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

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SUMMARY

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

1. Introduction

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

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

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

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

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

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

2. Material and methods

2.1. Study site

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

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

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

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