Stormwater storage among remnant, degraded and restored urban prairies and wetlands of varying ecological quality

Colleen O'Brien[1,2], Jennifer Jenkins[3], Vivien Rivera[1], Liliana Hernandez Gonzalez[1,4], Jordan Gurneau[1], Upasana Larson[1], Karl Gnaedinger[3], Emilie Pfeiffer[3], Shane Tripp[3], Colin Phillips[5], Martha Lopez-Salazar[6], William M. Miller[7], Aaron I. Packman[1]

[1]Department of Civil & Environmental Engineering, Northwestern University, Evanston, IL 60208, USA [2] Weston & Sampson Engineers, Boston, MA 02108, USA [3] The Nature Conservancy, Markham, IL, 60428, USA [4]Lynker Leesburg, VA, 20176, USA [5]College of Engineering, Utah State University, Logan, UT, 84322, USA [6]Department of Biology, Northeastern Illinois University, Chicago, IL 60625, USA [7]Department of Chemical & Biological Engineering, Northwestern University, Evanston, IL 60208, USA

Corresponding author: Aaron Packman (a-packman@northwestern.edu)

Key Points:

- Groundwater level and electrical conductivity data were used to track stormwater input and hydrologic responses within a complex of urban prairies and wetlands.
- Prairie areas with significant engineered drainage had shorter response and relaxation times following rain events.
- Stormwater storage was significantly related to soil type but not to habitat quality.

Abstract

In response to increasing intensification of land use and more frequent and severe flooding, urban green spaces and natural areas are being relied upon to provide additional stormwater storage. Natural grasslands and wetlands provide extensive ecosystem services, including stormwater storage. These types of ecosystems were once widespread across the globe, but much of this habitat has been lost due to conversion for agriculture and urban development, and many remaining prairie-wetland ecosystems have experienced degradation. However, there has been limited research into how this degradation and subsequent restoration impact the stormwater storage these areas provide. To improve our understanding of the impacts of ecosystem degradation and restoration on stormwater storage and hydrologic response, we installed a network of groundwater level and electrical conductivity sensors at Indian Boundary Prairies, a prairie and wetland complex in southern Cook County, IL, USA. We used the resulting 15-month time series to estimate stormwater storage across locations that have experienced varying levels of historical degradation and more recent restoration by The Nature Conservancy. Our analysis indicates that the prairies store nearly half of the stormwater runoff originating from the surrounding urban neighborhoods. Variations in stormwater storage reflected underlying soil and habitat structure; poorly drained loams in wetland and swale areas retained water for longer than the loamy fine sands of the sand ridge. However, storage did not vary with habitat quality. Low-quality areas at Indian Boundary Prairies likely retain intact soil structure and hydrologic function, therefore, stormwater behavior appears governed more by these subsurface properties than by above-ground vegetation. This suggests that the primary ecohydrological function of these greenspaces is stormwater infiltration followed by evapotranspiration that reduces soil moisture and groundwater levels between storms. These findings highlight the ecosystem services provided by restored urban prairies and their ability to contribute to local flood reduction.

1 Introduction

Climate change is increasing the intensity and frequency of precipitation events globally (IPCC, 2023) and this trend is expected to continue. Increased rainfall can strain existing stormwater infrastructure and lead to more frequent flooding. Green infrastructure (GI) has become an increasingly common means of managing stormwater and reducing flooding, particularly in urban areas (Ali et al. 2025; Green et al. 2021; Khodadad et al. 2023; Maragno et al. 2018). Embedded greenspaces in urban and semi-urban areas provide a myriad of benefits. Prairies and wetlands provide ecosystem services including stormwater storage and flood reduction (Watson et al. 2016; Schulte et al. 2017). Globally, there has been increased interest in restoration of grassland and wetland ecosystems to increase stormwater storage and reduce flooding (Culbertson 2008; Acreman et al. 2007; Tomscha et al. 2021). However, there has been limited research into how degradation, impacts of urbanization, and subsequent restoration may impact the stormwater storage performance of prairie-wetland ecosystems and the ecosystem services they provide.

To understand the impacts of habitat quality on stormwater storage provided by prairie-wetland ecosystems, we installed a sensor network across three prairies in the Indian Boundary Prairies complex, a 1.9 km^2 prairie-wetland complex in southern Cook County, IL, just south of the city of Chicago and surrounded by urban, industrial, and suburban developments (The Nature Conservancy n.d.). The Great Lakes and Midwest U.S. regions were historically home to extensive prairie and wetland habitat, but much of this habitat has been lost, fragmented or redeveloped over the past century (Dahl 1990; Hu et al. 2017; US Army Corps of Engineers, Rock Island District n.d.; Winkler, 2004). Many of the remaining prairie ecosystems have experienced significant degrees of degradation (Stein et al. 2013).

Sensors were installed across three prairies with a gradient of habitat quality: Gensburg-Markham Prairie, Sundrop Prairie, and Paintbrush Prairie. These prairies vary in their history of development, degradation, and subsequent restoration. Gensburg-Markham Prairie is a high-quality intact prairie –the best remaining in the Chicago megaregion – while Sundrop and Paintbrush Prairies experienced more extensive development leading to a greater degree of degradation and have been partially restored by The Nature Conservancy. We determined stormwater retention and hydrologic response of each prairie and assessed these dynamics relative to habitat degradation, and restoration to better understand the relationship between habitat quality and stormwater storage provided by natural areas within cities.

2 Materials and Methods

2.1 Study Site

Indian Boundary Prairies is a network of remnant and restored high-quality tallgrass prairies jointly owned and managed by Northeastern Illinois University and The Nature Conservancy (TNC) in the municipalities of Markham, Midlothian, and Harvey, Illinois, approximately 65 km south of downtown Chicago. Markham is home to approximately 11,400 residents (U.S. Census Bureau, 2020); Midlothian is home to approximately 14,300 residents (U.S. Census Bureau, 2020) and Harvey has a population of approximately 20,300 residents (U.S. Census Bureau, 2020). All three municipalities are both located within the Little Calumet River watershed, which flows northward across the rural-suburban-urban gradient and discharges into the Calumet River at the southern border of the City of Chicago. These communities and others within the watershed experience significant flooding. Midlothian experiences frequent storm-sewer backups, in addition to street and yard flooding (Center for Neighborhood Technology 2016). From 2010 to 2020, the Calumet Region had a total of 556 flood insurance claims per 10,000 residents, 85% greater than the average number of insurance claims in Cook County (the county in which Chicago, Midlothian, Markham, and Harvey are located) (Center for Neighborhood Technology 2023). This watershed is also the focus of a new regional stormwater credit trading program, StormStore, designed to increase investment in green infrastructure to mitigate flooding (Metropolitan Planning Council 2020).

Indian Boundary Prairies includes seven prairies: Gensburg Markham Prairie, Markham Prairie North, Markham Prairie South, Markham Prairie East, Dropseed Prairie, Sundrop Prairie and Paintbrush Prairie (Figure 1). Much of IBP is designated as an Illinois Nature Preserve and a National Natural Landmark due to the presence of intact, endemic, and rare assemblages of native plant and animal species, including high-quality tallgrass prairie communities that are now rare in the region due to extensive historical loss (Illinois Department of Natural Resources, n.d.; National Park Service, n.d.; Winckler 2004). In this study, *habitat quality* refers specifically to ecological conditions as assessed using aboveground vegetation characteristics, including plant community composition, floristic diversity, and the presence of remnant prairie or wetland species. The categories of habitat quality are described further in Section 2.4. We use the term *remnant* to describe areas that retain native plant communities and have experienced limited historical disturbance relative to surrounding landscapes. The individual prairies vary in their history of development and extent and degree of degradation; however, all contain remnant natural areas, as defined above, and have undergone some level of ecological restoration. All of the prairies are vegetated with prairie species or woody vegetation and do not contain turf grass.

Gensburg-Markham Prairie (GMP) is one of the highest quality prairies in the state; it was ditched but never developed or used for intensive agriculture or urban development.

GMP is bordered by Markham Prairie North and Markham Prairie South, which are more recently protected and restored prairies with greater degrees of degradation. Markham Prairie North and Gensburg-Markham Prairie are separated by a large drainage ditch. Gensburg-Markham and Markham Prairie South are only intermittently hydrologically connected. A kilometer northwest of GMP, Paintbrush and Sundrop Prairies experienced more extensive duration of plowing for gardens, leading to degradation of these areas. Both prairies have undergone restoration by TNC and include some high-quality remnant areas. Consequently, GMP provides high quality habitat with minimal historical soil disturbance or land development and supports extraordinarily rich biodiversity across its 40-hectares whereas Paintbrush and Sundrop Prairies display more internal heterogeneity in habitat quality, including a mix of soil fill, restoration, and remnant undisturbed natural areas.

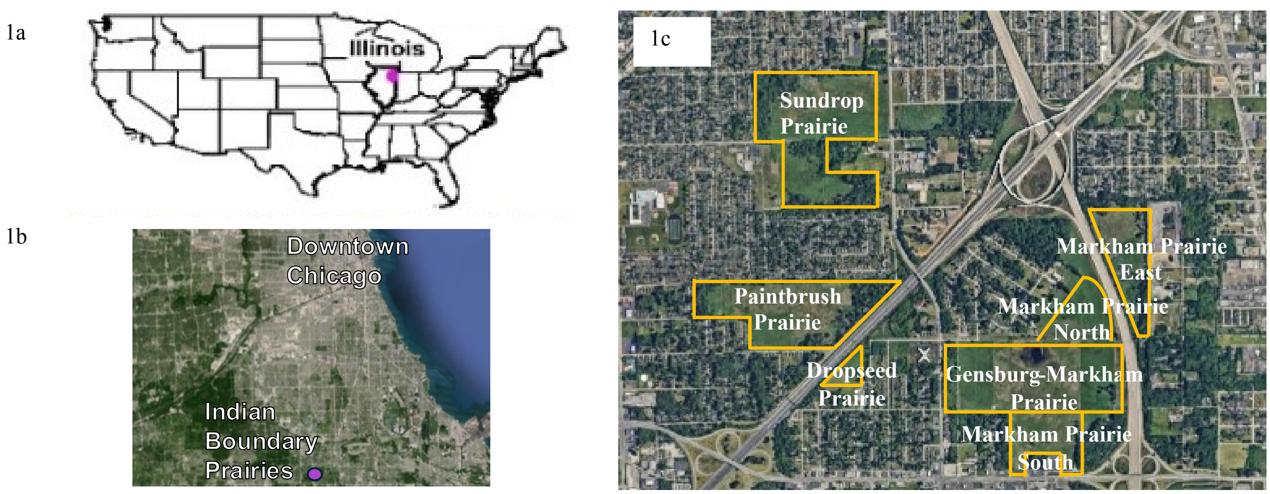


Figure 1. a) A map of the United States showing the location of Gensburg Markham Prairie as a pink dot. b) Location of Indian Boundary Prairies relative to downtown Chicago. c) Location of the prairies within the Indian Boundary complex and surrounding community.

2.2 Instrumentation

In summer 2016, fourteen subsurface water level sensors (InSitu LevelTroll 400) were installed at Gensburg Markham Prairie in piezometers at depths of 1 meter below the ground surface (Hernandez et al., 2017). The sites are denoted as Water Level Well (WLW 1-14); two sensors (WLW7 and WLW11) were damaged or malfunctioned and are not included in this analysis. One subsurface sensor was deployed at a depth of 2 meters below the highest-elevation area of the prairie (WLW13). Sensor locations were selected based on flow paths and were arranged along three transects across key features of the prairie. The first transect runs longitudinally across the wetland on the northern portion of the prairie. The second transect runs longitudinally from the sand ridge, a sandy elevated area on the western side of the prairie through the swale on the eastern side of the prairie. The third transect runs perpendicular to the sand ridge crossing into the wetland (Figure S1). Pressure data from LevelTroll 400 sensors was corrected using barometric pressure from an InSitu BaroTroll collocated with WLW8 to obtain water depth above the sensor and then added to the surveyed sensor elevation to yield water surface elevation in meters above mean sea level (based on NAVD 88). Measurements were recorded every 30 minutes.

In September 2020, twelve subsurface water level sensors were installed in piezometers in Sundrop Prairie, and six sensors were installed at Paintbrush Prairie. Sensor locations were selected in areas where stormwater flow onto or off the prairie was suspected based on topographic flow routing and field observations of stormwater flow and habitat degradation. The piezometers were installed to depths of approximately 1.5 meters below the ground surface. Six of the piezometers at Sundrop Prairie are equipped with Solinst, Levelogger Junior Edge, Model 3001 water level sensors that measure water level based on changes in pressure (SD-WL1, SD-WL2, SD-WL3, SD-WL4, SD-WL5, SD-WL6). The logger measurements were corrected for barometric pressure based on readings from a Solinst, Barologger Edge, Model 3001, installed in a shed owned by The Nature Conservancy on the border of the prairies. Six additional piezometers at Sundrop are equipped with Solinst, Levelogger Edge, Model 3001, which measures electrical conductivity in addition to water level (SD-EC1, SD-EC2, SD-EC3, SD-EC4, SD-EC5, SD-EC6). Two sensors (SD-EC4 and SD-EC5) were damaged or malfunctioned and are not included in this analysis. At Paintbrush Prairie six piezometers are equipped with sensors measuring electrical conductivity and water level (PB-EC1, PB-EC2, PB-EC3, PB-EC4, PB-EC5, PB-EC6), and one piezometer (PB-WL1) is equipped with a water level sensor. All sensors collect data hourly.

2.3 Soil Characteristics

Based on data from the USDA-NRCS Soil Survey Geographic (SSURGO 2.2) Database, the three prairies are underlain by the following soil types: Selma loam, Gilford fine sandy loam, Watseka loamy fine sand, Kankakee fine sandy loam, Hoopeston fine sandy loam, Plainfield loamy sand, and Oakville fine sand. Selma, Gilford, and Hoopeston represent poorly to somewhat poorly drained loamy soils typical of depressional wetland settings (USDA–NRCS, Official Soil Series Descriptions). Unlike Gilford and Hoopeston soils, Selma soils lack a sandy component, comprised exclusively of fine loam. Plainfield and Oakville are well drained sandy soils with rapid infiltration characteristic of dunes and sand ridges in this region (USDA–NRCS, Official Soil Series Descriptions). Kankakee are well drained soils, and Watseka are somewhat poorly drained soils; both are commonly formed on outwash plains and stream terraces.

At Gensburg–Markham Prairie, these soil characteristics are closely aligned with the land surface morphology, with Watseka loamy fine sands underlying the sand ridge and Selma loam and Hoopeston fine sandy loam in the adjacent swale and wetland complex (Hernandez Gonzalez et al., 2019; Gonzalez et al., 2023). Paintbrush Prairie is heavily dominated by Selma loam with some small areas of Hoopeston fine sandy loam along the periphery and southern portion of the prairie. Sundrop Prairie displays a broader range of soil types, with Selma loam and Hoopeston fine sandy loam being the most dominant, particularly in the northern part of the prairie. However, some areas in the southern part of the prairie are underlain by Kankakee fine sandy loam and Oakville fine sand. In addition, small sections of the northern part of the prairie are underlain by Gilford fine sandy loam and Plainfield loamy sand. Borings at Sundrop and Paintbrush Prairies also encountered fill in some parts of these two prairies, particularly in the southern portion of Sundrop Prairie that was characterized by the SSURGO database, and may have previously been, Kankakee fine sandy loam. For the statistical analysis described in Section 2.7, SSURGO soil types were used except in locations where fill was confirmed, in which case the mapped soil type was recategorized as fill. These contrasts between loam, fill, and sandy soil types, and their spatial distribution play an important role in shaping the stormwater storage and hydrologic response described in Section 3.4.

Soil cores were obtained during installation of each piezometer. Sub-samples from each core section were characterized manually and visually in the field according to ASTM method D2487 (American Society for Testing and Materials 2020). Soil porosity was estimated from bulk density and particle density. The bulk density was estimated based on the average values for each assigned Unified Soil Classification System (USCS) soil group

(United States Department of the Army 2012). Particle density was assumed to be 2.65 g/cm3, which is typical for clays. Estimated soil porosities ranged from 0.29-0.35.

2.4 Habitat Characteristics

Habitat type and habitat quality were assessed as part of ongoing conservation management and restoration efforts at Indian Boundary Prairies. Habitat types include wet-mesic prairie, sedge meadow, and degraded prairie or woodland. Habitat quality classifications were based on field observations of vegetation type, floristic diversity, and the presence of remnant prairie or wetland plant species within these areas, particularly those on the list of Endangered and Threatened Species in Illinois (Illinois Endangered Species Protection Board, 2020). Observations were primarily focused on aboveground plant communities and did not include extensive assessments of belowground physical degradation (e.g., soil compaction, altered structure). In many cases, the observed degradation was relatively superficial, such as past gardening or light plowing, and may not have substantially altered soil structure or hydrologic function. Importantly, degradation at Indian Boundary Prairies differs from more intensive landscape modification common in urban development (e.g., grading, excavation, turf installation), which may have more severe impacts on stormwater storage capacity.

Habitat quality was categorized into three levels: high, medium, and low. High-quality areas were defined as remnant prairie ecosystems that retained ecological integrity and supported native prairie or wetland species, including state-protected and conservative indicator species. Medium-quality areas were sites with high-diversity restorations or partially degraded remnant prairie. Low-quality areas were characterized by reduced plant diversity and lower levels of ecological restoration but were still vegetated with prairie or woody species. The extent of restoration efforts and resulting improvements in habitat condition were also documented as part of ongoing management activities, typically starting from a condition of low habitat quality.

2.5 Hydrologic Time Series

Python was used to process data collected from all sensors to support time-series and statistical analyses. A script was used to filter data from sensors that were dry based on pressure measurements. To assess long-term seasonal patterns in hydrological response, filtered data were smoothed using a Gaussian filter (Barzegar, Adamowski, and Quilty 2021). In this context, the hydrologic response refers to the change in groundwater levels within each prairie following a precipitation event, including the speed and duration of water level rise and return to baseline. To analyze the response and storage from precipitation events, the rising and falling (recession) limbs of the hydrographs observed in the Gaussian filtered data were fitted to a power law distribution, $y=kt^n$, following the methods of Dralle et al. 2017, where y is the groundwater level and t is time. The regression was fit to the falling limb following the peak when the slope became negative. Two precipitation events in May 2021 and June 2021 had multiple consecutive days of rain and displayed long-term seasonal responses in the system and in their associated hydrographs extending from weeks to months. To observe each prairie's hydrological response over this longer time scale, these consecutive events were treated as one large storm, rather than multiple consecutive storms.

To assess event-scale hydrologic responses of the prairies, storm response hydrographs were extracted from the time series. A spline with three degrees of freedom was fitted to the groundwater level time series using the one-dimensional univariate spline fitting function in Python (Jones, Oliphant, and Peterson 2001, Patterson et al. 2020). Previous research has shown splines to be an effective method of estimating derivatives from noisy data (Patterson et al. 2020; Craven and Wahba 1978; Thomas, Vogel, and Famiglietti 2015; Ragozin 1983). The Gaussian filtered time series was then subtracted from the spline fitted data to separate the event-response dynamics from longer-term changes in water level due to seasonal patterns (Figure S2). Events were identified using the derivative of the spline-fitted data, which is equivalent to the slope of water level over time. When this derivative exceeded the noise threshold, an event was identified. To determine this threshold, we calculated the standard deviation of the rate of change in water level during periods with minimal precipitation (<0.2 inches on the day of and the day prior) for each sensor and defined the noise level as twice this value. Events were cross-checked with rainfall data to ensure the event was a response to a precipitation event. Responses were analyzed in terms of time from baseline to the hydrograph peak, as well as water levels before and after the event to represent the short-term sustained change in water level due to stormwater input. Response times for each event were calculated based on the time between the initial response, when the derivative exceeded the noise threshold, to the time of the peak. Relaxation times were calculated from the time of peak to the time after which the derivative was no longer greater than the noise threshold. The relaxation time reflects the rate at which water drains following a precipitation event. Sites with longer relaxation times retain water for longer periods, whereas sites with shorter times exhibit more rapid drainage. We compared relaxation times across sites to assess differences in stormwater retention behavior and to evaluate the influence of ecological factors such as habitat quality, soil type, and prairie structure.

Electrical conductivity response was used to identify areas in Paintbrush and Sundrop Prairies receiving stormwater input. The derivatives of electrical conductivity and water level measurements were calculated for each identified hydrologic response event. Electrical conductivity response was then categorized following a scheme adapted from Singley et al. 2017, which groups responses into four categories: concentrating (Category 1), flushing (Category 2), source depletion (Category 3) and diluting (Category 4). Concentrating (Category 1) occurs when the water level decreases and the electrical conductivity increases, leading to a higher concentration of dissolved salt ions in the water. Flushing (Category 2) occurs when both the water level and electrical conductivity increase, indicating mobilization and transport of salts into groundwater. Source depletion (Category 3) occurs when both the water level and electrical conductivity decrease, indicating that the source of water and available salts has decreased. Lastly, diluting (Category 4) occurs when the water level increases, but the electrical conductivity decreases, leading to a lower concentration of salt ions in the water. Concentrating (Cat. 1) and flushing (Cat. 2) would be most representative of an influx of stormwater, which is high in dissolved salts and potentially metals (Gonzalez et al., 2023; Pellerin et al., 2007). In contrast, diluting (Cat. 4) likely represents an influx of precipitation falling directly onto the prairies or an increase in the groundwater table, both of which contain low-conductivity water. Source depletion (Cat. 3) is expected on the falling limb of the hydrograph, as pre-existing salts are removed from the soil and inflow from the rain event tapers off. Well locations where we consistently observed elevated electrical conductivity levels and hydrograph peaks coinciding with strong flushing or concentrating electrical conductivity responses were considered likely to receive off-site stormwater input.

We classified published observations from Gensburg-Markham Prairie identically to the new measurements from Sundrop and Paintbrush prairies for comparison. Gonzalez et al. 2023 measured electrical conductivity from water samples collected from February to August 2018, using a FieldScout EC Probe. The samples were subsequently analyzed for chloride using Ion Chromatography. Gonzalez et al. used this analysis to identify locations within Gensburg-Markham Prairie with elevated electrical conductivity and chloride concentrations from off-site stormwater runoff, particularly from road salt.

2.6 Flow routing and stormwater storage

A workflow developed in the ArcGIS Pro (esri) 3D Analyst Toolbox was used to develop a digital elevation model (DEM) of the prairie from LiDAR data collected during the 2022 flyover of Cook County (Cook County Bureau of Technology, 2023). The DEM was further processed to develop a flow routing model of the prairie's surface water based on flow accumulation, calculating the contribution of upslope surfaces to water depth on downslope surfaces (Rivera et al., 2025). Changes in measured groundwater levels were converted into stormwater storage volumes by multiplying the change in groundwater level by the soil porosity at that location and a catchment area associated with each piezometer, delineated based on a digital elevation model of the prairies using the Watershed function ArcGIS Pro. Water level sensors provided continuous measurements across the surface-groundwater interface (Gonzalez et al., 2023, Rivera et al., 2025). Changes in water level were segmented into groundwater and surface water based on the position of the water surface relative to the local ground elevation. This analysis was extended to stormwater response, with changes in water levels above the ground surface categorized as surface water storage, and changes in levels below the ground surface classified as groundwater storage.

We estimated the storage volume for each measurement location across Paintbrush, Sundrop and Gensburg-Markham prairie for three storm events: May 8-9, 2021, with 5.7 cm of rainfall, June 24-26, 2021, with 12 cm of rainfall, and October 24-25, 2021, with 10 cm of rainfall. These storms were chosen because they were the largest magnitude events over the period analyzed that elicited a response at almost all well locations.

2.7 Statistical analysis

To estimate the relationship between stormwater storage volume and characteristics of each sensor location, we normalized the storage at each well location by the drainage area and the total event rainfall. We then compared results within and between prairies based on four characteristics of each sensor location: distance along flow path, soil type, habitat quality, and the prairie in which it is located. We conducted Kruskal-Wallis tests based on three different measurements: a dimensionless ratio of storage volume per area per rainfall amount, the hydrograph response time, and hydrograph relaxation time. For each factor that was statistically significant based on the Kruskal-Wallis test, a Dunn's post-hoc test with Bonferroni correction was conducted to determine statistically significant differences among groups. We calculated these statistics for 15 identified storm events between January 2021-March 2022. These 15 precipitation events were selected for analysis because they produced a response at the majority of well locations. However, not all locations showed a response for each of the 15 events, therefore some well locations have a smaller sample size than others. A subset of 12 storm events produced an electrical response at the majority of well locations, and these were used to calculate the average change in electrical conductivity following a precipitation event. Limited response in water level was observed at one well location in the sand ridge of Gensburg Markham Prairie (WLW8) and therefore this location was excluded from the analysis for both stormwater storage and hydrograph slopes.

3 Results

3.1 Surface and groundwater connectivity

There are multiple major flow paths across Sundrop Prairie (Figure 2). Surface water enters the prairie at multiple points along its western border from surrounding neighborhoods in Midlothian. It then flows northeast to the center of the prairie and connects to a flow path that runs along the northern edge of the prairie and receives water from surrounding neighborhoods northwest of the prairie. These two flow paths converge at an ephemeral wetland near the northern border of Sundrop. Surface water also enters the prairie from a ditch along the northeastern edge, flowing south across the prairie until eventually exiting the prairie near the eastern edge. In the southern half of the prairie, surface water enters from the eastern edge flowing north and then enters a ditch which bisects the prairie and runs west to east along an access road that divides the northern and southern portions of the prairie. Surface flow between the two portions of the prairie only occurs occasionally after large rain events when surface water flows north across the road.

At Gensburg Markham Prairie, surface water flows from southeast to northwest through a swale on the western side of the prairie to a wetland on the northern edge and eventually connects to the Bel Aire Creek ditch which runs along the northern border of the prairie. The second major flow path enters the prairie near its southwestern edge and flows east along the southern border, eventually connecting with the major flow path traveling northwest through the swale. This flow path receives some surface water from Markham Prairie South and drainage from some suburban developments to the south.

At Paintbrush Prairie, there are two predominant flow paths. In the first, surface water enters the prairie from surrounding neighborhoods to the southwest in Markham. This water flows north through a drainage ditch along the western edge, pivots east, and eventually enters a drainage ditch that runs along the northern border of the prairie. The second major flow path runs northeast across the center of the prairie eventually joining the northern ditch, which exits the prairie at its northeastern corner.

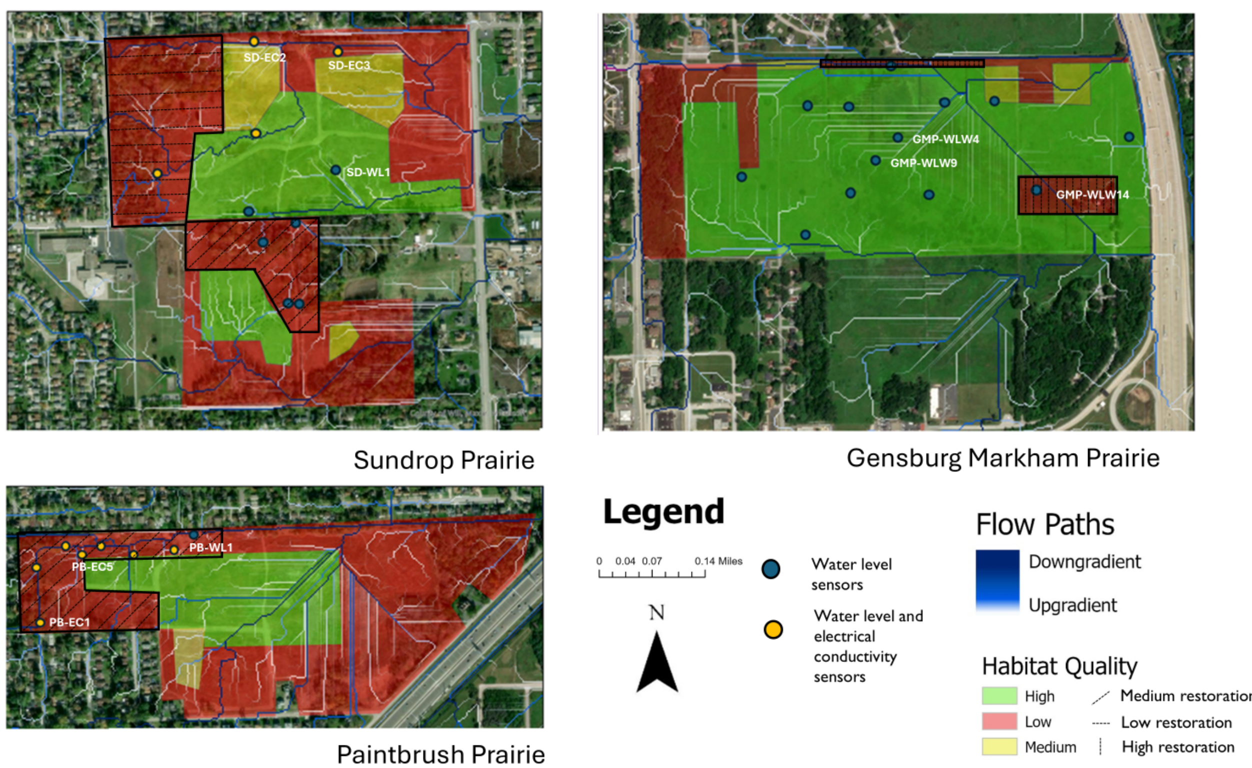
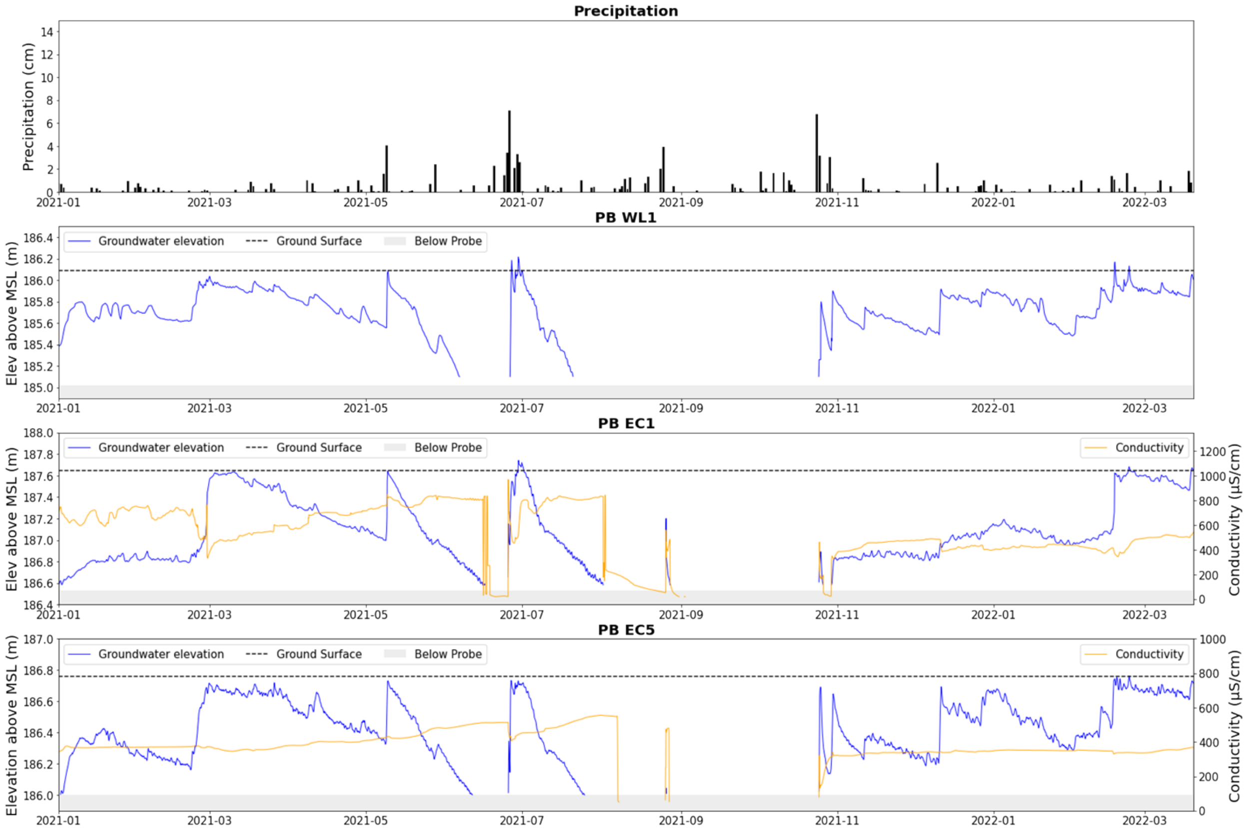


Figure 1. Surface water flow routing and direction across the three prairies: Sundrop Prairie, Gensburg Markham Prairie and Paintbrush Prairie. Habitat quality determined by The Nature Conservancy shows low-, medium- and high-quality areas across the prairies along with the extent of restoration (low, medium and high) within the low-quality habitat areas.


Precipitation
Precipitation (cm)
PB WL1
Groundwater elevation
Ground Surface
Below Probe
Elev above MSL (m)
PB EC1
Conductivity
Conductivity (µS/cm)
PB EC5
Elevation above MSL (m)
2021-01
2021-03
2021-05
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2022-01
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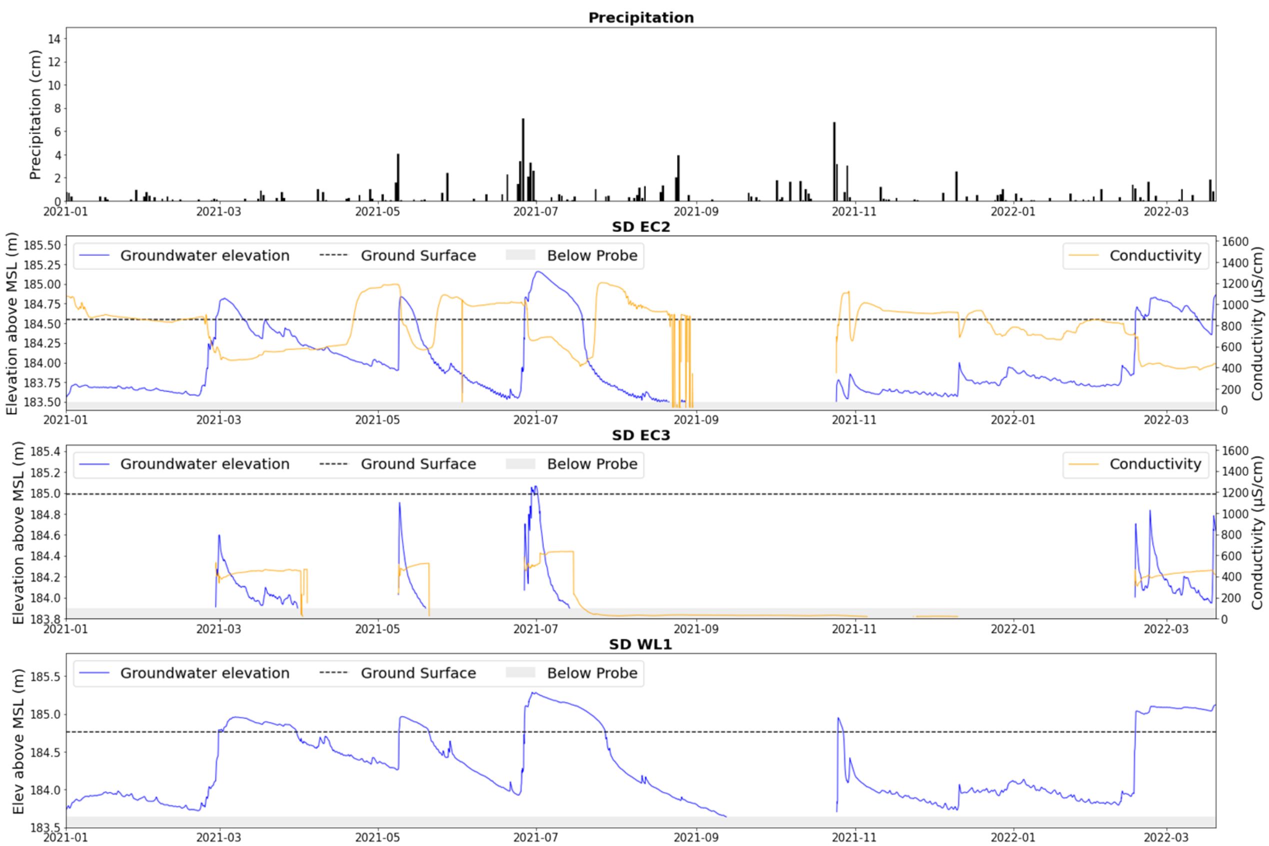
Precipitation
Precipitation (cm)
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Groundwater elevation
Ground Surface
Below Probe
Conductivity
Elevation above MSL (m)
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SD WL1
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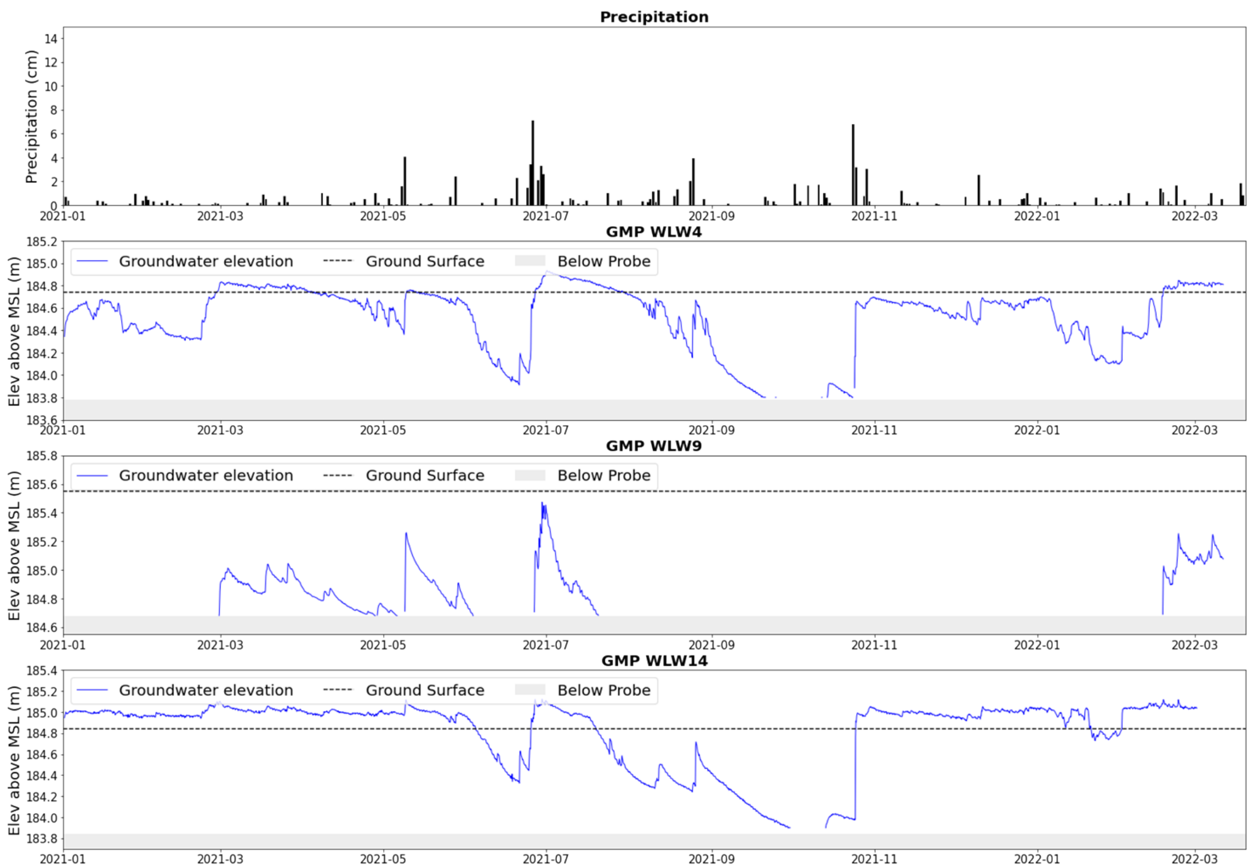

Figure 2. Time series of precipitation and groundwater levels in selected wells across the three prairies. Tick marks represent the first day of each month. The data show clear seasonal patterns in precipitation and corresponding groundwater responses, with higher water levels in spring and early summer followed by pronounced drawdown during late summer. The time series capture both surface water presence and groundwater levels, directly illustrating wetland hydroperiod dynamics. Groundwater levels for all sensors are shown in Figures S3-S8.

In the long-term time series of groundwater levels, we observe strong seasonal variation in water level, which is typical in this region because of seasonal variations in precipitation and ET (Figure 3). Precipitation in this region is driven by spring and fall rainfall, intermittent summer thunderstorms, and winter snow, which together shape seasonal recharge patterns. The locations shown in Figure 3 were selected to show a distribution of habitat types, habitat quality, and geographic distribution across the three prairies. In Sundrop, SD-EC2 is located on the northern edge of the prairie in a medium-quality area with an ephemeral wetland, SD-EC3 is located on the northern edge near the drainage ditch, and SD-WL1 is in a high-quality area towards the center of the prairie within an ephemeral wetland. In Gensburg-Markham Prairie, GMP-WLW4 is within a high-quality area in the wetland; GMP-WLW9 is in a high-quality area along the sand ridge, and WLW14 is in a low-quality area within the swale. In Paintbrush, all the sensors occupy low-quality areas that were impaired by soil fill and/or stormwater runoff, and therefore candidates for restoration by TNC. PB-WL1 is along the northern edge of the prairie near the drainage ditch, PB-EC1 is within the drainage ditch on the western edge of the prairie, and PB-EC5 is further towards the interior closest to the northeastern corner of the prairie.

We observed a period during which groundwater levels dropped below the sensor (dry well conditions) at most well locations corresponding to a period of more limited rainfall in Fall 2021 (Figure 3). At SD-EC3 and GMP-WLW9, these conditions extended until February 2022, lasting approximately 6 months. GMP-WLW9 is located along the sand ridge, an area with highly permeable soils, which accounts for the rapid hydrograph recession and deeper groundwater levels (>1.5 meters below the surface). SD-EC3 is located near the northern edge of Sundrop Prairie in an area characterized by silt and clay soils in the top 1.5 meters of the soil column. Despite these finer surface soils, the relatively rapid drainage observed at this location suggests higher subsurface permeability, which is consistent with the presence of sandy paleo-lake shoreline deposits known to occur in this region and to be interwoven with finer materials or overlain by more recent prairie soils.

Within the wetland areas of Sundrop and the swale and wetland areas of Gensburg-Markham Prairie, the water level frequently rose above the ground level. The water level was above the ground level intermittently throughout the spring and summer in the Sundrop wetlands (SD-EC2, SD-WL1) and periodically across all seasons in the GMP swale (GMP-WLW14) and wetlands (GMP-WLW4, GMP-WLW5) (Figure 3; Figure S7). Water level recession was generally slow in these areas. Further, once surface water was established, it was typically maintained for long periods of time (weeks to months). This was particularly true in the main seasonal wetland in GMP, which had standing surface water for approximately 69% of the period of observation (GMP WLW14) (Gonzalez et al., 2023, Rivera et al., 2025). Conversely, low-lying channels in Paintbrush showed much more rapid responses in water levels after storms but only rarely reached the ground surface (PB-EC1, PB-WL1), suggesting rapid propagation and infiltration of stormwater through the drainage network originating at the western boundary of this prairie (Figure 2).

3.2 Storm Event Dynamics, Stormwater Storage, and Habitat Quality

Hydrologic responses are shown in Tables 1-3 for three rainfall events, one in March, one in October, and the last in December 2021. These three rain events were chosen because they induced a measurable response in most regions of the three prairies, and they cover a range of precipitation magnitudes and antecedent conditions.

Table 1: Hydrological response across the three prairies on March 25-26, 2021, with a total of 0.97 cm of rainfall. Response characteristics at all well locations for this precipitation event are included in Tables S1-S3. We observed no measurable increase in water level at GMP-WLW4.

Sensor Name	**Description**	**Response Time** (hours)	**Relaxation Time** (hours)	**Initial Water Level** (m)	**Change in Water Level** (m)
SD-WL1	High quality wetland area with sandy loam soils	84	244	184.84	0.04
SD-EC1	Low quality prairie/wooded area with loam soils	22	284	185.30	0.06

SD-EC2	Medium quality wetland area with loam soils	31	201	184.33	0.09
GMP WLW4	High quality wetland area with loam soils	--	--	--	--
GMP-WLW9	High quality sand ridge area with loamy sand soils	23	293	184.91	0.11
GMP-WLW14	Low quality swale area with loam soils	57	254	185.03	0.02
PB-EC1	Low quality ditch area with fill soils	31	32	187.49	0.03
PB-EC2	Low quality ditch area with loam soils	17	27	186.93	0.03
PB-EC5	Low quality prairie area with loam soils	16	26	186.47	0.04

In the March 2021 rain event, precipitation lasted consistently for approximately 6 hours beginning the evening of March 25 and continuing into the early morning of March 26 with a cumulative total of 0.97 cm of rainfall. Prior to this rainfall event, there had been five small rain events in the preceding two weeks with a total rainfall of approximately 2 cm. The groundwater depth was above the sensor elevation at all locations prior to the rain event and had experienced a significant change in groundwater elevation about a month prior due to snowmelt. This precipitation event produced only small increases (0.01-0.13 m) in water level across all of the sensors (Table 1, Tables S1-S3). At Gensburg-Markham Prairie, measurable responses were spatially variable. Several wells showed no measurable response, while increases of approximately 0.10-0.12 m were observed at wells located along wetland-sand ridge or wetland-swale boundaries and at one well located near drainage ditches (WLW10) (Table S3). This spatial pattern suggests that localized hydrologic connectivity, lateral redistribution of water, and the influence of nearby drainage features may have contributed to the observed responses. At Paintbrush, response times and relaxation times were generally the shortest among the three prairies (Table S1). These locations also frequently had increases in water level less than 0.1 meters. These relatively small increases in water level are consistent with the magnitude of the rain event. The limited response at some locations, especially in wetter areas of GMP, may be due to the higher water levels already present in these areas, in contrast to the sand ridge where the groundwater levels were much lower prior to the rain event. Quicker and smaller responses at Paintbrush suggest more rapid drainage or reduced connectivity with surface runoff inputs, consistent with the presence of ditches in these areas.

The October 2021 rain event was a major frontal storm event typical of transitional fall weather conditions in the U.S. Midwest and Great Lakes regions (Changnon & Kunkel, 2006; Zhang & Villarini, 2019), with precipitation lasting for approximately 28 hours, beginning in the morning of October 24 and ending the afternoon of October 25, and accumulating a total of 10 cm of rainfall. Prior to this rainfall event, conditions had been dry with approximately 3.6 cm of rainfall in the preceding two weeks and groundwater level more than 1.5 meters below ground surface, the depth at which the water level sensors were mounted, at nearly all well locations with the exception of some wells within the wetland and swale at GMP. At Sundrop, only four sensor locations (SD-WL1, SD-WL2, SD-EC1, SD-EC2) (Table S5) showed a measurable response to this storm, with the remaining wells having groundwater below the sensor elevation (-1.5 m). The wells that showed a stormwater response are located in ephemeral wetlands (SD-WL1, SD-EC2) or along the periphery of the prairie (SD-WL2, SD-EC1). SD-WL1, located in a high-quality wetland area with sandy loam soils, exhibited the largest overall increase in water level (1.14 m).

This demonstrates the seasonal variability in hydrologic response and the impact of soil type and landscape features. Even under dry conditions, the wetlands often retain water for longer periods relative to other areas, including the sand ridge, known to dry out quickly.

Table 2: Hydrological response to rainfall event on October 24-25, 2021, with a total of 9.9 cm of rainfall. Response characteristics at all well locations for this precipitation event are included in Tables S4-S6. Water level at GMP-WLW9 showed no observable change before or after the storm event.

Sensor Name	**Description**	**Response Time** (hours)	**Relaxation Time** (hours)	**Initial Water Level** (m)	**Change in Water Level** (m)
SD-WL1	High quality wetland area with sandy loam soils	13	97	183.84	1.14
SD-EC1	Low quality prairie/wooded area with loam soils	13	94	184.47	0.32
SD-EC2	Medium quality wetland area with loam soils	15	100	183.43	0.36
GMP-WLW4	High quality wetland area with loam soils	15	94	184.65	0.50
GMP-WLW9	High quality sand ridge area with loamy sand soils	--	--	--	--
GMP-WLW14	Low quality swale area with loam soils	12	390	184.92	0.38
PB-EC1	Low quality ditch area with fill soils	16	112	186.54	0.37
PB-EC2	Low quality ditch area with loam soils	16	103	186.38	0.52
PB-EC5	Low quality prairie area with loam soils	13	108	185.51	1.05

Overall, relaxation times were similar across the three prairies. GMP displayed slightly faster response times than Sundrop. However, GMP also hosted the longest relaxation time observed across all sites at WLW14, located within a low-quality swale. The shortest response times were observed at Sundrop (Table S4), particularly at PB-EC4, located adjacent to a ditch on the northern edge of the prairie, likely reflecting direct surface flow into the ditch and adjacent area.

Table 3: Hydrological response to rainfall event on December 10, 2021, with a total of 2.54 cm of rainfall. Response characteristics at all well locations for this precipitation event are included in Tables S6-S9. Water level at GMP-WLW9 showed no observable change.

Sensor Name	**Description**	**Response Time** (hours)	**Relaxation Time** (hours)	**Initial Water Level** (m)	**Change in Water Level** (m)
SD-WL1	High quality wetland area with sandy loam soils	14	44	183.76	0.23
SD-EC1	Low quality prairie/wooded area with loam soils	12	215	184.64	0.45
SD-EC2	Medium quality wetland area with loam soils	13	217	183.57	0.29
GMP-WLW4	High quality wetland area with loam soils	16	104	184.50	0.02
GMP-WLW9	High quality sand ridge area with loamy sand soils	--	--	--	--
GMP-WLW14	Low quality swale area with loam soils	20	631	184.97	0.06
PB-EC1	Low quality ditch area with fill soils	15	47	186.86	0.05
PB-EC2	Low quality ditch area with loam soils	14	95	186.54	0.15
PB-EC5	Low quality prairie area with loam soils	14	95	186.03	0.33

The last rain event, in December 2021, is notable given the lack of significant rain events during the winter season historically. Recent studies, however, demonstrate a rise in winter precipitation event frequency and magnitude – attributing the increase to climate change (Trenberth, 2011; Bryan et al., 2015; Akinsanola, 2024). Precipitation lasted for approximately 7 hours beginning in the afternoon of December 10 and ending that same evening. In the two weeks prior to this event there had been only one rain event with approximately 0.69 cm of rainfall. However, pre-storm groundwater levels were relatively high before the December 10 event at most locations with the exception of wells within the sand ridge at Gensburg-Markham

Prairie (GMP-WLW1, GMP-WLW8, GMP-WLW9), wells in an area with fill along the southeastern edge of Sundrop (SD-WL5, SD-WL6), and a well in silty soil along the northeastern edge of Sundrop (SD-EC3). SD-EC1, located within a low-quality prairie and wooded area in Sundrop, had the largest overall increase in water level (0.45 m). Paintbrush had the shortest response time on average (Table S7), and GMP had slightly longer response times (Table S9). Wells at GMP on average also had the longest relaxation times, while wells at Paintbrush had on average the shortest relaxation times. Sites that exhibited stronger responses were in lower-quality areas or wetland areas, indicating higher connectivity with surface runoff in wetland areas or less vegetation uptake in lower quality areas.

Across all three storm events, relaxation times differed significantly among prairies (Kruskal-Wallis, $p = 0.003$). Paintbrush consistently exhibited shorter relaxation times than Sundrop and Gensburg-Markham Prairies. One potential explanation is the prevalence of engineered drainage features at Paintbrush, where many monitoring wells are located adjacent to drainage ditches that may facilitate more rapid drainage and reduce water residence times. In contrast, the longer relaxation times observed at Sundrop and Gensburg-Markham may reflect greater opportunities for temporary storage within wetlands, swales, and other low-lying landscape features.

Three different storm events were selected to assess storage volume across the prairies: May 8-9, June 24-26, and October 24-25 all during 2021. Calculated storage and precipitation volumes for each prairie and each storm are shown in Table 4. Together, the May and June events resulted in the total storage of 314,100 m^3 of precipitation across the prairies, 4.3 times the direct precipitation on the prairie surfaces, indicating significant runoff inputs and storage of off-site stormwater. During the May storm, the three prairies stored over 134,900 m^3 of precipitation, including approximately 103,600 m^3 of off-site stormwater (Figure 4). In June, the prairies stored approximately 179,200 m^3 of precipitation, including approximately 137,000 m^3 of off-site stormwater (Figure S10). Both the May and June storms exhibited significantly longer recession periods relative to other storms within the 15-month period. The average recession period for the May event was 34 days at Paintbrush Prairie, 31 days at Sundrop Prairie, and 28 days at Gensburg-Markham Prairie. For the June 2021 event, the recession period at both Paintbrush and Sundrop was 43 days, and the recession period at GMP was 34 days (Table S13). The longest recession periods for these storms were generally observed in the wetland areas of Sundrop and Gensburg-Markham Prairies (SD-WL1, SD-EC2, GMP-WLW4), indicating wetlands provided long-term storage of off-site stormwater input over multiple weeks.

For the October 2021 event, antecedent conditions were dry, with low groundwater levels at many locations across the prairies. At Paintbrush, seven of eight sensor locations provided observable responses (PB-EC6 did not.), storing approximately 18,000 m^3 of precipitation, 2.7 times greater than the direct rainfall volume of 6,600 m^3 (Figure S11). At Sundrop Prairie, only four locations produced observable responses (SD-EC1, SD-EC2, SD-WL1, and SD-WL1), Storing approximately 18,300 m^3, 1.9 times greater than the rainfall volume of 9,500 m^3 (Figure S11). Groundwater remained below sensor elevations at the remaining locations during and immediately after the storm. At Gensburg-Markham Prairie, swale, wetland, and ditch locations provided responses. Three locations in the sand ridge, GMP-WLW8, GMP-WLW9, and GMP-WLW12, did not produce observable responses, likely due to dry conditions produced from rapid drainage and low organic matter content (Hernandez et al. 2019). The total storage volume for the nine locations that responded is approximately 64,700 m^3, 2.2 times greater than the estimated rainfall volume of 29,800 m^3 (Figure S11). For this event, the three prairies stored a total of 101,000 m^3 of stormwater, including approximately 55,100 m^3 of off-site stormwater. However, this is an underestimate of total storage across the prairies as it only reflects locations where the groundwater response was captured by the sensors.

Table 4: Stormwater Storage and Precipitation Volumes for each Prairie and Storm Event

Prairie	**Date of Storm Event**	**Total Storage Volume** (m^3)	**Rainfall Volume** (m^3)	**Storage to Rainfall Ratio**
Paintbrush Prairie	May 8-9, 2021	11,300	4,000	2.8
	June 24-26, 2021	24,500	5,200	4.7
	October 24-25, 2021	18,000	6,600	2.7
Sundrop Prairie	May 8-9, 2021	71,600	13,700	5.3
	June 24-26, 2021	83,100	19,000	4.4
	October 24-25, 2021	18,300	9,500	1.9
Gensburg-Markham Prairie	May 8-9, 2021	52,000	13,600	3.8
	June 24-26, 2021	71,600	18,000	4.0
	October 24-25, 2021	64,700	29,800	2.2

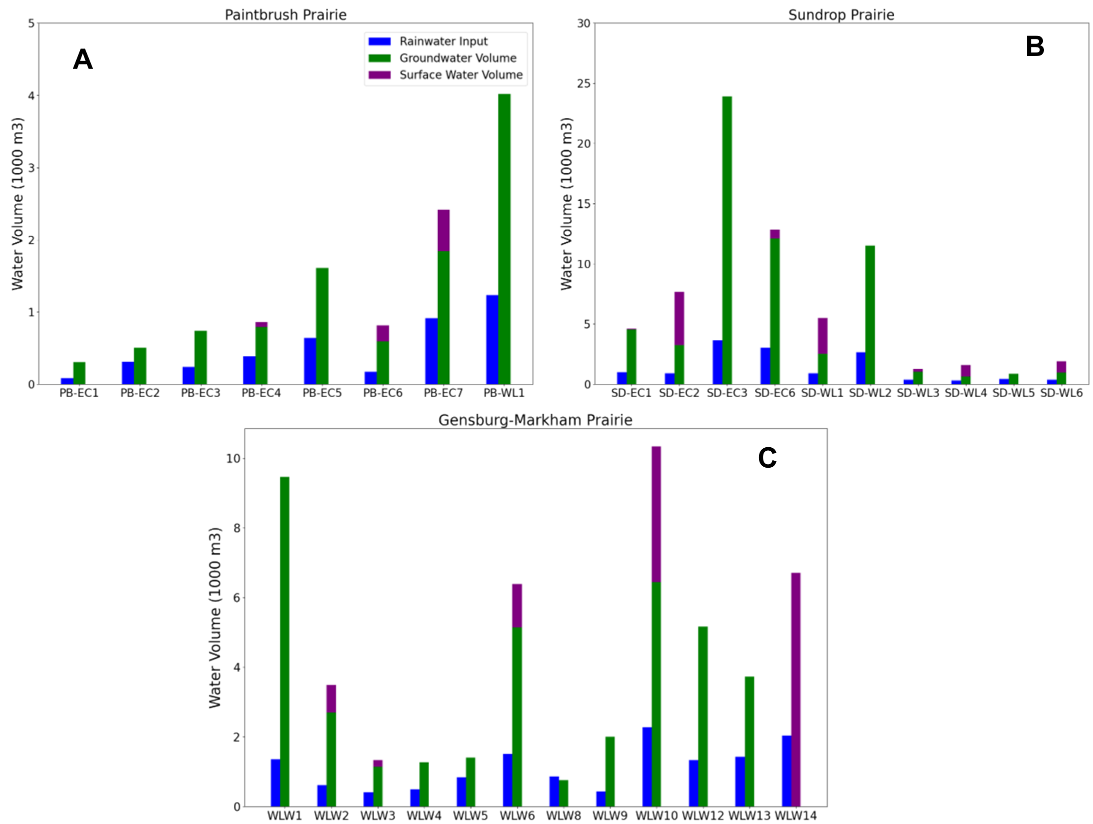

Figure 4. Groundwater and surface water storage relative to precipitation for May 2021 rainfall event: A. Shows the water budget for Paintbrush Prairie. B. Shows the water budget for Sundrop Prairie. C. Shows the water budget for Gensburg-Markham Prairie.

As described in the Methods, we assessed the hydrologic response of each observed location based on four characteristics: distance along flow path, soil type, habitat quality, and the prairie in which it is located. A Kruskal-Wallis test for 15 storms between January 2021-March 2022 showed that only variation in storage volume per unit area per unit rainfall amount across soil types was statistically significant. Dunn's post-hoc test indicated that there was a statistically significant difference in storage between areas with Watseka loamy fine sand and Selma loam, with approximately 35% less storage volume per area per rainfall amount provided by the loamy fine sands based on the median value (Figure S12). This behavior reflects the integrated dynamics of the sand ridge, where soil type, topography, and groundwater depth together influence stormwater response. The depth of the groundwater table in these areas means that the full response in water level following a rain event is often insufficiently captured and therefore does not represent the full storage capacity provided by these areas. The association with sandy soil type most likely does not represent decreased storage but rather the rapid drainage and groundwater flow from the high-permeability sand ridge to lower-lying swale and wetland areas. While there was some variation in storage based on distance along the flow path, prairie, and habitat quality, none of this variation was large enough to be statistically significant. Storage was similar amongst all categories of habitat quality, and somewhat greater at Sundrop than Paintbrush and GMP but not enough to be statistically significant.

We repeated the Kruskal-Wallis tests for hydrologic response time and relaxation time and relaxation time. Variations among response times (the time required for water levels to rise following a rainfall event) were only statistically significant for soil type. Similar to the results for storage, Dunn's post-hoc test indicated that there was a statistically significant difference in response times between areas with Watseka loamy fine sand and Selma loam, with approximately 40.5% longer response times among the Watseka loamy fine sands (Figure S13). Despite Watseka's sand component and anticipated faster response time, Hernandez Gonzalez et al., 2019 showed that the top 50 cm of Watseka soils at Gensburg-Markham Prairies contained higher levels of organic matter (OM) compared to the top 50 cm of Selma soils, ranging from 13-23% OM versus 6-13% OM in Selma soils. OM composition is associated with increased water retention in mineral-rich soils (Hudson, 1994), attributed to enhanced binding of water molecules between absorbed carbohydrates and clay surfaces (Kelch et al., 2025). No statistically significant variation in relaxation times (the time required for water levels to return to pre-storm conditions) was observed among soil types. However, there was a significant variation in relaxation times between prairies and habitat quality (Figure 5 and Figure 6). Dunn's post-hoc test indicated that there was a statistically significant difference in the relaxation times at Paintbrush and Gensburg-Markham Prairie, with approximately 57% longer relaxation times at GMP (Figure 5). This difference captures the hydrologic flashiness observed in the response at Paintbrush in locations with soil fill and direct runoff from off-site urban developments (Figure 3), and the more attenuated response associated with ephemeral wetlands at Gensburg-Markham Prairie. While many of the wells at Gensburg-Markham Prairie are located within and adjacent to the sand ridge, there are significantly more wetland wells at Gensburg-Markham relative to Paintbrush and Sundrop Prairies.

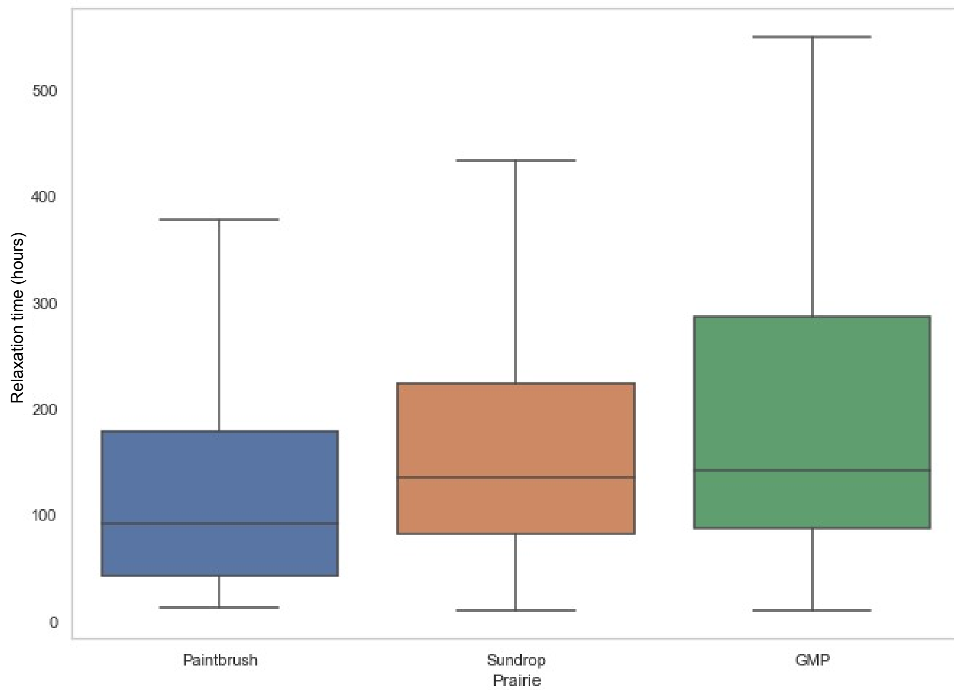

Figure 5. Box plots showing the relaxation time grouped by prairie for fifteen precipitation events between January 2021-March 2022. The colored box denotes the interquartile range with the median marked inside, and the whisker lines show the range across the fifteen events. Relaxation times are significantly longer at GMP than at Paintbrush.

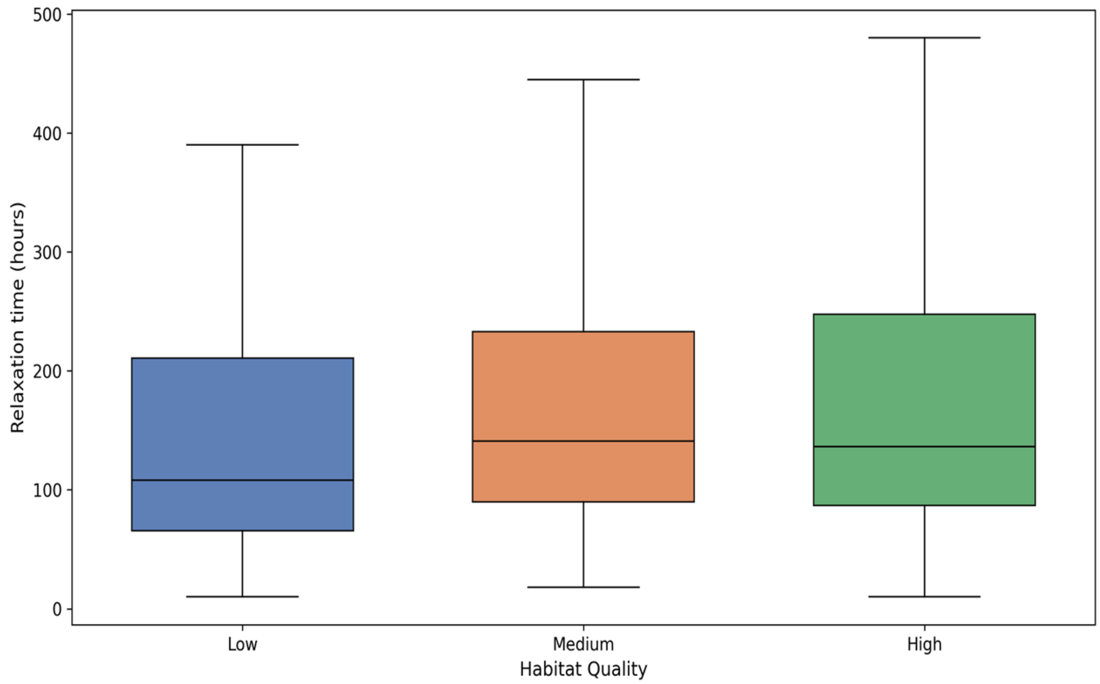

Figure 6. Box plots showing the relaxation time grouped by habitat quality for fifteen precipitation events between January 2021-March 2022. The colored box denotes the interquartile range with the median marked inside, and the whisker lines show the range across the fifteen events. Relaxation times are significantly longer in high quality areas than in low quality areas.

3.3 Conductivity Dynamics and Stormwater Input

Electrical conductivity responses following rain events were categorized according to the relationship between the derivatives of the water level and electrical conductivity following the methods of Singley et al., 2017 (as described in the Methods section). The electrical conductivity response was categorized for 12 rain events between January 2021-March 2022 (Table S10). In addition, two storm events in May 2021 and June 2021 were analyzed to determine the maximum electrical conductivity during the storm event, the increase in conductivity and categorize the conductivity response following the classification scheme adapted from Singley et al. 2017 (Tables S11-S12).

In the May 2021 storm, a typical late-spring/early-summer convective storm (Table S11), electrical conductivity levels within Paintbrush were elevated at PB-EC1 and PB-EC2 in a low quality area on the western edge of Paintbrush adjacent to a drainage ditch. Significant increases in addition to flushing behavior (when both the water level and electrical conductivity increase) were also observed at these two locations, in addition to PB-EC3, located adjacent to the drainage ditch in the northwestern corner of the prairie. Similar flushing behaviors were observed at nearly all of the other sensors in Paintbrush with the exception of PB-EC4, which is located on the northern edge of the prairie adjacent to the drainage ditch and shows no major changes in conductivity. However, the magnitude of change in conductivity was low across all wells in Paintbrush for this March 2021 storm relative to other precipitation events. At Sundrop, SD-EC1, SD-EC2, and SD-EC6, all located in the northwestern corner of the prairie along flow paths running from west to east, showed elevated conductivity levels but no major increases following the rain event. SD-EC3, located along a flow path in the northeastern portion of the prairie, showed a significant increase in conductivity, due to the water level being below the sensor prior to the storm and, therefore, showing a major increase in conductivity when the water level reached the sensor. Flushing was observed at all the sensors at Sundrop with the exception of SD-EC2, which decreased in conductivity.

In the June 2021 storm, another typical convective storm but with drier antecedent conditions (Table S11), large increases in electrical conductivity were observed because water levels were below the sensors at most locations prior to the storm. Consequently, the conductivity increases reported in Tables S11 and S12 include the initial increase associated with water levels reaching the sensor elevation, in addition to changes occurring during the storm itself. As stormwater infiltrated and water levels rose into the sensor zone, previously dry or unsaturated soils were reconnected with overlying surface inputs, leading to sharp changes in solute concentrations. In addition, we observed primarily flushing behavior at most sensors in Paintbrush with the exception of PB-EC4, a low quality ditch area with loam soils and PB-EC5, a low quality prairie area with loam soils. At Sundrop, SD-EC1 and SD-EC3 showed flushing behavior, followed by diluting. The initial flushing behavior likely reflects the movement of stormwater runoff carrying salts and metals from adjacent roads or disturbed soils into ditch adjacent areas or low-lying parts of the prairie. Areas that did not exhibit flushing behavior, like PC-EC4 and PB-EC5, suggest slower infiltration, limited solute availability, or reduced hydrologic connectivity with surface inputs. SD-EC2 also exhibited flushing after an initial period of dilution. The initial dilution may be due to surface water mixing, followed by the arrival of mobilized solutes as infiltration progressed.

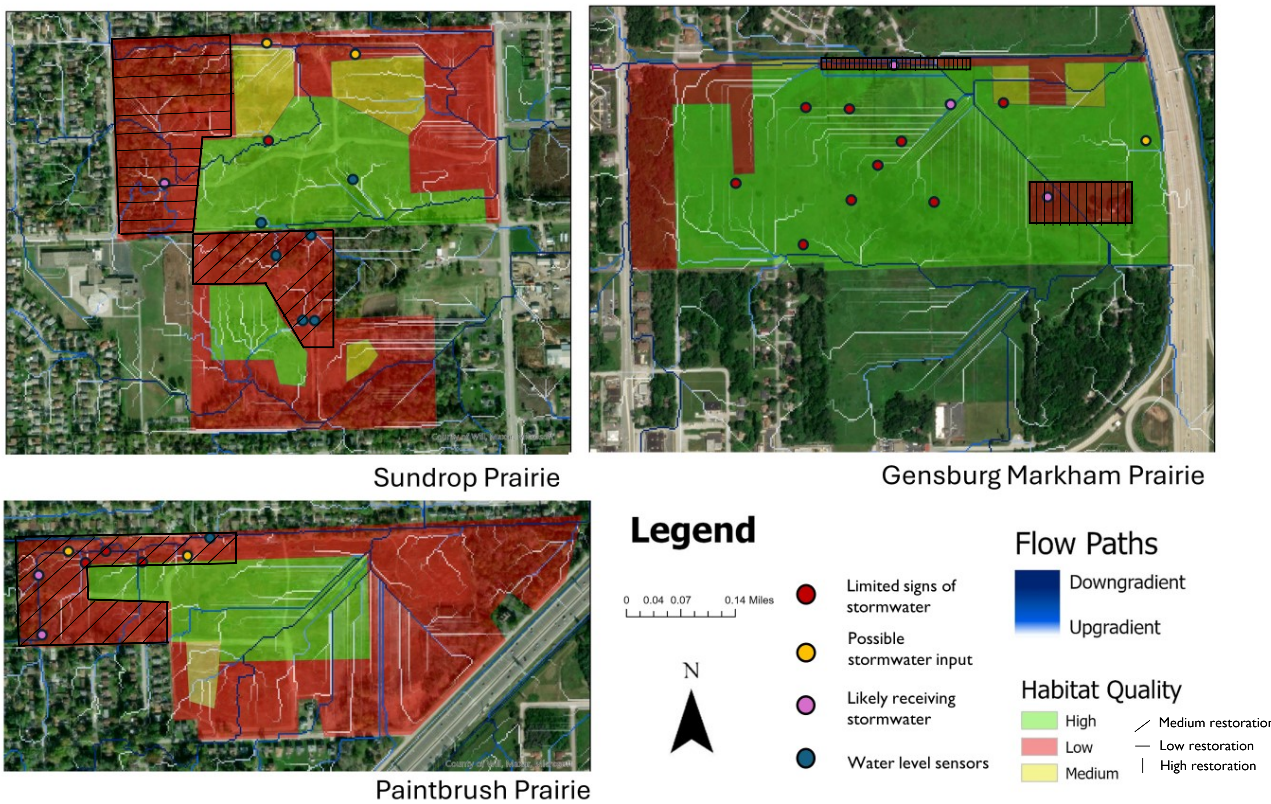

Figure 7. Flow routing and locations likely receiving offsite stormwater input across the three prairies. At Sundrop Prairie, SD-EC1 shows evidence of stormwater input. At Paintbrush Prairie, PB-EC1, PB-EC2, and PB-EC3 show evidence of stormwater input. Lastly, at Gensburg-Markham Prairie, GMP-WLW14, GMP-WLW4 and GMP-WLW5 show evidence of stormwater input. Areas shown as likely receiving stormwater were identified using electrical conductivity patterns, including elevated baseline conductivity, frequent flushing behavior, and pronounced conductivity responses to rainfall.

We integrated observations across 12 precipitation events between January 2021-March 2022 to map areas likely to receive offsite stormwater input across the three prairies (Figure 7). Locations were identified as likely receiving stormwater input based on multiple lines of evidence rather than any single metric. Specifically, locations exhibiting (1) consistently elevated electrical conductivity relative to other monitoring locations, (2) frequent flushing behavior following precipitation events, characterized by concurrent increases in water level and electrical conductivity, (3) substantial increases in electrical conductivity following rainfall events, and/or (4) rapid hydrologic responses and proximity to known flow paths or drainage features were interpreted as likely receiving stormwater-derived inputs. Locations lacking these characteristics, particularly those with consistently low conductivity values and minimal conductivity response following rainfall, were interpreted as having limited stormwater influence.

All locations showed predominantly flushing behavior across these precipitation events (Figure S9) apart from SD EC2. However, the magnitude of increase in electrical conductivity varied significantly between locations. At Paintbrush, PB-EC1 and PB-EC2 showed consistently elevated conductivity levels (Figure 1, Figure S5 and Tables S10 and S11). These locations, in addition to PB-EC3, also displayed frequent flushing behavior and large increases in conductivity after rain events. Together, these observations indicate that these locations (PB-EC1, PB-EC2, PB-EC3) likely receive stormwater input. PB-EC6 also showed elevated conductivity (Figure S6), flushing behavior, and significant increases in conductivity. However, the magnitude of increase in conductivity was much smaller than that of PB-EC1, PB-EC2 and PB-EC3. PB-EC4, PB-EC5 and PB-EC7 showed very little responsiveness in electrical conductivity, with only minor increases following storms. This limited response suggests that these locations receive little to no stormwater-derived input and are less hydrologically connected to offsite flow paths. Overall, Paintbrush exhibited a relatively consistent spatial pattern, with evidence of stormwater influence concentrated near drainage ditches and flow paths, while locations farther from these features showed limited conductivity responses and weaker indications of stormwater input.

At Sundrop, patterns were more heterogenous. SD-EC1 located in a wooded area along the western edge of the prairieshowed consistently elevated conductivity levels, significant increases in conductivity following rain events, and consistent flushing behavior, along with short response times, all of which indicate that this location receives substantial stormwater input. SD-EC2, located in a medium quality wetland site, had consistently elevated electrical conductivity levels but largely displays diluting behavior following rain events with small changes in electrical conductivity. This pattern suggests that SD-EC2 may receive water high in solutes, but experiences limited flushing during storm events, potentially indicating longer residence times, greater storage capacity, or weaker hydraulic connectivity to inflowing stormwater sources. SD-EC3 exhibited large increases in electrical conductivity following several precipitation events, which may indicate stormwater input. However, it is difficult to determine whether these increases reflect stormwater-derived solutes or simply the water level rising into the sensor measurement zone, as the water level was frequently below the sensor prior to major rainfall events. Lastly, the lower conductivity observed at SD-EC6, together with its response to only a few large rain events, suggests that offsite stormwater does not flow directly to this location but is instead routed or moderated by flow across the prairie and/or through shallow subsurface pathways.

4 Discussion

Analysis of groundwater levels (Sections 3.1 & 3.2) provides estimates of stormwater storage in the three prairies and electrical conductivity (Section 3.3) provides information on the source location of stormwater inputs, with higher conductivities associated with input of water from surrounding urban areas. Based on these observations, Paintbrush Prairie likely receives and stores stormwater that enters at the western and northern edges of the prairie. This stormwater runoff most likely originates from surrounding neighborhoods in the northwestern portion of the city of Markham, and the southern portion of the village of Midlothian. Electrical conductivity data shows that Sundrop Prairie likely also receives stormwater at the western and northern edges of the prairie. Based on flow path data, this runoff likely originates from neighborhoods in the south of Midlothian. Using the digital elevation model, we estimated that an approximate 3.5 km^2 area of Markham and Midlothian likely contributes runoff to the prairies. Using the EPA's National Stormwater Calculator for a typical block in this area (Environmental Protection Agency, 2023) we estimate that the total urban runoff volume from this area following the May 2021 precipitation event with 5.7 cm of rainfall was approximately 177,000 m3. Paintbrush and Sundrop Prairies are estimated to receive and store 47% of this runoff. The prairies provide long-term stormwater storage spanning multiple weeks to months, particularly in the beginning of the growing season from late spring to early summer. In addition, observed wetland areas tend to have the longest recession periods with no variation between wetlands in higher and lower quality areas. These results suggest that the prairies may provide meaningful flood mitigation for surrounding neighborhoods by retaining a substantial fraction of runoff generated during large precipitation events. Although the storage capacity is not sufficient to eliminate flooding risk, it likely reduces peak flows and delays runoff delivery to downstream stormwater systems, providing an important buffer for the communities of Markham and Midlothian.

Across the prairies, there is no statistically significant variation in storage volume normalized by catchment area and rainfall based on habitat quality, suggesting even low-quality prairie habitats, with relatively undisturbed subsurface soil structure (unlike landscaped turf grass plots) and vegetated with prairies and woody species, can store comparable amounts of stormwater per area as high quality areas. These findings prioritize preservation of subsurface soil structure over surface habitat characteristics for stormwater management. In addition, we saw no statistically significant variation in stormwater storage based on the degree of restoration of degraded areas. One possible explanation is that, despite reduced biodiversity, the underlying abiotic structure of the prairies, including plants with deep roots, soil composition and drainage patterns, may still be largely intact in these degraded areas. This physical integrity could help maintain similar levels of stormwater storage across sites, even if their ecological quality differs based on observations of terrestrial biodiversity and the presence of endemic flora. As a result, the above-ground habitat quality of a site vegetated with prairie or woody species may not be strongly predictive of its ability to store stormwater if the hydrologic form and structure are preserved.

While our results demonstrate the potential for both natural and ecologically degraded urban greenspace to increase regional stormwater storage and subsequently reduce local flooding, it is worth noting that the degradation observed at IBP is not representative of most anthropogenic impacts to landscapes and ecosystems. The prairies, while having experienced varying degrees of degradation, retain intact remnants that have not been subjected to extensive soil disturbance, land development or excavation, or complete removal or replacement of native vegetation. Therefore, they still provide significantly greater habitat function and ecological integrity than highly altered environments like intensive agriculture, urban land clearance, or large-scale compaction, filling, and construction. These impacts are common across roads, manufacturing facilities, large commercial and transportation projects, and intensive residential development. Additionally, even in these lower quality areas, deep-rooted prairie species support substantial stormwater storage capacity, regardless of reduced biodiversity (Rivera et al. 2025; Schulte et al. 2017b). In contrast, in more heavily disturbed urban or rural landscapes, the capacity for stormwater storage is significantly altered by extensive soil compaction, impervious surface, and stormwater control infrastructure (Shuster et al. 2014; Zhang et al. 2018). Therefore, while our findings highlight the potential value of stormwater storage in both degraded and natural green spaces, they should not be generalized to landscapes that have undergone more intensive modification, nor should they be interpreted to suggest that degradation broadly has no impact on stormwater storage.

Beyond stormwater storage, the only statistically significant variations observed were hydrologic response times based on local soil type and relaxation times across prairies. This is likely due to the structure of the prairies themselves. The steepest relaxation times were found in Paintbrush Prairie locations adjacent to ditches that receive off-site flow and transport it along the western and northern edge of the prairie (Figure 5, Table S1, S4, S7) . Gensburg-Markham Prairie, which had the longest relaxation times, is characterized by a swale area that leads to a large ephemeral wetland that receives and stores water on seasonal timescales (Figure 5, Table S3, S6, S9). These features attenuate hydrological responses. However, it is worth noting that all the wells in Paintbrush are located in areas with low quality, while the majority of the wells in Gensburg-Markham Prairie are located in areas with high habitat quality. Therefore, the comparison is not uniform because of the distinct characteristics of each prairie, and installation of additional wells within high quality areas of Paintbrush would allow for further comparison of high-quality native habitat and degraded habitat within a single prairie.

While this study provides critical information on the hydrological benefits of degraded natural areas, there are several limitations. The depth of the groundwater table during dry periods within the sandy ridge of Gensburg-Markham Prairie and portions of Sundrop Prairie prevented us from fully capturing the hydrologic response at these locations. This makes it challenging to make any concrete conclusions on the impacts of well-drained sandy soils on stormwater storage. In addition, more detailed quantitative data on habitat quality, such as could be obtained from a floristic quality assessment, and the type and precise extent of restoration, would allow for a more in-depth analysis of how different plant communities and different types of restoration efforts impact the stormwater storage capacity. Lastly, analyzing the impact of restoration over a longer time scale is needed to reveal delayed or cumulative effects on stormwater storage capacity that are not evident in short-term studies, such as gradual improvements in soil structure, root system development, or hydrologic connectivity as restored vegetation becomes more established. Floristic quality assessment and long-term analysis would also facilitate evaluation of offsite stormwater effects on habitat quality.

5 Conclusions

This study demonstrates that intact, restored, and degraded prairie habitats all have the potential to provide substantial stormwater storage and contribute to local flood mitigation. Across the study sites, we observed similar storage volumes per unit area among habitats spanning a range of ecological conditions, indicating that conventional measures of habitat quality do not fully capture the hydrologic services provided by urban greenspaces. Our analysis suggests that stormwater storage and runoff attenuation are influenced by a combination of physical and hydrologic characteristics, including soil properties, topography, and hydrologic connectivity, in addition to vegetation composition and habitat quality. These findings underscore the importance of considering multiple ecosystem services when evaluating the value of urban natural areas and prioritizing conservation and restoration efforts. While high-quality habitats provide numerous ecological benefits and remain critical conservation priorities, lower-quality and highly altered sites may also retain meaningful stormwater storage capacity. These results demonstrate the need for comprehensive assessments to understand the full value of ecosystem services provided by urban greenspaces. The persistence of stormwater storage in degraded areas further emphasizes the value of protecting and enhancing remnant green spaces, not only for flood mitigation but also as flexible tools for climate adaptation in developed landscapes. Overall, our findings demonstrate that evaluating urban natural areas through multiple ecosystem service lenses provides a more complete understanding of their ecological and hydrologic value, recognizing that ecological condition and hydrologic function may not always align.

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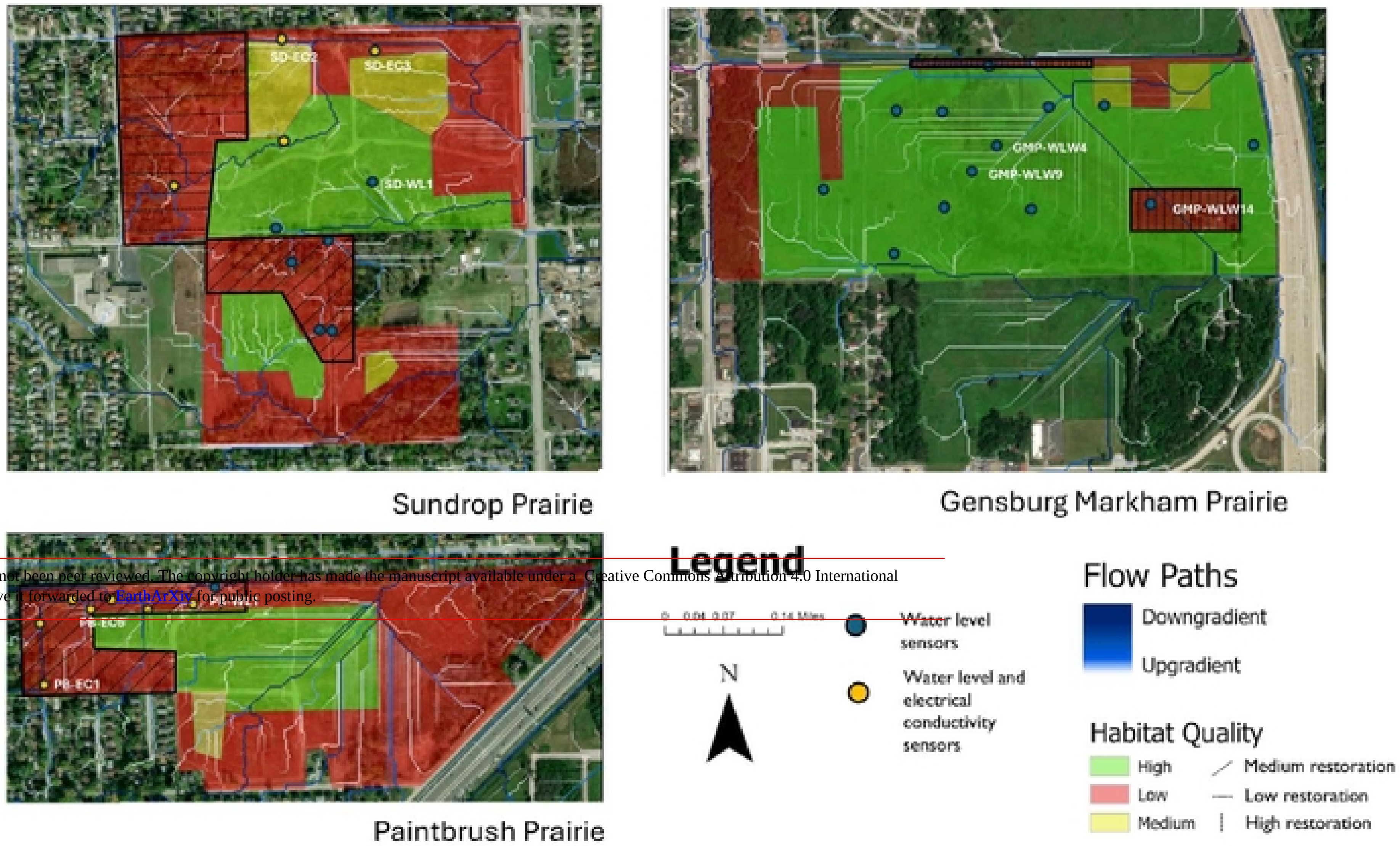
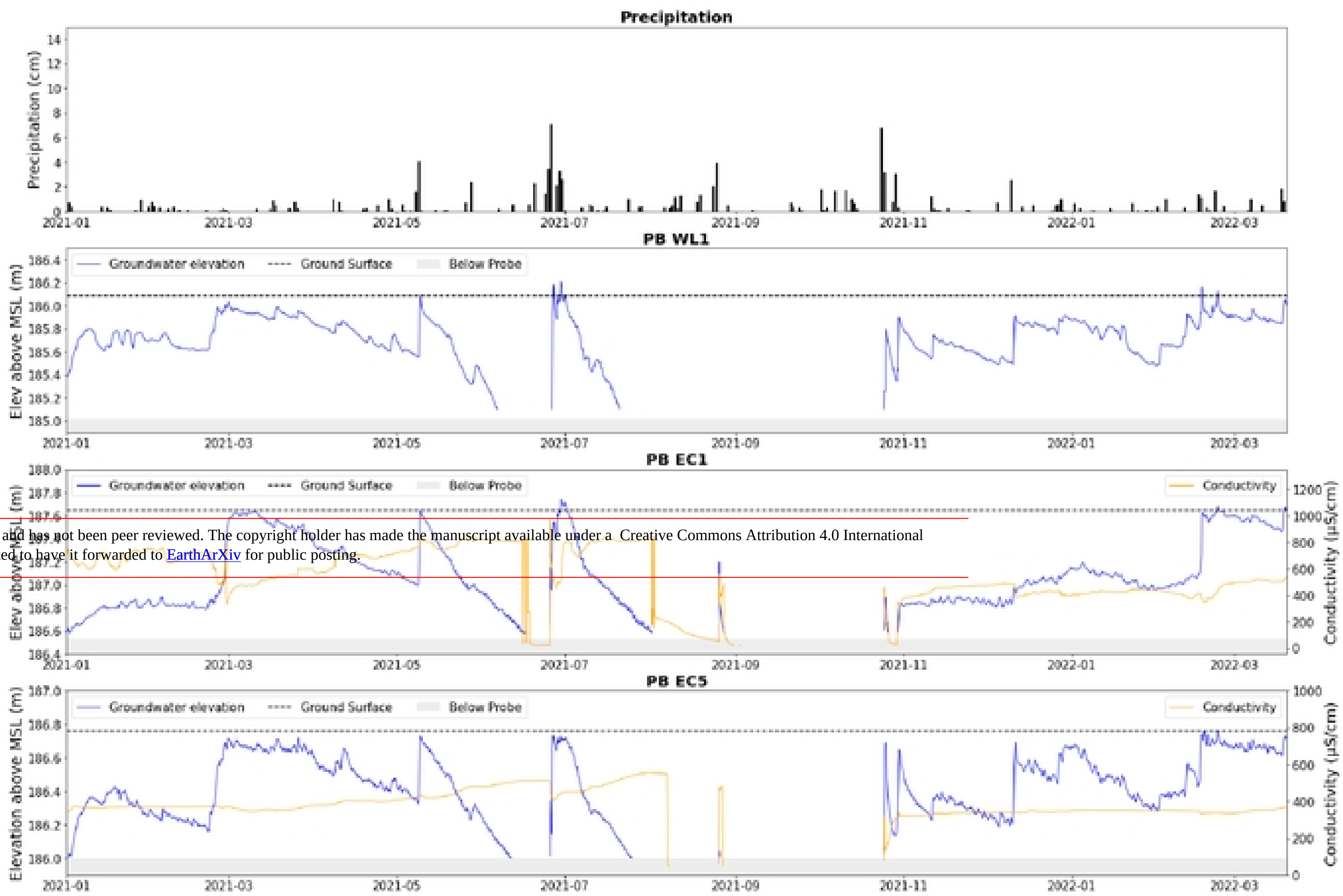
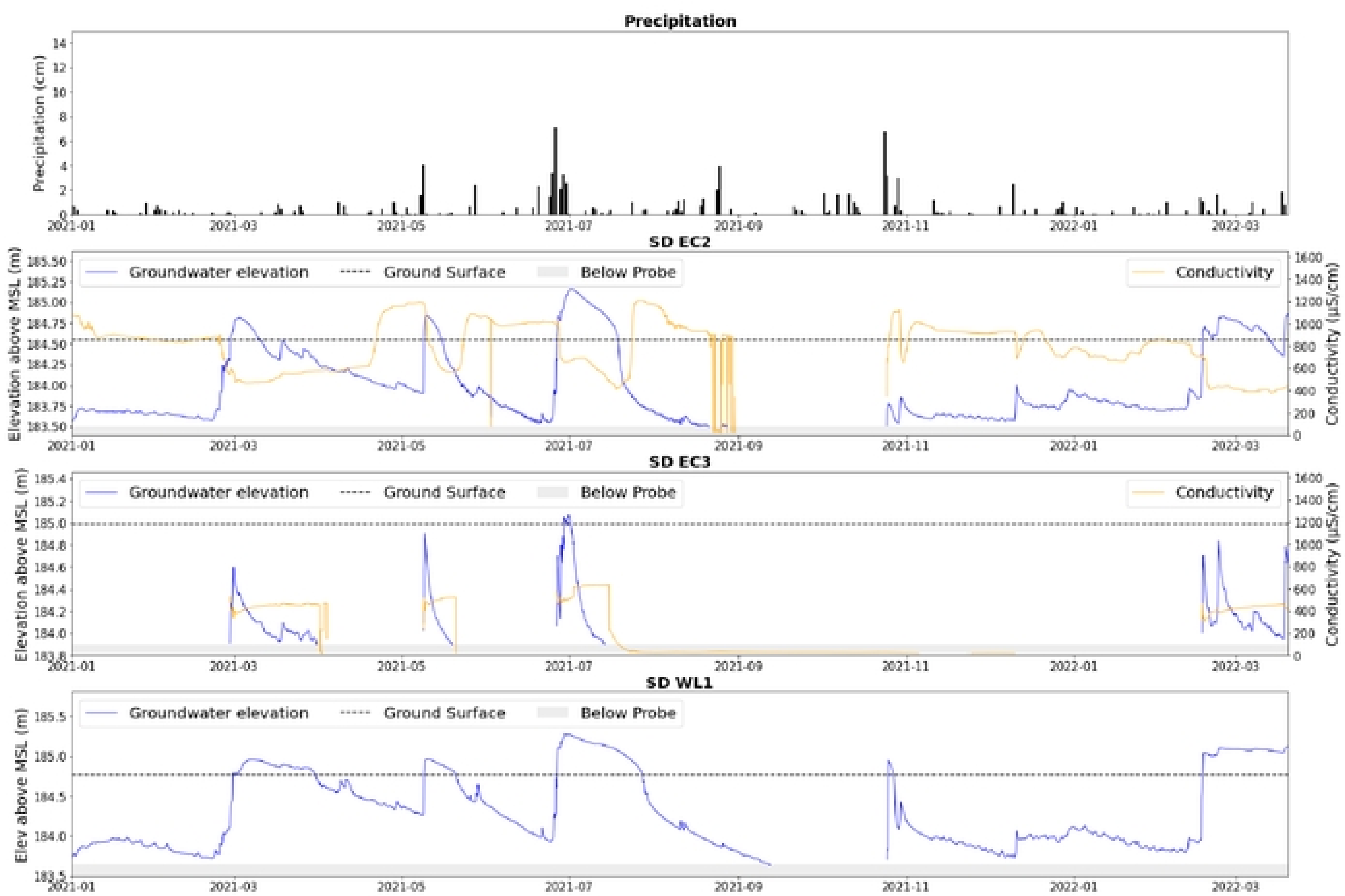


Figure 2. Surface water flow routing and direction across the three prairies: Sundrop Prairie, Gensburg Markham Prairie and Paintbrush Prairie. Habitat quality determined by The Nature Conservancy shows low-, medium- and high-quality areas across the prairies along with the extent of restoration (low, medium and high) within the low-quality habitat areas.

Figure2


Precipitation
Precipitation (cm)
PB WL1
Groundwater elevation
Ground Surface
Below Probe
Elev above MSL (m)
PB EC1
Conductivity
Conductivity (µS/cm)
PB EC5
Elevation above MSL (m)
2021-01
2021-03
2021-05
2021-07
2021-09
2021-11
2022-01
2022-03


Precipitation
Precipitation (cm)
SD EC2
Groundwater elevation
Ground Surface
Below Probe
Conductivity
Elevation above MSL (m)
Conductivity (µS/cm)
SD EC3
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2022-01
2022-03

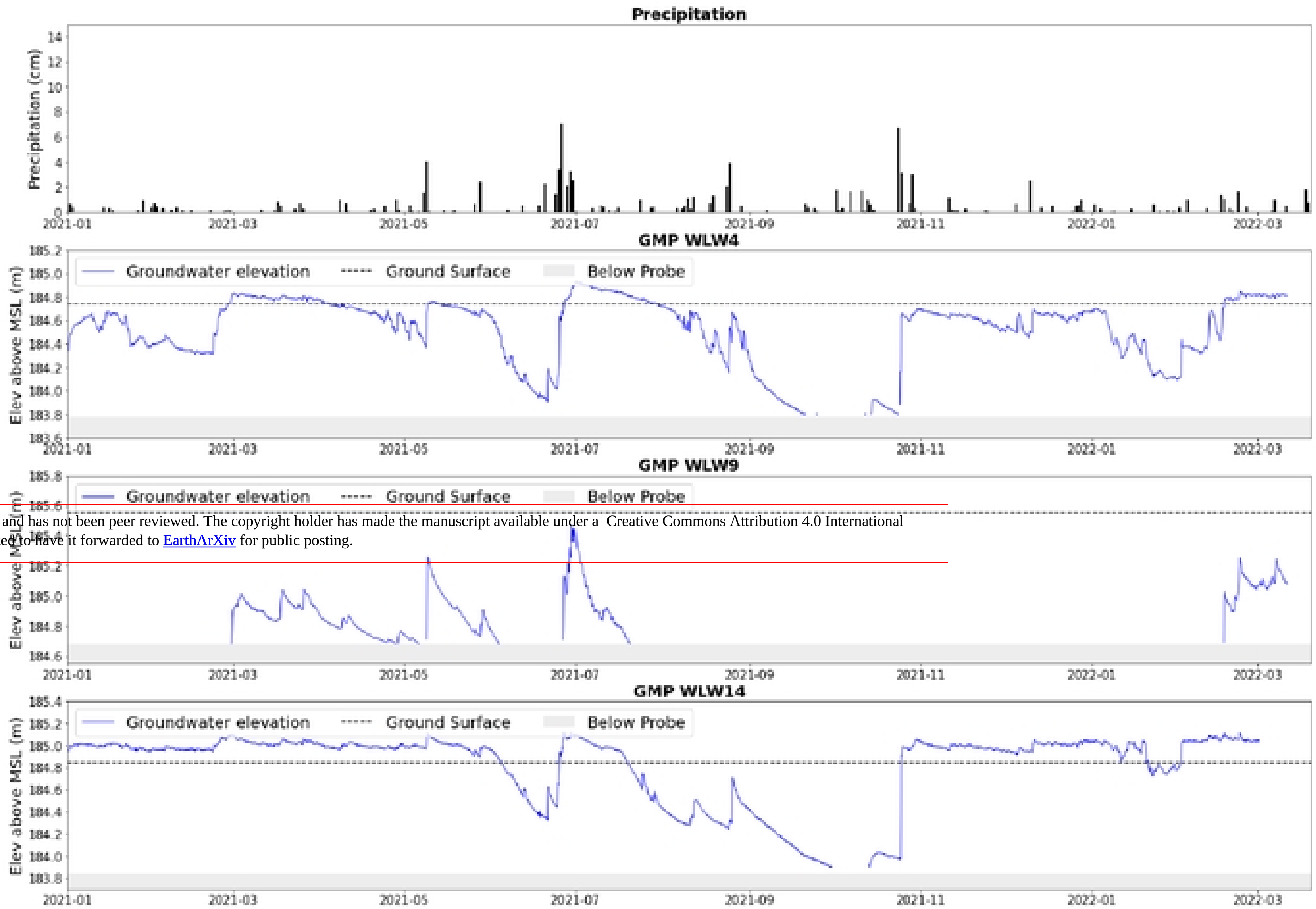

Figure 3. Time series of precipitation and groundwater levels in selected wells across the three prairies. Tick marks represent the first day of each month. The data show clear seasonal patterns in precipitation and corresponding groundwater responses, with higher water levels in spring and early summer followed by pronounced drawdown during late summer. The time series capture both surface water presence and groundwater levels, directly illustrating wetland hydroperiod dynamics. Groundwater levels for all sensors are shown in Figures S3-S8.