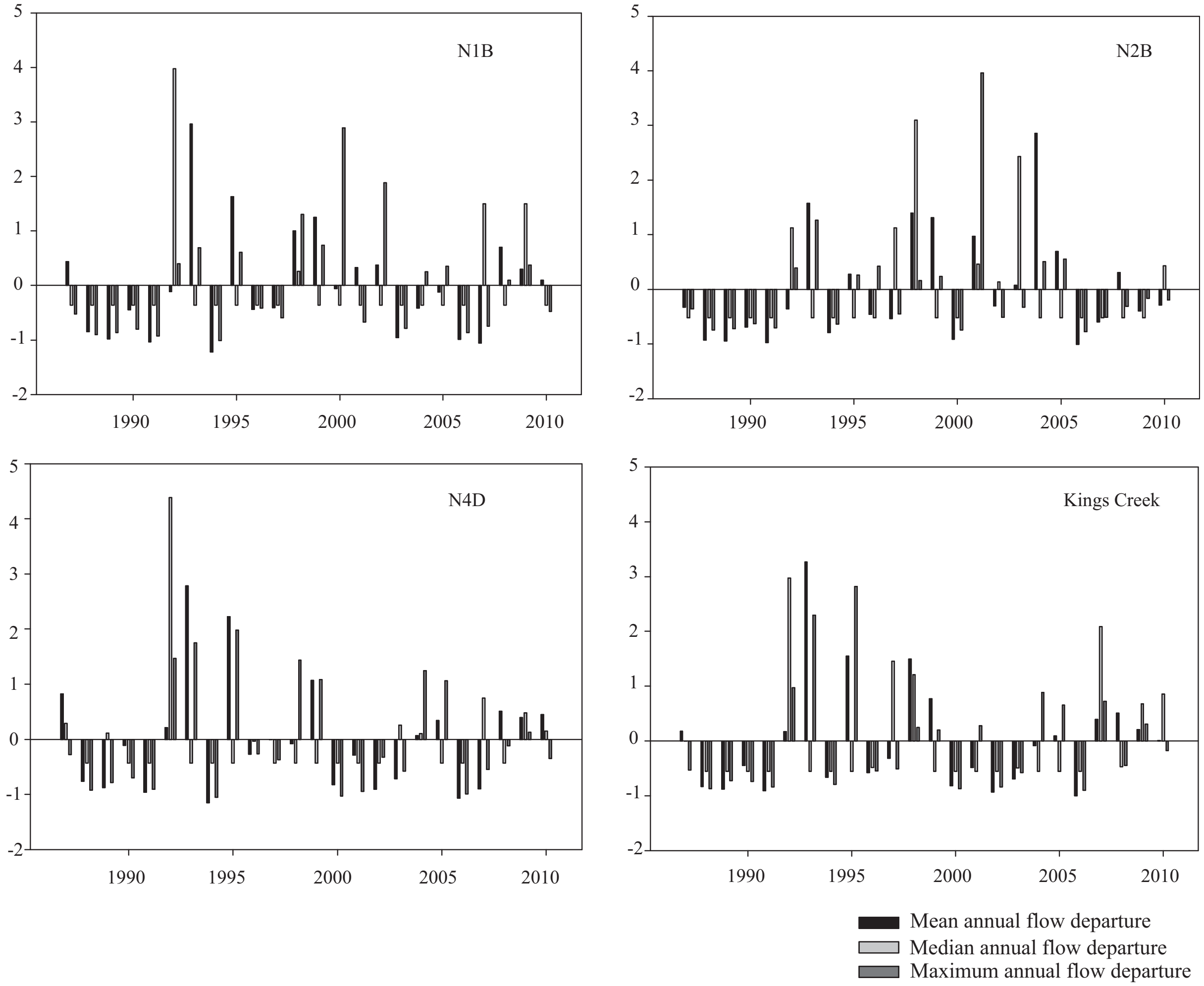

Fig. 7. Standardized departure analyses of streamflow at Konza.

streamflow and annual precipitation through time (Fig. 6A). In some years, streamflow increased with respect to precipitation across all gages as indicated by increased slope of the double mass curves (Fig. 6A). Similarly, double-mass curve plots of annual flows in the headwater gages versus the Kings Creek gage demonstrated that there were numerous and systematic breaks in the relationship between streamflow in the headwaters versus Kings Creek (Fig. 6B). Examination of the flow and precipitation records did not reveal any seasonal or individual precipitation event variables that were coincident across all breaks in slope.

For all gages, standardized departure analyses of annual mean, median, and maximum daily streamflow indicated that there was not a visible step-shift or gradual increase or decrease in streamflow at Konza. Departure analyses indicated that there were extreme variations in positive and negative departures for all gages (Fig. 7). The departures were inconsistent between watersheds with no synchronization of high or low departures. Positive departures were consistently of a much larger magnitude than negative departures throughout all gages.

4. Discussion

Our results demonstrated that characteristics of intermittency, the frequency and duration of zero-flow periods, were highly correlated. Stream gages characterized by decreased baseflow persistence had lower mean annual discharge, as observed in other studies of intermittent streams (e.g. Larned et al., 2010a). Likewise, the persistence of baseflow increased with watershed area, as observed by Snelder et al. (2013). The more sustained flow at the Kings Creek gage when compared to the smaller headwater streams is consistent with Steward et al. (2011) who found slight enhancement of recharge beneath upland intermittent streams and enhanced baseflow at Kings Creek. However, our results deviated widely from previous studies with respect to relationships between measures of climate inputs (precipitation) and streamflow.

Overall, the associations between streamflow and precipitation were stronger than those for PDSI, which is contrary to past work within the larger Great Plains region which found that streamflow in the perennial headwaters of the Platte River were more correlated with regional than local conditions (Daniels, 2007). The diversity within Great Plains hydro-climatic regimes is substantial enough that the two sites may not be very comparable. Our study system in the Central Great Plains is located at the juxtaposition of many different climatic teleconnections, which complicates the application of broadly calculated values like PDSI, to the patterns we saw at Konza (Goodin et al., 2003). Variation in rainfall across catchments is a familiar problem to rainfall-runoff modelers, and our precipitation analyses demonstrated that even local precipitation was very heterogeneous across the small land surface area that Konza encompasses, further complicating relationships between PDSI and local streamflow at the study site. Therefore, it is unsurprising that the broadly calculated PDSI moisture variable is not a strong of a predictor of stream discharge.

Regression relationships between Konza's total annual precipitation and both mean and peak annual discharges yielded weak relationships and did not correspond across watersheds. The lack of significant relationships in regression results indicated that missing variables play a significant role in determining mean annual and peak annual discharges. Relationships between precipitation and flood discharges were also poor, which is not surprising given the estimated partitioning of $\sim$75% of precipitation to evapotranspiration losses from the watershed. However, the desynchronization of flood flows between watersheds with similar vegetation coverage and longitudinally through the Kings Creek network suggests something more than evapotranspiration flux is at work producing the poor precipitation-discharge relationships. The intermittent headwater stream peak flood discharges are poorly correlated with those at the Kings Creek gage, but N01B and N02B were more strongly correlated to each other than any of the other streams.

The observed breaks in double mass curve plot slopes suggest a threshold-driven process is controlling the headwater streams discharge regimes. Double mass plot slope breaks are not coincident in timing with any major landscape disturbance, including burning, that would provide a reasonable anthropogenic driver of altered tributary hydrologic response, leaving only internal watershed or climate processes as possible explanations. Variations in soil moisture storage, groundwater table fluctuations, and spring seepage have all been observed as important controls on streamflow in other intermittent stream systems (e.g. Fleckenstein et al., 2006; Larned et al., 2010a, 2010b). The desynchronization of measured peak streamflow may also be attributable to variation in precipitation heterogeneity (Zégre, 2009). Because this analysis only focused on a small portion of the headwaters of the Kings Creek drainage, it makes a conclusive explanation of the causes of desynchronization difficult. For example, locally intense precipitation may have fallen within sub-basins not used in this analysis, producing disparities between streamflow recorded in gaged headwaters and the main Kings Creek gage.

In any arid environment, evapotranspiration is a substantial control on water delivery to stream channels. Past studies have modeled very high rates of evapotranspiration (75% of precipitation) at Konza (Steward et al., 2011). Precipitation loss through evapotranspiration can reach over 83% in more southerly portions of the Great Plains (Wine and Zuo, 2012). Long-term records indicate that terrestrial plant production at Konza is highly variable depending on the balance between annual precipitation and potential evapotranspiration (Knapp and Smith, 2001), and this variability is amplified in the system's streamflow, producing several orders of magnitude variation in stream discharge (Dodds et al., 1996). However, evapotranspiration losses are insufficient to explain the extreme decoupling between discharge and precipitation inputs observed at Konza. Furthermore, the observed time lag time between peak precipitation in the spring and peak flood discharges in the summer suggests that a critical threshold of watershed storage must be exceeded prior to initiation of connected streamflow and flood flow response to precipitation inputs.

A number of watershed processes related to watershed storage compartments may be acting alone or in combination to produce the strong threshold response in the precipitation-streamflow relations observed as episodic changes in the slope of the double-mass curves plots. While subsurface flow is widely recognized as an important contributor to streamflow generation, we are less certain of the specific processes and process pathways involved (e.g. McGuire and McDonnell, 2010). Precipitation infiltration and runoff pathways at Konza may include slow percolation through soils, bypassing of the soil matrix and rapid flow through large macropores, surface water runoff via saturation overland flow, subsurface flow through shallow alluvial materials, and downslope emergence as spring flow. Each of these pathways produces differential streamflow and groundwater recharge response rates throughout a basin (Tsypin and Macpherson, 2013) and would fundamentally regulate the temporal and spatial stream discharge regime in a network.

Previous efforts to develop a water budget model for Konza and the surrounding regional streams have suggested that enhanced recharge along intermittent headwater stream channels within the watershed is the cause of the increased baseflow at the lower Kings Creek gage (Steward et al., 2011). This model assumes that surface water inputs to tributary stream channels traverses downslope within shallow alluvial fill materials, bypassing detection by headwater gages, and emerges at the base of the valley as enhanced baseflow in Kings Creek. Field observations of stream wetting behavior support this general hypothesis in that the extreme upper portions of the network appear to wet first and extend in the down-network direction during wet years to achieve full network connectivity (WK Dodds, personal observation). However, the upstream wetting front appears to be driven by baseflow generated high in the watershed, suggesting that deeper groundwater interactions are also an important source of input to the proposed alluvial fill pathway. Groundwater storage zones high in the watershed may simply fill first, causing them to "spill", and create wetted channel reaches at network extremities disconnected from lower reaches. This spatially localized "fill and spill" dynamic would produce the type of disconnection between precipitation and measured discharges at the headwater gages, while also explaining the enhanced recharge observed at Kings Creek. Other studies have demonstrated the influence of topography on watershed fill and spill dynamics (e.g. Sayama et al., 2011), lending support to the idea that the specific surficial geology layers could also be influential.

Another potential explanation is that the observed soil macropores may temporarily, but fundamentally, alter hillslope-channel hydrologic connections. Macropores have long been recognized as important pathways for preferential flow in soils (e.g. Beven and Germann, 1982). Based on findings from studies of smaller macropore features (Zhang et al., 2013), it is reasonable to assume that during dry periods the substantial macropores in the soil surface provide pathways for preferential flow deep into the soil. Combined with fractures in the geologic layers, this may allow direct recharge to groundwater bearing limestone layers, bypassing shallow subsurface matrix flow paths to the stream channels. This rapidly recharged groundwater could emerge at springs in the geological sections below the headwater gages but upstream

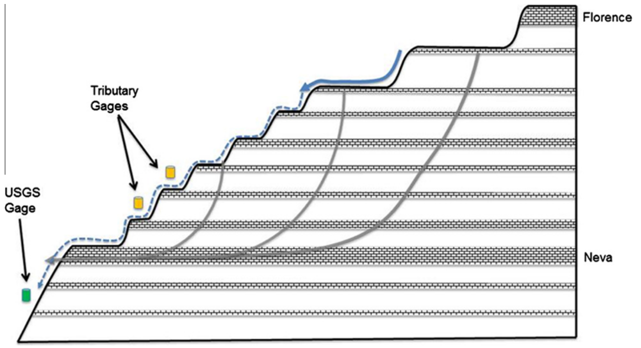

Fig. 8. Conceptual model of potential groundwater flow pathways through the geological matrix (solid line) and alluvial near-channel zones (dashed line) within the study watershed, bypassing the 3rd order tributary stream gages.

of the Kings Creak gage (Fig. 8), producing a disconnection between headwater streamflow and precipitation as well as the observed disconnection between headwater gages and the Kings Creek gage. Although we do not have data on relative spring flow from each layer, the Neva limestone layer is a particularly thick layer located between the tributary sub-basin gages and he main Kings Creek gage and may be contributing substantial groundwater contributions to Kings Creek (Fig. 8). During wetter periods, increased soil moisture would result in the macropores closing, which eliminates or greatly reduces the rapid recharge pathway and forces infiltrated precipitation to transit via the soil matrix as through-flow, even potentially saturating source areas, and producing stormflow runoff in the headwater channels. The closure of macropores represents a filling threshold within the soil moisture storage zone that could drive a threshold-type response as observed in our results. Although past work on groundwater-surface water interactions at Konza (Macpherson and Sophocleous, 2004) suggested flow through macropores was not substantial within the alluvial valley bottoms, we suggest that the hillslopes may be the main location for this direct recharge through large macropores.

In all likelihood, a combination of the above physical processes are working in concert with evapotranspirative fluxes to result in the stochastic threshold behavior observed at Konza. For example, very large precipitation events in the late summer may not manifest as streamflow because of high infiltration through large macropores in dry soils and high evapotranspiration removal of water from the soil and shallow groundwater matrices before shallow subsurface flow reaches the stream channel. In contrast, in early spring when evapotranspiration demand is low but soil moisture and groundwater tables are generally higher, the same precipitation volume may manifest as a large streamflow volume. Both soil moisture and evapotranspiration are very temporally dynamic at Konza, and the absence of continuous measurements of these variables makes a conclusive explanation for the lack of relationship between mean and peak annual discharges difficult. Testing these hypotheses is presently precluded by a lack of understanding of macropore dynamics in relation to soil moisture thresholds in the Konza soils, as well as a lack of understanding of sub-surface flow paths through the site's varying geologic layers, and would clearly be a profitable area for future research.

5. Conclusions

In this study, we used long-term streamflow and climate records to characterize the hydrology of an intermittent prairie headwater stream network in the central Great Plains, USA. Results demonstrated a desynchronization of hydrologic regimes among adjacent headwater catchments as well as longitudinally through the network, which suggests watershed conditions strongly control intermittent headwater stream hydrologic response and connectivity. There were strong correlations between precipitation and the total number of zero-flow days and the number of zero-flow periods. Correlations were less strong for PDSI with the frequency and duration of zero-flow days. Basin averaged total annual precipitation poorly predicted mean annual and peak annual discharges. Double mass plots of precipitation to streamflow indicated that there were numerous systematic breaks showing higher streamflow than precipitation and higher streamflow in the headwaters that was not seen at Kings Creek. Standardized departure analyses indicated that there were no gradual or step changes in streamflow at Konza, but a longer period of recorded streamflow would be more useful to fully characterize trends in streamflow. Therefore, it is important to consider local processes, like water-table fluctuations, soil moisture conditions, subsurface flow pathways, and preferential flow through soil macropores as important factors influencing the hydrology of intermittent prairie streams. Since the geology and soils at Konza are representative of the broader Flint Hills physiographic province (Mandel, 2008), it is quite likely that streamflow and precipitation are similarly desynchronized throughout the headwater networks of the region, and potentially in other areas in moderately xeric climates underlain by layered limestones.

While the number of studies of intermittent streams has greatly increased in the last decade, especially their ecology (e.g. Datry et al., 2011, 2014; Larned et al., 2010b), there is still much work needed to understand the hydrology of intermittent streams. In particular, detailed coincident observations of soil moisture conditions, water table fluctuations, macropore dynamics, and streamflow are needed over a broad range of hydrologic and geomorphic regimes. Measurements of network expansion and contraction due to variable moisture reserves have recently been completed (e.g., Jaeger and Olden, 2012; Godsey and Kirchner, 2014) but a comprehensive understanding of the controls on intermittent streamflow is still lacking. Quantifying characteristics of streamflow continuity and connectivity are important for understanding ecological responses to expansion and contraction cycles. The degree of continuity will influence the resistance or the ability of biota to endure and/or avoid a disturbance. In light of predicted global climate change, intermittent flow is expected to become more common (e.g. Larned et al., 2010b; Jaeger et al., 2014), improved understanding of the hydrology of intermittent streams should become a key priority for hydrologists and watershed managers. Results of this study demonstrate that there is a complex hydrology, both spatially and temporally, at Konza and further studies that combine surface hydrology and hydrogeology would be beneficial in understanding the mechanisms of the precipitation-discharge relationship.

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