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Upland Rootzone Soil Water Deficit Regulates Streamflow in a Catchment Dominated by North American Tallgrass Prairie

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Abstract: Intermittent tallgrass prairie streams depend on surface runoff and are highly susceptible to hydrological disturbances such as droughts. The objective of this study was to investigate the timing of intermittent streamflow pulses and upstream rootzone soil water deficit in a watershed dominated by tallgrass prairie. The study was conducted from July to December 2021 in the Kings Creek watershed located within the Konza Prairie Biological station, Kansas, USA. Hourly precipitation and soil moisture observations in the 0–10, 10–30, and 30–50 cm depth were obtained from a hydrological network consisting of 16 monitoring stations across the Kings Creek watershed. Rootzone soil water storage (S) was computed at hourly time steps as the sum of the soil water storage of each soil layer. A drained upper limit (DUL) was estimated as the soil moisture remaining 24 h after the soil had been thoroughly wetted during large (~100 mm) rainfall events. A lower limit (LL) was estimated as the lowest rootzone soil water storage during the study period. Hourly soil water deficit (D) was computed as $D = (DUL - S)/(DUL - LL)$. The study period had 19 precipitation events totaling 436 mm, and only 14 out of the 19 precipitation events exceeded a common canopy and litter interception threshold of 4 mm for tallgrass prairies in this region. Only two precipitation events resulted in measurable streamflow, and the inception of these two streamflow events was associated with a negative weighted soil water deficit (i.e., $S > DUL$). This pilot study revealed that upland rootzone soil water deficit plays a major role controlling the timing of streamflow in the Kings Creek watershed and possibly in other catchment areas with intermittent prairie streams.

Keywords: tallgrass prairie; in situ soil moisture; streamflow; runoff; hydrological network; Konza Prairie

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1. Introduction

Native tallgrass prairies used to cover 70 million hectares across North America, but with nearly 95% of the original area lost to agriculture and urbanization, tallgrass prairies are one of the most endangered ecosystems in the continent [1]. The remaining tallgrass prairies in the U.S. Great Plains provide essential ecosystem services and are characterized by intermittent streams with distinct periods of flooding and drying that control biogeochemical processes, downstream water quality, and ecological dynamics of biotic communities in the terrestrial–aquatic ecotone [2,3]. Given the complex hydrology and sensitivity of intermittent streams to hydrological disturbances, there is need to better understand the hydrologic drivers of streamflow to better manage and preserve tallgrass prairie ecosystems [4]. This is even more relevant in a climate change scenario, in which the U.S. Southern Great Plains is projected to have less summer precipitation and drier soil moisture conditions by the end of the century [5–7].

The U.S. Southern Great Plains is a region characterized by humid continental hot summers with year-round precipitation concentrated in the summer months [8]. Nevertheless, only a fraction of the annual precipitation events in catchment areas dominated by warm-season prairie grasses result in runoff, which in turn results in intermittent streamflow [3]. Since the precipitation-runoff process is highly conditioned by the antecedent soil moisture conditions [9], the low runoff volume and the intermittent discharge observed in prairie streams of this region is likely associated to upstream soil moisture conditions. While we were unable to find a study documenting the impact of antecedent soil moisture conditions on the precipitation-runoff process on prairie streams, this relationship has been documented in other ecosystems. For instance, a previous study in a small mountainous catchment area in northern Italy resulted in runoff when the top 30 cm of the soil profile reached 45% volumetric water content [10]. Similar findings have been observed in the Tarrawarra catchment area in Australia, in which the inception of surface runoff occurred when the volumetric soil water content was between 41% and 46%. Nonetheless, there is a general lack of knowledge about the role of upstream soil moisture conditions in intermittent streamflow of prairie streams. Part of the reason for this lack of knowledge is because hydrologic records that include collocated streamflow, precipitation, and rootzone soil moisture information for small watersheds dominated by tallgrass prairies are scarce and rarely complete [11]. Since intermittent prairie streams depend on surface runoff rather than baseflow, the hypothesis of this study is that prairie streamflow discharge occurs when the upstream soil water deficit is dominated by gravitational flow. The objective of this study was to investigate the timing of intermittent streamflow pulses and upstream rootzone soil water deficit in a watershed dominated by tallgrass prairie. This is a pilot study focused on a period characterized by large (>100 mm d^{-1}) precipitation events followed by rapid (~3 weeks) soil moisture drydowns driven by high atmospheric demand and an actively growing vegetation.

2. Materials and Methods

2.1. Description of Catchment Area

The study was conducted from 12 June to 31 December 2021 in the Kings Creek watershed (39°06′07.47″, 96°35′40.88″), which is located in the Flint Hills region of northeastern Kansas, U.S. The Kings Creek watershed is contained within the Konza Prairie Biological Station (KPBS), which was established in 1971 by the Nature Conservancy and Kansas State University, and is part of the Long-Term Ecological Research (LTER) network supported by the National Science Foundation. The Kings Creek catchment area has a spatial extent of 11.5 km^2 and belongs to the larger Wildcat Creek–Kansas River watershed (hydrological unit code 1027010102). The Kings Creek is a second order wadable stream that drains an area dominated by a mesic native tallgrass prairie mostly composed of perennial warm-season grasses. The Kings Creek watershed has a rolling terrain with elevation ranging from 335 to 445 m a.s.l. Lowland areas around the streamflow gauge are characterized by deep silt loam soils with 1–3% slopes of the Reading (fine-silty, mixed, superactive, mesic Pachic Argiudolls) soil series, while backslopes and upslopes are characterized by well-drained soils of the Benfield–Florence complex with 5 to 30 percent slopes. Soils of the Benfield series (fine, mixed, superactive, mesic Udertic Argiustolls) formed over residuum of weathered shales and soils of the Florence series (clayey-skeletal, smectitic, mesic Udic Argiustolls) formed over residuum of weather limestone [12] with presence of limestone and shale fragments at or near the soil surface. The Kings Creek watershed is subdivided into smaller catchment areas that have different grazing and fire treatments. The area that drains in the south branch of the creek is characterized by a tallgrass prairie grazed by native herbivores such as the American bison (*Bos bison* L.), while the north branch is characterized by ungrazed prairie.

2.2. Measurements

In the Kings Creek watershed, streamflow has been monitored since 1979 by a stream gauge (#06879650) maintained and operated by the United States Geological Survey (USGS) (Figure 1) that measures water temperature, discharge rate, and stream height above a reference level at 15-min intervals. At the beginning and end of the study period, streamflow was below the measurement level, meaning that there was negligible or no stream baseflow recorded in the discharge time series. In addition, the Kings Creek watershed has been recently instrumented with 16 stations that constitute the Konza Pulse Hydrological Network, which monitors meteorological conditions including precipitation, air temperature, relative humidity, barometric pressure (model ATMOS 14, Meter, Inc., Pullman, WA, USA), solar radiation, wind speed, and wind direction (model ATMOS 41, Meter, Inc., Pullman, WA, USA) at hourly intervals.

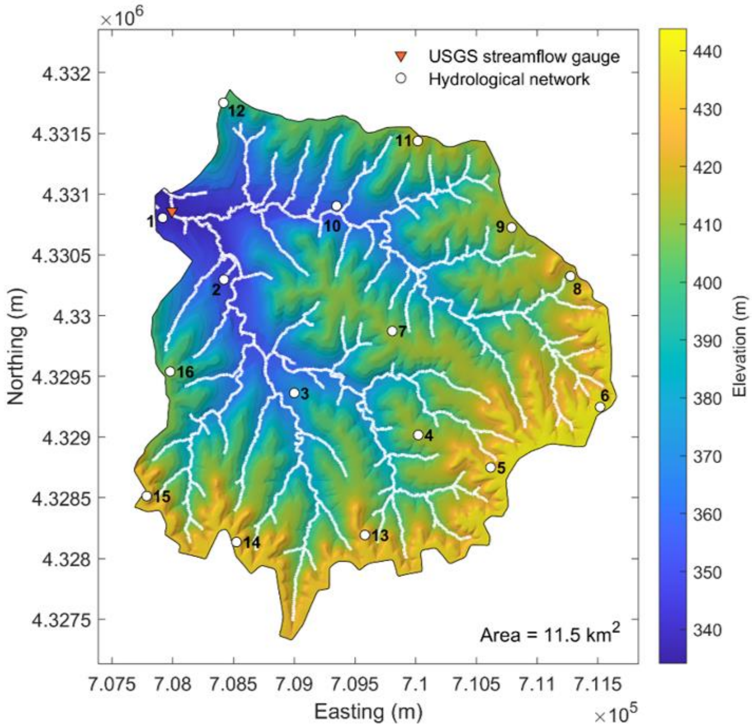

Figure 1. Map of the Kings Creek watershed showing terrain elevation, the predominant channel network, the United States Geological Service streamflow gauge (red triangle), and the 16 stations of the Konza Pulse Hydrological Network that monitor atmospheric and soil variables (white circles with numbers). The streams in this map are intermittent and typically exhibit temporal channel drying (i.e., zero flow).

Each station also measures soil moisture at 5, 20, and 40 cm depth. Each soil moisture sensor (model Teros 12, Meter, Inc., Pullman, WA, USA) measures volumetric water content, soil temperature, and bulk electrical conductivity. At each station, sensors were installed at the center of the soil layer they represent. For instance, the sensor centered at 5 cm represents the 0–10 cm layer, the sensor centered at 20 cm depth represents the 10–30 cm layer, and the sensor centered at 40 cm represents the 30–50 cm layer. Sensors were installed with the three prongs oriented vertically to better represent the soil moisture conditions across each soil layer. The reported depths for each layer correspond to the central prong of the sensors. The hourly soil water storage (S_t) in the top 50 cm of the soil profile was computed as the sum of the soil water storage of individual soil layers as follows:

$$S_t = \sum_{i=1}^{n} \theta_i z_i \tag{1}$$

where n is the number of soil layers (i.e., three layers) in the soil profile, θ_i is the volumetric water content (cm^3 cm^{-3}) of layer i, and z_i is the thickness (mm) of layer i. The hourly relative soil water deficit (D_t) for each of the 16 stations in the catchment area was computed as:

$$D_t = \frac{DUL - S_t}{DUL - LL} \tag{2}$$

where *DUL* is the empirical drained upper limit (mm), *LL* is the lower limit (mm). The *DUL* was determined by first identifying the most prominent peaks in the time series of rootzone soil moisture after substantial precipitation events, and then selecting the soil water storage after 24 h from the occurrence of the peak (Figure 2). This method of determining the *DUL* is aligned with the typical definition of field capacity and represents a practical method to leverage high-temporal resolution soil moisture observations. For the soils in this study, the lower limit was defined as the minimum value of the rootzone soil moisture time series. The denominator in Equation (1) is sometimes referred to as the water holding capacity of the soil. The maximum soil water storage, the *DUL*, the *LL*, and the water holding capacity for each station is presented in Table 1. The hourly soil water deficit at the watershed scale was estimated using the median value of all 16 stations and using a distance-weighted average that accounted for the distance of each soil moisture monitoring station to the point of discharge where the streamflow gauge is located. The inverse distance weights were estimated as follows:

$$W_i = \frac{\frac{1}{d_i}}{\sum_{i=1}^{n} \frac{1}{d_i}} \quad (3)$$

where W_{i} represents the weight of station *i* and *d* represents the distance from each station to the streamflow gauge.

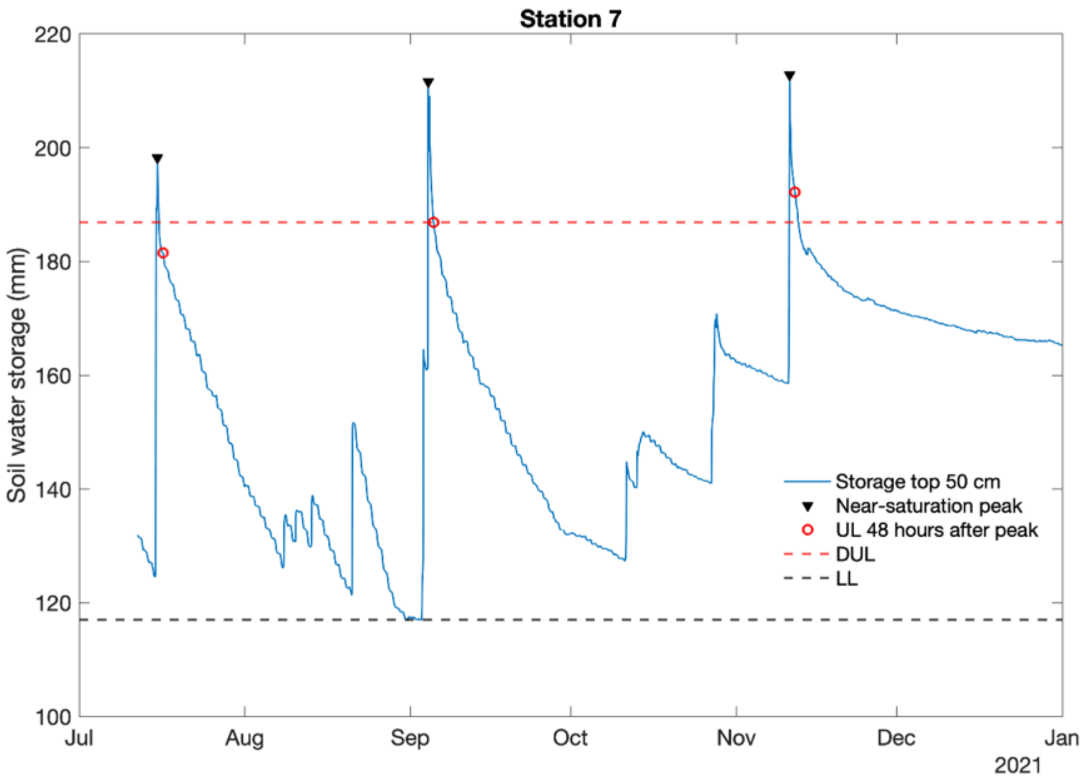

Figure 2. Example for station 7 illustrating near-saturation points, 24-h storage following near-saturation peaks, the drained upper limit (*DUL*), and the lower limit. All parameters were derived directly from the time series of soil water storage in the top 50 cm of the soil profile.

The dense instrumentation, the protected tallgrass prairie, and the different physiographic properties make the Kings Creek watershed a unique site for investigating the coupling between soil moisture and streamflow mechanisms. A distinct advantage of in situ soil moisture information is that it provides high-quality and high temporal resolution observations that can be coupled with collocated measurements of precipitation and streamflow for a more comprehensive study of the hydrologic drivers of intermittent streamflow.

Table 1. Saturation, drained upper limit (*DUL*), lower limit (*LL*), and water holding capacity (WHC, estimated as *DUL-LL*) in the top 50 cm of the soil profile for the 16 stations of the Konza Pulse Hydrological network.

Station	Latitude	Longitude	Elevation	Saturation	DUL	LL	WHC
#	dec deg	dec deg	m	mm	mm	mm	mm
1	39.10160	−96.59559	336	194	176	115	61
2	39.09692	−96.58991	340	221	193	104	89
3	39.08837	−96.58351	370	212	179	105	74
4	39.08501	−96.57183	412	206	188	120	68
5	39.08246	−96.56503	437	198	149	59	90
6	39.08672	−96.55446	442	216	176	102	74
7	39.09276	−96.57404	408	213	187	117	70
8	39.09647	−96.55694	414	223	199	115	84
9	39.10020	−96.56243	415	222	214	111	103
10	39.10214	−96.57902	359	218	196	134	62
11	39.10680	−96.57113	413	213	182	105	78
12	39.11001	−96.58951	397	212	182	106	76
13	39.07770	−96.57716	430	181	158	72	87
14	39.07743	−96.58938	434	200	168	84	85
15	39.08101	−96.59780	430	208	168	85	83
16	39.09020	−96.59525	404	211	183	99	85

3. Results and Discussion

During the 173 days from 12 July to 31 December 2021, the Kings Creek catchment area received a total precipitation of 436 mm (SD = 66.2 mm), a value that represents 52% of the annual precipitation for this region, based on the long-term (1981–2010) record for the Manhattan station of the Kansas Mesonet [13] located 12 km from the Kings Creek watershed. From July to December 2021, there were a total of 19 precipitation events based on a minimum inter-event time (MIT) of 12 h without measurable precipitation. The MIT criterion of 12 h is similar to that of previous runoff studies [14] and was selected to aggregate precipitation spells from the same storm that could lead to streamflow. The largest precipitation event occurred on 15 July 2021 and resulted in a rainfall total of 88.4 mm. The highest hourly precipitation intensity of 55.2 mm h^{-1} was recorded in station 8 on 3 September 2021. Previous studies show that the selection of the MIT criteria affects the intra-event rainfall intermittency [15,16]; thus, future studies could further investigate the role of intra-event rainfall intermittency and streamflow intermittency. Only 14 out of the 19 precipitation events resulted in precipitation totals exceeding 4 mm (Table 2). This is significant because precipitation events <4 mm are mostly intercepted by mature plant canopies and plant litter in this region [17,18].

Streamflow was recorded for a total of 12 out of the 173 days in the study period and the cumulative streamflow only represented 0.5% of the total precipitation volume. Despite the multiple precipitation events during the study period, only the two events on 15 July and 4 September 2021 generated streamflow (Figure 3). Days with measurable streamflow were associated with negative rootzone soil water deficits. The distance-weighted average rootzone soil water deficit predicted the two streamflow events and correctly discriminated a storm that could have resulted in a third streamflow event. On the other hand, a simple median soil water deficit including all monitoring stations was able to identify the first two streamflow events on 15 July and 4 September 2021, but it was unable to discriminate the event on 10 November 2021 that did not result in a measurable streamflow. Conditions of gravity-driven soil water flow (i.e., soil water content surpassing the drained upper limit) the in upper portions of the landscape may not result in streamflow since there is a known delay until the flow paths between the hillslope and riparian zone become connected [10], and substantial surface and sub-surface runoff can be stored in deep lowland soils before reaching the channel network.

Table 2. Precipitation amount, precipitation median intensity, precipitation duration, and relative soil water deficit in the top 50 cm of the profile before and after the 14 precipitation events totaling >4 mm from 12 July to 31 December 2021 at the Kings Creek catchment area. Precipitation and soil water deficit metrics are the median of the 16 monitoring stations.

Event	Date	Precipitation Amount	Precipitation Intensity	Precipitation Duration	Initial Soil Water Deficit	Final Soil Water Deficit
		mm	mm h^{-1}	h		
1	15 July 2021	88.4	32.3	11	0.82	−0.32
2	1 August 2021	4.29	2.6	8	0.71	0.71
3	8 August 2021	21.1	9.89	6	0.87	0.74
4	10 August 2021	10.3	8.90	4	0.78	0.72
5	13 August 2021	8.31	6.00	3	0.80	0.76
6	21 August 2021	21.6	14.9	2	0.91	0.66
7	31 August 2021	8.30	8.30	1	0.96	0.96
8	3 September 2021	65.9	41.9	10	0.97	0.40
9	4 September 2021	56.5	33.6	10	0.20	−0.27
10	30 September 2021	24.0	7.42	12	0.91	0.70
11	11 October 2021	13.9	6.35	4	0.73	0.61
12	13 October 2021	43.5	10.8	28	0.74	0.22
13	28 October 2021	47.6	29.6	7	0.39	−0.24
14	16 December 2021	14.1	5.40	7	0.21	0.21

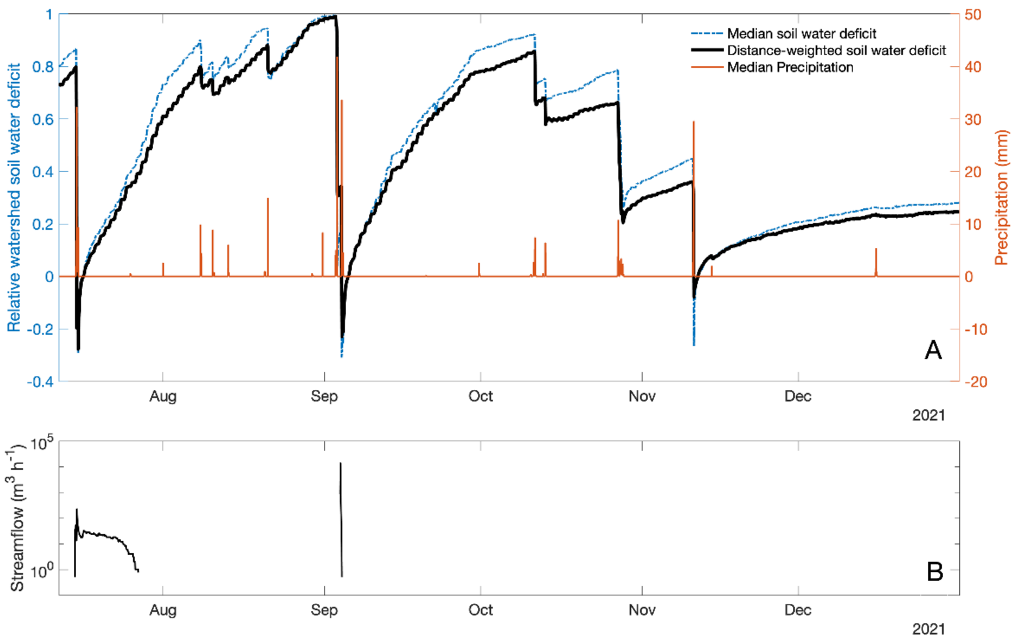

Figure 3. (**A**) Hourly relative soil water deficit and precipitation for the Kings Creek watershed for the period 12 July to 31 October 2021. (**B**) Hydrograph showing hourly streamflow recorded by gauge # 6879650 managed by the United States Geological Survey. Hours without observations correspond to baseline streamflow below the detection limit of the streamflow gauge.

This is particularly relevant in prairie ecosystems of this region that can exhibit rapid drydown due to a combination of well-drained soils, high atmospheric demand during the summer period, and an actively growing vegetation. For instance, during July and September, the soil water deficit went from field capacity conditions (i.e., point of zero deficit) to a soil water deficit > 0.8 in about 3 weeks. Our observations in the Kings Creek watershed agree with previous studies documenting that most intense flash droughts in the U.S. typically occur over the central Great Plains [19]. The large (change in deficit > 0.5) and rapid rate of drought intensification associated with flash droughts [20] not only affect biomass production and net carbon sequestration, but can also affect streamflow conditions and the terrestrial–aquatic ecotone.

One limitation of this study is that the hydrological record only spanned a period of six months. Nonetheless, the study captured a wide range of precipitation events spanning from <1 to 88 mm (Table 1), and rootzone soil moisture conditions ranged from near-saturation conditions to low values that approximately correspond to the permanent wilting point for these soils. A distinct advantage of this study is that working with hourly soil moisture observations allowed us to accurately differentiate the stage of gravity-driven and capillary. During this hydrologically short period, rapid soil moisture drydowns driven by high atmospheric demand and an actively growing vegetation also lead the soil moisture values to remain nearly stagnant for several days, which provides some evidence that the soil moisture conditions were at or were near the minimum soil moisture retention value. Future studies using a longer time series of rootzone soil water storage at this and other densely instrumented catchment areas will be necessary to draw a more general connection between soil water deficit and streamflow to improve precipitation-runoff partitioning, develop flood warning systems, and generate accurate seasonal streamflow forecasts. For instance, a recent study including watersheds from this region demonstrated that seasonal streamflow forecasts solely based on precipitation can be inaccurate in rainfall-dominated basins and that accounting for antecedent soil moisture conditions can reduce forecast errors by 55% [19].

4. Conclusions

This study was conducted in a catchment area dominated by tallgrass prairie in which an upland rootzone soil water deficit exerted a strong control on the intermittent streamflow of a wadable creek. Short periods of streamflow were related to periods in which the catchment-level rootzone soil water deficit was consistently above the point of gravity-driven soil water flow. Our findings show that upland rootzone soil water deficit plays a major role in controlling the timing and amount of streamflow in the Kings Creek watershed and possibly in other catchment areas with intermittent prairie streams. Longer studies (i.e., multiple years) are required to better understand the relationship between soil water deficit and streamflow at fine (i.e., minute, hourly) temporal resolutions. This study also re-emphasizes the value of spatially distributed hydrological networks that monitor in situ rootzone soil moisture that could be combined with parsimonious hydrological models and machine learning models for operational catchment-level streamflow forecasting.

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