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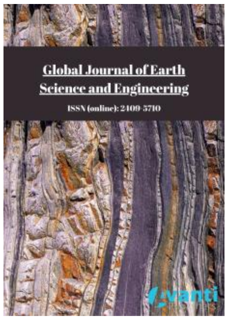

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An Urban Lake Drainage Catena: Influences of Terrain, Soils, and Precipitation

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ABSTRACT

Urban lake drainage systems are heavily impacted by terrain, soil characteristics, and precipitation, which influence water infiltration and groundwater movement. This study focused on the drainage catena around Lake Nokomis in Minneapolis, Minnesota, where local residents have experienced wet basements and yards. The primary goal was to identify the factors contributing to these water-related problems, particularly soil permeability and how it responds to precipitation. By conducting soil borings, using pressure transducers, and measuring saturated hydraulic conductivity (Kfs), the study compared upland and lowland areas. Findings indicated that upland soils, primarily composed of sandy fill, had much higher infiltration rates, with Kfs values ranging from 72.4 cm/hr to 149 cm/hr. In contrast, lowland areas characterized by lacustrine and organic soils exhibited significantly lower Kfs values, ranging from 1 cm/hr to 14.8 cm/hr. Between 2022 and 2024, wet and dry seasons occurred, yet recorded more than 127.5 cm of rain and snow water equivalent, further contributing to groundwater rise and surface water presence in low-lying regions. The study concluded that increased precipitation, coupled with specific hydrogeologic conditions, was the main factor causing elevated groundwater levels and surface saturation in these areas. To address these challenges, Minnesota's water management authorities are encouraged to implement strategies that consider the increasing magnitude and intensity of precipitation events due to climate change. Incorporating hydrogeologic assessments into urban planning is recommended to better manage water infiltration, reduce flood risks, and strengthen the resilience of drainage systems to changing climate patterns.

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1. Introduction

Soil permeability or soil hydraulic conductivity is the ability of soil to transmit water. Soil scientists and researchers use it to determine soil health and estimate how water moves through different soil types and textures [1]. Globally, farmers use soil hydraulic conductivity to make agriculture decisions, determine irrigation rates, and estimate nutrient leaching and erosion rates. Ultimately soil hydraulic conductivity governs water flow and affects every soil application. It is the key to understanding the water balance within the soil [1]. Maintaining a healthy soil structure appears to be a critical factor in the soil health equation. Soil structure, along with soil hydraulic conductivity may be the two most important variables for healthy soil in any drainage catena. But what happens when human activity disrupts the natural landscape?

Removing marshes and prairies comes with a cost. Ultimately, converting a wetland or a prairie to an urban landscape (i.e., trails, paths, parks, roads, commercial buildings, neighborhoods, etc.) will have more of a negative impact on the overall landscape health and structure of the soil [2]. In general, urban landscapes and the development of impermeable surfaces will increase runoff and pollution in nearby streams and lakes.

A specific example of this phenomenon can be seen in Lake Nokomis in Minneapolis, Minnesota. Up until 1910, Lake Nokomis was known as Lake Amelia and originally served as a reservoir to maintain the constant flow of water over Minnehaha Falls. The Parks board bought Lake Nokomis in 1908. In 1911, the southwest corner of the lake was rented out to a cranberry farmer. From 1914-1917, Lake Nokomis was dredged out and beaches and bath houses were constructed. Additionally, Theodore Wirth, the Parks superintendent, decided to create a nearby lagoon that would relieve Nokomis of its reservoir activities [3]. In the 1940s a garbage dump was established next to Mother Lake. Much of the garbage made its way into Lake Nokomis, thus Minneapolis decided to close off the inlet that connected Mother Lake and Lake Nokomis. However, the inlet was reopened when the dump moved locations. In the 1970s, Minneapolis began to care about the water quality of Lake Nokomis and regretted the removal of marshes and wetlands that once surrounded the lake. To improve water quality in Lake Nokomis, Naturescape installed a wetland prairie in 1999 [3].

The hydraulic properties of surface soils are influenced by the drainage catena (upland to lowland topography and land use). Worldwide, soil texture and structure determine how water from irrigation, rainfall, and snowmelt is managed—whether it infiltrates the soil or becomes runoff [4, 5]. Organic soil, peat/muck has a larger organic matter (OM) content, a lower bulk density (BD), and up to almost 100% pore space with isolated or closed pores compared to mineral soils [6- 8]. Macropores have a significant impact on hydraulic properties [9] and are a crucial component of the pore structure in peat soils [10, 11]. Human-induced disturbances such as machine disturbance during construction are one management technique that affects the pore-size distribution and pore continuity, which in turn affects the hydraulic properties of the soil. Converting land from native trees, shrubs, forbs, and grasses, increases the runoff/infiltration ratio [12].

Morainic formations lack a systematic particle arrangement with depth and show notable heterogeneity over small distances. Hydraulic conductivity in fine-grained till, like clayey till, is typically slow but may become rapid in surface layers because of fissure development. Hydraulic conductivity typically decreases with grain size in the unsaturated zone [13]. In fine-grained till the primary porosity is low due to the small grain size and tight packing of clay particles. However, particle size does not totally define water flow. Fine-grained till can develop secondary porosity, so the overall hydraulic conductivity can vary. In the surface layers of clayey-till, secondary porosity from fissures or cracks can create temporary pathways for water to move more easily. This localized increase in hydraulic conductivity is due to the introduction of additional pore spaces that were not present in the primary structure of the till. While secondary porosity from factors like soil structure changes (via freeze/thaw or deep-rooted plants) channels, can create pathways for water movement, and the overall effect in fine-textured soils can be important when basements flood. Nevertheless, compared to coarser soils, where primary porosity is higher, secondary porosity can move larger volumes of water.

Histosols, rich in organic material (peat and muck), generally exhibit low hydraulic conductivity. However, due to organic material mixing mainly in upper soil layers, conductivity may increase with depth in these horizons. Upslope locations, typically with Orthic Podzols, exhibit higher overall hydraulic conductivities throughout the soil profile compared to low-lying locations with Podzols and Gleysols [14].

In the decade prior to this investigation, from 2012 to 2021, the Minneapolis, Minnesota metropolitan area saw significantly high precipitation, with rainfall totaling the equivalent of eleven years in just ten years [15]. However, the two years directly before the study, 2020 and 2021, were characterized by drought conditions [15]. Livdahl [16] found that a significant portion of rainfall during the study period contributed to groundwater recharge. The US Geological Survey (USGS) took monthly water level measurements from the installed monitoring wells and estimated changes in surficial aquifer storage around Lake Nokomis. This component reflects how the storage of water in the near-surface aquifer changed over time due to precipitation and some other factors. The USGS will document their work in a separate report.

Other factors influencing changes in surficial aquifer storage include elevated evapotranspiration rates, which diminish the amount of water available for groundwater recharge. During times of high evaporation or active vegetation transpiration, reduced water infiltrates into the groundwater system [17]. The permeability and porosity of the soil also influence the volume of water that can infiltrate and recharge the aquifer. Generally, sandy soils facilitate greater infiltration than clayey soils [18]. If the soil is saturated from prior rainfall, any additional rain is likely to lead to increased surface runoff rather than further infiltration [19]. Development and urbanization often lead to a rise in impervious surfaces, such as roads and buildings, which in turn increases runoff and decreases groundwater recharge. Urban activities, like lawn irrigation, can either enhance groundwater recharge or boost surface runoff, depending on the irrigation methods and timing [20, 21]. Heavy, intense rainfall tends to increase runoff and decrease infiltration, while gentle, prolonged rainfall allows more time for water to infiltrate [22]. The distribution of rainfall over time affects groundwater recharge. For example, frequent but light rains might result in consistent recharge, whereas infrequent heavy rains might cause significant recharge but less frequently [23]. In addition to this, pronounced catena slopes can increase surface runoff and reduce infiltration compared to flatter areas [24].

Groundwater discharge into Lake Nokomis is relatively minor, contributing minimally to lake levels. Additionally, the study observed negligible evapotranspiration directly from the groundwater system, suggesting that groundwater levels remained sufficiently deep below the land surface to prevent significant loss through evaporation [16]. Large lakes are typically driven by differences in net water balances related to snowmelt, precipitation, and evaporation. Groundwater and surface-water exchanges have less of an impact on seasonal or annual changes in water levels and storage in large lakes compared to smaller lakes [25, 26]. Water levels in lakes that are hydrologically related to aquifers can drop as a result of declining groundwater levels in aquifers [27]. Increased extraction of groundwater from the aquifers within the groundwater basin surrounding a lake may lower both groundwater and lake levels. This is due to a decrease in the amount of groundwater entering the lake and an increase in water outflow from the lake to the aquifers [28]. Additionally, directing surface water away from the lake's watershed could diminish leakage or replenishment to nearby groundwater systems, resulting in decreased groundwater levels and potentially reducing groundwater influx into the lake [28]. Coates [29] also found that declines in groundwater levels due to groundwater extraction in and around the City of St. Paul had led to higher water losses from numerous lakes [28]. Seepage rates and water levels monitored in nearshore and deep-water locations of White Bear Lake show that groundwater predominantly enters the lake near its shores, while groundwater primarily comes from deeper downgradient zones. Measurements of seepage rates in nearshore locations generally exceed those measured in deep-water sites. This suggests that groundwater inflow rates at most nearshore sites surpass the outflow of lake water from deep-water sites [27]. These can be difficult measurements to make and require specialized equipment. More importantly, given the wet basements in the Nokomis Lake area, we desired to learn if important amounts of new rainfall/snow-melt entered the soil near the lakeshore compared to upland locations as inferred by Schaufler [15].

Cresswell [30] investigated how soil structure impacts hydraulic conductivity in agricultural environments. Their study employed deterministic models such as SWIM to simulate the effects of long-term tillage practices on infiltration and runoff under particular rainfall conditions. However, this research focused mainly on agricultural fields, where key issues include crop water availability and soil erosion but didn't address urban lake settings. Similarly, [31] explored the reduced infiltration capacity of disturbed urban soils in connection with bioretention stormwater control, but they did not specifically address the unique dynamics of urban lakes or the complex interactions between urban land use and nearby water bodies. Thomas and John [32] have demonstrated that urban landscapes greatly impact soil permeability, especially near urban lakes, where human activities have disrupted natural soil structures. Urban landscapes with impervious surfaces are commonly seen as obstacles to groundwater recharge, but they often develop fractures that introduce secondary permeability, enabling some level of infiltration. Research has shown that local climate conditions and human activities, like construction and landscaping, have substantial impacts on soil profiles and properties. These interventions can influence critical factors such as soil water retention, salinity, and acidity, which are essential for urban planning and infrastructure development [33]. However, many of these studies lack the detailed, fine-scale insights that would be particularly useful for urban homeowners and planners.

This study fills these gaps by investigating saturated hydraulic conductivity (Kfs) in a neighborhood around an urban lake, providing important data on how soil permeability differs between upland and lowland areas across multiple seasons. The research will offer key insights for urban water management and infrastructure planning, aiding in the creation of sustainable strategies to reduce the effects of urbanization on water infiltration.

2. Materials and Methods

2.1. Introduction to the Research Area

Situated in the southeast corner of Minneapolis, Minnesota, is an urban lake known as Lake Nokomis as shown in Fig. (**1**). A dam and weir connect the lake to Minnehaha Creek, situated in the northwestern portion of the lake. The lake and surrounding area were more like an open-water wetland or shallow lake before reconstruction in the

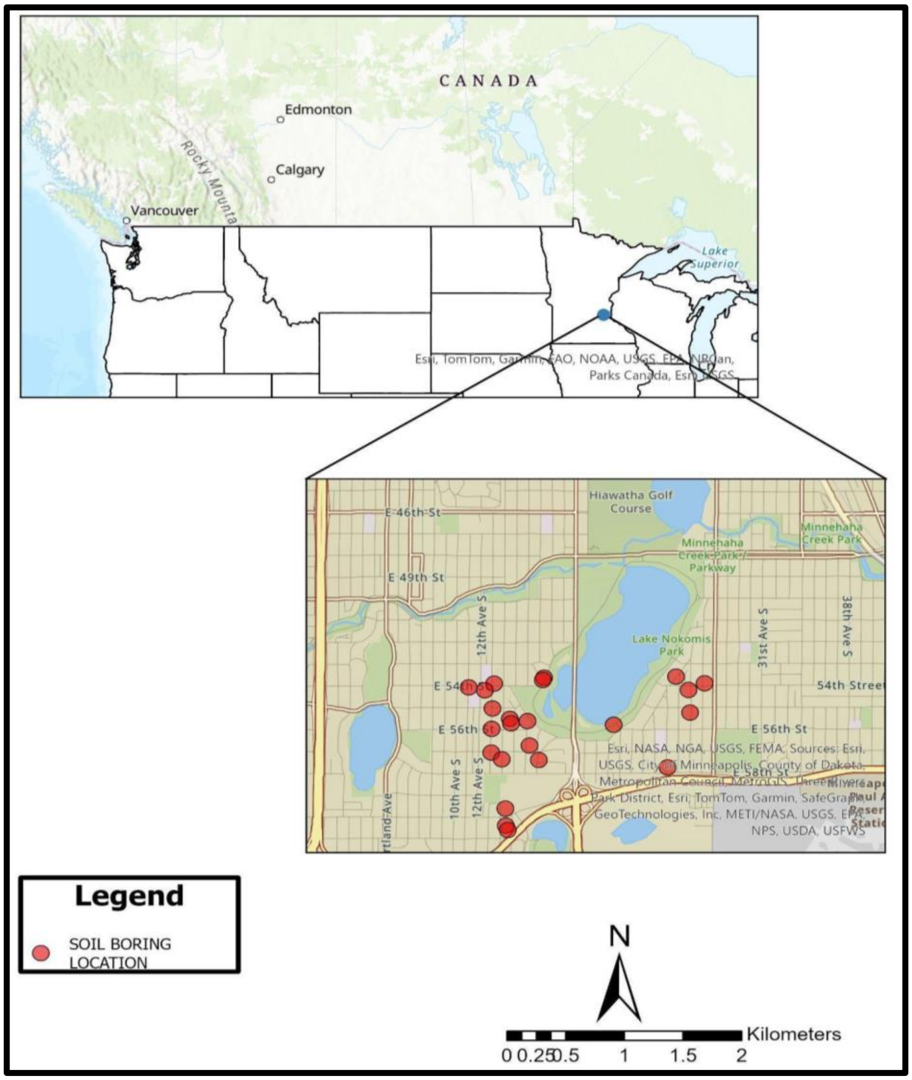


Figure 1: Area of concern showing Lake Nokomis area soil borings, Minneapolis, MN, USA.

early 1900s. Soil borings confirmed deep loamy sands over 3 m thick with some borings exhibiting lacustrine fines and/or peat/muck deposits that appear to have been buried post-European settlement. The early 1900s saw the excavation of the lake. In order to improve the surrounding region and make it more development-friendly, the excavated material was utilized as fill [15], suggesting a very humanly disturbed sequence of fill over native material. The site is a relatively active area with high recreational use and foot traffic.

2.2. Sampling and Monitoring Methods

Soil borings were conducted over multiple days to validate implied mapped survey data. Sand and open hand augers with extensions and a Giddings truck-mounted auger were used to drill 7.62 cm diameter holes at most study site locations. A tarp was laid on the ground to horizontally define soil layers. A utensil was used to push cohesive soil out of the auger. Large buckets were used to store excess soil. WD-40 was used on threaded joints for removing the handle and/or extension pipe. Representative soil samples were placed in sealed bags and brought back to the University of Minnesota lab. Lastly, we used a stadia rod to measure the depth of borehole advancement to design well placement and construct soil boring profiles.

Infiltration data collection occurred over one field day at two different catena’s representing different land and vegetative characteristics. These sites were distinguished as urban prairie/sedge, and disturbed/mowed lawns. Three (including one backup) SATURO Dual-Head Infiltrometers were utilized for data analysis of field-saturated hydraulic conductivity (Kfs) and infiltration rates as shown in Fig. (**2**). Surface litter was removed to a minimal extent at the beginning of each site test to reduce error. Kfs data was measured in centimeters per hour (cm/hr). The SATURO cylinder was driven into the ground by the use of a rubber mallet until flush with the soil surface. Through the process of obtaining Kfs data, the land surface is brought to a near-saturated surface. 284 liters of water (pre-filled with clear public tap water in plastic buckets) were used to supply water to the SATURO hose connection.

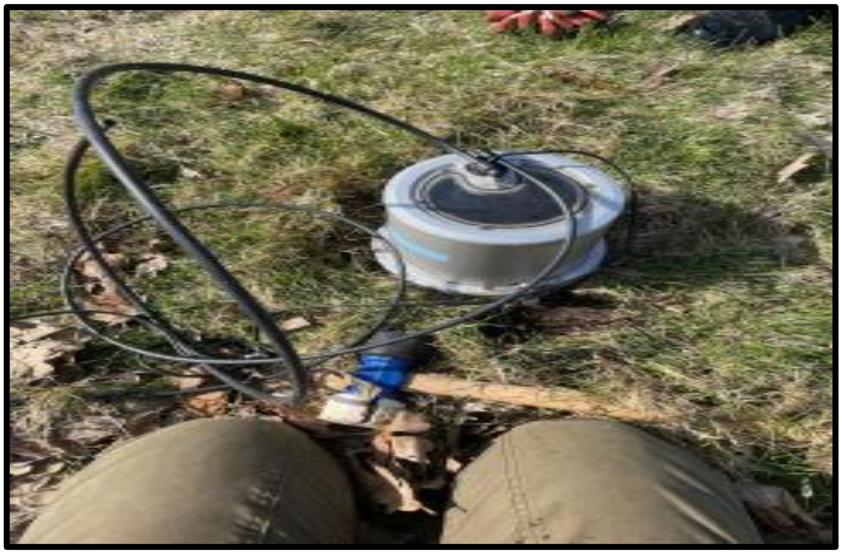


Figure 2: SATURO dual-head infiltrometer.

Three runs (or tests) were performed at each site in August 2022, April 2023, and April 2024 which accounted for 18 runs in total. With three error/failed runs in the use of the SATURO infiltrometers, 15 total tests were completed to obtain the appropriate amount of data. Each run occurred for 95 minutes, including two cycles for each test. The complete predetermined parameters set on the infiltrometer include pressure head (cm), soak time (min), pressure cycles (2), insertion depth (cm), and run time (min) similar to Table **1**.

We chose the SATURO infiltrometer over traditional infiltrometers and the Modified Phillips-Dunne (MPD) as the SATURO infiltrometer has the advantage of providing Kfs values in real-time due to its automated functionality. In contrast, traditional methods such as the MPD necessitate manual data extraction and analysis after the experiment. This real-time capability can greatly improve the efficiency of field measurements and shorten the time required for data processing. The automated features of the SATURO reduce the potential for human error during data collection. In contrast, traditional methods often depend on manual recording, which can introduce inaccuracies [34]. The SATURO is designed to address challenges like lateral flow and soil capillarity, which frequently affect infiltration measurements. The SATURO employs a dual-head system that measures infiltration rates by accounting for three-dimensional flow. This represents a notable advancement over single-ring methods, which may overlook complex soil dynamics. The SATURO's capability enables a more precise depiction of how water interacts with the soil structure. The SATURO is designed to be user-friendly, making it accessible to researchers with limited experience. Its streamlined setup process enables faster deployment in the field, which is especially advantageous for time-sensitive projects [35]. Another reason was that according to [36] the SATURO infiltrometer, especially in its single-ring and double-square configurations, demonstrated notable water savings of 57% and 66%, respectively, compared to the conventional double-ring infiltrometer. This underscores the effectiveness of SATURO infiltrometers in minimizing water use during infiltration tests.

Table 1: SATURO parameters used.

Parameter	Units	Value
Pressure Head 1	cm	5
Pressure Head 2	cm	10
Soak Time	min	15
Pressure Cycles	-	2
Hold Time	min	20
Insertion Depth	cm	10
Run Time	min	95

Bore holes were made and PVC pipes with a meter of slotted screen were installed to check the water table depth. The dug soil was placed back into the hole and any excess soil was removed from the site to maintain ascetics.

Building on the insights gained from the soil borings, we strategically installed a network of monitoring wells throughout the Nokomis Project Area. The well installation process was designed to capture the variability in groundwater conditions across different parts of the study area, particularly in relation to the identified aquitard layers. Emphasis was placed on areas that also had a history of resident water issues. The wells were categorized based on their position relative to the aquitard layers, with the naming convention updated accordingly. Wells with screens located above an aquitard were designated as "P" for perched, indicating that they are likely to capture perched water tables. Wells with screens located below an aquitard or in areas where no aquitard is present were designated as "NP" for non-perched. This distinction is critical for understanding the vertical distribution of groundwater and the impact of aquitard layers on water movement. Paired wells were installed at specific locations where perched water tables were suspected. These pairs included a shallow perched well (e.g., P-Sc1-S) and a deeper non-perched well (e.g., NP-Sc2-S), allowing for direct comparison of hydraulic head levels and water chemistry above and below the aquitard. This setup was instrumental in assessing the degree of water retention by the aquitards and the responsiveness of the perched water tables to precipitation events. The well installation process for the lake water budget also considered the topography and land use patterns in the area. Wells were placed in both upland ("U") and lowland ("L") areas to capture the full range of hydrologic conditions. The data collected from these wells provided valuable insights into the dynamics of groundwater recharge, the influence of aquitard layers on water movement, and the potential for future infrastructure challenges related to saturated soils.

To accurately monitor and analyze the groundwater dynamics within the Nokomis Project Area, pressure transducers were installed in the monitoring wells and above ground (Barometers) to compensate for air pressure.

These devices were used to obtain continuous, high-resolution data on the water table fluctuations and hydraulic head changes in response to various environmental factors, particularly precipitation events.

Pressure transducers are instruments that measure the pressure exerted by the water column above the device, which can be directly related to the water level in the well. The pressure recorded by the transducer is directly related to the water pressure and the air pressure. This measurement is crucial in monitoring water levels and understanding aquifer responses to atmospheric changes [37]. By continuously recording pressure data, these devices provide detailed information on the variations in groundwater levels over time. The transducers were programmed to record pressure readings at regular intervals of 15 minutes, allowing for the capture of short-term fluctuations in groundwater levels, such as those caused by individual rainfall events, as well as longer-term trends related to seasonal changes or prolonged wet periods.

Once the pressure data was collected, was air pressure compensated and converted into water level data using established hydrostatic principles. Hydrostatic principles rely on the relationship between the pressure exerted by a liquid column and the height of that column [38]. Here, the height corresponds to the water level in a well (Fig. **3**).

The basic principle used is given by Pascal's law:

$P=\rho gh$……(1)

Here:

P: pressure exerted by the water column,

ρ: density of water,

g: acceleration due to gravity, and

h: height or depth of water column.

$h=P/\rho g$…….(2)

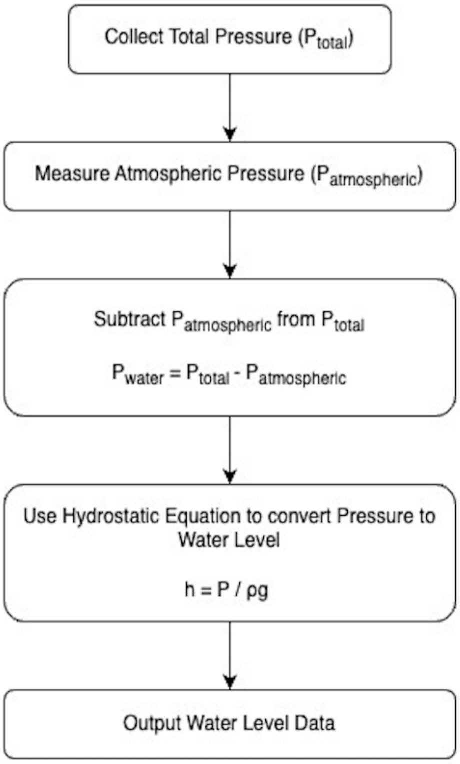


Figure 3: Flow chart showing data processing from the pressure transducer.

The pressure recorded by the transducer accounts for both atmospheric pressure and the pressure from the water column. To determine the water level, the atmospheric pressure is first removed by subtracting it from the total pressure. The remaining pressure, which reflects the water pressure, can then be converted into the water level using the hydrostatic equation (2).

The mean annual precipitation is 68-83 cm, and the mean annual air temperature is 4-8 degree Celsius. Minneapolis, MN has had above-normal precipitation and snow data observed for 2023. Snow accumulation has totaled 127.5 cm, 229.1 cm, and 74.93 cm from 2022 to 2024, and precipitation has totaled 58.34 cm, and 57.63 cm for these years [39].

2.3. Data Analysis Methods

To assess whether there was a statistically significant difference in the saturated hydraulic conductivity (Kfs) values between upland and lowland areas for each of the years (2022, 2023, and 2024), we conducted independent two-sample t-tests. This method was selected because it is specifically suited for comparing the means of two independent groups, in this case, upland and lowland regions, when the data are continuous and assumed to follow an approximately normal distribution.

The Kfs values were organized by location (upland and lowland) and year (2022, 2023, 2024), with each year treated as an independent sample. A two-sample t-test, appropriate for comparing independent groups, was conducted for each year to test the null hypothesis that there is no significant difference in Kfs values between the upland and lowland areas. The analysis was performed in R, using a significance level of α = 0.05.

3. Results

We validated the soil mapping in the study areas that were classified as U1A (Urban land-Udorthents, wet substratum) and U2A (Udorthents, wet substratum). Mineral fill topsoil was always found over sand and/or lacustrine/organic soil as shown in Fig. (**4a**,**b**). Landforms were classified as stream terraces, outwash plains, and moraines but our observation found lacustrine features. Slopes range from 0 to 2 percent on both soil map units, historic shorelines in some locations were steeper, pointing to more clearly defined upland and lowlands. We validated that these areas contained wet substratum; defined as soils that have been disturbed to the point of filling or draining topsoil [40].

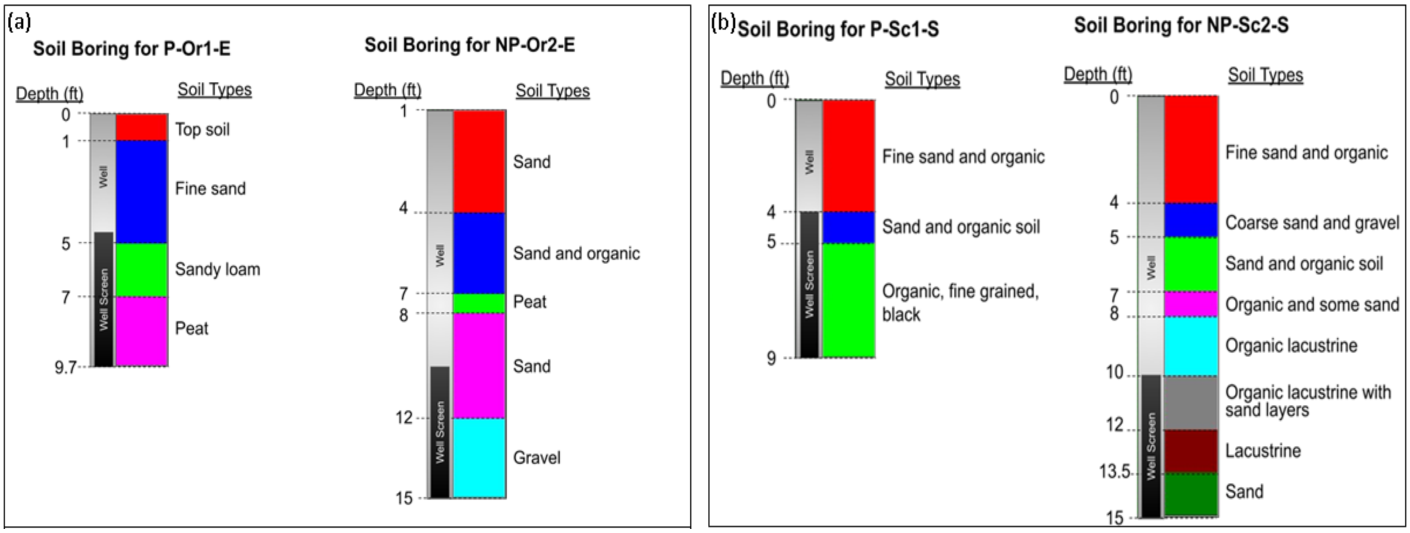


Figure 4: (a) Vertical soil profile illustrating the different soil layers at one of our sites; with (a) Orv Shallow (left) and Orv Deep (right) and **(b)** Scatena Shallow (left) and Scatena Deep (right), showing variations in soil composition and structure across the soil horizon.

At each test site, the SATURO was utilized to obtain the field-saturated hydraulic conductivity (Kfs) values of the specific test, calculated by the "*brain*", or computer, of the machine in centimeters per hour as shown in Fig. (**5**, **6**). Generally, upland sites have higher Kfs values than lowland locations. The results from the upland sites showed high values as anticipated. In 2022, we recorded Kfs values of 72.43 cm/hr, 40.07 cm/hr, and 149 cm/hr. In the following years, 2023 and 2024, the values slightly decreased to 43.69 cm/hr, 24.33 cm/hr, 31.83 cm/hr and 20.27 cm/hr, 38.2 cm/hr, 75.9 cm/hr, respectively. In comparison with the lowland test results, the disturbed lawn soil had a looser soil structure with more pore space which allows water to infiltrate more easily and quickly. Upland tests occurred on slightly sloped summits meaning the water infiltrating the soil was less likely to accumulate and be pulled by gravity compared to lower flatter portions of the slope.

Significantly lower Kfs values were observed in lowland test sites. In 2022, we measured 14.83 cm/hr, 65.37 cm/hr, and 1.71 cm/hr. The values decreased further in 2023 to 1.35 cm/hr, 1.00 cm/hr, and 0.00 cm/hr. In 2024, the values were 10.53 cm/hr, 59 cm/hr, and 14.37 cm/hr. These results are notably lower compared to the upland datasets. The results presented will be further addressed in the discussion section.

Figure 5: All Kfs data (in cm/hr) obtained in 2022, 2023, and 2024 from each test at each of the 3 sites.

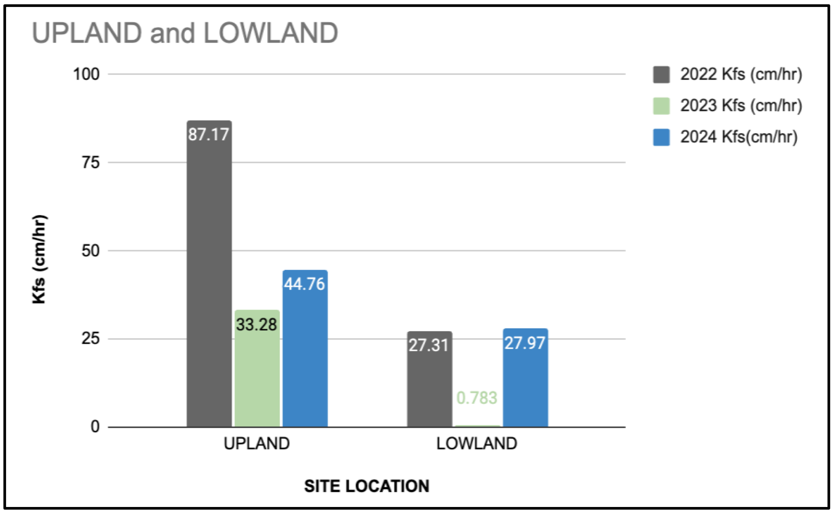
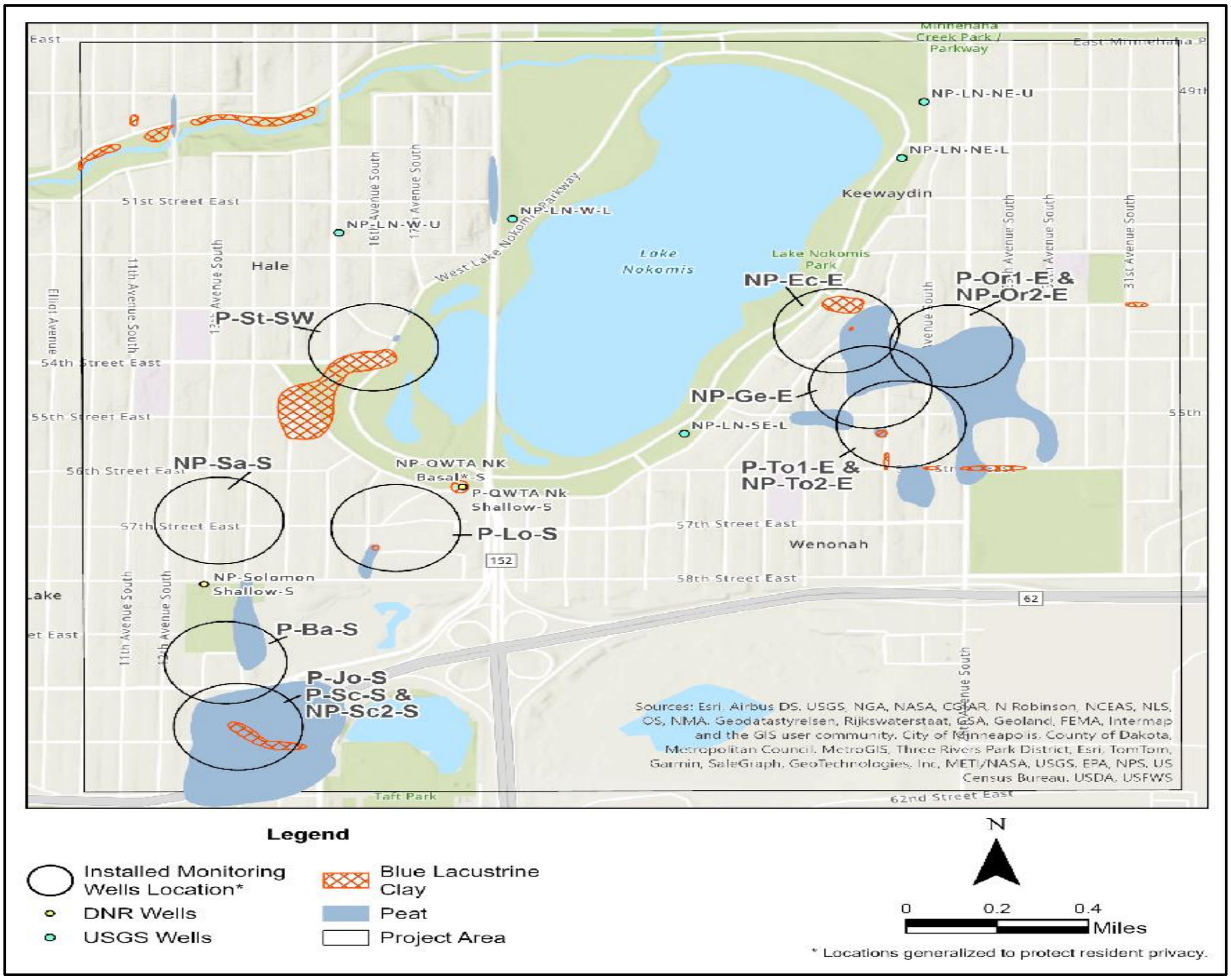


Figure 6: Average Kfs (cm/hr) of each site.

If we are talking about average Kfs (cm/hr) values, in 2022, the Kfs value for the upland site (87.17 cm/hr) is significantly higher compared to the lowland site (27.31 cm/hr). This indicates that the soil in the upland site has higher permeability, allowing water to infiltrate more quickly compared to the lowland site.

In 2023, there is a noticeable decrease in the Kfs values for both the upland site (33.28 cm/hr) and the lowland site (approximately 0.78 cm/hr). However, the drop was more pronounced in the lowland site, suggesting that soil permeability had significantly reduced in the lowland environment. In 2024, the Kfs value for the upland site (44.76 cm/hr) showed a slight increase compared to 2023, indicating some recovery of infiltration capacity or variability in soil conditions. The lowland site also showed an increase in Kfs value (27.97 cm/hr) compared to 2023, but yet remained lower than the upland site. We did a simple t-test in the "R" and found that for the years 2022 and 2024 the p-value was greater than α level of 0.05 which means that there is no significant difference between the means of the data from the upland and lowland sites. Whereas the p-value (0.028) was less than 0.05 in the case of the 2023 results, which indicates that there is a statistically significant difference between the means of the data from the upland and lowland sites.

From Fig. (**7**, **8**), it is clear that Perched wells that are P-Or1-E and P-Sc1-S experienced a significant fluctuation in water levels as the aquitard present here prevents the downward movement of water. During wetter periods, such as the summer rainfall beginning in July 2022 and again from April 2023 onward, water levels in these perched wells increase in response to precipitation. This is because perched aquifers, being shallower and situated above a confining layer, are more responsive to surface water inputs. A similar trend was observed in the wetter months of 2024. The spike in the precipitation indicates the quick recharge in these wells as shown in Fig. (**8**).



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, City of Minneapolis, County of Dakota, Metropolitan Council, MetroGIS, Three Rivers Park District, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

Figure 7: Spatial distribution of monitoring wells across the study area, illustrating both perched (P) and non-perched (NP) wells in relation to various soil layers, including blue lacustrine deposits, clay, and peat. The map highlights the project area, indicating well locations with reference to underlying geological formations that may impact groundwater recharge and flow. This figure emphasizes the relationship between well placement and the different soil horizons influencing groundwater movement within the study area, providing context for the hydrogeological analysis.

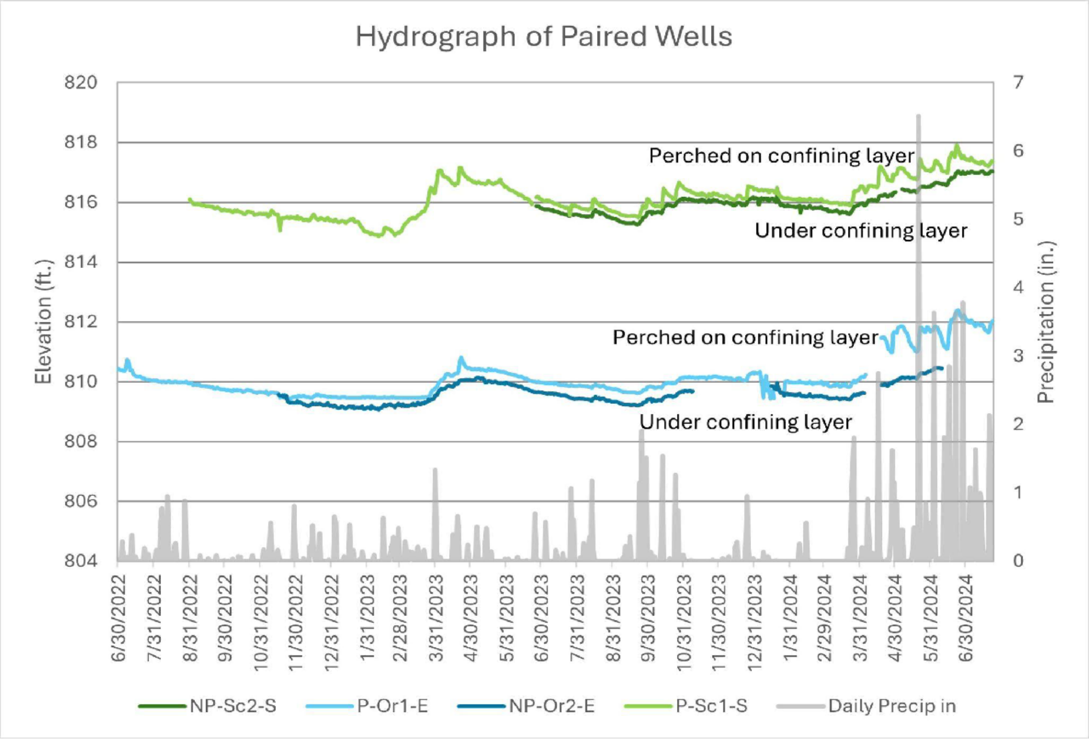


Figure 8: Hydrograph showing groundwater levels in paired perched (P) and non-perched (NP) wells over time, with daily precipitation data included for comparison. The perched wells exhibit relatively stable water levels, reflecting the influence of a confining layer that prevents rapid infiltration. In contrast, non-perched wells show greater fluctuations in groundwater elevation, which suggests more direct interaction with the water table below the confining layer, also highlights how perched wells maintain elevated water levels independent of significant precipitation, while non-perched wells are more responsive to changes in surface water input, indicating varying recharge dynamics.

Whereas NP-Sc2-S and NP-Or2-E showed stable trends with very few fluctuations over time. While water levels do react to precipitation events, the variations are less pronounced, indicating that these wells are primarily recharged by regional groundwater flow rather than direct infiltration from rainfall.

To examine the effects of the aquitards on water tables, area precipitation records were obtained from the MSP airport station. Precipitation and water table elevations were plotted and patterns between water level responses to precipitation in wells with screens above an aquitard (low permeability soil layer such as peat and lacustrine clay) and those with screens below or where no aquitards were observed. From Fig. (**8**), it is clear that in the summer of 2022, both perched and non-perched wells experienced rising water levels, likely due to seasonal rainfall. Perched wells reacted more rapidly and displayed more significant increases. In the fall and winter of 2022, as precipitation decreased, water levels in perched wells started to drop more noticeably, while non-perched wells remained relatively steady. In the spring and summer of 2023, another phase of increased precipitation led to rising water levels in perched wells, while non-perched wells showed smaller, more delayed increases. The significant rise in rainfall during the spring of 2024 followed a similar pattern, with perched wells exhibiting more dramatic responses to precipitation, while non-perched wells displayed more gradual fluctuations. Here, we converted 15 minutes measured water levels to average daily water levels which corresponds to the daily precipitation we retrieved from the MSP airport.

4. Discussion

The three lowland sites had the lowest observed field-saturated hydraulic conductivity. It can be inferred that this was due to the high-water table in this area and the large amount of snowmelt accumulation in April 2023. The saturated soil of the lowland sites had a higher antecedent moisture content compared to the upland sites. The higher antecedent moisture was likely related to the depth of the water table and the hydrogeologic conditions associated with the landscape catena. This aligns with research by Schaufler [15] found that the years from 2010 to 2019 were the wettest period in the Lake Nokomis area, resulting in a relatively higher water table and increased water retention in the suspected "*peat soils*". Conversely, shallow groundwater levels trended downward during the dry periods of 2020 to 2021 [15]. This trend has led to higher Kfs values in areas away from the lake where the soil's unsaturated zone likely increased, but not where soil boring data revealed lacustrine deposits. Near the lake, however, the soil is at or near saturation, leading to lower Kfs values. In such areas, water may not infiltrate through the already saturated soil pores, instead potentially moving laterally on the surface or ponding. This distinction in hydrological conditions between areas near and away from the lake underscores the variability in soil permeability and water movement influenced by local water table dynamics. The upland sites were observed to have the highest Kfs values likely due to coarse-grained fill material and slope position, which increased the gravitational water movement. Another reason is the underlying stratigraphy; these sites may have had less restrictive lacustrine layers, resulting in more infiltration compared to lowland sites. Macropores in the soil contributed to higher water-conducting rates, as previously discussed by Bodhinayake *et al*. [41], further supporting these observations.

While our findings indicate lower Kfs values in lowland sites due to high water retention and proximity to the water table, contrasting results have been reported in other studies. For example, Avner *et al* and Craft *et al*. showed that lowland areas such as those found in floodplain soils typically accumulate significant amounts of organic matter due to the deposition of nutrient-rich sediments during flooding [42, 43]. This buildup enhances soil fertility and can influence saturated hydraulic conductivity (Kfs) by modifying the soil's structure and porosity. Research by Zhang *et al*. [44] found a strong positive correlation between larger root systems, more developed soil macropore networks, and increased saturated hydraulic conductivity (Ks) in forested wetland soils, underscoring their critical influence on soil water movement and hydrological processes. This differs from our observations in the Lake Nokomis region, where lowland areas showed decreased infiltration rates, likely due to limited vegetation and more compacted soil layers.

Additionally, other studies have observed increased Kfs values in lowland areas under specific climatic conditions, such as extended droughts or reduced snowmelt levels. Tran *et al*. and Luo *et al*. observed that desiccation cracking in Luvisol soils, particularly in lowland areas, is that the formation of cracks significantly alters soil hydraulic behavior by creating preferential flow paths for water, which increases infiltration but also accelerates evaporation and reduces irrigation efficiency [45, 46]. This contrasts with our findings, where snowmelt and soil saturation reduced Kfs values, indicating that regional climate differences and land-use history are key factors influencing hydraulic conductivity across various landscape positions.

The underlying stratigraphy of both lowland and upland sites played a significant role in influencing Kfs values. Groundwater near Lake Nokomis could up-well in varying locations depending on near-shore stratigraphic features as inferred by Fig. (**4a**,**b**). Where lacustrine/organic deposits were present directly below a test, as observed in test 3 of 2023, no water would infiltrate because of the aquitard nature of the soil layers. This reflects the findings of McDaniel *et al*. [47], who explored the connection between soil properties, particularly fragipans, and hydrological processes like water storage, runoff, and subsurface lateral flow. The findings showed that fragipans have a strong impact on water movement, leading to saturation-excess runoff during heavy rain or snowmelt. Subsurface lateral flow, which can represent up to 90% of early spring precipitation, is greatly influenced by the presence of fragipans. The research highlighted the importance of understanding soil structures like fragipans to better predict water behavior in sloped areas. Sites with less restrictive soils allowed for greater infiltration, with the absence of aquitard layers facilitating higher Kfs values.

This difference highlights the importance of soil structure in water movement, which was further supported by the fact that perched wells showed sudden changes in water levels in response to precipitation, whereas non-perched wells exhibited more stable water levels due to recharge from regional groundwater flow rather than direct infiltration from precipitation as shown in Fig. (**7**). Along with the underlying stratigraphy of the soil, precipitation played a crucial role in understanding this pattern, as shown in Fig. (**7**). Perched wells exhibited a rapid rise in water levels following precipitation events in summer 2022 and spring 2023, resulting in a temporary rise in the water table. In contrast, non-perched wells showed more gradual fluctuations, indicating a greater influence of groundwater input compared to surface water input. We only measured it in an urban setting next to a lake but testing in a non-urban prairie region with more blocky soil structure from deep-rooted plants and high organic content has been shown to correlate a positive relationship with Kfs [34]. High Kfs values are typically observed in areas with deep soil structure, no aquitard layers, and minimal surface disturbance, often displaying the highest hydraulic conductivity values [41].

The correlation of water infiltration in the soil is negative with respect to the bulk density of the soil [48]. Sites near roadsides, where human disturbance is common, showed higher Kfs values due to coarse-grained fill and gravitational water movement. However, the extent of the disturbance was not fully known. Fragipans impact the physical and hydraulic properties of soils, including bulk density, porosity, and water retention. These properties influence infiltration rates. Similarly, rock fragments can either enhance or reduce infiltration, depending on their distribution and specific characteristics [49]. Urbanization frequently leads to the covering of natural soils with impervious surfaces such as pavement, significantly decreasing soil permeability and disrupting natural water flow patterns [50]. Similarly, construction activities lead to soil compaction, which reduces both its porosity and permeability. The use of heavy machinery and frequent traffic compresses the soil, diminishing its capacity to absorb water [51]. These findings suggest that land use and anthropogenic factors can impact soil permeability and Kfs values.

The altitude of the water table reflects the land surface configuration, typically showing higher elevations in upland areas compared to lowland areas as shown in Fig. (**9**). This difference in elevation creates a groundwater flow pattern that moves water from higher to lower regions. A notable characteristic of this flow pattern is the occurrence of downward flow at breaks where the water table slopes downward, and upward flow at breaks where the water table slopes upward. In certain landscapes, especially where the water table intersects the lower parts of steeper land surfaces, seepage faces may develop. These seepage faces contribute to the formation of wet areas and are expressed through the dominant vegetation [52]. Sedges and cattails were observed in the lowland catena. So, in upland areas where the water table sits at higher elevations, saturated hydraulic conductivity (Kfs) in this catena position will naturally be higher. This is due to the typically well-drained soils and fewer obstacles to water movement found at higher altitudes. Kentucky Bluegrass and Ryegrass do not thrive in saturated soils. Consequently, water infiltrates the soil more readily, resulting in higher Kfs values. The downward flow components generated at downward breaks in the water table's slope facilitate rapid drainage and contribute to the soil's relatively higher permeability.

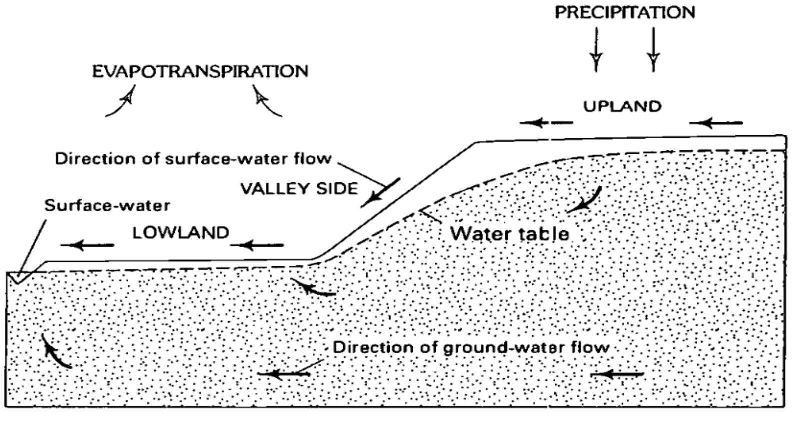


Figure 9: Fundamental hydrologic landscape unit or drainage catena showing the general movement of surface water, groundwater, and atmospheric water [48].

Conversely, in the lowland catena where the water table resides at lower elevations, Kfs values tend to be lower. Lowland soils are susceptible to waterlogging or saturation because the water table is nearer to the land surface. Plants can pull water upward and evapotranspire the groundwater. This additional hydrologic pathway can further complicate tests that measure Kfs. This condition often reduces hydraulic conductivity by limiting drainage and increasing water retention. Additionally, where the water table intersects the lower portions of steeper land surface slopes, the presence of seepage faces can exacerbate drainage issues, particularly during the winter season.

The observations were loosely following the past data observations of a previous study; however, exact coordinates were close but not perfect during collection. For example, the lowland site locations were not in exact placement in all three years. Therefore, the boundaries of the lowland may have been poorly determined as the vegetation boundaries may have shifted. The borings for the wells showed that each site had a clear and observable difference in the soil structure and composition. Seasonality changes in soil moisture resulting from August to April made data comparisons challenging, as data later in the year was gathered before the winter season. With the amount of snowmelt received in April, the field-saturated hydraulic conductivity values were much lower than that of August data. Obstructions during field-saturation runs caused error messages to appear on the SATURO data screens. The obstructions included earthworms and pieces of glass; these errors were unavoidable due to the nature of the test and the inability to view soil quality and conditions under the SATURO cylinder as shown in Fig. (**7**). However, earthworm observations resulted in errors in some SATURO tests that may have contributed to an increased rate of water infiltration as shown in Fig. (**10**).

Apart from this, limitations were identified as time constraints, lack of past data to supplement findings and account for seasonality, and SATURO functioning errors. An increase in the number of SATURO tests would allow for further assessment of different landscapes and Kfs values, as well as additional cycles and runs at each testing site. It is important to note that the current results may be influenced by the inherent variability of infiltration testing. Increasing the number of SATURO tests could also potentially provide more reliable and consistent data, helping to clarify the differences between upland and lowland infiltration rates. This increase in testing could address the current lack of statistically significant differences observed, as more data points might lead to a more robust analysis. The temporal fluctuations of soil moisture were not accounted for due to this time constraint. As studied by [53], infiltration rates vary according to temperature changes during northern latitude seasons. Lack of data over multiple seasons could be identified as a potential source of error, as well as a lack of substantial pre-development data.

Figure 10: Earthworms/glass bottle obstruction errors in data collection.

To address the limitations and expand on the findings of this study, future research should aim to broaden the temporal and spatial range of data collection by examining a wider variety of landscapes, including both urban and rural areas, and assessing the long-term impacts of seasonal and climate variations on soil permeability. Moreover, studying the effects of expanding impervious surfaces due to urbanization on groundwater recharge and flood risks would offer crucial insights for city planning. Utilizing advanced hydrological modeling could enhance our comprehension of water movement through different soil types. Investigating new soil alterations/restoration methods such as deep-rooted prairie grasses to boost hydraulic conductivity could lead to more efficient water management and climate resilience in urban environments.

5. Conclusion

In conclusion, this study explored the variations in water table fluctuation and field-saturated hydraulic conductivity (Kfs) across an urban lake drainage catena, considering the upland and lowland areas near Lake Nokomis, Minneapolis, Minnesota. The results revealed notable differences in the soil permeability based on the drainage catena and underlying soil features. Upland sites consistently showed higher Kfs values where thicker coarser soil texture, improved drainage, and the effects of gravity were not constrained by fragipan or aquitard soil characteristics. Whereas lowland sites typically had lower Kfs values, largely due to the presence of aquitard layers, saturated soil conditions, and high antecedent moisture levels from snowmelt and precipitation events. The aquitard layers best explain the shape of hydrographs shown in Fig. (**8**).

The impact of human-driven changes to the landscape, such as the addition of lacustrine and organic deposits, played a significant role in influencing groundwater behavior. Perched aquifers were more responsive to precipitation, whereas non-perched aquifers maintained steadier groundwater levels, illustrating variations in subsurface water flow. Additionally, seasonal fluctuations in Kfs underscored the complex relationship between soil characteristics and water infiltration, particularly within an urban environment. These results provide important insights for managing urban water, especially in tackling flood risks, improving stormwater management, and promoting sustainable development. Grasping the relationship between soil hydraulic characteristics, landscape topography, and subsurface geology is crucial for informing future urban planning and addressing water-related issues in the face of changing climate conditions.

Conflict of Interest

The authors declare that there is no conflict of interest.

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HD, KH – data analysis, figure creation, and writing, MV, AH, and BR field supervision of data collection by undergraduate students, JM project oversight, writing, and main editor.

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