HYDROLOGY AND GEOMORPHOLOGY OF SELECT GREAT PLAINS RIVERS

by

KATIE HELEN COSTIGAN

B.S., University of Connecticut, 2008
B.A., University of Connecticut, 2008
M.S., University of Nevada, Reno, 2010

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Geography
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Abstract

Great Plains rivers are unique systems that vary from large, continental scale, to small intermittent streams with grain sizes that range from cobbles to silt. These rivers have been subject to widespread hydrologic alteration both within the channel and the watershed, which has resulted in an alteration in their hydrologic and geomorphic regimes. Although there is an acknowledgement of this alteration, to date there has not been a synthesis of the hydrology of Great Plains rivers or of their longitudinal morphologies. Chapters in this dissertation provide the first comprehensive analyses of the hydrology and morphology of Great Plains rivers over a range of spatial and temporal scales. In the first study, I found that there was no uniform pattern of hydrologic alteration throughout the Great Plains, which is likely attributable to variable system-specific reservoir management objectives, land use changes, and climatic regimes over the large area the Great Plains encompass. Results of this study are the first to quantify the widespread hydrologic alteration of Great Plains rivers following impoundment. In the second study, I found an apparent decoupling between local moisture conditions and streamflow in intermittent prairie streams. Results of this study used statistical models to identify relationships between flow intermittence, mean annual flow, and flood flow characteristics with moisture to characterize flow in an intermittent prairie stream. In the final study, I found that the downstream trends in hydraulic geometry and substrate characteristics of the Ninnescah River were consistent with the expected trends proposed by hydraulic geometry and substrate theories. However, there were points that deviated from the expected trends, most notably where a substantially large tributary enters the Ninnescah River and as the Ninnescah River approaches the Arkansas River, and causal explanations for these deviations were explored. Results of this study are the first of its kind to assess the longitudinal hydraulic geometry and substrate characteristics of a large sand-bed river over a large spatial scale. To our knowledge, there have been no comparable studies that attempted to describe hydrologic and geomorphic characteristics of prairie streams.

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Preface

The contents of this dissertation represent concepts and approaches developed in collaboration with my major professor and members of my dissertation committee. Although the work is my own, the chapters are presented in third person for the sake of peer-reviewed publication. Chapter 2 is published with Melinda Daniels as a coauthor in the *Journal of Hydrology*, volume 444-445, issue number 11, on pages 90-99. Chapter 3 is formatted for publication in the journal *Hydrological Processes* with Melinda Daniels and Walter Dodds as coauthors. Chapter 4 is formatted for publication in the journal *Water Resources Research* with Joshuah Perkin, Melinda Daniels, and Keith Gido as coauthors.

Chapter 1 - Introduction

The rivers of the Great Plains comprise perhaps the most scientifically overlooked streams in the continental United States [*Matthews*, 1988], yet they are dynamic and unique ecosystems that support migratory waterfowl, an endemic fish community and provide a variety of recreational and ecosystem services. The geographical setting of the region is in the arid rain shadow of the Rocky Mountains, which produces characteristically flashy hydrologic regimes, with large floods interspersed within periods of prolonged drought [*Dodds et al.,* 2004]. The typical annual regime varies somewhat with latitude and longitude through the Great Plains region, with more northern systems experiencing an early snow-melt flood pulse and a later spring/early summer convective storm driven flood pulse while. More southerly systems are influences by monsoons, hurricanes, and dry line thunderstorms. Channels are wide, have sand-beds, and high turbidity. Planforms typically range from semi-braided to meandering. Records of streamflow for grassland streams are typically scarce, short, and rarely complete [*Shook and Pomeroy*, 2012] and sand-bed channels are often overlooked for geomorphic analyses.

The extreme floods and droughts that characterize the Great Plains have led to the development of many flood-control and water storage reservoirs within the region. In addition to construction of impoundments on major rivers of the region, other anthropogenic activities including unsustainable groundwater extraction practices and widespread land cover conversion of catchments from grassland to agriculture have also contributed to the alteration of Great Plains rivers. Great Plains rivers are extremely responsive to altered discharge and sediment supply and hence susceptible to anthropogenic disturbances within the catchments [*Montgomery and Buffington*, 1997]. While low-order Great Plains rivers do not typically have large impoundment structures, they are commonly impacted by groundwater extraction, small impoundments (less than a meter in height), and land cover conversion within catchments.

Human constructed dams have been a feature in the fluvial landscape for at least the last two millennia, while more natural dams like ice, wood, and landslide have been a constant feature of the landscape. The construction of large modern dams, those with a storage equal to or greater than 10^6ac ft or more [*Graf*, 2006], have produced a dramatic change in the magnitude of hydrologic, geomorphologic, and ecological impacts on large rivers. Dams provide numerous societal benefits including: reliable water supplies, recreation, flood control, navigation, hydroelectric power, and irrigation [*World Commission on Dams*, 2000]. However, dams are also the most significant source of anthropogenic hydrologic disturbance on rivers in the United States [*Graf*, 1999] and worldwide [*Dynesius and Nilsso*, 1994; *Vorosmarty et al*., 1997]. Hydrologic alteration by large dams have been assessed for individual dams, series of dams on a river network [*Galat and Lipkin*, 2000], and within multi-network national studies [*Magilligan and Nislow,* 2005]; yet, to my knowledge, no studies have yet examined in detail the specific impoundment-driven changes to hydrologic regimes of Great Plains rivers. Without a comprehensive understanding of the nature of the hydrologic regime alterations, sound recommendations cannot be made to address dam management modifications for in-stream discharge needs, habitat maintenance, channel stability, or other ecosystem management objectives of this region.

Smaller intermittent streams comprise approximately 60% of the total river length in the conterminous United States [*Nadeau and Rains*, 2007]. Intermittent streamflow is a feature of most grasslands, and the Great Plains of the USA are particularly characterized by periods of flooding and drying [*Dodds et al.,* 2004]. Many headwater streams have been subjected to widespread watershed land cover that has the potential to have radically altered hillslope and channel hydrologic and geomorphic regimes. Konza Prairie Biological Station, in particular, has been subjected to woody encroachment. Between 1939 and 2002 Konza has seen an increase in riparian vegetation of nearly 70% [*Briggs et al*., 2005]. Konza's streams are characterized as harsh, with intermittent discharge regimes, and typically have high flood frequency and low predictability [*Samson and Knopf*, 1994]. Due to their harsh conditions, it is the abiotic factors that structure biotic assemblages of intermittent prairie streams [*Dodds et al.,* 2004; *Fritz and Dodds*, 2005]. Although the importance of abiotic factors controlling the structure of biotic assemblages is well acknowledged, to my knowledge there has been no analysis of the hydrology of intermittent prairie streams.

Changes in hydrologic regimes can trigger changes in geomorphic regimes of rivers. Geomorphic profiles of rivers are representative of watershed evolution, geologic structure, and sedimentary dynamics of the basin [*Sinha and Parker*, 1996]. Hydraulic geometry (e.g. width, depth, velocity, and friction) has been explored extensively but remains a core technique in understanding river systems [*Knighton,* 1998]. The hydraulic geometry of regimes anabranching [e.g. *Tabata and Hickin*, 2003; *Latrubesse*, 2008; *Kemp*, 2010; *Pietsch and Nanson*, 2011], desert [e.g. *Merritt and Wohl,* 2003; *Ralph and Hesse*, 2010], and mountain rivers [e.g. *Lee and Ferguson*, 2002; *Brummer and Montgomery,* 2003; *Comiti et al.,* 2007; *David et al.,* 2010; *Green et al.,* In Press] have been well documented. Numerous studies have examined the downstream fining of sediments but most were based on data from small, gravel-bed streams over a length less than 200 km [*Church and Kellerhals*, 1978; *Ferguson et al.,* 1996; *Rice*, 1998; *Constantine et al.,* 2003]. An understanding of the hydraulic form and sedimentary characteristics of sand-bed rivers is fundamental for addressing concerns of stream restoration, aquatic ecology, conservation biology, and construction within floodplains. The geomorphic and sedimentary longitudinal patterns of large alluvial sand-bed rivers have yet to be analyzed.

To address these research needs, this dissertation describes multiple research approaches including meta-analyses, field observations, and geographic information systems to characterize the hydrology and geomorphology of Great Plains rivers across multiple spatial and temporal scales. In Chapter 2, I document hydrologic regime shifts on dammed rivers for type, duration, direction, and magnitude using the Indicators of Hydrologic Alteration [*Richeter et al.,* 1996]. I analyze the hydrologic records of nine large rivers with a mainstem impoundment as well as a record from a river without a mainstem impoundment to provide an example of a comparable regional hydrologic regime without the presence of impoundments. In Chapter 3, I used stream flow data from Konza Prairie Biologic Station to characterize flow intermittency, mean annual flows, and peak flood flows among intermittent prairie streams with varying physiography, vegetation, and management regimes. This study examines the hydrology of intermittent prairie streams in the context of moisture variability within the area for a 25-year period of record to identify correlations and relationships between flow characteristics and moisture indices. In Chapter 4, I use field measurements supplemented with geospatial data from 11 study sites to document the longitudinal changes in hydraulic geometry and substrate of large sand-bed river. I identify the longitudinal patterns of hydraulic geometry and sediment characteristics of a large sand-bed river and identify sites that deviate from what we might have expects and provide causal explanations for these deviations. Finally, in Chapter 5 I summarize conclusions of this research.

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Chapter 2 - Damming the Prairie: Human Alteration of Great Plains River Regimes

Abstract

Many studies have investigated post-impoundment hydrologic regime alteration; however, the Great Plains of the United States are often excluded from these analyses. The goal of this analysis was to evaluate the pre and post-impact hydrologic regimes of Great Plains rivers. The hydrologic records of nine large rivers were analyzed to quantify the magnitude, duration, and direction of hydrologic alteration attributable to impoundment. An additional tenth system, the Red River of the North, was included in the analysis to provide an example of a comparable regional hydrologic regime without the presence of impoundments on the main-stem of the network. Hydrologic regimes were analyzed using the Indicators of Hydrologic Alteration, a model that estimates 33 hydrologic and ecologically relevant parameters. For many of the parameters, the magnitude, duration, and direction were similar across the systems. The results showed a significant increase in the 1 through 90 day minimum discharges and a significant decrease in the 1 through 90 day maximum discharge; though the magnitude of alteration decreased with increased temporal averaging. The most dramatic alterations were large increases in the number of annual hydrograph reversals and faster rise and fall rates. Results of this study are the first to quantify the widespread hydrologic alteration of Great Plains rivers following impoundment.

Introduction

Dams have been a feature in the fluvial landscape for at least the last two millennia. However, the construction of large modern dams produced a dramatic change in the magnitude of hydrologic, geomorphologic, and ecological impacts on large rivers. Although the first large American dams were constructed during the early 1900s, the 1960s represent a very significant dam building era in the United States, when a quarter of all existing US dams were constructed (U.S. Army Corps of Engineers, 1996). Dams provide numerous societal benefits, including reliable water supplies, recreation, flood control, navigation, hydroelectric power, and irrigation

(World Commission on Dams (WCD), 2000). However, dams are also the most significant source of anthropogenic hydrologic disturbance on rivers in the United States (Graf, 1999) and worldwide (Dynesius and Nilsson, 1994; Vorosmarty et al., 1997). River ecosystems have evolved within the context of the natural hydrologic regime (Lytle and Poff, 2004), adapting to patterns of variation in the delivery of water, nutrients, energy, sediments, and habitats, but now many of these regime patterns have been fundamentally altered by dams (Sparks et al., 1998; WCD, 2000; Nislow et al., 2002).

The first scientific studies of downstream dam impacts began to emerge in the 1980s as the degree of post-impoundment downstream ecosystem alteration became increasingly apparent (Baxter, 1977; Graf, 2005). This magnified interest in how dams affect the hydrology, geomorphology, and ecology of rivers, and produced a concentrated effort to understand the impact of impoundments. Since that time, there have been numerous assessments of the impacts of dams on rivers (eg. Graf, 2006). To address the need for consistency in assessments, Richter et al., (1996) developed an analytical model, the Indicators of Hydrologic Alteration (IHA), to statistically characterize the variability in hydrologic regimes with biologically relevant attributes and quantify the hydrologic alterations associated with a disturbance, often a dam. The IHA model has been widely used to determine hydrologic alteration by individual dams, series of dams on a river network (Galat and Lipkin, 2000), and within multi-network national studies (Magilligan and Nislow, 2005). Results of these studies have been mixed, with wide variation in the nature of hydrologic regime alteration. Some commonalities in all cases are the presence of significant changes in the number of discharge reversals and in rise and fall rates of the hydrograph (Galat and Lipkin, 2000; Magilligan and Nislow, 2005; Perkin and Bonner, 2011). Analysis of the parameters estimated by IHA indicates that there is redundancy in the parameters (Olden and Poff, 2003); however, IHA still provide a useful estimation of hydrologic parameters.

While post-impoundment impacts on Great Plains river ecosystems have been identified, no study has yet examined in detail the specific impoundment-driven changes to the hydrologic regime that are, in part, driving the decline of these ecosystems. Without a comprehensive understanding of the nature of the hydrologic regime alterations, sound recommendations cannot be made to address dam management modifications for in-stream discharge needs, habitat maintenance, channel stability, or other ecosystem management objectives. We address this gap in knowledge by assessing hydrologic regime shifts for their type, duration, direction, and magnitude using IHA for ten river systems distributed across the Great Plains region. Due to the varying climate throughout the Great Plains region, it is difficult to differentiate between climatic and anthropogenic sources of hydrologic alteration of rivers. We tested the hypotheses that impoundment would result in: 1) muted discharge magnitudes at both the high and low extremes, 2) reduction of low discharge durations, and 3) increased rise and fall rates. The results of this research illustrate the extent to which impoundments have affected the hydrology of Great Plains rivers and document opportunities for naturalization of Great Plains river discharge regimes.

Regional Context

Despite the presence of numerous large flood-control reservoirs in the Great Plains, no study has regionally assessed the post-impoundment alteration of the region's hydrologic regimes. The Great Plains of the United States encompasses the area from the Prairie Provinces of Canada to the Rio Grande, and from the Rocky Mountains to the Missouri River; including the majority of ten US States: Colorado, Kansas, Montana, North Dakota, Nebraska, New Mexico, Oklahoma, South Dakota, Texas, and Wyoming. This region is semi-arid and historically dominated by grassland biomes. Generally, most rivers flow eastward within the Arkansas, Missouri, and Red River of the south drainage basins and eventually drain into the Mississippi River; however, there are many exceptions including the Colorado River and Rio Grande draining to the Gulf of Mexico, and the Red River of the North draining northward into Lake Winnipeg, Canada. Channels are wide, sand bedded, and with high turbidity. Planforms typically range from semi-braided to meandering.

The rivers of the Great Plains are perhaps the most scientifically overlooked streams in the continental United States (Matthews, 1988), yet they are dynamic and unique ecosystems contain species that need to be conserved, are important for migratory waterfowl, and support fisheries and recreational uses. The geographical setting of the region is in the arid rain shadow of the Rocky Mountains, which produces characteristically flashy hydrologic regimes, with large floods interspersed within periods of prolonged drought (Dodds et al., 2004). The typical annual regime varies somewhat with latitude and longitude through the Great Plains region, with more northern systems experiencing an early snow-melt flood pulse and a later spring/early summer convective storm driven flood pulse while. More southerly systems are influences by monsoons, hurricanes, and dry line thunderstorms. The natural range of hydrologic extremes has been altered by anthropogenic activities such as the construction of flood-control impoundments, unsustainable groundwater extraction practices, and widespread land cover conversion of watersheds from grassland to agriculture. Global climate change is likely to affect these streams even more with general circulation models predicting more frequent intense precipitation events with longer intervening dry periods (Knapp et al., 2002; Milly et al., 2005). The unique assemblage of aquatic fauna found in Great Plains rivers is adapted to frequent intermittence of smaller streams, historically high flood frequencies with low predictability, and to periodic episodes of extreme drought that produce long periods of no flow, especially in smaller streams and rivers as well as to high sediment loads and turbidity in larger rivers (Poff and Ward, 1989; Dodds et al., 2004).

Riparian vegetation patterns are closely associated with the geomorphological dynamics of the channel and floodplain surfaces (e.g. Hupp and Osterkamp, 1985). It is unsurprising then that post-impoundment riparian vegetation changes are also closely linked to both geomorphic and hydrologic adjustments following impoundment. Previously braided rivers typically experience an initial pulse of recruitment by pioneer species (for example, the dramatic increase in Populis-Salix woodlands along the Platte River) as vegetation occupies the formerly active channel areas and areas that were frequently disturbed floodplain become available for colonization. This phase is followed by declines in pioneer species and replacement by mature woodland species. Along previously meandering rivers, recruitment of pioneer species dramatically declines following impoundment due to the reduction in channel migration, point bar formation and floodplain disturbance (e.g. Johnson, 1998). Hydrologic regime components critical to vegetation establishment include timing and magnitude of peak flows, fall rate, and base flow magnitudes (Shafroth et al., 1998).

Ecological and geomorphological studies have documented that impoundment construction has profoundly impacted river ecogeomorphology in the Great Plains. The post-impoundment morphologic responses vary somewhat depending on the initial pre-impoundment conditions as well as the local surficial geology, but Great Plains rivers are especially susceptible to downstream effects of dams because they are typically fine-grained alluvial rivers without confining canyon walls (Graf, 2005). In the absence of flow augmentation, meandering rivers tend to decrease their migration rates and incise, while braided rivers dramatically narrow and may deepen into a single-threaded meandering planform (Williams and Wolman, 1984; Friedman et al., 1998). With flow augmentation, meandering channels exhibit increases in width-depth ratios, substrate size, and exposed depositional bar area (Kellerhals et al., 1979; Dominick and O'Neill, 1998) after which bed degradation may ensue if channel armoring is absent or broken (Church, 1995). Regulated Great Plains river reaches have up to 91% less standard active area than unregulated rivers (Williams, 1978; Graf, 2006).

Methods

System Selection

To analyze post impoundment hydrologic alteration within the Great Plains, selected systems: 1) were within the Great Plains physiographic region, 2) had U.S. Geological Survey streamflow gages immediately downstream of a main-stem dam with mean daily discharge data for at least 15 years pre-impoundment and 30 years post-impoundment, and 3) did not have discharge diversions prior to the dam construction. While it would have been preferable to use systems with greater than 15 years of pre-impoundment discharge records, these data do not exist. During the system selection process it became apparent that most Great Plains USGS gages were constructed concurrently with dams, and many of these gages were decommissioned soon after dams were completed, greatly limiting the number of acceptable data sets. Nine gaged systems met our selection criteria, located on the Arkansas, Canadian, Kansas, Lower Missouri, Upper Missouri, Pecos, Red (of the South), Republican, and Wakarusa Rivers (Figure 2.1). We also sought unregulated "control" systems, but no gaged unregulated large rivers remain in the Great Plains. As an alternative, we included a gage site on the unregulated main-stem of the Red River of the North; however, the upstream major tributaries of this system are impounded. This tenth system represents the best available opportunity to assess how current discharge regimes compare to historical (defined as pre 1968 following Perkin and Gido, 2011) discharge regimes for the region. The dams in this analysis are not run of the river dams and as such any flow reversals are due to management of the dam and are not a result of the a short dam height.

Indicators of Hydrologic Alteration

Gage records were analyzed using the IHA model developed by the Nature Conservancy (Richter et al., 1996) to determine hydrologic shifts of Great Plains Rivers in response to dam construction. Parameters were developed by Richter et al., (1996) because of their close relationship to ecological functioning as well as for their ability to reflect human induced changes to discharge regimes for a wide range of disturbances (Mathews and Richter, 2007). Analyses were conducted on mean daily discharges for the water year (October-September) for the period of record prior to dam construction (reference) and then again after the dam construction was completed (disturbance). In the case of the Red River of the North, historic (pre 1968) and current hydrologic conditions were evaluated. IHA measures central tendency (mean, median) and dispersion (range, standard deviation, percentiles, coefficient of variation and coefficient of dispersion) to determine the inter-annual variation between the two periods (Richter et al., 1996) to compare reference and disturbance periods. The IHA also provides information on discharge regimes without the presence of a disturbance. From mean daily discharge, IHA computes 33 intra- and inter-annual flow parameters that fall into five major groups: 1) magnitude of monthly stream discharge conditions, 2) magnitude and duration of annual extreme discharge conditions, 3) timing of annual extreme discharge conditions, 4) frequency and duration of high and low pulses, and 5) rate and frequency of discharge condition change.

Group 1 includes the magnitude and timing of the mean value of discharge for each month. Group 2 includes the magnitude and duration of the 1, 3, 7, 30 and 90 day mean annual minimum and maximum discharge. Group 3 reports the Julian date of each one day annual minimum and maximum discharge. Group 4 is the magnitude, frequency, number, and duration of the number of low and high pulses within each year. Pulses are a sequence of days in which discharge exceeds the 75^{th} or falls below the 25^{th} percentile of the pre-impoundment ranked daily discharges. Group 5 includes the means of the positive and negative differences between consecutive daily means as well as the number of hydrograph falls, rises, and reversals. A rise is a sequence of continuously rising mean daily discharges and a fall is a sequence of continuously decreasing mean daily discharges. Reversals are a change in a sequence from a fall to a rise or vice versa. Because IHA uses mean daily discharges, reversals are not at the diel scale; rather, it measures the day to day variation in hydrographs. Zero discharge days are excluded from this analysis because many study systems are large perennial rivers that do not typically experience discharge flow days because of their size, but might experience zero discharge days where impoundments are coupled with groundwater withdrawal (eg Perkin and Gido, 2011).

Statistical Analysis

Student's paired t-tests were used to determine if means for each of the response variables were statistically different from one another where significance was defined as $p \leq 0.05$. A principle component analysis (PCA) was used to capture variation in changes to the parameters estimated by IHA for the pre and post impoundment. A correlation matrix was constructed that allowed for removal of IHA estimated parameters that were highly correlated ($r > 0.8$) from the PCA analysis. The second axis of the PCA distinguishes rivers and the third axis distinguishes the natural and regulated river regimes. Using the PCA we were able to determine a coarse relative magnitude of system alteration with which to compare the ten study systems.

Results

Selection criteria provided ten gaging stations in the Great Plains that were distributed over this physiographic region (Figure 2.1), and the effects of these dams on hydrological indices were captured with IHA. In some cases, these impoundments altered the total annual discharge dramatically (Table 2.1). The Canadian River experienced an 88% decrease in mean annual discharge, while the mean annual discharges of the Kansas River and the Red River of the North have increased by 44%, and 123%, respectively. However, in the Upper and Lower Missouri Rivers and the Red River of the South, the mean annual discharge has been altered by only 1% or less (p 0.32, 0.99, 0.83, respectively).

Magnitude of monthly stream discharge conditions

Impoundment produced stark variations in the timing of monthly discharge releases from those observed in the reference regimes, although there was no uniform pattern of variation across the study region. In some cases, such as the Missouri River, discharges increased in August through February (Table 2.2; Figure 2.2). In contrast, the Red River of the North experienced its greatest increases in discharge in February and March. There was not a strong pattern of change in mean monthly discharges for the other study sites even though many of them were significantly altered. The Arkansas, Canadian, and Republican rivers all experienced a decrease in every month's mean discharge, whereas the Wakarusa River and the Red River of the North experienced an increase in every month's mean discharge. Six of the rivers in the study experience a significant alteration in their monthly discharges for each month.

Magnitude and duration of annual extreme discharge conditions

The volume of water released through impoundments has altered the magnitude of the 1, 3, 7, 30 and 90-day mean annual minimum and maximum discharges dramatically (Table 2.3, 2.4). The magnitude of the 1-day minimum discharge increased, on average, by 124%. The mean annual 1-day minimum discharge increased at seven of the ten systems included in this study, five of which are statistically significant. The Wakarusa River experienced the greatest alteration in the minimum discharges with an average increase of over 230% for all the discharge periods calculated by IHA with the 1, 3 and 7-day discharges have all increased by over 300%, the 30-day by 120%, and the 90-day by 96%. The Pecos River was the least altered, with an average decrease of 10% in the minimum discharge, none of which are different from the pre-dam period. The influence of the impoundments with the minimum discharges decreased as the period the discharge was determined over increases.

Maximum discharges also shifted, though not to the degree of minimum discharges (Table 2.4). The Canadian River was most altered, with an over 80% decrease in all of the maximum discharges calculated by IHA. The Red River of the North was the only system to experience significant increases in each of the maximum discharge categories. The Pecos River was again the least altered, with an average alteration of 16%, none of which were significantly different. None of the nine main-stem dammed rivers included in this study experienced an increase in the 1-day maximum discharge. Similar to the minimum discharges, as the time frame of interest for mean annual maximum discharge increased, the impact of the impoundments on maximum discharges diminished. However, the Red River of the North again stood apart with significant increases among all maximum discharge categories.

Timing of annual extreme discharge conditions

No clustering of timing for 1-day minimum or 1-day maximum discharge days was observed for the study region, neither for reference nor disturbance regimes (Table 2.5). However, the mean date of the 1-day minimum discharge of all the rivers in this analysis shifted by 82 days, with the Canadian, Kansas, and Pecos Rivers all shifting more than 120 days. The Kansas and Pecos river 1-day minimum discharge shifted from late May and early June to late October and early November, respectively. Following impoundment, Canadian River 1-day minimum discharge shifted from 12-November to 12-July. The date average of the 1-day maximum discharge shifted by 32 days, which was not as dramatically as the shift of the 1-day minimum discharge. The Lower Missouri River experienced the greatest temporal shift: from 4-May to 9-September, 129 days later.

Frequency and duration of high and low pulses

Among post-impoundment disturbance regimes, the overall average number of days with decreased low and high pulses was 78% and 83% of historical values, respectively (Table 2.6). The overall average decrease in the duration of low pulses and high pulses were 87% and 76%, respectively. Seven systems experienced a significant decrease in the number of high pulses, with the other two systems exhibiting a significant decrease in the number of high pulses, and the Red River of the North having a significant increase in the number of high pulse counts (Table 2.6). Six systems experienced a significant decrease in the duration of the high pulses, with the remaining three sites exhibiting a negative percent change in the duration, and the Red River of the North having a significant increase in the duration of high pulses. Seven systems exhibit a significant decrease in the number of low discharge pulse counts and four showed a significant decrease in the duration of low discharge pulses. All systems except for the Upper Missouri River show a decrease in the number and duration of low discharge pulses, the Upper Missouri River indicated a zero net alteration following impoundment. In contrast, the Red River of the North experienced a significant increase in high pulse number and count.

Rate and frequency of discharge condition change

In six of ten study systems, the number of hydrograph reversals changed significantly (Table 2.7). Among these six, five indicated an average increase of 45% in the number of reversals. The Republican River experienced a decrease in the percent discharge reversals. The percent change in rise rate significantly decreased in all the rivers except the Pecos River and the Red River of the North, with an overall average percent decrease in raise rates of 65%. Seven systems experienced a significant decrease in the percent change in fall rates, the Red River of the North exhibited a significant increase in the fall rate, and the two remaining systems did not have significant differences. The average decrease in the fall rate among study systems was 54%.

Overall hydrologic impact assessment

A comparative assessment of hydrologic regime alteration across sites is difficult because, as presented above, the impacts are numerous and variable across sites. Both sites on the Missouri River have the most altered hydrologic regime variables, with significantly different 1, 3, 7, 30 and 90-day minimum and maximum discharges and an average of 81 and 69 day shifts to the 1-day minimum and maximum mean annual discharges. In contrast, the Pecos River is not significantly altered in any of the minimum or maximum discharge averaging periods, reversals, or rise and fall rates. Principal components analysis was conducted to objectively evaluate the overall degree of impact across our study sites. Results indicate that the Missouri River sites are in fact the most altered, while the Kansas and Wakarusa Rivers are the least altered systems used in this analysis (Figure 2.3).

Discussion

Our results indicate dramatic post-impoundment alteration of Great Plains river hydrologic regimes. Analyses supported the hypotheses that impoundment results in muted discharge magnitudes at both the high and low extremes, low discharge durations were reduced, and rise and fall rates increased. Our findings are consistent with other geographically extensive studies in that uniform, consistent trends in the hydrologic response of the rivers were not detected across the study region (Magilligan and Nislow, 2005), likely due to variable system-specific reservoir management objectives, land use changes, and climatic regimes. This was evident in the analysis of characteristic discharge, where distinctly different impacts were detected across systems. Mean annual discharge on the Canadian River decreased by 88%, which represents an additional decrease of 16% from that observed in a 1996 analysis of the system (Bonner and Wilde, 2000). Discharge decreases were also present at the Arkansas and Republican rivers. In contrast, mean annual discharge remained fairly stable post-impoundment at both systems on the Missouri as well as the Red River of the South, while the Kansas, Pecos, Wakarusa, and Red River of the North have all experienced increases in mean annual discharge. The Arkansas, Canadian, and Pecos Rivers are all subject to legal water compacts that dictate a minimum amount of acre-feet to be held or released, which aids in explaining some of the specific alterations of these systems. It is possible that reduced mean annual discharges may partially be the results of increased evaporation and/or infiltration and loss to groundwater. However, it is more likely that water withdrawals (both direct and through alluvial aquifer wells) and diversions for irrigation are responsible for these reductions in mean annual discharges as seen in this analysis.

Our results also demonstrated no uniform pattern of variation in monthly discharges across the study region. In some cases, such as the Missouri River, reservoirs are used to maintain downstream discharges for barge navigation, resulting in the impoundments storing water from March through July and then augmenting the discharge of the river August through February. The Red River of the North experiences its greatest increases in mean monthly discharges in February and March, attributable to seasonal shifts of warmer temperatures earlier in the year, to snowmelt and rain on frozen ground (Villarini et al., 2011), and to channelization and dam construction on tributary streams (Aadland et al., 2005). The Arkansas and Canadian Rivers both have a decrease in every month's mean discharges.

We did detect near-uniform patterns of change in the analyses of magnitudes of the mean maximum and minimum discharges, and low and high pulses, and reversals. All but three systems (Pecos, Red of the South, and Republican) experienced increases in 1, 3, 7 and 30 day minimum discharges, although only five of these were statistically significant. All but one system (the Red River of the North) experiences reductions in 1, 3 and 7 day maximum flow following impoundment; seven of these were statistically significant (Table 2.4). The impact on minimum and maximum discharges decreases as the temporal scale of analysis lengthens, particularly to the 30 and 90 day minimum and maximum discharge statistics, a finding which is consistent with results from similar studies of impounded hydrologic regimes (Magilligan and Nislow, 2005). Post-impoundment changes to the Julian calendar timing for 1-day minimum discharge varied considerably across systems, averaging more than a three-month shift in timing across all systems and ranging from dramatic adjustments of over 120 days on the Kansas, Pecos and Canadian Rivers (Table 2.5). Alteration of the timing of 1-day maximum discharge was more muted, averaging about a one month shift with the exception of the 129 day shift at Lower Missouri River system. As with the 1-day maximum discharges, we detected an almost uniform overall decrease in low (with the exception of the Upper Missouri) and high (with the exception of the Red River of the North) pulses count and duration following impoundment (Table 2.6). The number of reversals increased at all study systems, other than the Republican River, where agricultural diversions may be the driver of this exception (Table 2.7) (Wu et al., 2009). Rise/fall rates declined at all systems other than the Pecos and the Red of the North. These relatively uniform alterations to the magnitudes of the mean maximum and minimum discharges, low and high pulses, and reversals are seen across the Great Plains region despite the varying hydrologic regimes and impoundment controls and are coincidental with changes observed at other gages evaluated in this region and throughout the continental United States (Magilligan and Nislow, 2005), suggesting that these particular metrics are relatively uniformly impacted by dams across geographical regions and reservoir management schemes.

Overall, it appears that both sites on the Missouri River have the most altered hydrologic regimes, with significantly different 1, 3, 7, 30 and 90-day minimum and maximum discharges and an average of 81 and 69 day shifts to the 1-day minimum and maximum mean annual discharges, respectively (Figure 2.3). These rivers being the most altered is unsurprising since it is well known that the hydrologic regime of the Missouri River is highly controlled to support barge navigation and for flood prevention (e.g. Sparks et al., 1998), which is especially evident given the increased monthly discharges to support barge navigation through the winter and decreased monthly discharges in the spring during upstream snowmelt events. The Kansas and Wakarusa Rivers are the least altered systems used in this analysis (Figure 2.3).

The consistent outlier in the study group was the Red River of the North, the one study system with no main-stem impoundment. This system has experienced significant changes to its hydrologic regime, but almost uniformly in opposing directions to the other study systems. Major differences include dramatically increased mean annual, mean monthly maximum daily discharges, increased high pulse counts, and increased rise and fall rates. While tributary dams could be responsible for some of the observed regime modifications, dams do not tend to increase total discharge (McClelland et al., 2004). Rather, the Red River of the North's uniquely altered hydrologic regime is likely the result of four factors: 1) the absence of a main-stem dam to control main-channel discharge patterns, 2) the widespread installation of agricultural drainage tile systems in the watershed, 3) increased precipitation over the study period, and 4) a decrease in surface storage in prairie potholes. Increases in both discharges and peak discharges are the product of expanded drainage tile systems, widespread channelization, and expansion of the stream network through ditching (e.g. Bluemle, 1997), which act to decrease surface and soil moisture storage, intercept groundwater recharge pathways, increase total runoff volume, greatly reduce lag time to peak discharge, increase peak discharge magnitudes, and generally produce more severe and frequent flooding than under natural watershed conditions (e.g. Poff et al., 1997; Melesse, 2004). During the late 19th and early 20th centuries, the prairie potholes in the Red River of the North's valley were completely drained (Dahl and Allord, 1996), with North Dakota losing 49% of its wetlands (Dahl, 1990). These anthropogenic watershed alterations may be compounded by the increasingly wet climate in the Great Plains region (Garbrecht et al., 2004; USGCRP, 2009). The lack of a main-stem dam limits the ability to moderate the anthropogenically enhanced river discharge and peak discharge magnitudes at the gaging site, producing the altered hydrologic regime parameters analyzed in this study.

Conclusions

This is the first study to systematically investigate impoundment-driven hydrologic alteration of rivers across the Great Plains physiographic region. The extent and magnitude of hydrologic alternations detailed by this study have tremendous implications for ecogeomorphology of Great Plains river systems. Exacerbating the well-known negative effects of physical fragmentation by dams, the dramatically altered hydrologic event frequencies, timing and magnitudes are likely contributing to the decline of native species. For example, the reduction of high pulse frequencies, durations and the shifting of peak discharge timings by more than a month in several cases is likely disrupting the reproductive timing for fish species in these systems. Similarly, reductions in low discharge pulse frequencies, durations and magnitudes and shifts in low discharge timing is likely disrupting the recruitment of riparian pioneer vegetation species. Hydrologic regime modifications detailed in this study are probably, in addition to sediment starvation, some of the primary drivers of the downstream geomorphic adjustments other studies have documented following impoundment construction. In particular, the elimination of the largest flood peaks and overall reduction in high pulse frequencies could be limiting rates of meander migration.

In light of the degree and permanency of the modifications brought by impoundment, it is difficult to arrive at management recommendations to mitigate these hydrologic regime alterations. Best management practices that use reservoir releases to approximate pre-impact hydrologic regimes are of course desirable (Poff et al., 1997; Pegg et al., 2003; Propst and Gido, 2004; Magilligan and Nislow, 2005), but adoption of these measures is often politically difficult and in many instances may not be possible given the need to protect developed floodplains, support navigation, and manage down-network discharges. Even modified reservoir management would not address the physical fragmentation caused the by physical barrier of a dam, and it is important to recognize that even the most ecologically minded reservoir management is unlikely to produce a fully functional naturalized hydrologic regime and certainly not a naturalized sediment regime (Schmidt et al., 1998). While some have suggested dams could be redesigned to release sediment consistent with natural sediment transport events (Lignon et al., 1995), even this would not address the detrimental effects on the unique life history requirements of pelagic-spawning fishes or otherwise migratory stream organisms (Agostinho et al., 2007). Furthermore, formerly active floodplains have been encroached upon by urban development that will prohibit restoration of historically representative large flood discharges.

Despite the limited options for hydrologic regime restoration, the timing and duration of high and low discharges can be managed as part of a long-term discharge prescription designed to improve ecosystem functioning (sensu Poff et al., 1997; Toth et al. 1998; Prospts and Gido 2004). In particular, the ecological needs of specific native assemblages of fish or plants can be targeted by adaptive ecosystem management efforts (Perkin and Bonner, 2011), and to our knowledge no attempts at this management technique exist within the Great Plains. As a beginning, rivers of the Great Plains would benefit from naturalizing discharge regimes by reducing discharges from the fall through winter, readjusting the timing of high pulses to that of the pre-impoundment, and reducing the number of hydrograph reversals, and moderating rise and fall rates (sensu Galat and Lipkin, 2000; Pegg et al., 2003). Conservation of Great Plains rivers should include protecting existing connectivity and natural discharge regimes while seeking opportunities to naturalize altered discharge regimes (Dynesius and Nilsson, 1994; Schaefer et al., 2003; Franssen et al., 2006).

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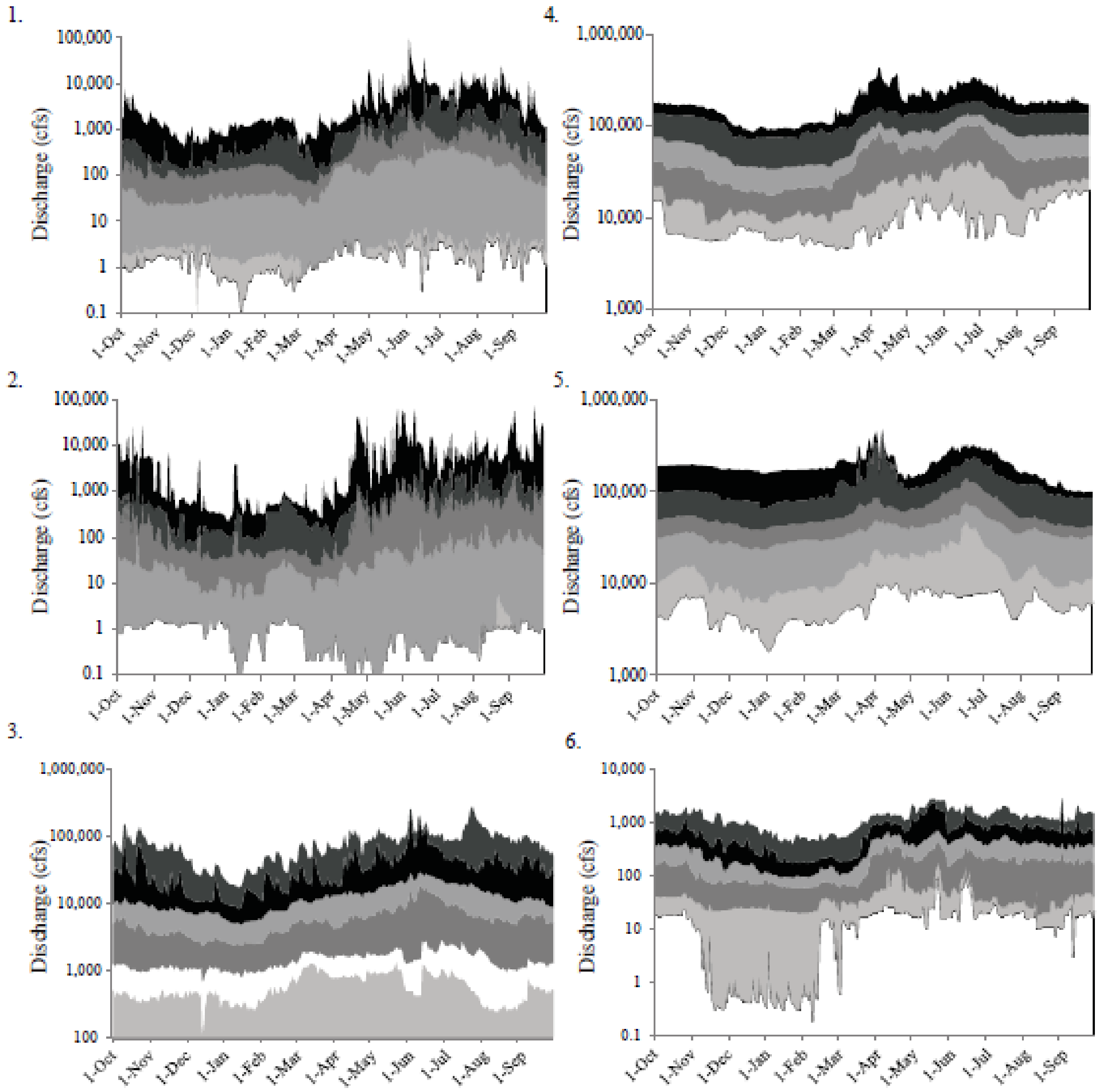
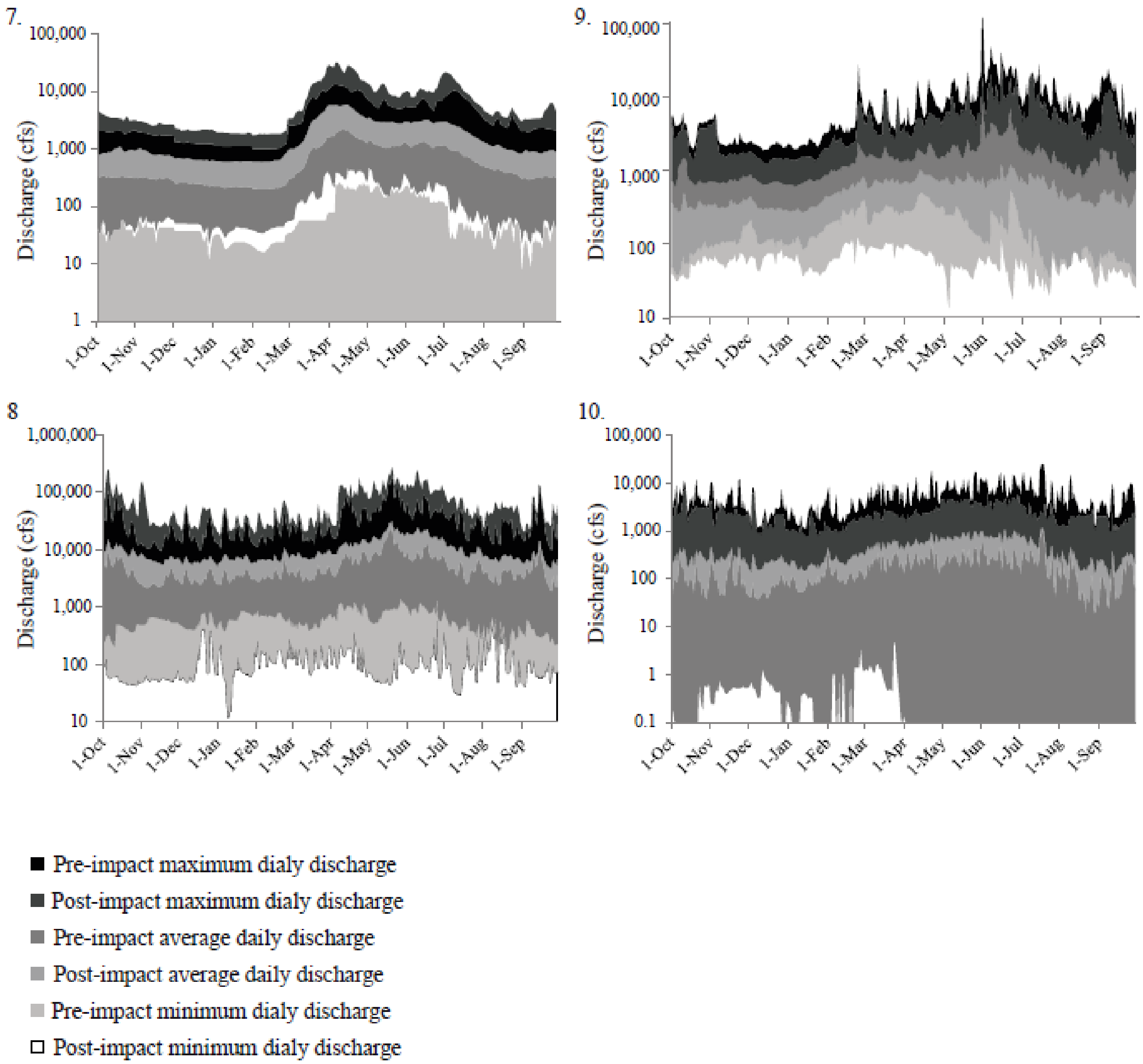
Figure 2.1 Location of systems used for analysis, where grey circles indicate gage sites used for analysis. The boundary of the Great Plains, USA is delineated in light grey.

Figure 2.2 Mean daily discharge for the pre-impact and post-impact time periods.

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0.1
1-Oct
1-Nov
1-Dec
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
1-Aug
1-Sep
Pre-impact maximum dialy discharge
Post-impact maximum dialy discharge
Pre-impact average daily discharge
Post-impact average daily discharge
Pre-impact minimum dialy discharge
Post-impact minimum dialy discharge

Figure 2.3 Principal component analysis of the uncorrelated (r > 0.8) parameters calculated by IHA for pre (in grey) and post (in black) alteration of the systems used in this analysis.

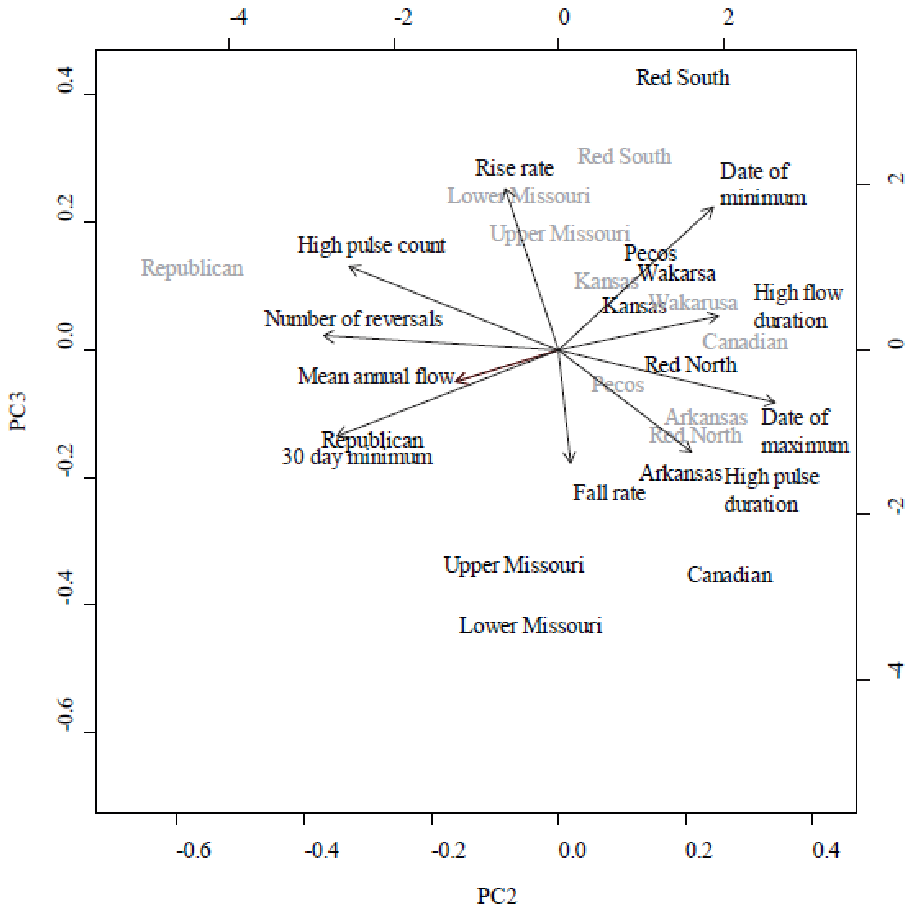

Table 2.1 Characteristics of systems used in the analysis, where Q is discharge in cubic meters per second.

River	State	Dam(s)	Dam Height (m)	Reservoir Storage (km^3)	Mean annual Q pre-impact	Mean annual Q post-impact	% change
Arkansas	CO	John Martin	36.0	0.75	8.27	3.40	-59**
Canadian	NM	Ute	40.2	0.50	9.66	1.19	-88**
Kansas	KS	Tuttle and Milford	47.9 and 44.8	2.78 and 1.41	104.87	147.42	41**
Lower Missouri	NE	Gavins Point	14.3	0.67	727.18	735.11	1
Upper Missouri	MT	Garrison	64.0	30.21	624.10	624.39	0
Pecos	NM	Brantley	43.9	1.19	3.31	4.39	33**
Red of the North	ND	None	--	--	15.15	33.73	123**
Red of the South	TX	Denison	50.3	6.40	137.25	138.13	1
Republican	NE	Harlan County Lake Dam	32.6	1.02	25.06	8.81	-65**
Wakarusa	KS	Clinton Lake	35.4	0.45	5.32	7.62	44**

† If a significant difference between the two periods at the 1% level exists, it is designated with **.

Table 2.2 Percent change in mean monthly flows following impact, where Q is discharge.

	October Q	November Q	December Q	January Q	February Q	March Q	April Q	May Q	June Q	July Q	August Q	September Q
Arkansas	-69**	-73**	-70**	-72**	-65**	-28*	-55*	-60**	-68**	-25**	-69**	-38**
Canadian	-92**	-68**	-75**	-82**	-37**	-52**	-93**	-93**	-93**	-77**	-84**	-88**
Kansas	38**	90**	121**	62**	52**	110**	87**	53**	-19**	76**	36**	-3
Lower Missouri	68**	61**	82**	57**	37**	-28**	-43**	-6**	-44**	-25**	46**	64**
Upper Missouri	14**	22**	51**	71**	74**	-15**	-10*	-15**	-50**	-27**	46**	49**
Pecos	75**	239**	99**	-5	34**	43**	0	1	51**	45**	13**	11
Red of the North	138**	140**	124**	140**	179**	192**	139**	102**	84**	98**	97**	126**
Red of the South	-12	80**	3	22**	18*	22**	-5	-36**	31**	33**	33**	-51**
Republican	-50	-45**	-52**	-55**	-58**	-55**	-56**	-62**	-82**	-62**	-63**	-68**
Wakarusa	78**	60**	92**	44**	51**	53**	21*	79**	22*	6	42*	104**
Mean decrease	56	62	66	54	53	38	44	45	59	43	72	50
Mean increase	69	99	82	66	64	84	82	59	47	51	43	71

Ϯ If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with

Table 2.3 Percent change in the means of pre and post-impact minimum discharges, where Q is discharge.

River	1-day min Q	3-day min Q	7-day min Q	30-day min Q	90-day min Q
Arkansas	249**	202**	165**	49	-9
Canadian	6	9	6	12	52*
Kansas	29	29	29	22	39*
Lower Missouri	96**	96**	95**	75**	53**
Upper Missouri	119**	128**	128**	108**	73**
Pecos	-18	-13	-11	-8	-2
Red of the North	131**	138**	143**	162**	137**
Red of the South	-76**	-51**	-7	34	9
Republican	-26*	-30*	-32*	-41**	-57**
Wakarusa	324**	318**	312**	120**	96*
Mean decrease	40	31	17	25	30
Mean increase	124	120	114	66	66

Ϯ If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with **.

Table 2.4 Percent change in the means of pre and post- impact maximum discharges, where Q is discharge.

River	1-day max Q	3-day max Q	7-day max Q	30-day max Q	90-day max Q
Arkansas	-83**	-83**	-78**	-68*	-63*
Canadian	-91**	-88**	-88**	-82**	-85**
Kansas	-19	-14	-1	30	41*
Lower Missouri	-66**	-64**	-61**	-43**	-24**
Upper Missouri	-56**	-54**	-50**	-41**	-27**
Pecos	-6	9	23	17	23
Red of the North	120**	123**	137**	137**	120**
Red of the South	-56**	-49**	-37*	-8	4
Republican	-75**	-73**	-73**	-66**	-65**
Wakarusa	-56**	-51**	-28	3	22
Mean decrease	56	60	52	51	53
Mean increase	120	66	80	52	42

ƚ If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with **.

Table 2.5 Timing of 1-day minimum and 1-day maximum discharge, where Q is discharge.

River	Pre impact 1-day min Q	Post impact 1-day min Q	# Days different	Pre impact 1-day max Q	Post impact 1-day max Q	# Days different
Arkansas	175	99	76	198	181	18
Canadian	316	193	123	208	236	28
Kansas	180	304	124	189	180	9
Lower Missouri	353	51	63	124	252	129
Upper Missouri	361	264	98	136	145	9
Pecos	184	311	127	182	241	59
Red of the North	213	269	56	124	129	5
Red of the South	232	291	59	183	171	12
Republican	291	241	50	158	189	31
Wakarusa	260	299	39	167	174	7
Mean			82			31

Ϯ If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with **.

Table 2.6 Percent change in the means of pre and post-impact impact conditions for low and high pulse numbers and durations, where Q is discharge.

	% change low pulse count	% change low pulse length	% change high pulse count	% change high duration
Arkansas	-89**	-89	-64**	-79
Canadian	-87**	-95**	-80**	-39
Kansas	-84	-94	-87	-88**
Lower Missouri	-99	-100	-85**	-93**
Upper Missouri	0	0	-87*	-91
Pecos	-71**	-98	-95**	-93**
Red of the North	-53**	-30	96**	68*
Red of the South	-93**	-97**	-90**	-89**
Republican	-52*	-89**	-74**	-34**
Wakarusa	-77**	-95*	-88	-82**
Mean decrease	78	87	83	76
Mean increase	--	--	96	68

Ϯ If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with **.

Table 2.7 Percent change in the means of pre and post-impact impact conditions for hydrograph reversals and rise and fall rates, where Q is discharge.

River	% Change reversals	% Change, rise rate	% Change, fall rate
Arkansas	6	-85**	-84**
Canadian	49**	-95**	-94**
Kansas	6	-35**	-31**
Lower Missouri	58**	-75**	-64**
Upper Missouri	143**	-63**	-44**
Pecos	17	1	23
Red of the North	5	69**	58**
Red of the South	87**	-48**	-2
Republican	-10**	-74**	-74**
Wakarusa	36**	-46**	-40**
Mean decrease	10	65	54
Mean increase	45	35	41

† If a significant difference between the two periods at the 5% level exists, it is designated with *. If a significant difference between the two periods at the 1% level exists, it is designated with **.

Chapter 3 - Hydrology of intermittent tallgrass prairie headwater streams

Abstract

This paper examines the hydrology of intermittent prairie streams of the Konza Prairie Biologic Station (Konza) located in Northeastern Kansas. Flow records from four gaging stations were used to quantify flow intermittence, annual flows, and peak discharge events. 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 least amount of zero-flow days and the fewest durations of zero-flow while the smallest basin had the most zero-flow days and the highest frequency of 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 and the number of zero-flow days and the number of zero-flow periods. Basin averaged total annual precipitation poorly predicted mean annual and peak annual discharges. Double mass plots of stream flow to precipitation and stream flow in the headwaters to stream flow at the larger site demonstrate many instances where flows at Konza are desynchronized between watersheds that likely attributed to unaccounted for variation in climatic heterogeneity and to the timing of runoff processes. Results of this study suggest that local watershed-scale processes, such as water-table fluctuations and soil moisture conditions, control the hydrologic response of intermittent prairie streams, decoupling them from sub-annual weather patterns.

Introduction

Headwaters are the areas in a channel network where channelized flow originates and are the interface between terrestrial and riverine ecosystems, representing a dynamic mix of colluvial and alluvial processes [MacDonald and Coe, 2007]. Representing a network's outermost links, headwater streams are tightly hydrologically, geomorphically, and biologically linked to hillslope processes [Horton, 1945; Hack and Goodlett, 1960; Hewlett and Hibbert, 1967; Likens *et al*., 1977; Dietrich and Dunne, 1993; Gomi *et al.,* 2002]. Headwaters are also important for longitudinal (downstream) linkages with larger streams and are major contributors of energy and matter to those larger streams [Gomi *et al*., 2002; MacDonald and Coe, 2007]. Due to their comparatively small size and connectivity to hillslopes, headwater streams are particularly responsive to perturbations within the watershed [e.g. Benda *et al*. 2005]. Headwater streams 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, which may be intermittently or perennially flowing. 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 about 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]. Intermittent streamflow is a feature of most grasslands; and the Great Plains of the USA are characterized by distinct periods of flooding and drying [Dodds *et al.,* 2004]. Small headwater streams of the Great Plains are considered to be harsh, with intermittent or perennial discharge regimes, and typically have 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], even though there are long periods of zero-flow [Dodds and Oakes, 2008].

The hydrologic regimes of Great Plains streams are extremely variable, with floods and periods of prolonged no-flow commonly occurring in a single year [Dodds *et al.,* 2004]. Temporary cessation of flow causes a temporary ecotone to develop that maintains diversity of aquatic and terrestrial systems and regulates the transfer and transformation of energy and materials of a system [Steward *et al.,* 2011]. Intermittent streams and their riparian zones can be hot spots for biogeochemical processes in arid to semi-arid regions [McIntyre *et al*., 2009]. Unsaturated riparian soils are a possible source of nitrogen after periods of zero-flow [Bernal *et al.,* 2007] that is rapidly mobilized due to increased groundwater levels [Butturini *et al.,* 2003]. The extreme variation in hydrology and associated abiotic habitat elements structures the biotic assemblages of intermittent prairie streams [Lake, 2000; Dodds *et al.,* 2004; Fritz and Dodds, 2005]. 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 or scouring flood event [Murdock *et al.,* 2010, 2011].

Despite the acknowledged importance of abiotic factors controlling the structure of biotic assemblages, to our knowledge there has been no analysis of the hydrology of intermittent prairie streams in the Central Great Plains. Some attention has been devoted to large river floods which are common but independent of decadal precipitation trends [Schumm and Lichty, 1963; Julian *et al.,* 2011], but to our knowledge there has been no systematic analysis of hydrologic regimes on smaller intermittent headwater streams in the region. Headwater streams of the Great Plains are an integral component of the riverscape of the Great Plains and the intermittent and ephemeral channels are equally important to the perennially flowing channels [Wohl *et al.,* 2009]. The Central Great Plains is located at the juxtaposition of many different large-scale atmospheric pressure and circulation systems; and various teleconnections with global atmospheric phenomena (e.g. ENSO) are weakly correlated with the precipitation regime [Goodin *et al.,* 2003]. Within the last several decades, drought severity and duration have increased [Andreadis and Lettenmaier, 2006] 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 [Knapp *et al.,* 2002; Milly *et al.,* 2005].

These climate projections imply that global climate change is likely to change precipitation regimes dramatically, which may increase the prevalence of intermittent stream flow regimes [Larned *et al*., 2010b]. Yet, there is a general lack of knowledge of the characteristics of intermittent stream flow because hydrologic records from small prairie streams are typically scarce, short, and rarely complete [Shook and Pomeroy, 2012]. Confounding the data limitation is a general lack of knowledge of the applicability of standard hydrologic indices developed for perennial 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, intermittent streams have received comparably little attention.

The overall objective of this study was to characterize the flow regime of intermittent prairie headwater streams in the Central Great Plains, USA. Our working hypothesis was that, as already demonstrated with larger river regimes in the region, intermittent stream hydrologic regimes would demonstrate little correlation with large scale atmospheric patterns and instead be correlated with local precipitation events. We examine 25-year hydrologic records from four small sub-basin gaging stations located in a headwater intermittent stream network to explore relationships between stream flow and precipitation as well as hydrologic relationships spatially within the network. To our knowledge, no comparable studies exist that attempt to describe flow characteristics of intermittent prairie streams in the Central Great Plains of North America.

Material and Methods

Study site

This study was conducted within the Konza Prairie Biological Station, which is owned by The Nature Conservancy and Kansas State University and operated as a field research station by the Kansas State University Division of Biology and as an NSF-funded Long Term Ecological Research (LTER) facility (hereafter referred to as Konza). Konza comprises 3,487 ha of native tallgrass prairie in the Flint Hills region of Northeastern Kansas (Figure 1). For the purposes of this study, we used flow records from three intermittent headwater streams and one main trunk stream (Kings Creek) that drains most of Konza. All watersheds are completely within the boundary of Konza and are composed entirely of tallgrass prairie. Kings Creek has been monitored by a U.S. Geologic Survey (USGS) stream gage (06879650) since 1979. Though Konza was established in 1981, monitoring of headwater streamflow did not being until 1987 when permanent trapezoidal concrete weirs were installed. The four weirs monitor approximately half the total drainage area of the Kings Creek gage, with half the watershed being completely unmonitored. All of the headwater sub-basins used in this study (N01B, N02B, and N04D) are grazed by *Bos bison* (American bison) with burn rotations from 1 to 4 years (Table 3.1). The streams used in this analysis are intermittent; with complete channel drying in all but spring-fed reaches a common seasonal feature of these streams.

Konza is located within a temperate climate, and the mean annual precipitation for the study period (1987-2011) was 780 $mm \cdot yr^{-1}$ with 75% falling in the April through September growing season (Figure 3.2a). Approximately 52 $mm \cdot yr^{-1}$ of the total precipitation falls as snow

[Haydem, 1998]. Intense but localized convective storms produce most of the headwater flood events, typically in the summer months (Figure 3.2b; 3.2c). The high intensity precipitation events usually only produce flooding if the watershed is close to or completely saturated [Gray *et al.,* 1998]. Dodds *et al.,* [1996] found that approximately one third of the annual hydrologic export of Konza is through the stream channel while transmission losses to groundwater account for the remaining export. Storm precipitation events recharge the aquifers within a few hours through preferential flow and stream-groundwater interactions [Tsypin and Macpherson, 2012].

The Flint Hills physiographic province is underlain by flat to slightly dipping (0-0.19°; Oviatt, 1998), Permian-aged sedimentary rocks [MacPherson and Sophocleous, 2004]. Local stratigraphy consists of alternating layers of 1–2 m thick thinly-bedded chert-bearing limestones and 2–4 m thick less resistant mudstones [Macpherson, 1996; Oviatt, 1998]. Stream networks dissect the landscape, exposing these alternating layers. Limestone layers form benches on hillslopes and knickpoints in stream channels, while mudstones erode more gradual slopes, producing a terraced topography. Within the Kings Creek drainage system, the Florence Limestone formation is the highest and youngest layer, and the Neva Limestone Member is the base later [Oviatt, 1998]. Many seasonal freshwater springs emerge from limestone formation exposures, particularly from the Neva formation 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 valleys [Ransom *et al*., 1998].

The vegetation at the site is mesic native tallgrass prairie, which is dominated by perennial warm-season grasses. The Flint Hills region contains the largest continuous tract of unplowed native tallgrass prairie remaining in North America [Samson and Knopf, 1994]. Between 1939 and 2002 woody riparian vegetation at Konza has expanded by nearly 70%, extending from the Kings Creek mainstem riparian corridor upstream along the stream network and along the headwater tributaries [Briggs *et al*., 2005]. Woody plants dominate the valley bottoms while grasses dominate the hillslopes.

Based on a modeling study, mean annual precipitation at Konza can be partitioned into 14% direct runoff, 2% as lateral flow through the soils, 9% as groundwater recharge, and evaporation accounts for the remaining 75% [Steward *et al*., 2011]. A conceptual model of the hydrologic system at Konza and important surficial and groundwater fluxes are identified in

Figure 3.3. Soil moisture conditions are an important control on the hydrologic system at Konza. Soil moisture is highest after precipitation events in the spring and summer and lowest in the late summer and fall [Tsypin and Macpherson, 2013]. There are numerous fractures in the limestone and surface fissures at Konza [Tyspin and Macpherson, 2013] that likely influence surface-groundwater interactions. Rain gage measurements from locations in each study sub basin demonstrate that event specific precipitation is heterogeneously distributed across the site.

Data

The gages on N01B, N02B, and N04D are maintained by the Kansas State University Department of Biology, and data are available for a 25 year period (1987-2011) (http://www.konza.ksu.edu/knz/pages/data/knzdata.aspx). These gages record discharge at five minute intervals during stormflow or three hour intervals during baseflow conditions. Discharge for Kings Creek has been monitored since 1979 by the USGS (http://www.usgs.gov/) and is recorded in 15-minute intervals. Total daily precipitation data is recorded at the Konza weir sites and individual gage streamflow and precipitation were used to assess the relationship between precipitation and streamflow. The Kings Creek gage does not have a precipitation gage so precipitation data recorded at Konza Headquarters (between N02B and Kings Creek) was used. Peak discharge events were extracted from the record and matched with events at the other basins following Perkins and Jones [2008]. The analysis used peak discharges and precipitation measurements for the period of overlapping records for all basins. Since less than 6% of the precipitation that falls at Konza is in the form of snow, there was no need to classify events based on snow water storage.

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, 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).

Data analysis

Hydrologic characterizations employ a wide range of indices, but only two are commonly used to describe flow intermittence: the frequency and duration of zero-flow events [Poff, 1996; Knighton and Nanson, 2001]. Analysis focused on the relations between discharge, precipitation, and PDSI within the Konza dataset. Following Daniels [2004], simple linear regressions were completed for correlations between maximum annual and mean annual discharge to total annual precipitation. Peak discharges and their associated event precipitation were log-transformed prior to model fitting and linear regressions and correlations were used [Jones and Perkins, 2008].

While regression analyses provide useful information about relationships of data, double mass curves are a simple visual method that is widely used to study the consistency and long-term trends in hydro-meteorological data sets. Double mass plots [Searcy and Hardison, 1960] are the plots of the cumulative amounts of a quantity of interests at a station under consideration against the cumulative amounts of a neighboring station. If the variables plot as a straight line on a double mass plot then they are consistently proportional over time, and the slope of this line is the ratio between the two variables. Changes in the gradient of a double mass curve are indicative of changes in the original relationship between variables including 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. Standardized departure analyses of annual stream flow statistics (i.e. annual mean, median, and maximum daily streamflow) were 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. Departure analyses are useful for determining how the magnitude daily flows change over time [McCabe and Wolock, 2002]. Departure analyses were conducted for minimum, median, and maximum flows. Since all of the streams have periods of zero-flow, departure analyses were conducted using mean annual flows rather than minimum flows.

Results

Flow intermittency

Discharge regimes at Konza are characterized as intermittent with all gages experiencing periods of prolonged zero-flow days annually. No gauging station had zero-flow recorded exclusively in the winter, indicating that freezing was not a 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 (Table 3.2).

Kings Creek experienced the least amount of zero-flow days with an average duration of 192 days (±76; standard deviation) per year of zero-flow recorded at the gage site (Table 3.2). N02B had the most zero-flow days with an average duration of 265 days (±50) per year of zero-flow (Table 3.2). Kings Creek also had the lowest amount of zero-flow days recorded in 1998 with only 28 days that year experiencing zero-flow (Table 3.2). N02B has the highest amount of zero-flow days recorded in 2006 with 356 days that year experiencing zero-flow (Table 3.2). Trends in the number of zero-flow days follow 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. Unsurprisingly, there were significant negative correlations between the number of zero-flow days and mean annual precipitation. The relationship was the strongest for N02B (-0.75, $p<0.001$) but Kings Creek (-0.66, $p<0.001$), N01B (-0.55, $p=0.006$), and N04D (-0.45, $p=0.03$) were also strong.

The frequency of zero-flow periods varied between watersheds. Kings Creek had an average frequency of zero-flow periods of 3.25 per year while N02B had the average frequency of zero-flow periods of 6.6 per year (Table 3.2). Kings Creek also had the least amount of zero-flow day frequencies with 1998 and 2010 only having one period of drying. N02B had the highest frequency of zero-flow days with 19 zero-flow periods in 2009 (Table 3.2). As with the number of zero-flow days, the frequency of zero-flow days also shows trends with respect to watershed size where the largest watershed has the most infrequent periods of zero-flow and the smallest watershed having the most frequent periods of zero-flow. The frequency for zero-flow periods were highly correlated with mean annual precipitation for the headwater gages (N01B 0.52, $p=0.009$; N02B 0.45, $p=0.03$; N04D 0.57 $p=0.004$)

The frequency and duration of zero-flow days were uncorrelated for all the watersheds except N02B, which is significantly negatively correlated (-0.48; p=0.018). Regressions of number of zero-flow days with PDSI and total annual precipitation revealed negative correlations between the number of zero-flow days with PDSI and total annual precipitation (Table 3.3). Correlations are significant for all watersheds but are more strongly negatively correlated for precipitation than they are for PDSI (Table 3.3). Correlations for the frequency of zero-flow periods are not as significant or strong for precipitation or PDSI as correlations for total number of zero-flow days are (Table 3.4). The correlation of frequency of zero-flow days were significant for N04D and N02B (p=0.04 and p=0.05) against PDSI while N01B and Kings Creek were insignificant (p=0.37 and p=0.20, respectively; Table 3.4). 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 (Table 3.4).

Annual flows

Mean annual discharge of the four watersheds used in this analysis were dominated by discharge events that occur between April and July (Figure 3.2B). Correlations of mean annual discharge and total annual precipitation reveal that the relationship for the smaller watersheds of this study is 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 (Figure 3.4A; Table 3.5). 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 occur in the same time period as mean annual discharge events occur, in April through July (Figure 3.2C). Overall, the linear regressions for peak annual discharge were more significant than those for mean annual discharge (Figure 3.4B; Table 3.6). N01B has the strongest relationship ($F_{2, 28}$= 15.04, r^2=0.4, p <0.001).

Flood flows

The majority of peak discharges matched a large precipitation event within 12-hours, but some were up to 36-hours apart (Table 3.7). The most extreme floods that occur at Konza were the product of strong conductive thunderstorm events that occurred in the summer time, with the exception of N01B that had a peak discharge event in November (Figure 3.5). Extreme peak discharges of record were 232.8 and 168.5 m^3s^{-1} (17 July 1993 and 22 July 1992), both of which were seen at the Kings Creek gage. Of the top 30 discharge events seen at Kings Creek gage, 26 of the events occur between April and July with August, September, October, and November each having one peak event, which are all low ranking events (23, 30, 27, 25, respectively). The events that did occur outside of the summer were not associated with rain-on-snow events. N01B is the only watershed that had an event that occurred outside of Spring or Summer as its peak discharge of record, which occurred on 3 November 1998. The peak discharge of N01B is the 25th largest seen at that Kings Creek gage (Table 3.7). The two peak discharge events seen at Kings Creek are within the top six for N01B and N02B. N04D did not experience Kings Creek's peak and the second highest discharge seen at Kings Creek is the tenth largest seen at N04D (Table 3.7). The timings and magnitude of peak flood events were not consistent between gages used in this analysis and are, for the most part, associated with unique precipitation events (Table 3.7).

Correlations of event rankings reveal that N01B (0.62, $p=0.004$) and N02B (0.66, $p < 0.001$) are more correlated than N04D (-0.02, $p= 0.91$) is to Kings Creek. Correlations between headwaters, excluding Kings Creek, demonstrate that correlations between the smallest gages are stronger (N01B to N02B: 0.510, $p= 0.006$) than those for the small gages and the larger headwater stream (N01B to N04D: 0.09, $p=0.66$; N02B to N04D 0.04, $p= 0.847$). Peak event discharge and event precipitation were highly uncorrelated and insignificant (N01B: 0.23, $p= 0.24$; N02B: 0.59, $p= 0.12$; N04D: 0.29, $p=0.13$; Kings Creek: 0.20, $p= 0.29$). Linear regressions on the peak event discharge and event precipitation demonstrate that the relationships for all the watersheds used in this analysis were all insignificant (Figure 3.4C; Table 3.8).

Trends and change points for hydro-climatic series

The dynamic relationship between annual rainfall and streamflow of all the gages as well as the relationship between streamflow at Kings Creek and the headwaters are shown in double mass curves (Figure 3.6a, b). A double mass curve of the cumulative annual discharge for the four gages against the cumulative annual precipitation at Konza indicate that streamflow increased compared with precipitation (Figure 3.6a). The change points on the double mass curve were consistent across all of gages. A double-mass curve analysis of the three Konza weirs annual flows against the Kings Creek gage annual flows demonstrated that there were numerous and systematic breaks in the relationship between streamflow in the headwaters and at Kings Creek (Figure 3.6b). The timing of breaks was consistent across all gages, but there was not a seasonality or large precipitation event that was driving the increases in tributary flow relative to Kings Creek or precipitation. For both the of the double-mass curves the breaks are subtle with the exception of N04D. After 2006, the N04D gage demonstrates that there is a large increase in streamflow in the watershed relative to precipitation or streamflow at Kings Creek. The slopes of the regression lines were inconsistent with some slopes higher or lower after the breakpoints than before for both double mass plots of precipitation and for the headwaters against Kings Creek.

For all the streamflow standardize departure analyses of annual mean, median, and maximum daily streamflow indicate that there is not a visible step-shift or gradual increase or decrease in stream flow at Konza. Departure analyses indicate that there are extreme variations in positive and negative departures for all of the sites (Figure 3.7). The departures are inconsistent between watersheds with no watersheds experiencing synchronization of high or low departures. Positive departures are consistently of a much larger magnitude than negative departures throughout all of the study sites.

Discussion

This study used statistical models to identify relationships between characteristics of flow intermittence (number of zero-flow days and number of zero-flow periods; Snelder *et al.,* 2013), mean annual, and flood flow characteristics with moisture characteristics (total annual precipitation, event precipitation, and PDSI) to characterize flow in intermittent prairie streams.

Following Poff [1996], all streams used in this analysis meet the standards for harsh intermittent classification (Table 3.2). The proximate cause of intermittency is likely water table fluctuations relative to the channels [Konrad, 2006; Larned *et al.,* 2010a; von Schiller *et al.,* 2011]. 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.

Results of this study reveal an apparent decoupling between discharge and precipitation inputs. This result suggests that the discharge response to precipitation input is controlled by both climatic and non-climatic processes within the watershed. Non-climatic processes that are controlling the streamflow include soil moisture storage, groundwater table fluctuations and spring seepage, as has been observed in other intermittent stream systems [e.g. Fleckenstein *et al*., 2006; Larned *et al.,* 2010a, 2010b]. The high rates of evapotranspiration measured at Konza, and throughout the Flint Hills physiographic region, are responsible for up to 75% of precipitation loss [Steward *et al*., 2011] and is a key control on streamflow. While evapotranspiration accounts for a large proportion of precipitation loss at Konza, precipitation loss through evapotranspiration can reach over 83% in more southerly portions of the Great Plains [Wine and Zou, 2012].

There were significant associations between characteristics of intermittency and mean annual rainfall and PDSI. Consistent with Larned *et al.* [2010a], the characteristics of intermittency, the number of zero-flow days and frequency of zero-flow periods, are highly correlated. Snelder *et al.,* [2013] determined that intermittent streams with larger catchments have sustained base flow for most of the year when compared to streams draining smaller catchments, which was consistent with the findings of Kings Creek having the lowest frequency of zero-flow periods and number of zero-flow days when compared to the headwater streams. While many of the streams at Konza have persistent pools and headwater springs, the gage sites at Konza were not close to these features. Similar to Larned *et al*. [2010a], sites that were characterized by large numbers of zero-flow days had little flow permanence and lower mean annual discharge. Daniels [2007] found that streamflow in the perennial headwaters of the Platte River were more correlated with regional than local conditions, which was not the case seen in the intermittent prairie streams of this analysis. Overall, the associations between intermittency and rainfall were stronger than those for PDSI; the PDSI is more of a regional metric than a local metric, and that may be the reason why it does not perform as well as characterizing flow intermittency. Konza is located at the juxtaposition of many different teleconnections and broadly calculated values [Goodin *et al.,* 2003], like PDSI, are not representative of the patterns we see at Konza. Rapid and cyclic water table fluctuations associated with localized precipitation events [Butturini *et al*., 2002] as well as the fracture in limestone and surficial soil cracks as seen at Konza [Tsypin and Macpherson, 2013] are likely responsible for mean annual precipitation being more strongly correlated with the intermittency characteristics than the more broadly calculated PDSI. PDSI values are calculated over areas hundreds of km^2, and as such are regionally averaged values that cannot capture more local variations in lithology and topography that modulate streamflow regimes. This research demonstrated that local precipitation events are very heterogeneous throughout the comparatively very small area Konza encompasses, further complicating relationships between PDSI and local streamflow at the study site scale. Therefore, it is unsurprising that the broadly calculated moisture variable is not as strong of a predictor as the local precipitation measurements are for discharge.

Regression relationships between Konza's total annual precipitation and both mean annual and peak annual discharge were poor. Regressions of mean annual discharge and total annual precipitation do not explain much of the variance. For the largest streams in this analysis there is exceptionally little variance explained in mean annual discharge (less than 1%), but explanatory power improved for the smaller streams (N01B 28%, N02B 32%). Due to N01B and N02B flows being more similar to those of Kings Creek and N04D demonstrate that the intermittent streams at Konza do not all behave in the same manner. There are clear trends with respect to contributing area, where the larger streams have more sustained baseflow than the smaller headwater streams. However, the poor regression results indicate that there are variables not used in this analysis that play a more significant role in determining mean annual and peak annual discharges. In particular, it is likely that evapotranspiration is having a very large influence on the precipitation-discharge relationship because evapotranspiration equates to 75% of precipitation volume. Antecedent soil moisture is also likely having a substantial influence on the precipitation-discharge relationship. For example, there may be periods when there are very large precipitation events in the late summer that do not manifest as large discharge events because of high infiltration into dry soils and high evapotranspiration diversion 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 higher, a comparatively small precipitation event may manifest as a large discharge event. 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 annual and peak annual discharges difficult.

Rain peak discharge events involve a range of event sizes, where rain may fall over all or part of the basin, and soils may be saturated to unsaturated, but there is no snowpack or snowmelt contributing to streamflow. Extreme floods are regional events that are typically the product of large convective thunderstorms in the summer months. Departure analyses appear to demonstrate that high flood flows are controlling the hydrology of Konza due to the much higher magnitude of positive departures compared to negative departures. Simultaneous peak discharges throughout the upper portions of the network amplify flows at Kings Creek. However, there are many instances where flows at Konza are desynchronized between watersheds and longitudinally. The intermittent headwater stream peak discharge events are poorly correlated with those seen at Kings Creek, but N01B and N02B were more strongly correlated to each other than any of the other streams. The apparent desynchronization of measured peak streamflow may be attributed to variation in precipitation heterogeneity and to the timing and pathways of runoff processes [Zégre, 2009]. Routing of water though the channels is important but typically occurs under circumstances where saturation excess runoff is the dominate mechanism for runoff [Samuel and Sivapalan, 2008]. Event precipitations may be low, only a portion of the basin may receive rain, and varying amounts of soil moisture conditions are likely contributing to the desynchronization of flow between watersheds and longitudinally along the stream network. The lack of complete instrumentation of the upper tributaries to Kings Creek makes a conclusive explanation difficult. For example, locally intense precipitation may have fallen within ungaged sub-basins, producing disparities between streamflow recorded in gaged sub basins and the main Kings Creek gage.

To further assess intermittent streamflow, double mass curves were plotted between cumulative annual streamflow at the four gages and cumulative annual precipitation. To quantify the relationship between flow in the headwaters and Kings Creek, double mass curves were plotted for cumulative annual streamflow in the headwaters against cumulative annual streamflow at Kings Creek. The observed breaks in slope 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.

The alternating higher and lower slope breaks in the double-mass plot are indicative of changes in the relationship of flow in the tributaries than we would expect for a given precipitation or relative to Kings Creek. It seems most likely that the periods when there is an increase in the slope of the double-mass curves (more headwater contribution to cumulative stream flow at the Kings Creek gage) are the result of temporary but fundamental alterations to hillslope-channel hydrologic connections. Precipitation takes many pathways at Konza where precipitation can slowly percolate through soils, bypass the soil matrix and rapidly flow through large macropores, or become part of surface water runoff. Each of these pathways produces differential streamflow and groundwater recharge response rates [Tsypin and Macpherson, 2012] and fundamentally regulates the stream discharge regime in this system. During dry periods, the substantial surface macropores in the soils, combined with fractures in the limestone layers, may allow direct recharge to groundwater, bypassing shallow subsurface matrix flow paths to the stream channels. This rapidly recharged groundwater likely emerges at springs in the geological sections below the headwater gages but upstream of the Kings Creak gage, producing a disconnection between headwater streamflow and precipitation as well as the observed disconnection between headwater gages and the Kings Creek gage. During wetter periods, soil moisture increases would result in the macropore cracks closing, eliminating or greatly reducing the quick recharge pathway and forcing infiltrated precipitation to transit via the soil matrix as throughflow, producing stormflow runoff in the headwater channels. There are periods when there is not as much flow in the headwaters as we might expect, which is further support that there is more groundwater recharge within the watershed that is manifesting as a more sustained baseflow at Kings Creek [Steward *et al*., 2011] and not as much surface water flow in the headwaters.

The breaks in the slope of these double-mass plots, the absence of any clear relationship between precipitation and streamflow, and the departure analyses results provide a substantial body of evidence to support the notion that streamflow and precipitation at Konza are desynchronized. Since the geology and soils at Konza are representative of the entire Flint Hills physiographic province [Mandel, 2008], it is quite likely that streamflow and precipitation are similarly desynchronized throughout the uplands of the region. Although Macpherson and Sophocleous [2004] suggested flow through macropores was not substantial within Konza floodplains, the hillslopes may be the main location for this direct recharge. Our results contradict somewhat the Steward *et al.*, [2011] modeling study that indicated enhanced recharge through tributary streambeds is strong in the upland region of Konza. Since our results indicate increase baseflow at the Kings Creek gage in the absence of streamflow in the tributaries, we suggest that hillslope macropore recharge to groundwater may be a major source of this enhanced headwater basin recharge phenomenon. 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.

Conclusions

In this study, long term streamflow and climate records permitted the characterization of the hydrology intermittent prairie streams. Results demonstrate a desynchronization of hydrologic regimes between neighboring headwater catchments as well as longitudinally through the network, suggesting watershed conditions strongly control intermittent headwater stream hydrologic response. 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 total number of zero-flow days and the number of zero-flow periods. Basin averaged total annual precipitation poorly predicted mean annual and peak annual discharges. Double mass plots of precipitation to stream flow showed that there are numerous systematic breaks showing higher stream flow than precipitation and higher stream flow in the headwaters that was not seen at Kings Creek. Standardized departure analyses indicated that there were no gradual or step changes in stream flow at Konza, but a longer period of recorded stream flow would be more useful to fully characterize trends in stream flow. Therefore, it is important to consider local processes, like water-table fluctuations and soil moisture conditions, which are an important factor influencing the hydrology of intermittent prairie streams.

While the number of studies of intermittent streams has greatly increased in the last decade [Datry *et al.,* 2011], there is still much work needed to understand the hydrology of these important parts of river networks. Further work is needed on intermittent streamflow. In particular, detailed coincident observations of soil moisture conditions, water table fluctuations, and stream flow are needed over a broad range of hydrologic and geomorphic regimes. In addition, analyses on the longitudinal gradients, where the channel expands and contracts due to changing hydrology, have yet to be completed [Doering *et al.,* 2007; Larned *et al*., 2010b]. In light of predicted global climate change, intermittent flow is expected to become more common [Larned *et al*., 2010b], improved understanding of the hydrology of intermittent streams should become a key priority for hydrologists and watershed managers.

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Figure 3.1 Study site locations within the Konza Prairie Biologic Station, Kansas.

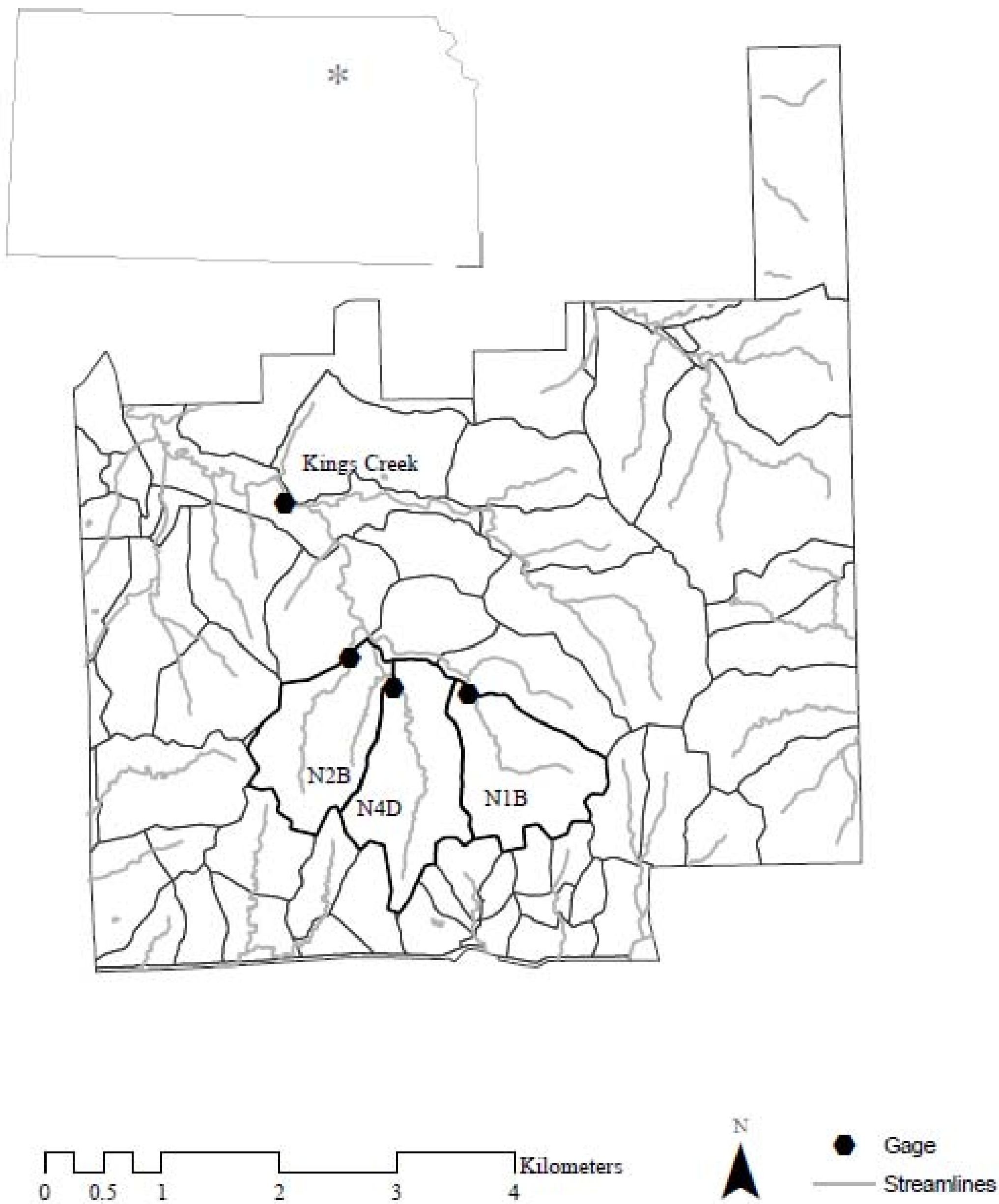

Figure 3.2Konza Prairie Biologic Station's (A) mean monthly precipitation (1987-2011), (B) mean monthly discharge (1987-2011), and (C) maximum monthly discharge (1987-2011).

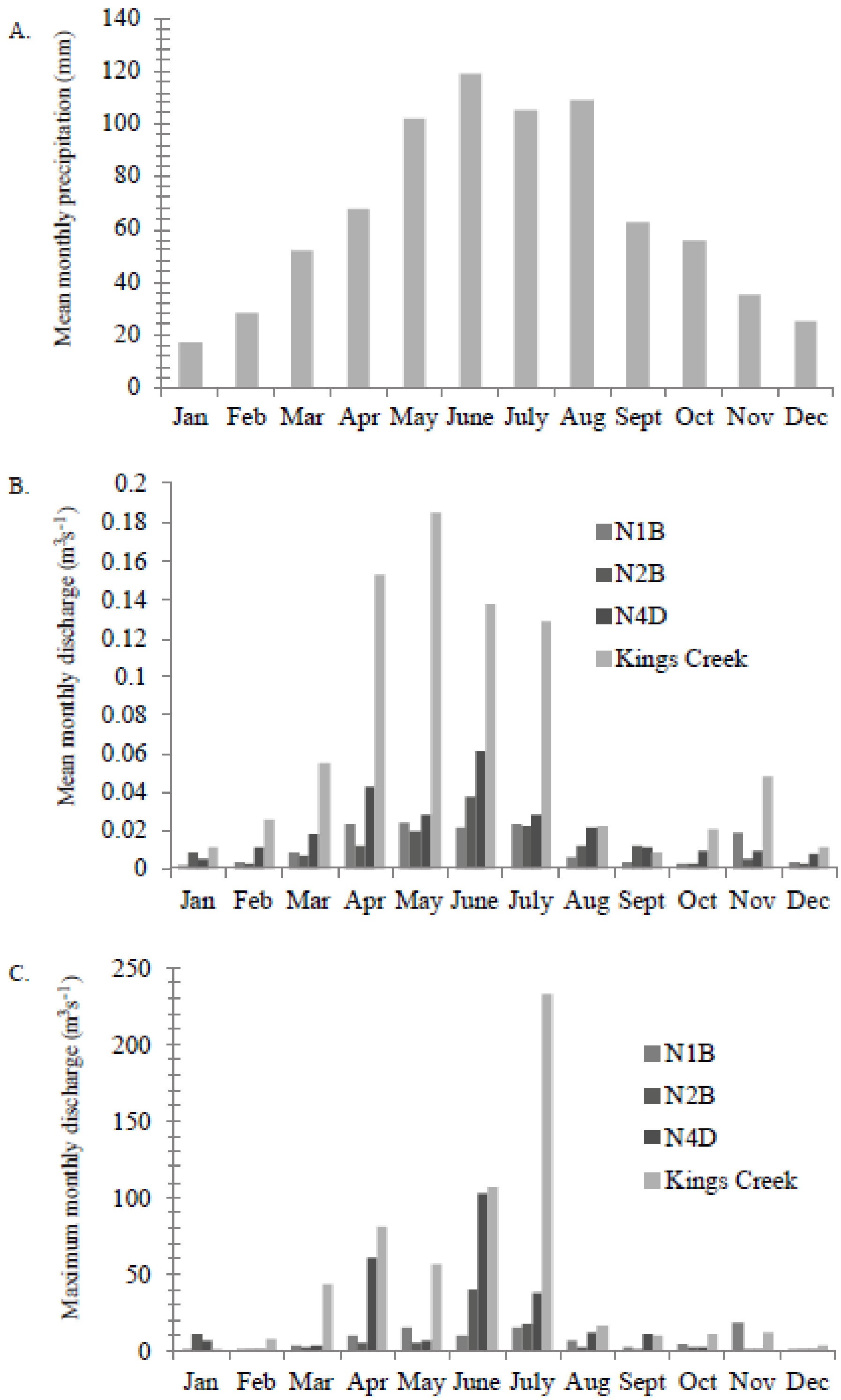

Figure 3.3 Conceptual diagram of the hydrologic system of Konza adapted from *Steward et al.*, [2011]. The grey arrows depict precipitation and the black arrows are scaled to the relative magnitude of different water flux pathways.

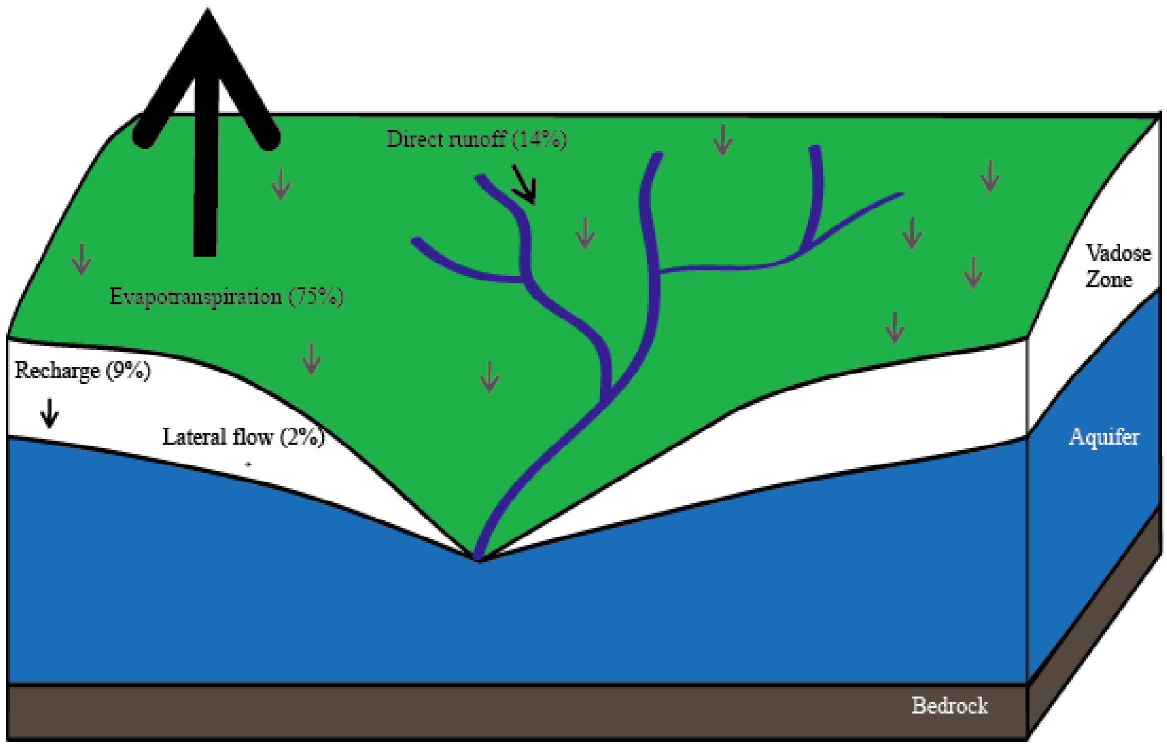

Figure 3.4 Konza Prairie Biologic Station's (A) mean annual discharge (1987-2011) and (B) peak annual discharge (1987-2011) as a function of total annual precipitation and (C) peak event discharge (1987-2011) as a function of the event's discharge.

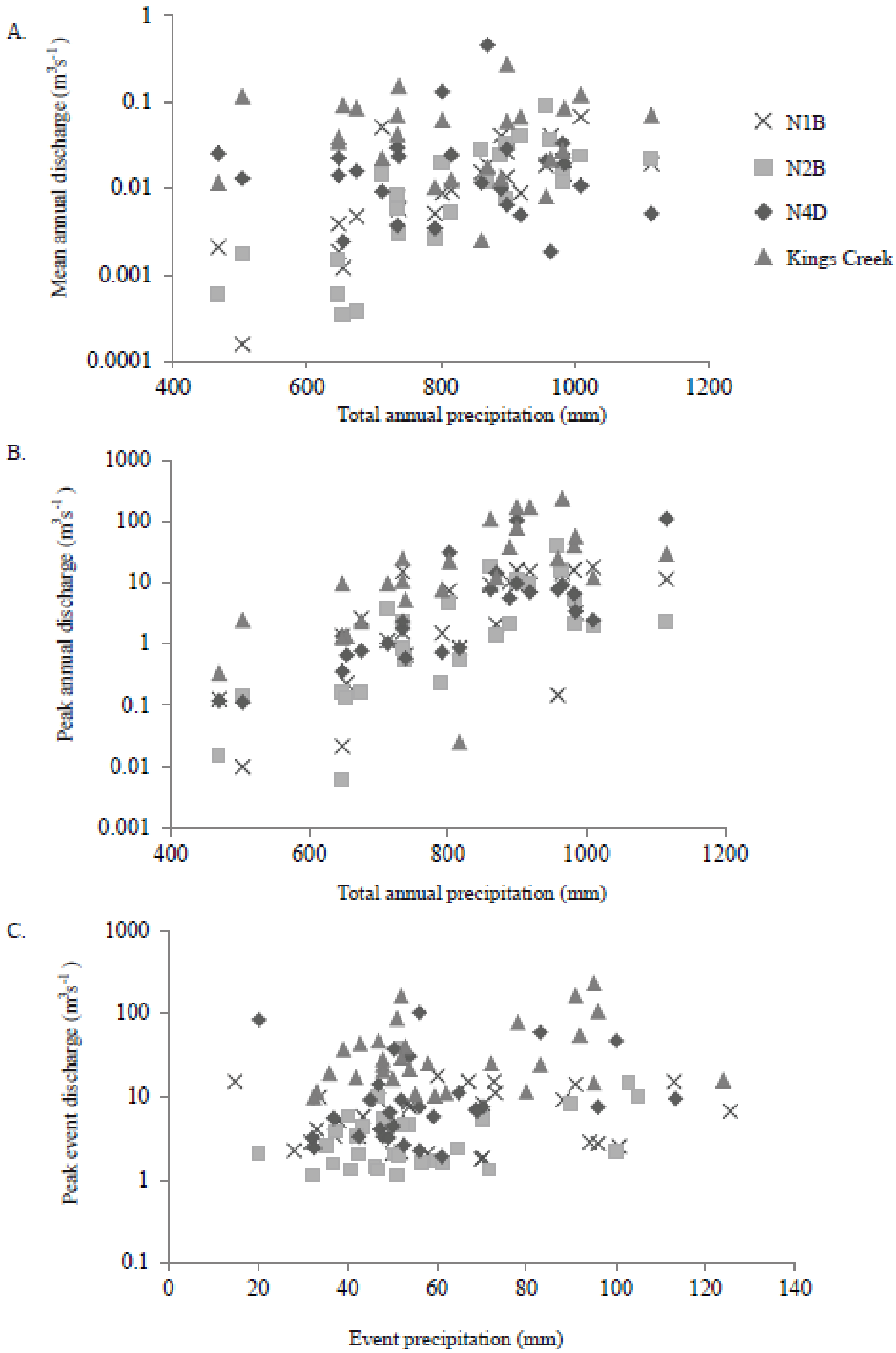

Figure 3.5 Timing of the 30 peak discharge events in each of the study gages during the period of record (1987-2011).

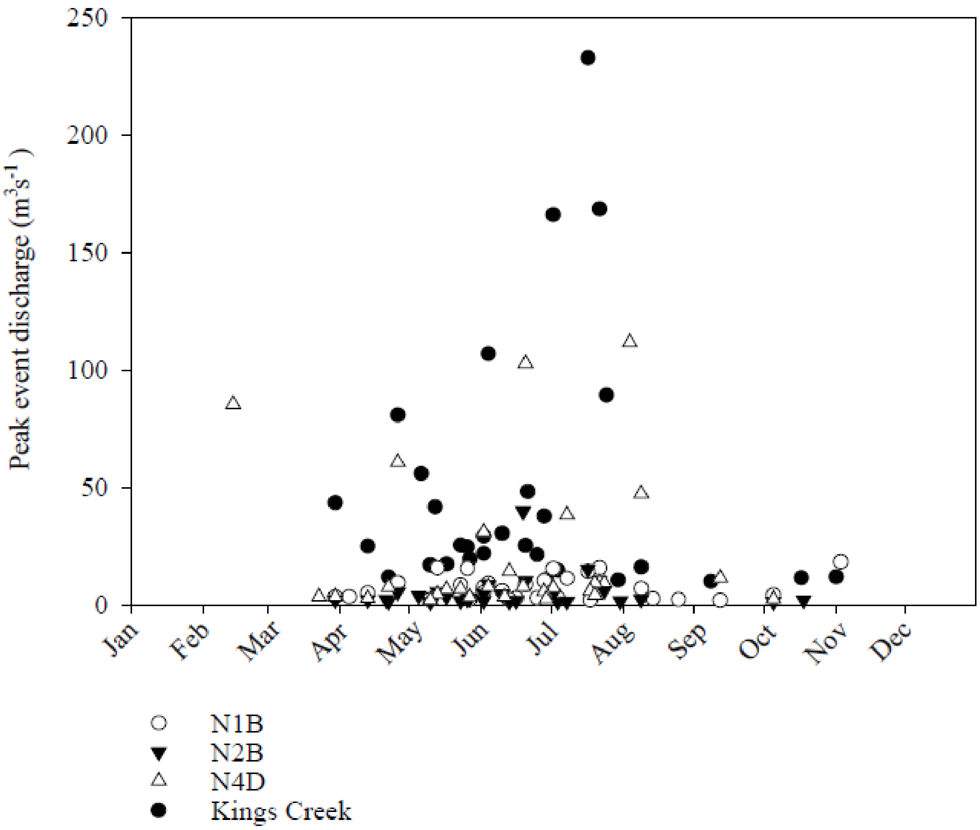

Figure 3.6 Double mass curves for total annual (A) streamflow and precipitation at Konza and (B) streamflow in the headwaters and Kings Creek. Each data point represents one year of record, beginning in 1987 at the origin and ending in 2011.

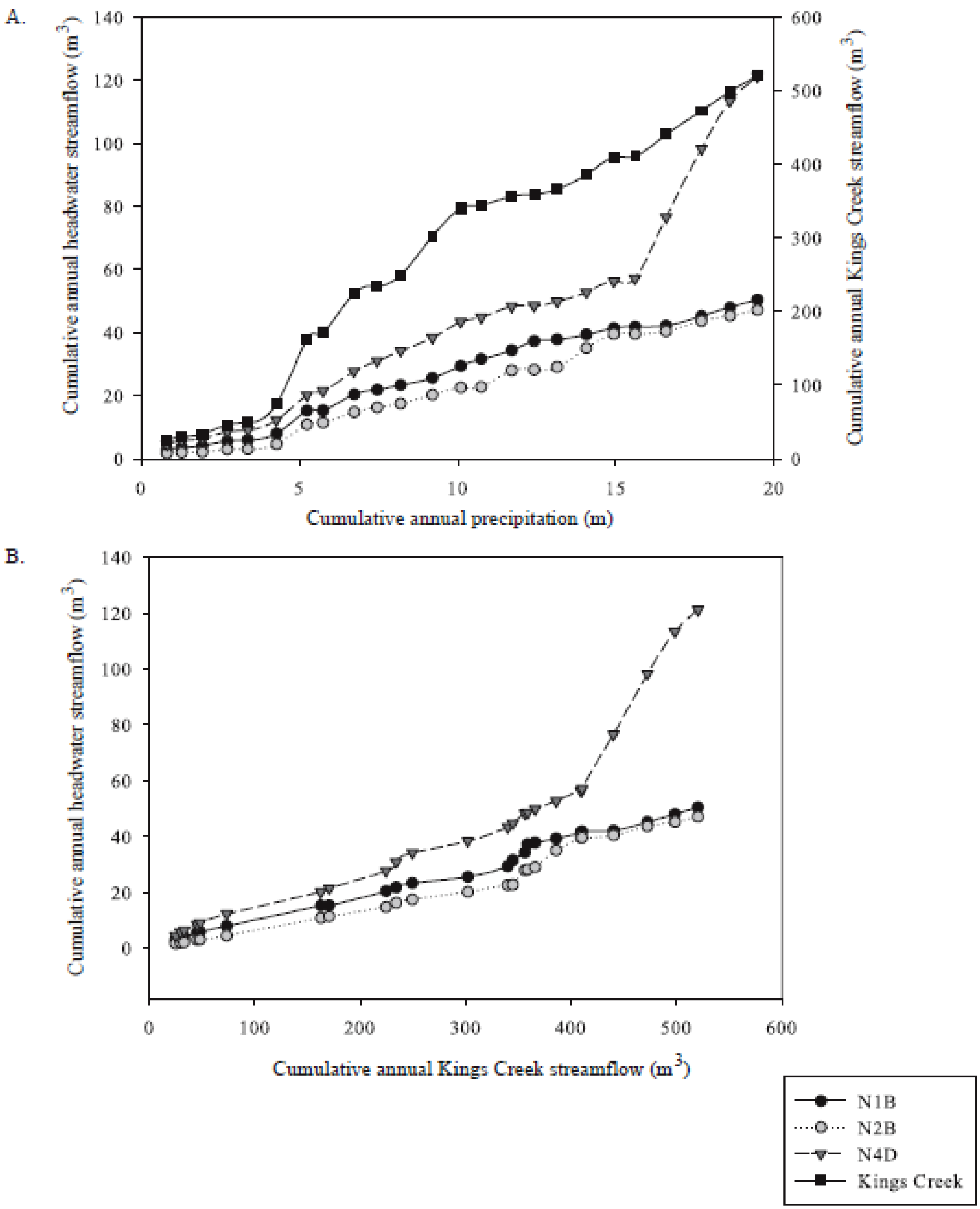

Figure 3.7 Standardized departure analyses of stream flow at Konza.

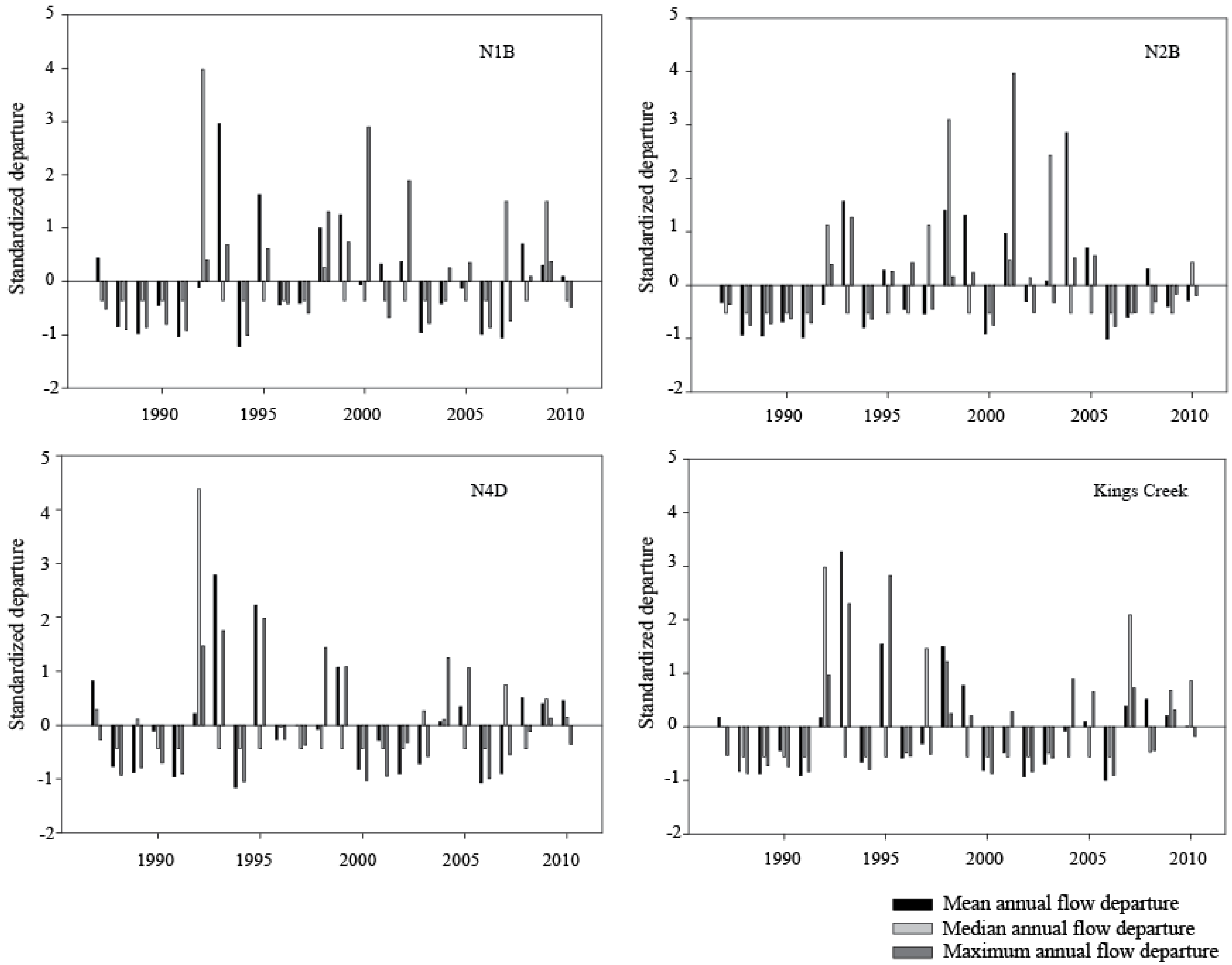

Table 3.1 Konza watershed descriptions

	Area (ha)	Burn frequency
Kings Creek	259	--
N01B	118.8	Annual
N02B	120.7	Biannually
N04D	135.5	4- years

Table 3.2 Average (standard deviation), maximum, and minimum number of zero-flow days for the number of zero-flow days and zero-flow 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

Table 3.3 Correlation matrix of number of zero-flow days 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	-0.55	-0.75	-0.45	0.51
		0.0005	0.01	0.00003	0.03	0.01
Kings Creek		1	0.7	0.83	0.54	-0.65
			0.0001	0.000001	0.006	0.001
N01B			1	0.76	0.83	-0.52
				0.00002	0	0.01
N02B				1	0.62	-0.69
					0.001	0.0002
N04D					1	-0.43
						0.03
PDSI						1

Table 3.4 Correlation matrix of number 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

Table 3.5 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	0.0003
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 3.6 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 $y = a + bx$. SEb 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 3.7 Rankings of the top 30 peak discharge events at study gages with respect to Kings Creek where PPT is the total event precipitation and Q is the peak discharge seen at the gage.

N01B				N02B				N04D				Kings Creek			
Date	PPT (mm)	Q (m^3s^{-1})	Rank	Date	PPT (mm)	Q (m^3s^{-1})	Rank	Date	PPT (mm)	Q (m^3s^{-1})	Rank	Date	PPT (mm)	Q (m^3s^{-1})	Rank
11/3/1998	66	18.2	25	6/19/2001	58	39.8	15	8/4/2008	91	111.7	--	7/17/1993	95	232.8	1
5/13/1995	55	15.6	10	7/17/1993	95	15.0	1	6/20/2009	47	102.6	8	7/22/1992	91	168.5	2
7/22/1992	91	15.6	2	7/22/1992	91	10.2	2	2/15/2007	16	85.3	78	7/2/2004	52	165.9	3
5/26/1996	83	15.4	17	6/20/2009	47	10.1	8	4/26/2009	78	60.6	6	6/4/2005	96	106.8	4
7/2/2004	52	15.3	3	6/4/2005	96	8.4	4	8/9/2008	124	47.3	23	7/25/1993	51	89.2	5
7/17/1993	95	14.1	1	7/24/1993	51	5.9	5	7/8/2008	43	38.3		4/26/2009	78	80.7	6
7/8/2008	43	11.1	--	4/26/2009	78	5.4	6	6/2/2011	54	30.9	18	5/6/2007	92	55.8	7
6/28/1999	39	10.1	11	5/13/1995	55	5.3	10	6/13/2010	58	14.3	52	6/21/2009	47	48.1	8
4/26/2009	78	9.3	6	6/2/2011	54	4.7	18	9/12/2008	78	11.3	36	3/30/2007	43	43.3	9
6/4/2005	96	9.1	4	7/2/2004	52	4.6	3	7/22/1992	91	9.5	2	5/12/1995	53	41.6	10
6/20/2009	47	8.5	8	6/10/2005	52	4.4	12	7/24/1993	51	9.2	5	6/28/1999	39	37.7	11
5/23/1995	72	8.4	14	5/5/2002	43	3.8	31	7/20/2010	26	9.1	68	6/10/2005	52	30.3	12
6/2/2011	54	7.5	18	5/17/1995	42	3.4	21	6/4/2005	96	7.6	4	6/2/2008	48	29.2	13
8/9/2008	124	6.8	23	5/27/1995	36	2.5	20	6/19/2001	58	7.6	15	5/23/1995	72	25.3	14
6/10/2005	52	5.8	12	5/26/1996	83	2.3	17	4/22/2010	80	7.5	26	6/20/2001	58	25.2	15
6/2/2008	57	5.1	13	8/9/2008	124	2.2	23	7/2/2004	50	7.1	3	4/13/1999	48	24.9	16
4/13/1999	48	4.9	16	4/21/2001	19	2.1	46	5/23/1995	72	6.7	14	5/26/1996	83	24.6	17
10/5/1998	33	4.1	79	3/30/2007	43	2.1	9	5/17/1995	42	6.5	21	6/2/2011	54	21.7	18
4/5/1999	38	3.3	42	4/13/1999	48	2.0	16	7/18/2008	57	5.9	47	6/25/1995	48	21.2	19
3/30/2007	43	3.3	9	10/18/1998	62	1.9	27	6/28/1999	39	5.6	11	5/27/1995	36	19.4	20
6/16/2009	44	2.9	34	6/16/2009	44	1.7	34	5/13/1995	55	4.5	10	5/17/1995	42	17.2	21
6/25/1995	48	2.8	19	5/23/1995	72	1.6	14	7/20/2009	49	4.0	--	5/10/1993	50	16.9	22
7/4/1992	79	2.8	54	6/2/2008	57	1.6	13	3/23/2009	8	3.4	--	8/9/2008	124	15.9	23
8/14/2006	79	2.5	85	7/31/1998	59	1.6	29	3/30/2007	43	3.4	9	7/4/1993	95	14.6	24
5/27/1995	36	2.3	20	7/8/2008	43	1.4	--	6/11/2005	52	3.3	12	11/1/1998	33	11.8	25

8/25/2006	42	2.2	64	6/13/2010	58	1.3	52	5/27/1995	36	3.3	20	4/22/2010	80	11.8	26
5/10/1993	50	2.1	22	7/4/1993	95	1.3	24	4/13/1999	48	2.7	16	10/17/1998	62	11.4	27
6/13/2010	58	2.1	52	4/22/2010	80	1.3	26	10/5/1998	33	2.4	79	06/29/03	55	10.7	28
7/18/2008	57	1.9	47	5/10/1993	50	1.1	22	6/29/2003	55	2.3	28	7/30/1998	59.4	10.5	29
9/12/2008	78	1.8	36	10/5/1998	33	1.1	79	5/10/1993	50	1.9	22	9/8/1989	32.5	9.9	30

Table 3.8 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	0.23	0.43	0.41	0.04	1.14	0.30
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.

Chapter 4 - Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river

Abstract

Downstream trends in hydraulic geometry and substrate characteristics were investigated along a 200 km reach of the Ninnescah River in south central Kansas, USA. The Ninnescah River is a large sand-bed, perennial, braided river that is located in the Central Plains physiography and is a tributary of the Arkansas River. Hydraulic geometry characteristics were measured at 11 sites that include, slope, sinuosity, bankfull channel width, and bankfull channel depth. The Ninnescah River follows the predicted trends of a river's central tendency for slope decreasing downstream and depth and width increasing downstream. There are localized divergences in the central tendency, most notability downstream of one substantial confluence. Surface grain samples were taken from the top 10cm of the bed at five equally spaced points across a wetted cross-section within each of the 11 reaches. Sediment analyses demonstrate a significant trend in downstream fining of surface grain sizes (D_{90} and D_{50}). As the Ninnescah River approaches the Arkansas River there is a systematic change where the river deviates from the central tendencies as the Ninnescah River adjusts itself to meet the Arkansas River. Overall, results demonstrate that the Ninnescah River follows the expected trends longitudinally. Results of this study are the first of its kind we could find to assess the longitudinal hydraulic geometry and substrate characteristics of a large sand-bed river.

Introduction

The hydrology and geomorphology of alluvial river channels are dependent on the climatic and sedimentological regimes of contributing basins. Longitudinal profiles of rivers are representative of watershed evolution, geologic structure, and sedimentary dynamics of the basin [*Sinha and Parker*, 1996]. *Leopold and Maddock* [1953] were the first to use the term 'hydraulic geometry', which is based on the assumption that the geometric and hydraulic properties of a river adjust in response to increasing discharge. As was originally proposed with the theory of hydraulic geometry, with increasing discharge there is expected to be a regular downstream trend that develops in channel characteristics, including width, depth, velocity, and friction, of river channels that formed in alluvium and are readily adjustable to changes in discharge. At a single cross-section, changes in the hydraulic geometry are a result of many processes that occur at different time scales and different flows [*Schumm and Lichty,* 1963; *Wolman and Gerson*, 1978; *Moody et al.*, 1999]. The geomorphic parameters driving the longitudinal patterns of hydraulic geometry include alternating degrees of channel confinement, tributary inputs, colluvial inputs (e.g. landslides), differential substrate erodibility, strong local controls on sediment supply, and spatial gradients and discontinutities imposed by Quaternary tectonics and landscape evolution [*Marston et al.,*1997; *Brardinoni and Hassan*, 2007]. Longitudinal changes in hydrologic regime can also drive discontinuity as, for example, a river may flow from a mesic to an arid climate zone and become an influent river. Empirically, it has been demonstrated that hydraulic geometry partially depends on bank strength, which is influenced by the cohensiveness of sediment and vegetation [*Leopold and Maddock*, 1953; *Parker*, 1979; *Hey and Thorne*, 1986; *Soar and Thorne*, 2001; *Xu*, 2002; *Church*, 2006*; Eaton and Church*, 2007; *Parker et al.,* 2007].

The longitudinal geomorphic regimes anabranching [e.g. *Tabata and Hickin*, 2003; *Latrubesse*, 2008; *Kemp*, 2010; *Pietsch and Nanson*, 2011], desert [e.g. *Merritt and Wohl,* 2003; Ralph *and Hesse*, 2010], and mountain rivers [e.g. *Lee and Ferguson*, 2002; *Brummer and Montgomery,* 2003; *Comiti et al.,* 2007; *David et al.,* 2010; *Green et al.,* In Press] have been well documented. In anabranching systems there is a trend of diminishing channel dimensions that is attributed to storage of waters in lakes, floodwaters, lagoons, and through transmission losses during overbank flow events [*Kemp*, 2010]. Desert systems, where channels breakdown in to smaller distributaries, show a decrease in channel dimensions especially channel width and area [*Ralph and Hesse*, 2010]. Bankfull channel widths increase as contributing areas increase for mountain systems [*Brummer and Montgomery,* 2003; *Green et al.,* In Press]. The varying trends in downstream hydraulic geometry of different river types are a result of differences in exterior and interior controls on drainage, differing rates of transmission loss, the presence or absence of riparian vegetation, and the differences in precipitation regimes [*Tooth*, 2000]. Hydraulic geometry has been explored extensively but remains a core technique in understanding river systems [*Knighton,* 1998] and is often employed as an environmental and engineering design tool (e.g. environmental flows analysis) [*Reid et al.,* 2010]. While the downstream trends in hydraulic geometry of rivers are generally well understood, relatively few studies have investigated the downstream patterns in hydraulic geometry of large sand-bed rivers.

Planform patterns are known to change, or metamorphose [*Schuum,* 1985], longitudinally and these transitions are important features within the riverscape. Changes in flow strength and sediment feed rate are the two classical, yet still debated, explanations for planform metamorphosis [*Kleinhans*, 2010]. Sand-bed rivers transition from meandering to braided planforms longitudinally as a function of stream power, which gradually increases in the downstream direction [*Kleinhans*, 2010]. No known 'hard' thresholds exist for the transition of meandering to braided planforms and it is widely accepted that this transition is gradual. Sand-bed channels are perhaps the least understood of the channel types, and there are many scales of bedforms that may coexist including ripples, bedload sheets, dunes, and lobes [*Montgomery and Buffington*, 1997]. Sand-bed rivers have live beds [*Henderson*, 1963] that are continuously transporting sediment at most stages, and as such they are effectively transport limited. Much of the floodplain sediments of sand-bed rivers are formed from noncohesive easily eroded banks, and fluctuations in channel width are large when compared to fluctuations in bed elevation [*Schumm and Lichty*, 1963; *Friedman et al.* 1996]. In sand-bed channels the large volumes of sand transport promote the formation of wider channels [*Osterkamp*, 1980].

Rivers are widely acknowledged to demonstrate downstream fining of bedload. Numerous studies have examined the downstream fining of sediments but most were based on data from small, gravel-bed streams over a length less than 200 km [*Church and Kellerhals*, 1978; *Ferguson et al.,* 1996; *Rice*, 1998; *Constantine et al.*, 2003; *Frings*, 2008]. Graphic mean grain sizes in anabranching streams show significant trends on decreasing particle sizes longitudinally [*Kemp*, 2010]. Mountain streams show an initial coarsening of mean grain size until a threshold of drainage area is reached [*Brummer and Montgomery,* 2003], followed by fining of sediment, which has been extensively documented [e.g. *Brummer and Montgomery,* 2003; *Green et al.,* In Press]. Sand-bed rivers often experience significant fining of sediment longitudinally, where tributary inputs do not significantly punctuate this fining trend [*Benda et al.,* 2004; *Frings,* 2008]. Lateral sediment sources, if sufficiently large or dissimilar enough, introduce material that has characteristics that were established independently of processes operating longitudinally in the main channel [*Rice and Church*, 1998]. Understanding these dynamics is critical because as sand-bed rivers where grain sizes transition from very coarse to fine sand and silt changes the dominate mode of sediment transport, bedform dimensions, and the size of over bank deposits [*Frings*, 2008].

Due to extreme climatic variability, the rivers of the Great Plains are some of the most dynamic in the world [*Matthews et al.,* 2005*; Dort,* 2009]. Rivers of the Great Plains are of three basic types; large rivers that originate in the Rocky Mountains, streams that originate on the prairie, and intermittent and ephemeral channels that originate on the prairie [*Wohl*, 2009], all of which may be straight or sinuous [*Schumm*, 1963]. During the historical period, large rivers of the Great Plains were characterized by very wide (1-2 km), shallow channels that were largely devoid of woody vegetation [*Williams,* 1978]. Historical studies in the region have demonstrated changes in channel geometry attributed to variable flow conditions, with sometimesdrastic changes associated with large floods [*Smith*, 1940; *Schumm and Lichty*, 1963; *Friedman et al.*, 1996]. While the 1930s were characterized by a prolonged drought in the Great Plains and an overall decrease in mean annual discharge, the decade was also punctuated by several extreme flood events [*Schumm*, 2005]. As a result of changing precipitation regimes coupled with irrigation have affected river of the Great Plains as exemplified by the Platte River where there was substantial channel narrowing and a reversal in hydraulic geometry whereby channel width decreased in the downstream direction [*Schumm*, 2005]. Channel sinuosity and migration patterns have also been altered by anthropogenic alterations within Great Plains watersheds [*Friedman et al.,* 1998].

Anthropogenic disturbances within Great Plains catchments are especially disruptive because Great Plains rivers are extremely responsive to altered discharge and sediment supply [*Montgomery and Buffington*, 1997]. Many rivers of the Great Plains have been transformed from sparsely wooded with wide channels to more modern configurations with extensive riparian woodlands and much narrower channels [*Frith,* 1974; *Williams,* 1978; *Currier,* 1982; *Currier et al,*. 1985; *Martin and Johnson, 1987*; *Sidle et al*., 1989; *VanLooy and Martin*, 2005]. While many rivers of the Great Plains have been substantially hydrologically and geomorphically altered by the expansion of woodlands there have also been concurrent changing land use patterns including pumping of groundwater, irrigated agriculture, intense grazing, extirpation of bison, and intensive road development [*Currier,* 1982; *Fausch and Bestgen*, 1997; *Falke and Gido*, 2006]. Great Plains rivers have also experienced widespread and dramatic changes to their hydrologic regimes resulting from construction of reservoirs that fragment riverscapes, retain sediments, and disconnect longitudinal hydrologic connectivity [*Pringle*, 2003; *Costigan and Daniels*, 2012].

Although previous studies of longitudinal channel and sedimentary characteristics have documented a variety of channel forms and environments. Large sand-bed rivers drain approximately half the global continental land [*Ashworth and Lewin*, 2012] but are poorly represented in the literature, which may be attributable to difficulties in access of large, sandy, lowland rivers [*Kemp*, 2012]. General circulation models of the Great Plains predict that in the future there will be more frequent, intense precipitation events with longer intervening dry periods [*Knapp et al.,* 2002; *Milly et al*., 2005]. As has been demonstrated on the Platte River [*Schumm*, 2005] with a change in the hydrology of a system there is likely to be widespread changes to the longitudinal channel and sediment characteristics. An analysis of the naturally occurring longitudinal geomorphic channel characteristics will provide valuable insight in to how these systems may be conserved in the future.

Previous studies have documented channel changes to Great Plains rivers through time, and more specifically with respect to channel response of riparian woodland expansion [e.g. *Frith,* 1974; *Williams,* 1978; *Currier,* 1982; *Currier et al.,* 1985; *Martin and Johnson, 1987*; *Sidle et al*., 1989; *VanLooy and Martin*, 2005] and changing precipitation regimes [*Smith*, 1940; *Schumm and Lichty*, 1963; *Schumm,* 2005]. Bankfull channel width and depth of mountain and lowland river systems are known to increase longitudinally associated with increases in contributing watershed area as well as additions of tributaries [*Leopold et al.,* 1964]. To our knowledge this is the first systematic longitudinal spatial analysis of the channel and substrate characteristics of a large Great Plains river.

This study examines the modern day longitudinal changes in hydraulic geometry and sedimentary characteristics along a 200 km reach of the Ninnescah River, a large, perennial, sand-bed river located in south central Kansas. We present field measurements supplemented with geospatial data from 11 study sites to document the longitudinal changes in hydraulic geometry and substrate. The objectives of this research are to investigate: (a) the longitudinal patterns in hydraulic geometry of a large sand-bed river; (b) where any abrupt changes in the pattern of hydraulic geometry can be detected; (c) any downstream grain size fining; (d) whether any abrupt changes in grain size (e.g. gravel-sand transitions and tributary inputs) can be observed. We expected the geomorphology of the Ninnescah River to follow the typical longitudinal progression where bankfull width and depth, bankfull width to depth ratio, and the bankfull area increase in the downstream direction. In addition, we expected mean grain sizes would systematically decrease in the downstream direction. We expected sites that are located close to significant sources of lateral sediment and water (e.g. geomorphically significant tributaries) would have punctuated sediment coarsening and channel widening and deepening.

Study System

The Ninnescah River originates on the prairie and is located in south-central Kansas, where the North and South Forks join to form the Ninnescah River proper (Figure 4.1). The river flows in an east-southeast direction through tall grass prairie in the High Plains, Red Hills, and Wellington Lowland physiographies of the Central Plains [*Mandel*, 2008]. The High Plains physiography is characterized by loess deposits of 3-5 m thick that overlie thick deposits of Pleistocene and/or Pliocene alluvium [*Mandel*, 2008]. The Red Hills region is characterized by red Permian-aged shale, sandstone, and siltstone [*Swineford*, 1955] and the Wellington Lowlands is characterized by Permian-aged sandstone and siltstone as well as salt deposits and gypsum. The Ninnescah River is a tributary of the Arkansas River, and the lower reach of the Ninnescah River intersects a broad, flat, alluvial plain that is underlain by thick deposits of Pleistocene sands and gravel [*Frye and Leonard*, 1952]. The Ninnescah drains primarily sandy areas and as a result channels are typically wide, shallow, and straight (*Schumm,* 2005; Figure 4.2). The upper reaches of the Ninnescah River (above site 4) are within the High Plains Aquifer (Figure 4.1), which in that region has experienced no significant change (-10%) in groundwater levels in recorded history [*Sophocleous*, 2000].

The Great Plains is the physiographic region of the US that has received the least amount of scientific attention [*Matthews*, 1988]. Rivers of the Great Plains are characterized by large floods interspersed within periods of prolonged droughts [*Dodds et al.,* 2004]. The annual hydrograph of the Ninnescah River is dominated by higher flows in the winter and low flows in the summer, although streamflow is partly regulated by Cheney Dam on the North Fork. There are three US Geological Survey (USGS) gages along the study reach, which measure increases in mean annual discharge from the headwaters to the mouth (0.48, 5.91, and 15.0 m^3s^{-1}; Table 4.1; see Figure 4.1 for location of USGS gages).

Morphometric parameters were measured within 11 study reaches located along 200 river kilometers of the Ninnescah River (Figure 4.1). The South Fork is the dominate fork and there are seven study reaches on this fork (1-7) and four on the Ninnescah River proper (8-11). Direct anthropogenic alterations to the Ninnescah River basin include: Cheney Reservoir (constructed in 1964) that is located on the North Fork of the Ninnescah River; Site 1 is impacted by a fishing lake and weir dam upstream, where water is diverted out of the river and into the lake and returned via an epilimnetic release; Site 4 is impacted by small diversion dam and associated reservoir; and Site 5 is impacted by a seasonal dam that is constructed annually.

Methods

Data Collection

Data collection was completed using field surveys supplemented with geographic information systems (GIS) based topographic and aerial image analysis of the study system. Channel characteristics measured in the field included local bed slope (S; m/m), bankfull width (B; m), and bankfull depth (Y; m). Bankfull depth and width were surveyed in the field at ten evenly spaced cross-sections within each study reach, and each reach was a length equal to ten channel widths, a scale over which reach stream morphology and processes are related [*Montgomery and Buffington*, 1997]. Sinuosity was extracted from aerial photographs flown in 2010 both within field sampling reaches and throughout the study system. The longitudinal profile of the study reach of the Ninnescah River was determined from digital 1:24,000 topographic maps. Using topographic maps for longitudinal profiles introduces only minor error when applied in plains environments [*Kemp*, 2010]. When possible, large meander bends were avoided and relatively undisturbed reaches (i.e. away from in-channel anthropogenic alterations) were selected for morphologic and sedimentary analyses.

To study the longitudinal variations in sediment sizes care must be taken to sample consistently. In gravel-bed rivers there is substantial local sorting [*Bluck*, 1982] and standard methods of grain sizes have been developed [*Wolman,* 1954] and thoroughly analyzed. Sand-bed channels have live beds [*Henderson*, 1963] that are continuously transporting sediment at most stages and have many scales of bedforms that may coexist including ripples, bedload sheets, dunes, and lobes [*Montgomery and Buffington*, 1997]. As with gravel-bed channels there are local depositional variations in sand-beds that may confound the apparent longitudinal patterns of grain sizes.

In an attempt to reduce any sampling error associated with the multiple bedforms present in sand-bed channels five samples were taken to determine an integrated, cross-sectional, mean grain size distribution. Examples of previous field sampling of sand-bed sediments include two grab samples of sand-bed material that were from near the channel margins [*Kemp*, 2010] and three grab samples where two were taken from the channel margins and one from the thalweg [*Lou et al*., 2012]. For this analysis, five samples along the wetted channel were taken to reduce any error associated with bedforms. The sample points included the two channel margins, thalweg, and two additional samples at the midpoint between the channel margins and thalweg. The materials from the top 10cm of the bed were collected at each sample point. Particle size analyses were performed using standard dry-sieve analysis methods because the majority of the samples had greater than 84% of their weight in the sand fraction. Prior to sieving, each sample was oven dried for 24 hours, cooled, and gently disaggregated. Large organic items were manually removed from the sample and discarded. Mean grain size, sorting, skewness, and kurtosis were calculated using the *Folk and Ward* [1957] formulae following *Blott and Pye* [2001].

Data Analysis

Analyses focus on general relations between longitudinal position and morphological and sedimentary characteristics of a large sand bedded river. Correlations between response variables (sinuosity, width, depth, width to depth ratio, sediment sizes) to location downstream from site 1 were determined with regression analyses. Following *Brummer and Montgomery* [2003] and *Kemp* [2010], regression analyses are fitted exponential relations where response variables were log transformed to meet the assumption of equal variance in the residuals. Principal component analyses (PCA), based on a correlation matrix of response variables, is used to summarize correlations between network location and stream attributes.

Results

Channel morphology

Channel structural parameters

The longitudinal profile of the Ninnescah River is concave (Figure 4.3a). Concavity of the longitudinal profile is maintained by decreasing bed slope through the system (Figure 4.3b). Bed slope and channel sinuosity (Fig 3c) of the upper three reaches (1-3) are much higher than the lower reaches of the Ninnescah basin. Overall, the sinuosity of the Ninnescah River system was 1.15. Reaches 1-3 have a predominately meandering planform configuration (sinuosity > 1.35) and the rest of the system, with the exception of site 11, is much less steep and less sinuous, resulting in a predominately straight braided planform configuration. Regression analysis of channel sinuosity is marginally significant ($F_{2,9}$= 4.9, p = 0.054, r^2=0.35) with sinuosity decreasing downstream (Table 4.2).

Bankfull channel parameters

The Ninnescah River conforms to the expected longitudinal morphologic progression, where bankfull channel width and depth increase. Bankfull channel width of the Ninnescah basin increases five-fold from 15.7 m at the upper most site (1) to 78 m at the lower most site (11) (Figure 4.3d), yet the widest bankfull widths in the system are the intermediate reaches (sites 7-10) where bankfull width is ~100m. Site 1 had a mean bankfull depth of 1.57 m and the site 11 had a mean bankfull depth of 1.74 (Figure 4.3e). Site 3 had many exposed, incised banks and there was a disproportionally large increase in bankfull depth at this site (Figure 4.4). Sites 9 and 10 had the highest bankfull depth of approximately 2m. The slope of the overall regression equation for bankfull depth was insignificant ($F_{2,9}$ =0.26, p = 0.62, r^2= 0.03; Table 4.2). Regression analyses demonstrated a significant ($F_{2,9}$ =108.9, p < 0.001, r^2=0.92) downstream trend in increasing channel width.

Bankfull width to depth ratios and area (Figure 4.3f, 4.3g) follow a similar pattern of bankfull depth and width of increasing longitudinally, with the intermediate reaches having highest values. As the drainage density of the river increases longitudinally, width to depth ratios increase significantly ($F_{2,9}$=64.3, p<0.0001, r^2= 0.88). A marked increase in width to depth ratios was measured coincident with the change in planform configuration from meandering to braided.

Sediment Characteristics

Grain size distributions for 50 of the 55 samples were unimodal. The 5 bimodal samples were obtained from site 1 where the second mode is a minor secondary peak of small gravel particles in an otherwise predominately sand sample. Since only one site had a small bimodal grain size distribution, aggregate analysis of grain size distribution employed standard parameters such as mean, median, sorting, skewness, and kurtosis. Overall, the sediments are predominately moderately sorted, coarsely skewed or symmetrical, and mesokurtic or leptokurtic in nature (Table 4.3; Figure 4.5).

The sorting coefficients ranged from 1.6 to 3.6, indicating a narrow range of moderately well to poorly sorted (Figure 4.5; Table 4.3). The upper two reaches of the study system are poorly sorted. Site 1 has the highest sorting coefficient but also has the lowest skewness and kurtosis coefficients. Site 5, located downstream of an ephemeral run-of-river dam is also poorly sorted. Between site 5 and 6 a systematic decrease in mean grain size, median grain size, sorting, skewedness, and kurtosis occurred. Between sites 7 and 8, where the North Fork joins the South Fork, a slight increase in the sorting coefficient, skewness (from symmetrical to coarsely skewed), and in kurtosis occurred.

The texture of sediment samples were described using the size scale of *Blott and Pye* [2001] (Figure 4.6). Site 1 was the only site with gravel as the dominate particle size fraction. Texture analysis demonstrated that the upper portions of the watershed had the highest proportions of sediment in the gravel size fractions and the further downstream the more sand fraction was present. Between sites 7 and 8 the North Fork joins the South Fork, forming the Ninnescah River proper and contributed to an increase in larger particles at site 8. The longitudinal trend is a decrease in the gravel fraction and increase in sand fractions, and site 11 had a very small percentage of gravel within the samples.

Trends in the percentiles of the substrate sediment indicate that the bed material of the Ninnescah River fines systematically downstream (Figure 4.7). Regression analysis indicated the surface D_{90} and D_{50} were modeled well (Table 4.2), but the relationship for D_{10} was not strong ($F_{2,9}$= 2.6, p=0.14, r^2=0.23). There are significant trends in downstream fining of D_{90} ($F_{2,3}$=11.7, p=0.008, r^2=0.57) and D_{50} ($F_{2,3}$=7.0, p=0.027, r^2=0.44). The slope of the regression for D_{90} are an order of magnitude steeper than D_{50} and D_{10}, with D_{50} slope steeper than D_{10}. Downstream fining of surface D_{50} is especially evident in the upper reaches of the system where D_{50} between site 1 and 3 decreased four- fold (2100 μm to 500 μm). Between sites 3 and 10 there was a slight fining trend in D_{50}. As the Ninnescah River approaches the Arkansas River (below site 11) D_{50} abruptly increases by 300μm between sites 10 and 11. Overall, measurements of surface D_{50} in the Ninnescah River range from 427 to 2133μm.

Overall assessment

The first two axes of the principal component analysis explained 85.6% of the variation in the response variables across the 11 sites (PCA axis 1= 68.9, axis 2=16.7%; Table 4.4). Longitudinal patterns along PC1 are strong for sites 1-7 and PC2 for sites 8-11 (Figure 4.8). Component one is characterized by similar loading magnitudes of all parameters, both positive and negative, with the exception of bankfull depth, which loads weakest along this principal component. Component two is characterized by highly positive (0.507) loading of D_{10} and highly negative loading of bankfull depth (-0.612). Principal component axis 3 explained 9% of the variation in the dataset and is characterized by highly negative loadings of bankfull depth (-0.716).

Discussion

This study characterizes the longitudinal patterns of channel hydraulic geometry and substrate of a large alluvial sand-bed river located in South-central Kansas. Our results complement similar previous studies of hydraulic geometry from other channel types that demonstrated channel width [e.g. *Montgomery and Gran*, 2001; *Brummer and Montgomery,* 2003] and depth [e.g. *Mueller and Pitlick*, 2005; *Splinter et al.,* 2010; *Green et al.,* In Press] increasing longitudinally. There are many examples where channel widths and depths decrease downstream including channel break down [*Ralph and Hesse,* 2010] and rivers transitioning from humid to semi-arid environments [*Kemp*, 2010].

While results of this study demonstrate that bankfull channel width increases in the downstream direction, there are no significant changes in bankfull channel depth in the downstream direction. *Wolman and Gerson* [1978] note that in dry land rivers, channel width approached a fairly universal asymptotical value of 100-200 m once the catchment area exceeds 50km^2, which we also observed in our study of the Ninnescah River. The finding that width increases significantly more than depth is consistent with previous studies that have attributed this to mean depth and mean velocity remaining constant throughout the system [*Ashmore and Sauks,* 2006; *Bertoldi et al.,* 2008] where the increases in discharge are accommodated by an increase in channel width. Multi-thread channels are characterized by very shallow cross-sections, and width increases faster than depth by activation of new threads. In addition, much of the floodplain sediments of the Ninnescah River form noncohesive, easily eroded banks and previous studies have demonstrated fluctuations in channel width are large when compared to fluctuations in bed elevation for channels with noncohesive banks [*Schumm and Lichty*, 1963; *Friedman et al.* 1996]. The low width to depth ratios in the upper portions of the watershed are a relic of low discharge in this region, resulting in narrow, shallow channels [*Splinter et al.,* 2010].

Where the North Fork joins the South Fork a slight change in bankfull channel width and a large increase in channel depth as the stream is adjusting to the new sediment and water loads from the tributary were documented. The North Fork of the Ninnescah River has an impoundment on it, which is likely the cause of the changes in channel width and depth documented at site 8. *Hackney and Carling* [2011] in their analysis found that overall there was a net narrowing of the channel downstream of confluences by 1%; however, there were sites with large amounts of narrowing and widening that is also confounded by large variations in the geology of the study area. Channels downstream of confluences have been shown to narrow 15% following impoundment with in the tributary network [*Curtis et al.,* 2010]. On the Ninnescah River we only see a slight change in channel width so the additional discharge from the North Fork could be accommodated by a local increase in channel depth rather than by widening, which has been seen elsewhere [e.g. *Lane,* 1955]. Results of this study demonstrate that on the Ninnescah River increased channel width plays a more significant role in maintaining channel conveyance than channel depth when there are lateral inputs of water from tributaries, which has been well documented [e.g. *Knighton*, 1987; *Best*, 1988; *Hackney and Carling*, 2011].

Due to the systematic decreasing of slope to the east, we expected to have finer-grained sediment in the lower reaches of the study. Results of sediment sampling reveal a grain size fining that is especially prevalent in the upper portions of the study system, between site 1 and 3. One of the most expressive forms of downstream fining is the gravel-sand transition [e.g., *Sambrook and Ferguson,* 1995], which occurs between 1 and 2 on the Ninnescah River. Punctuated trends in downstream fining, as seen on the Ninnescah, are often associated with discontinuities in slope [*Ferguson et al.,* 2006]. At the gravel-sand transition rivers reduce their slope resulting in decreases in bed shear stresses, which contribute to the abruptness of the gravel-sand transitions [*Frings*, 2011], although the gravel-sand transition is not always associated with a change in slope [*Shaw and Kellerhals,* 1982]. Between sites 1 and 3 a dramatic downstream decrease in slope developed that resulted in a decrease in shear stresses, which can result in coarser grains not becoming entrained and a decreased transport capacity of the system

[*Frings,* 2008]. Abrupt changes in longitudinal trends of slope represent critical transition points where there are departures from the central tendencies of a river [*Reinfields et al.,* 2004]. The slope discontinuity seen in the Ninnescah River is concurrent with the observed gravel-sand transition and not coincident with any external control such as variable geology or external sediment inputs that can cause changes in slope [e.g. *Ferguson,* 2003].

In addition to the gravel-sand transition observed in the upper portion of the watershed, there are significant trends in downstream fining of sediment throughout the Ninnescah River system. The two mechanisms for downstream fining are abrasion and selective transport of sediment. Abrasion of sediment leads to stable fining patterns and selective transport preferentially entrains finer grains earlier than coarser grains. In rivers with a concave longitudinal profile, like the Ninnescah, selective transport results in stable downstream fining, which causes it to be difficult to ascertain the relative importance of abrasion and selective transport [*Frings*, 2008].

Tributary junctions are locations in the network where channel and valley morphology change and where there is deviation from the central tendency expected under the Network Dynamics Hypothesis [*Benda et al.,* 2004]. The North Fork of the Ninnescah is the dominate tributary of the system and has a large impoundment on the river, which is likely the cause of the increase in mean grain size immediately downstream of the junction [*Kondolf*, 1997]. The downstream impact of dams on sediment grain size is often very significant (e.g., *Heath and Plater,* 2010). Geomorphically significant tributaries [*Benda et al*., 2004] are the most common source of grain-size discontinuities in gravel bedded rivers, typically resulting in an increase in the man grain size [*Frings*, 2008]. In sand bedded rivers that have large floodplains, tributary channels typically have the same gradient as the main channels, results in these rivers not having a stark discontinuity in the mean grain size [*Frings*, 2008]. It is generally believed that tributary inputs do not affect mean grain size distributions on sand-bed rivers because of network geometry, where the upper reaches have more tributary inputs than lower reaches [*Benda et al.,* 2004; *Frings*, 2008]. Consistent with previous research, our results demonstrate that the tributary sediments dominate the sediment distribution downstream of the confluence that is likely attributed to the impoundment on the North Fork of the Ninnescah [*Graf*, 1980; *Curtis et al.,* 2010]

Playfair [1802] noted that tributary streams join the principal stream at the level of the principal valley and that the tributary and main stream must be lowering at the same average rate in the vicinity of their junction. The Ninnescah River, in order to be accordant to Playfair's law, must adjust itself to meet the Arkansas River. The coupling of the Arkansas River and Ninnescah River is a control on the geomorphic function of the Ninnescah River. Results demonstrate at the furthest downstream site on the Ninnescah there is a marked increase, between site 10 and 11, in mean channel slope of 24%, increase in channel sinuosity by an order of magnitude, and decreases in channel width and depth by 20% and 14%, respectively. The Arkansas River is believed to have once followed the current course of the Ninnescah River [*Schoewe*, 1949]. Deflection northward of the Arkansas River was caused by gradual uplift of a large structure whose axis extended in a North-South direction and as uplift progressed the Arkansas River was forced to migrate northward around the anticlinal structure forming the Great Bend of the Arkansas River. Between sites 10 and 11 the Ninnescah River approaches the Arkansas, entering the Arkansas River Lowlands that is coincident with the termination of the anticlinal structure that forced the Arkansas River northward.

Conclusions

The present study presents results from field, lab, and geospatial analyses for the longitudinal linkages between reach-scale morphology and sedimentary characteristics of a large sand-bed river. Results demonstrate that channel structural components follow the typical expected hydraulic patterns longitudinally, with significant trends in increases in bankfull channel width and width to depth ratio, and a significant trend on decreasing channel sinuosity. Bankfull channel width does not have a significant longitudinal trend. The Ninnescah River has a significant trend in downstream fining of surface sediment (D_{50}, D_{90}) that is probably reflective of a combination of hydraulic sorting and sediment supply from the catchment. The North Fork of the Ninnescah River joining the South Fork has a disproportionally large influence on channel and sedimentary characteristics than what is typically believed. Once the Ninnescah River approaches the Arkansas River floodplain, there are deviations in the central tendency as the

Ninnescah River adjusts itself to meet the Arkansas. Our results build upon previous studies, with a new, underrepresented physiographic region.

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Figure 4.1 The Ninnescah River basin and its location in Kansas showing the location of field sites and U.S. Geologic Survey gages. Text in grey are the boundaries of the major physiographic regions within the Ninnescah River basin.

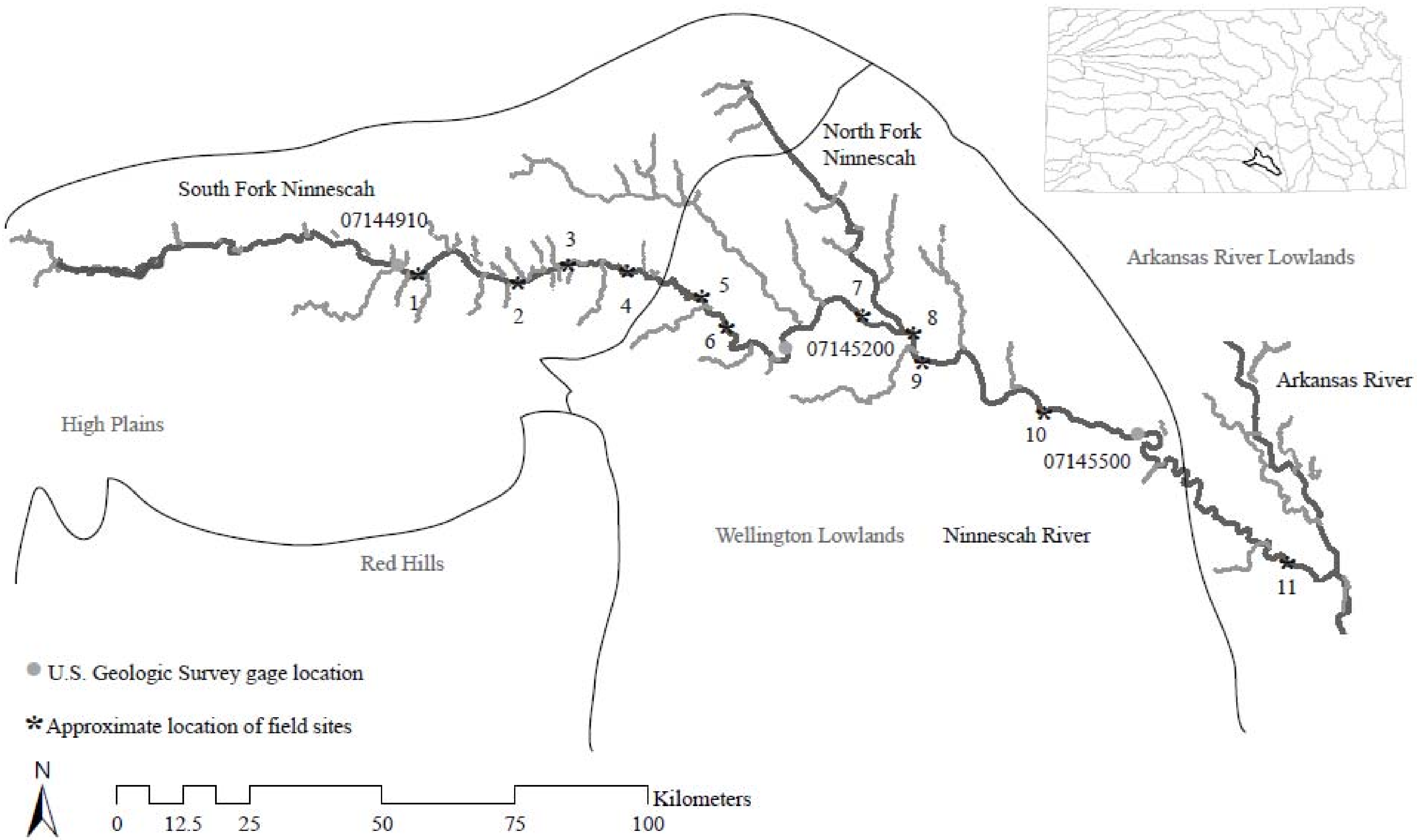

Figure 4.2 Photographs of field sites in downstream order. 1-6 are the South Fork of the Ninnescah River and 7-11 are the Ninnescah River proper.

Figure 4.3 Downstream trends in (a) the longitudinal profile, (b) bed slope, (c) channel sinuosity, (d) bankfull channel width, (e) bankfull channel depth, (f) bankfull channel width to depth ratios, and (g) bankfull channel area. The black dashed line denotes the location of the seasonal dam and the grey dashed line denotes the location where the North Fork meets the South Fork of the Ninnescah, forming the Ninnescah River proper.

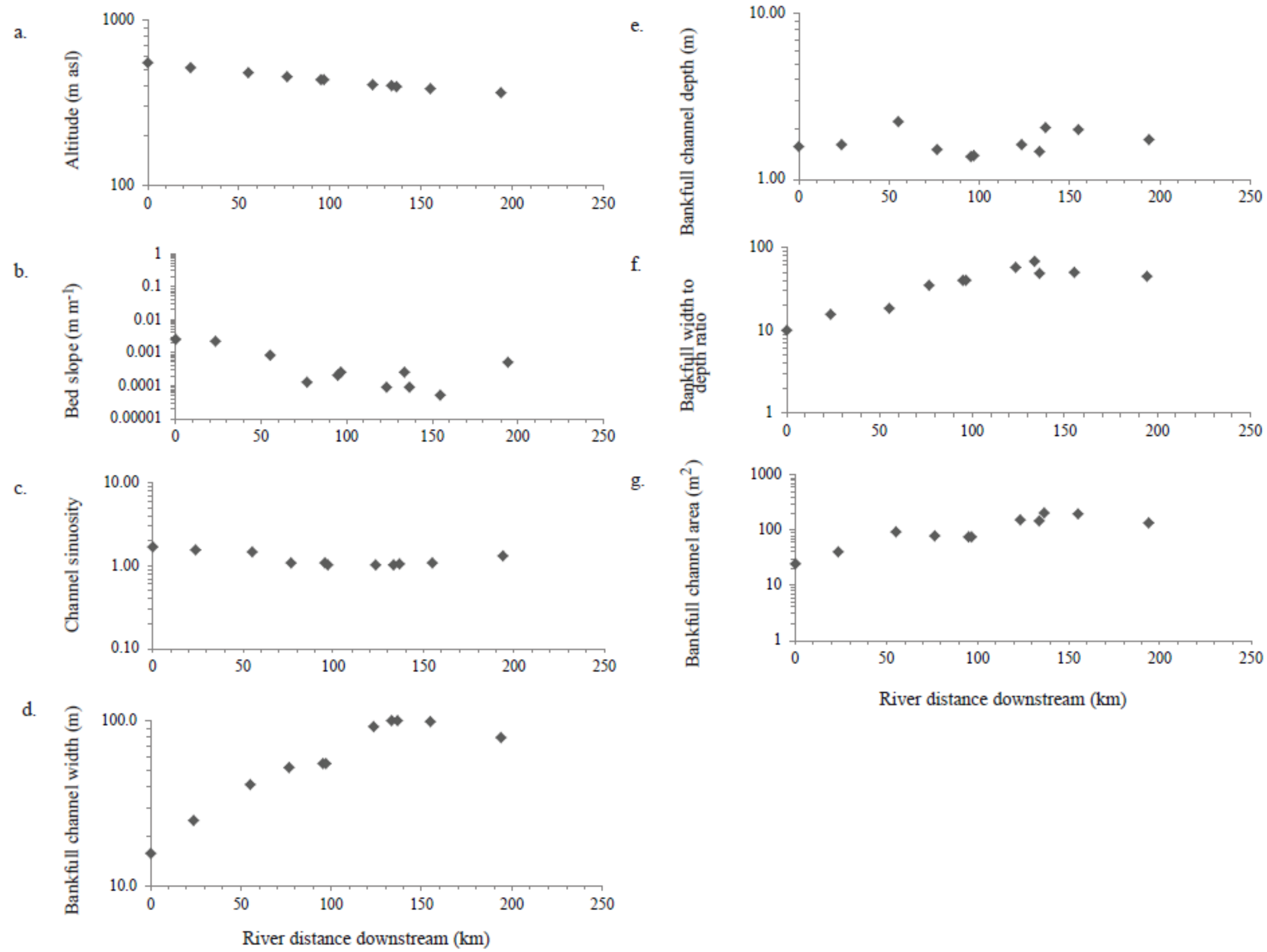

Figure 4.4 Photograph of a cut bank seen at site 3.

Figure 4.5 Downstream trends in sorting coefficient, skewness, and kurtosis.

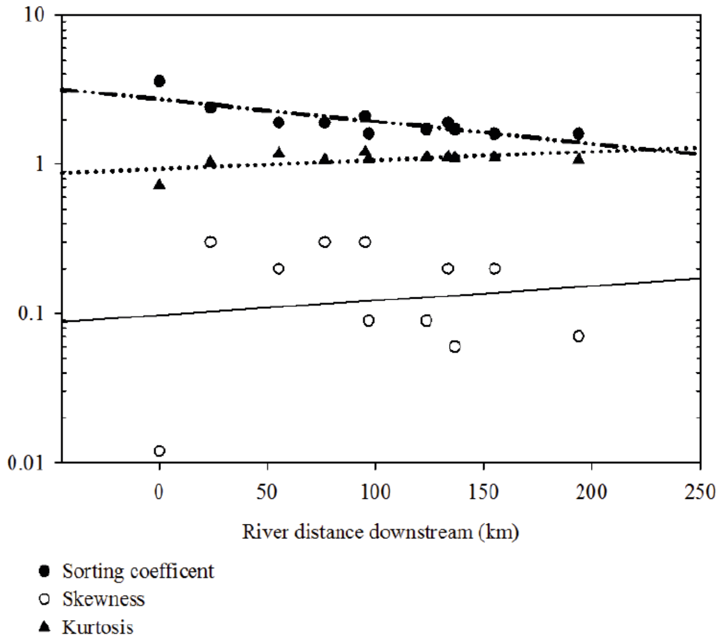

Figure 4.6 Analysis of sediment grain texture with gravel and sand size classifications from Blott and Pye [2001]

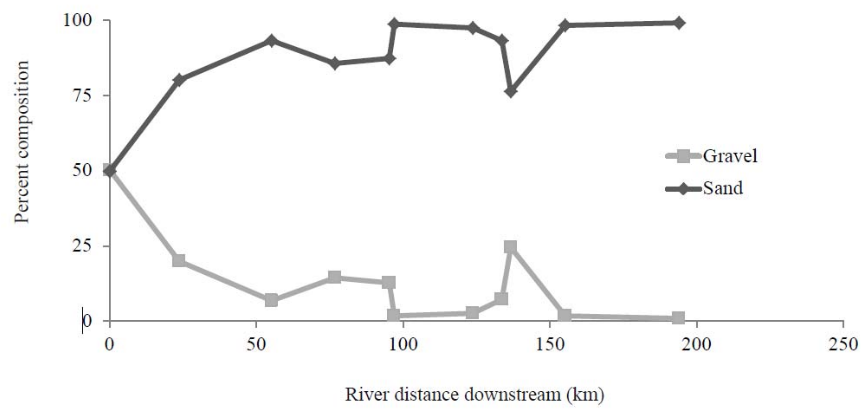

Figure 4.7 Downstream trends in grain surface sizes (D_{90}, D_{50}, and D_{10}).

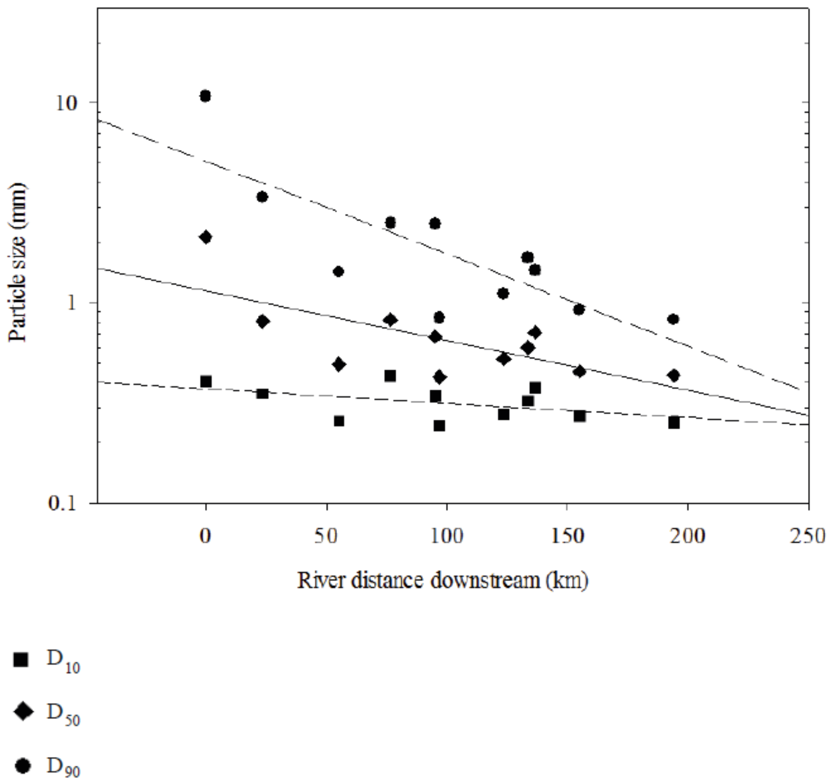

Figure 4.8 Results of principal component analysis for the first two principal components for channel sinuosity (Si), altitude (E), bankfull width (B), bankfull depth (Y), width to depth ratio (B:Y), slope (S), and grain size (D_{10}, D_{50}, and D_{90}).

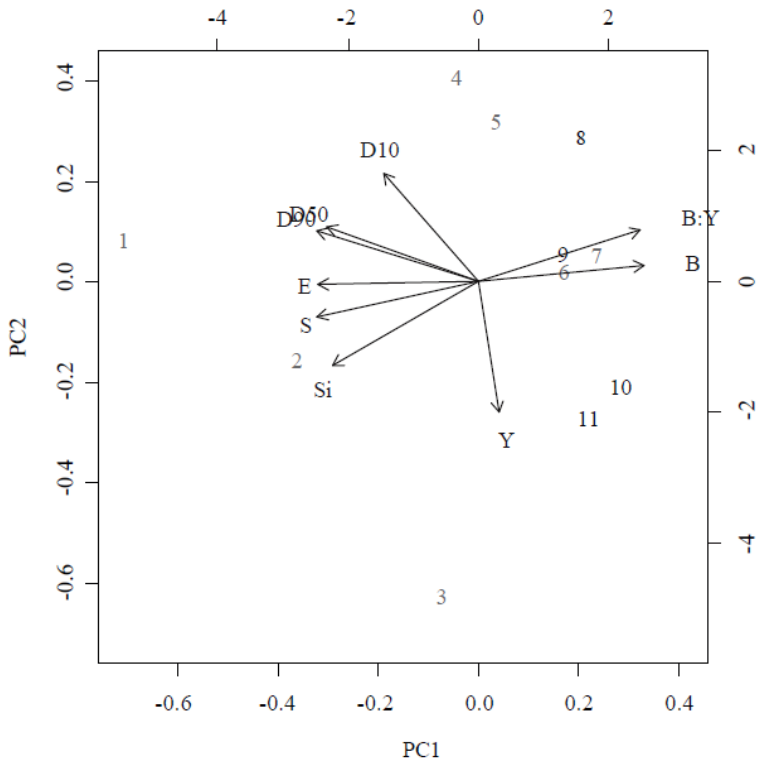

Table 4.1 Hydrologic characteristics of the Ninnescah River along study reach (standard error of mean).

Station Number	Station	Mean annual discharge (m^3s^{-1})	Contributing area (km^2)
07144910	SF Ninnescah in Pratt, KS	0.5 (0.04)	303.0
07145200	SF Ninnescah in Murdock, KS	5.9 (0.3)	1683.5
07145500	Ninnescah in Peck, KS	15.0 (0.9)	5514.1

Table 4.2 Parameter estimates for regression relationship between ln transformed values for channel sinuosity (Si), width (B), depth (Y), width to depth (B:Y), grain size (D_{10}, D_{50}, and D_{90}), and distance.*

	a	*b*	SE_b	r^2	*F*	*p*
ln Si	1.42	-0.0022	0.0015	0.35	4.9	0.054
ln B	15.13	0.4932	0.0442	0.92	108.9	<0.0001
ln Y	1.59	0.0008	0.0015	0.03	0.26	0.620
ln B:Y	9.56	0.2892	0.0335	0.88	64.3	<0.0001
ln D_{10}	0.40	-0.0005	0.0003	0.23	2.6	0.14
ln D_{50}	0.99	-0.0032	0.0013	0.44	7.0	0.027
ln D_{90}	4.04	-0.0209	0.0020	0.57	11.7	0.008

*Here *a* and *b* are parameters in the relation $ln\ y = ln\ a + bx$ where *x* is measured in km downstream from site 1. 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 4.3 Average particle size (standard error) characteristics with sorting, skewness, and kurtosis classifications from Blott and Pye [2001].

Site	Mean (μm)	Median (μm)	Sorting (σ_G)		Skewness (Sk_G)		Kurtosis (K_G)	
1	2064.3 (311.4)	2132.8 (383.2)	3.6 (0.2)	Poorly	-0.01 (0.06)	Symmetrical	0.72 (0.04)	Platykurtic
2	922.0 (95.9)	813.0 (80.4)	2.4 (0.1)	Poorly	0.3 (0.04)	Coarse skewed	1.02 (0.07)	Mesokurtic
3	535.9 (98.2)	494.6 (72.0)	1.9 (0.2)	Moderately	0.2 (0.02)	Coarse Skewed	1.18 (.12)	Leptokurtic
4	914.9 (82.7)	824.7 (57.2)	1.9 (0.1)	Moderately	0.3 (0.02)	Coarse Skewed	1.06 (0.05)	Mesokurtic
5	757.7 (67.2)	678.0 (46.6)	2.1 (0.2)	Poorly	0.3 (0.02)	Coarse Skewed	1.20 (0.06)	Leptokurtic
6	433.0 (14.0)	426.9 (15.5)	1.6 (0.02)	Moderately Well	0.09 (0.02)	Symmetrical	1.09 (0.03)	Mesokurtic
7	533.1 (12.9)	526.3 (16.3)	1.7 (0.02)	Moderately	0.09 (0.03)	Symmetrical	1.11 (0.03)	Mesokurtic
8	647.7 (44.0)	600.0 (39.3)	1.9 (0.2)	Moderately	0.2 (0.04)	Coarse Skewed	1.12 (0.03)	Leptokurtic
9	724.0 (40.1)	655.9 (22.0)	1.7 (0.1)	Moderately	0.06 (0.03)	Symmetrical	1.10 (0.04)	Mesokurtic
10	468.9 (20.3)	455.0 (21.9)	1.6 (0.05)	Moderately Well	0.2 (0.03)	Coarse Skewed	1.11 (0.03)	Mesokurtic
11	440.1 (13.1)	713.0 (45.7)	1.6 (0.03)	Moderately Well	0.07 (0.02)	Symmetrical	1.07 (0.03)	Mesokurtic

Table 4.4 Principal component loadings and explained variance for the first three components for channel sinuosity (Si), altitude (E), bankfull width (B), bankfull depth (Y), width to depth ratio (B:Y), slope (S), and grain size (D_{10}, D_{50}, and D_{90}).

	PC1	PC2	PC3
Si	-0.338	-0.392	0.027
E	-0.372	-0.015	0.144
B	0.386	0.076	-0.239
Y	0.048	-0.612	-0.716
B:Y	0.378	0.243	-0.044
S	-0.375	-0.165	0.125
D_{10}	-0.219	0.507	-0.566
D_{50}	-0.352	0.256	-0.237
D_{90}	-0.375	0.238	-0.120
Explained variance	2.489	1.226	0.898
Explained variance (%)	68.9	16.7	9.0
Cumulative % of variance	68.9	85.6	94.5

Chapter 5 - Conclusions

This dissertation begins to address the paucity of hydro-geomorphic knowledge specific to rivers of the Great Plains, perhaps the most scientifically overlooked streams in the continental United States [*Matthews*, 1988)]. Though no single dissertation could adequately address such a vast region, the three empirical studies presented herein represent important contributions to our understanding of Great Plains rivers with respect to other more intensively investigated systems. Scales of analysis range from the regional analysis of multiple large river systems to a small headwater tributary network. Rather than focus on contrast within the Great Plains, this dissertation focused on contrasting specific system type (e.g. headwater tributaries) behavior and/or form to well understood systems located outside of the Great Plains.

Chapter 2, Damming the Prairie: Human Alteration of Great Plains River Regimes, is the first study to quantify the widespread hydrologic alteration of Great Plains rivers following a wave of flood control dam construction in the 1960's. I found no uniform pattern of hydrologic alteration throughout the Great Plains, a finding likely attributable to variable system-specific reservoir management objectives, land use changes, and climatic regimes over the large area the Great Plains encompasses. The most dramatic hydrologic alterations observed were large increases in the number of annual hydrograph reversals and faster rise and fall rates.

Chapter 3, Hydrology of intermittent tallgrass prairie headwater streams, is among the first to systematically analyze the hydrologic regime of headwater tributary network in the Great Plains, and is the first to do so within the Central Great Plains. Results of this study used statistical models to identify relationships between flow intermittence, mean annual flow, and flood flow characteristics with moisture characteristics (total annual precipitation, peak precipitation, and Palmer Drought Severity Index) to characterize flow in intermittent prairie streams. I found an apparent decoupling between local moisture and streamflow in intermittent prairie streams. Results also demonstrated that, at times, the hydrologic regimes of immediately adjacent headwater streams can be decoupled. Furthermore, headwater tributaries can be decoupled longitudinally with gages short distances downstream.

In Chapter 4, Longitudinal variability in hydraulic geometry and substrate characteristics of a Great Plains sand-bed river, I found the downstream trends in hydraulic geometry and substrate characteristics of the Ninnescah River were consistent with the expected treads proposed by hydraulic geometry and substrate theories developed elsewhere. However, there were points that deviated from the expected trends, most notably where a substantially large tributary enters the Ninnescah River and as the Ninnescah River approaches the Arkansas River, and causal explanations for these deviations were explored. Taken together, the results of this study are the first of its kind to assess the longitudinal hydraulic geometry and substrate characteristics of a large sand-bed river over a substantial longitudinal reach.

The body of work presented herein significantly contributes to our understanding of the hydrology and geomorphology of Great Plains rivers. First, hydrologic alteration by dams on large rivers throughout the Great Plains varies depending on conditions within the watershed, but there were consistent trends with increases in the number of annual hydrograph reversals and faster rise and fall rates. Second, small intermittent streams are decoupled from short-term precipitation trends, and flow can be desynchronized between neighboring watersheds as well as longitudinally, suggesting that flow is partially controlled by processes acting at finer scales than climate. Third, the longitudinal hydraulic geometry and substrate characteristics of a large sand-bed river follow the expected trends that were developed for coarser-grained mountain streams, with few notable deviations.