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Hydrologic Thresholds of Ecosystem Resiliency: Have Wetlands on the Anoka Sand Plain Changed over Time?

Elizabeth Flage and Joe Magner

Department of Bioproducts and Biosystems Engineering, University of Minnesota, St. Paul, Minnesota 55108, USA

Abstract: Wetlands have long been used as environmental indicators for changes in climate and land use because they are sensitive to hydrologic change; however, wetlands set in transmissive groundwater can be more resilient to climate and land use change. In Anoka County, Minnesota, USA, a monitoring network was established in 1997 and maintained by the Anoka Conservation District to the present day to assess wetland hydrologic response over time. We examined a combination of data including water level (stage) from these wetlands, precipitation from local gages, pan evaporation data, and historical land use, including a measure of runoff flashiness, using regression and k-mean analysis. Results did not detect any clear trends over a 25-year time period, though some *p*-values showed potential. A clear statistical trend in the measured hydrologic parameters would suggest exceedance beyond historical thresholds of natural hydrologic variation and alert the need to better protect wetlands and groundwater from anthropogenic stress. Study results may provide useful information to management and regulatory decisions for wetland systems set in sandy soils. This is particularly important for Anoka County because most wetlands are intrinsically connected to the surficial ASP (Anoka Sand Plain) Aquifer, which overlay vulnerable deeper aquifers used for domestic water supply.

Key words: Climate, land use, wetland, environmental indicator.

List of Abbreviations

ASP	Anoka Sand Plain
ACD	Anoka Conservation District
DIY	Do it yourself
DNR	Department of natural resources
NLCD	National land cover database
NWI	National wetland inventory
WMA	Wildlife management area

1. Introduction

1.1 Wetland Definition and History

Wetlands, as defined by the United States Army Corps of Engineers [1], are areas on the landscape that are inundated for most, or all of the growing season. They sustain hydrophytic vegetation and produce distinct reduced soil characteristics. Three parameters define a wetland from an upland ecosystem: the hydrology, soil, and vegetation. Wetlands are valuable natural resources that provide sources and sinks for chemicals, perform chemical and hydrologic cycles, mitigate floods, and recharge groundwater aquifers [2]. They are a critical feature of chemical processing and hydrological cycles.

Of the three parameters that define a wetland, hydrology is the most important determinate of wetland establishment and maintenance. This is because wetlands are where groundwater surfaces, or surface water infiltrates. Hydrology is pertinent to hydrophytic vegetation establishment and creating anerobic conditions which define the reduced nature of the soil. Although hydrology directly impacts both wetland vegetation and soil, it is also impacted by certain factors, primarily the climate and the basin geomorphology [2]. Therefore, changes in climate and surrounding land use can impact a wetlands hydrology. Wetlands, to some extent, serve as a proverbial "canary in the coal mine" indicator of ecosystem resilience to slow but trending changes in climate and land use [2].

Corresponding author: Elizabeth Flage, MS, environmental scientist, research fields: wetlands, wetland hydrology, ecological restoration and vegetation.

Across the United States, there has been a considerable loss of wetlands. Between colonial settlement in the 1780s to the 1980s, it is estimated that the conterminous states lost 53% of preexisting wetlands [3]. Since 1980 the lower 48 states have continued losing wetlands but the rate of loss has slowed due to various factors. These include changes in crop prices, property values, land use trends, changes in regulation, and climate change [4]. With continued pressure from urbanization, high-capacity groundwater wells and a changing climate, it is important to study the changes in wetland hydrology, particularly in urbanizing counties like Anoka County, USA (Fig. 1). The evaluation of wetland hydrology and their alterations provides critical information for future water resource management. This study focused on the impact of an increase in precipitation due to climate change and the increase in impervious surfaces due to urbanization. It is urgently important to preserve wetlands in a landscape because they provide critical ecosystem services. With the loss of so many wetlands, as described above [3, 4], across the upper Midwestern USA landscape, have the remaining wetlands crossed a hydrologic threshold of ecosystem resiliency? In this manuscript the authors show that wetlands set into sand and gravel are resilient over time. Resiliency as used in this manuscript refers to the buffer capacity of a system to change.

1.2 Study Area

1.2.1 Wetlands

To answer the resiliency question, wetlands on the ASP (Anoka Sand Plain) were analyzed. The ASP is a unique geologic feature located in Anoka County in east-central Minnesota, USA (Fig. 1). Minnesota is located at the intersection of four distinct ecological provinces and is a water and wetland-rich state [5].

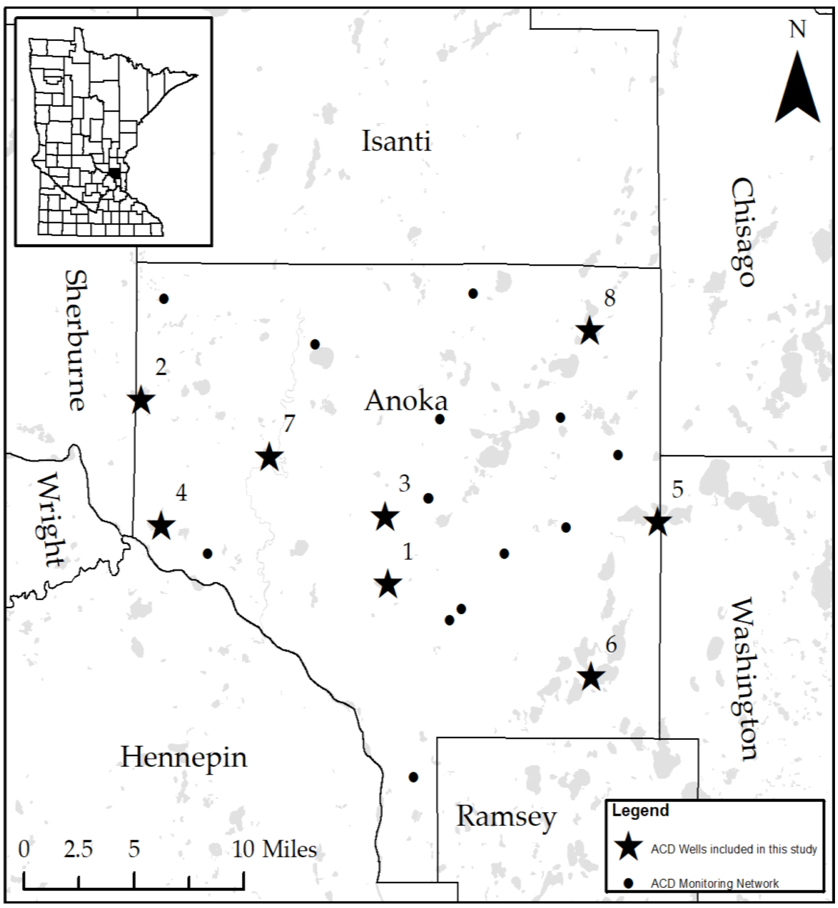

Fig. 1 Study wetland locations (stars) and additional wetlands within the monitoring network (circles) located within Anoka County in east-central Minnesota.

Dahl [3] estimated that wetlands covered more than 6 million hectares (ha) of the state before 1780. Since colonial settlement, it is estimated that most areas in Minnesota lost 50% of its wetlands with some areas losing up to 90% [6]. Wetland types vary from pothole prairie wetlands in the south and western sections of the state to boreal bogs in the north. Recently, the rate of wetland loss has slowed and, in some areas, reversed [4]. Notably, the gain in wetland acreage is countered by the changes in wetland types, particularly emergent wetlands being converted to deeper water habitats like deep marshes and ponds [7].

1.2.2 Landforms and Glacial History

Anoka County is within the ASP ecological subsection (Fig. 2; [8]). This subsection is characterized by unique glacial features that affect wetland placement, and surface and groundwater systems. The major landform present in the ASP is a broad sandy lake plain that is a remnant from multiple episodes of glacial advances, retreats, and stagnating meltwater [9]. During the Wisconsin Episode of glaciation, the Superior lobe advanced and retreated multiple times from different directions. Upon the retreat of the lobe, glacial lakes formed from meltwater, bringing different soil deposits from northern Minnesota and Canada. After the final advance and retreat of the Superior lobe, Glacial Lake Lind II was formed and eventually filled with sand. Anoka County was covered again with glaciers from the Grantsburg sublobe emanating from the Des Moines lobe in the southwest advancing to the northeast. The Grantsburg sublobe stagnated, forming multiple lakes which covered Anoka County. The sublobe then melted forming Glacial Lake Anoka. Fine-grained sand began to fill depressions and was left there when Glacial Lake Anoka was drained, leading to the formation of the current route of the Mississippi River [9].

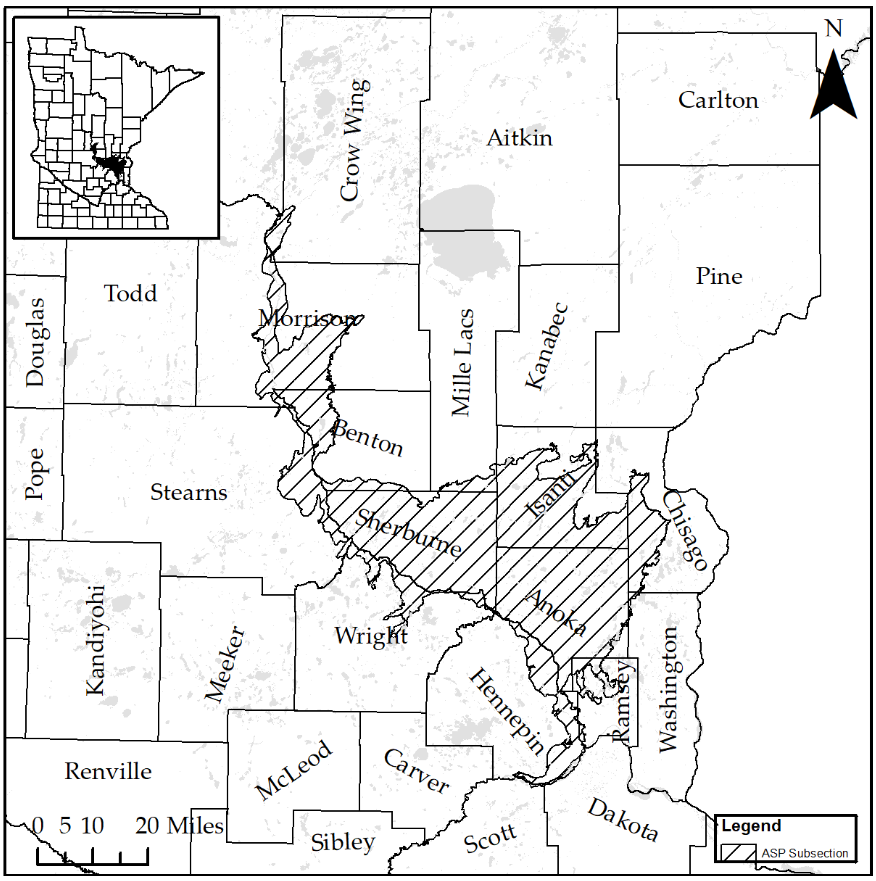

Fig. 2 Anoka county is located within the ASP subsection. This subsection is characterized by a broad sandy lake plain.

The Hudson Episode followed the Wisconsin Episode, and was characterized by extensive drying, vegetation changes, and organic matter accumulation. Anoka County was dominated by spruce and conifers, but as it dried the landscape became more open prairie and unvegetated [10]. This led to the creation of sand dunes which were active and moved across the northwest section of the county [11]. There were several cycles of drought and non-drought conditions, changing the vegetation and allowing the sand dunes to become active or stabilized. As a result, organic matter accumulated in the low-lying areas, eventually becoming wetlands and lakes. The filling of multiple glacial lakes produced extensive sandplains that are now part of the surficial ASP aquifer.

The sand and gravel of the ASP is the controlling geologic feature for the groundwater availability and pollution sensitivity of underlying aquifers [12]. The surficial ASP aquifer overlays buried sand and gravel and the deeper bedrock aquifers commonly used for water by municipalities and commercial operations. The aquitards between the ASP aquifer and the bedrock aquifers tend to be fractured, and do not lend substantial protection [12]. Trojan and others [13] found that recharge in the ASP aquifer occurred annually in the March, April, and May. Due to the downward gradient and shallow depth to groundwater, precipitation infiltrates directly into the subsurface and does not reside in surficial water bodies for long periods [12]. The surficial sand and gravel aquifers are not commonly used for water supply, but they can affect the underlying aquifers which are used for water supply. Wetlands, in this type of geology, provide a pathway for surface water to enter the groundwater system [2, 14]. Therefore, the wetlands in the ASP can affect the quality and pollution sensitivity of the underlying aquifers. Wetland hydrologic change could impact domestic water supply use.

1.2.3 Demographic

Anoka County has the fourth largest population (estimated at 362,648 people in 2019) and is one of the fastest-growing counties [15] in Minnesota. With a growth rate of 7.9%, Anoka County outpaces the overall growth rate for Minnesota of 6.3% [16]. The northern portion of the county is rural and currently mostly in agriculture (Fig. 3). The southern portion of the county is developed with high-intensity impervious land use in the southern tip, lessening in intensity from south to north. The deep groundwater system within the county is an essential domestic water supply, as 94% of Anoka County residents rely on groundwater for drinking water [17]. Because there has been rapid developmental pressure which, in combination with the unique ASP geology, makes this county particularly interesting and important to study environmental changes over time.

1.3 Climate and Urbanization Trends

It is evident from extensive studies that the climate is changing, precipitation is increasing, and typical rural areas are becoming increasingly urbanized. Dai and others [18] studied temperature and precipitation trends during the growing season in the Midwest from 1980 to 2013. They found that in Minnesota there was statistically significant warming in the minimum temperature during the early part of the growing season (April to June). They also found a decrease in the maximum temperature during the late growing season (July to October). It should be noted that there are well-documented trends of warmer winters that affect freeze times [19]. Keeler and others [20] predict there will be an increase in the number of days with highs greater than or equal to 35 ℃. Furthermore, they also predict a decrease in the weeks of frost up to 7-8 weeks.

In addition to Minnesota’s warming, the state is becoming wetter. Between 1895 and 2017, there has been an average increase of 8.6-cm of precipitation [19]. The increase in wetness across the state can be seen in the early growing season. The late growing season actually sees a trend of decreasing precipitation [18]. Keeler and others [20], predicted there will be a similar or decreased number of days with precipitation,

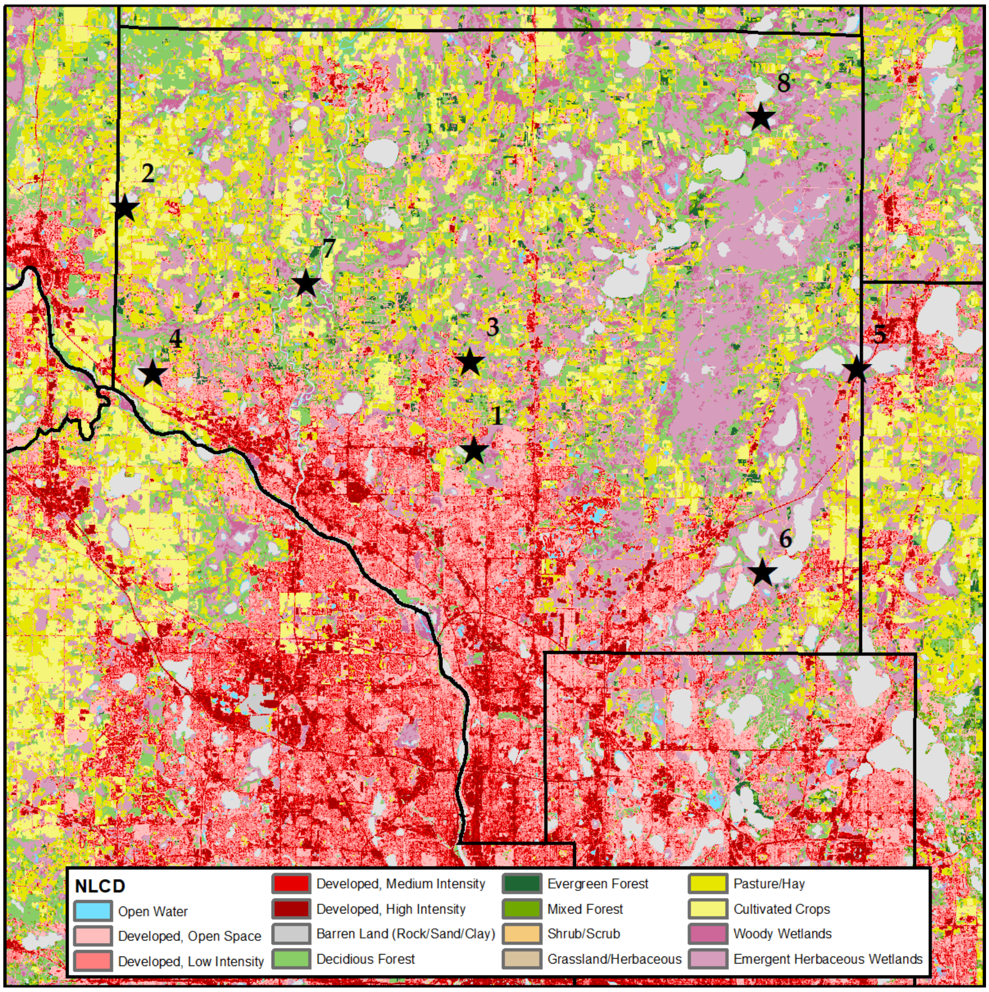

Fig. 3 Anoka County land use from the NLCD (National Land Cover Database).

but an increase in the extreme precipitation events, and an increase in the length of dry spells. This is significant as most of the recharge for the ASP happens during the early growing season. Currently, a high amount of water is infiltrating down into the aquifers. In the future, there could be a change in the recharge depending on infrastructure surrounding recharge areas of wetlands, and lakes systems. Johnson and others [21] found that an increase in temperature and a decrease in precipitation had the greatest effect on wetland hydrology, while an increase in temperature and an increase in precipitation had a counterbalancing effect.

Precipitation and temperature are not the only external factors to impact wetland hydrology. The surrounding land use can affect wetlands that are surface water fed, as well as, in extreme circumstances, wetlands that are primarily fed by groundwater. Because Anoka County population increased by 30,000 people between 2010 and 2020, demographers predicted that the population in Anoka County will increase by more than 112,000 people by 2040 [22]. An increase in population means an increase in urbanized development and concordant impervious surfaces. The impact of urbanization on wetlands is not well documented; however, Ehrenfeld [23] explored how urbanization can affect wetlands, especially restoration success. There were negative impacts to a wetland's ecology and hydrology, yet positive impacts due to people's buy-in and priority for an adjacent water body. People have certain expectations and regulatory authorities must be able to balance the science with the societal expectations [23].

Given this study, more research on the success and management of urban wetlands is crucial. There is still a distinct lack of research and knowledge about the impact of climate change on wetland hydrology. This study attempted to explore hydrologic resiliency over time with a changing climate and urbanizing land use conditions.

1.4 ACD Wetlands

The wetlands in this study are part of a monitoring network that was developed and is primarily managed by ACD. The wetland monitoring network was established to identify current and historic water elevation or stage trends to assist with wetland determinations and urban development regulation. Monitoring of several wetlands began in 1996 and more wetlands being added to the network with time. The most recent wetland was added in 2013 [24]. The network currently consists of 19 wetlands (Fig. 1). To minimize confounding factors, only 8 of the 19 wetlands were included in this study. More information about inclusion criteria can be found in the methods section. Descriptions of the wetlands, soil profiles, vegetation lists, NWI (National Wetland Inventory) maps, surrounding land use maps, and aerial imagery review can be found in Flage [25].

1.4.1 Bunker—Wetland 1

The Bunker wetland (wetland 1), located within the Coon Creek minor watershed, is predominately Fresh-Wet Meadow and approximately 0.4-ha. The surrounding land use includes a major road (Bunker Lake Boulevard Northeast) and residential housing to the north. To the south is Bunker Hills Regional Park which includes Bunker Lake, a water park, a golf course, and an open park with paved trails and a campground. Further out from the study site, the land use includes a high amount of commercial and residential development. Additionally, there is a lake (Bunker Lake) to the west and a larger wetland complex to the south. Upland forest and prairie are to the east and west. According to the ACD Water Almanac [24], the Bunker wetland is considered an isolated basin, is not connected to any ditches and does not have any constructed components within the wetland.

The ACD Water Almanac [24] notes there were suspicious water level readings from 2000 to 2005, causing them to re-delineate the wetland boundary and move the edge monitoring well downgradient to the new wetland edge. The re-delineation and relocation of the edge well (well 1a) was completed in 2005. The middle monitoring well (well 1b) was also installed at the end of 2005.

1.4.2 East Twin—Wetland 2

The East Twin wetland (wetland 2), located in the city of Nowthen, is a predominantly open water wetland with a wet prairie ring. The surrounding land use includes Twin Lakes City Park, roads, industrial and residential buildings, and farm fields. The Twin Lakes are located to the north and northwest of the wetland. The well is approximately 55-m from the lake. According to the 2019 ACD Water Almanac, the water levels within the wetland are influenced by the lake water levels. It is considered an isolated basin and not connected to any ditches. The city of Elk River is located southwest of the study wetland. Development around the Twin Lakes as well as wetland 2 increased during the 1990s and slowed into the 2000s.

1.4.3 Ilex—Wetland 3

The Ilex wetland (wetland 3) is in central Anoka County in the city of Andover. The wetland is within the bounds of Oak Hollow City Park, an undeveloped 2.2-ha park. The 3.9-ha wetland extends beyond the park boundaries into the surrounding neighborhoods. Wetland 3 was originally delineated as a fresh-wet meadow wetland, but the most recent NWI shows a shallow marsh surrounded by a wet prairie ring. The wetland is an isolated basin with no constructed components and no connection to ditches. The surrounding land use is developed neighborhoods which transition into farmland, wooded wetlands, and some low-intensity development. The area surrounding the wetland 3 has undergone significant development, especially due to residential neighborhoods.

There are two wells installed in the wetland 3, one on the wetland edge (well 3a) and one located in the middle (well 3b). According to the Water Almanac [24], the well 3a was installed in 1996. From 2000 to 2005 the water table was very low and seldom within 100-cm of the ground surface. This prompted a re-delineation of the wetland boundary. After the delineation was completed, well 3a was relocated downgradient and an installment well 3b was completed in 2006.

1.4.4 Lake Itasca Trail—Wetland 4

The Lake Itasca Trail wetland (wetland 4) is in the city of Ramsey on the western border of Anoka County, within two miles north of the Mississippi River. The wetland is 4-ha and is predominately fresh-wet meadow with pockets of shrub-carr wetlands. According to the Water Almanac [24], it is an isolated basin without connection to ditches or constructed components, but there is a large wetland complex to the northwest. The well was installed in 2013 and located 3.2-m east and 15-cm downslope of the wetland boundary. Wetland 4 is considered a Minnesota DNR (Department of Natural Resources) Public Water Wetland (2-339). The surrounding land use is mostly residential development with a golf course and industrial developments to the west. The historical aerial photo review revealed that the housing development to the north was built between 1997 and 2000. Additionally, the wetland was open water and then filled with vegetation between 2000 and 2003.

1.4.5 Lamprey Pass—Wetland 5

The Lamprey Pass wetland (wetland 5) is located on the eastern border of Anoka County in the city of Columbus. It is within the bounds of the Lamprey Pass Wildlife Management Area, which is managed for wildfowl by the DNR. It was originally delineated as a deep marsh wetland, but the most recent NWI shows a shallow marsh wetland with a pocket of open water in the center. Wetland 5 is an isolated 0.2-ha basin, with no connection to ditches and no constructed components. The wetland is 66-m east of Interstate 35. The surrounding land use is primarily the interstate and the WMA (Wildlife Management Area). Within the WMA there are two large lakes and several other wetland basins. Beyond the WMA, there are residential developments, a casino to the south, and Clear Lake to the east of Interstate 35. The historical land use has not changed significantly because the WMA has been managed for hunting since 1881. One major change has been the residential developments around Clear Lake to the east and the development of the casino to the south in the early 2000s.

1.4.6 Rice Creek Watershed District—Wetland 6

The Rice Creek Watershed District wetland (wetland 6) is in southeast Anoka County in the city of Lino Lakes. It is within the bounds of the Rice Creek Chain of Lakes Park Reserve. The well, located on the wetland boundary, is approximately 300-m from George Watch Lake and 244-m from Centerville Lake. The wetland is approximately 0.2-ha and primarily a wooded swamp. The immediate land use is the park which includes forest, multiple lakes, and wetland complexes. The 2019 ACD Water Almanac states that this wetland is an isolated basin, has no constructed components, and is not connected to any ditches. There is a road that runs along the east side. There are some low-intensity residential and park developments nearby. According to the historical aerial photo review, there has not been substantial change in the immediate land use.

1.4.7 Rum River Central—Wetland 7

The Rum River Central wetland (wetland 7) is in the city of Ramsey in west-central Anoka County. It is located 0.5 miles from the Rum River and within the boundaries of Rum River Central Regional Park. The wetland is 0.32-ha and was delineated as a shrub-carr wetland, but the most recent NWI maps display a fresh-wet meadow. The surrounding land use includes low-intensity residential developments to the west, Rogers Lake to the northwest, and a forest and river to the north, east, and south. According to the historical aerial photo review, there have not been any substantial changes since the well was installed in 1997.

1.4.8 Tamarack—Wetland 8

The Tamarack wetland (wetland 8) is in the northeastern corner of Anoka County in Linwood Township. It is 0.8-ha and within the boundaries of the Martin-Island-Linwood Lakes Regional Park. It is a shallow marsh wetland with a shrub-carr ring. The well was installed in 1999 on the boundary of the wetland. The Tamarack wetland is delineated as an isolated basin with no constructed components and no connection to ditches. Martin Lake is to the north and Tamarack Lake to the east. West of the wetland is a forest with some residential housing. Most of the regional park is located to the south of the wetland. There was significant development to the south of the wetland in the late 1990s and early 2000s. Otherwise, there has not been any substantial change.

2. Materials and Methods

2.1 Shallow Monitoring Wells

As previously discussed, the ACD monitors 19 reference wetlands across Anoka County. To monitor the wetlands, the ACD installed shallow monitoring wells outfitted with electronic pressure transducers to record the water levels. The first well was installed in 1996 and the most recent well was installed in 2013. This study references 8 of the 19 wetlands. Background information for the additional 11 wetlands can be found in the 2019 ACD Water Almanac [24].

One or two shallow monitoring wells were installed in each wetland. The wells were placed along the boundary of the wetlands. Wetlands 1 and 3 have an additional well in the middle of the wetland. The wells are made up of PVC (Polyvinyl Chloride) piping that is 1.5-m in length. The bottom meter is made of slotted PVC so that water can enter the well. The technical guidance that was used for installing shallow monitoring wells in these wetlands is outlined by the US Army Corps of Engineers [26] and the Minnesota Board of Water and Soil Resources [27]. The ACD used electronic pressure transducers to record the water level every 4 h within the growing season (generally April through October). Descriptions of the specific wetlands and monitoring wells can be found in the 2019 ACD Water Almanac [24]. Background information for the 8 wetlands in this study can be found in the introduction with additional information in Flage [25].

2.1.1 Inclusion Criteria

The raw water level data from all 19 wetlands were obtained from the ACD in 2019. The wetlands are included in the complete monitoring network range in their wetland type, hydrology, and hydrogeomorphology. To minimize confounding factors only wetlands that were isolated basins, not connected to ditches, had no constructed components, and had more than 5 years of water level data, are included in this study. This reduced the number of wetlands in the study from 19 to 8. Within the 8 wetlands studied there are 10 wells, with wetlands 1 and 3 having two wells each.

2.2 Statistical Analysis

2.2.1 Water Level Data

Water level data were obtained from the ACD in the form of Excel workbooks. There was one workbook per year with individual tabs with data from each monitoring well. The data were moved from yearly workbooks into workbooks for each well so that each well could be statistically analyzed. The data were then cleaned, and naming and formatting conventions were established. In the case of missing data, if it was less than a week missing then the rows were deleted from the workbook. If more than a week of data was missing, the data were interpolated using sites that were close in proximity and highly correlated. The missing data were calculated using the complete site’s data. To analyze the data, first, the average daily water level was calculated, on which most of the following analysis is based. It was found that the water level data were not linear, thus, the date was given a number in chronological order and then transformed by cosine and sine. Cosine tended to work best but the specific transformation depended on the site. A scatterplot and linear regression were produced using the transformed date and the average daily water level. Additional regressions for an individual well were calculated using the average monthly water level, maximum monthly water level, and minimum monthly water level.

2.2.2 Precipitation, Temperature, and Pan Evaporation Data

Monthly precipitation data were obtained from the Minnesota State Climatology Office using the Wetland Delineation Precipitation Data Retrieval tool [28]. The precipitation data provided by the Minnesota State Climatology Office are gathered by volunteer observers. The collection method inherently has some issues with missing data if the volunteer observers fail to collect data. To solve this issue a gridded database is used to fill in the gaps of missing data within a record and provide researchers with a complete data set. Gaps in the data are filled in by estimating the monthly precipitation totals for grid nodes that are spaced 10-km apart. This Kriging technique makes use of irregularly spaced data in the vicinity of a node to assign a value, creating a spatially and temporally complete data set. One issue with this technique is that it tends to wash out geographically isolated areas of high or low precipitation. These areas tended to be quite small, therefore this uniformity was acceptable. In the case of this study, one set of precipitation data was used for the entirety of Anoka County. Since Anoka County is a small and flat area, the spatial differences over time across the county are unlikely to be significantly different. The target location that was used is in Ham Lake, Minnesota (township 32N, section 7, range 23W) which is in central Anoka County.

Monthly pan evaporation values were obtained from the DNR. Pan evaporation values were collected at the University of Minnesota St. Paul Campus Climate Observatory using a class A evaporation pan [29]. Measurements were taken weekly by measuring the water level and then the water is refilled. The main constraint of this data is that sometimes the airflow underneath the pan is restricted due to soil buildup and gopher activity.

The temperature data used in this study were provided by the National Weather Service and accessed through the DNR [30]. The temperature data were an average monthly temperature for the Twin Cities area station. The average monthly temperature was then compared to the mean temperature monthly norms provided by the National Climatic Data Center [31]. The St. Paul 35W, MN station was the station used in this study. If the average monthly temperature was greater than the monthly normal, then the month was warm, if it was less than the monthly normal, then it was a cool month. Temperature data can be found in Flage [25].

2.2.3 Flashiness Index

To obtain information about the change in storage for the wetlands, the Richards-Baker Flashiness Index (Flashiness Index) was calculated for each well using the methodology outlined in Baker and others [32]. The average daily water level was transformed into a new datum by adding 19-cm. Then, the absolute value of the daily change was calculated by taking the absolute value of the average daily water level in the new datum minus the previous day. After the absolute value of daily change was calculated then all the daily values for a month were summed. The sum of the absolute value of water level in the new datum for the month was also calculated. The Flashiness Index was then calculated by taking the sum of daily change divided by the sum of water level for the month. This gave the Flashiness Index for each month of each year where there were data. Data for the Flashiness Index can be found in Flage [25].

2.2.4 Imperviousness

The NLCD (National Land Cover Database) maps were used to calculate percent imperviousness for this study. The 2016 NLCD was the best option for this study because it has many years of data readily available, covers the entire study area, and has a well-established methodology. The 2016 NLCD has a resolution of 30-m, provides land cover data at two- to three-year intervals from 2001 to 2016, and classifies degrees of development and the area of impervious surfaces. Within the impervious surface products, the NLCD calculates the amount of change during specific time periods. Specific methodology for the development of the 2016 NLCD is explained by Jin and others [33]. There are some constraints to the NLCD, as it relies heavily on high-quality satellite imagery. If high-quality imagery is not available, it affects the quality of the products. Despite this limitation, the results and quality control assure a high-quality product.

In this study, the imperviousness was calculated for the entire minor watershed of a study wetland. Originally, data from individual wetland catchments were going to be used, the scope was expanded to the minor watershed because delineating the catchment of the wetland only accounted for the surface water flow into the wetland. In many cases the catchment that was delineated only included the wetland basin and none of the surrounding land. Most of these wetlands are intrinsically connected to the groundwater system and that was not reflected in a surface water catchment delineation. The scope was therefore expanded to the minor watershed to include the surrounding land use which ultimately influences both the surface and groundwater flow into the wetland. To calculate the imperviousness for the minor watershed, first the imperviousness layer from the NLCD was clipped to the minor watershed using the clip raster processing tool. The NLCD imperviousness provides data on the number of raster squares that have some degree of imperviousness within them. The area of imperviousness was then calculated by taking the total count of raster squares that have imperviousness and multiplying that by the resolution (900-m^2; each side of the raster square is 30-m long). Then, this was added together to get the total amount of imperviousness and to calculate the percent imperviousness for the entire minor watershed. The total percent imperviousness for each site can be obtained in Flage [25]. The percent imperviousness was then used in the k-means clustering to establish trends.

2.2.5 Regressions, K-Means Clustering, and Threshold Definition

The two main statistical analyses performed were regressions and k-means clustering. Regressions, which were performed in Excel, showed trends within a wetland, whereas k-means clustering allowed the comparison of specific characteristics for multiple wetlands. The data used in the regressions were the water level data for the site, precipitation, pan evaporation, and temperature.

K-means clustering was performed in R-Studio. The data used in the clustering included the sample variance of the water level data, the minor watershed area in hectares, wetland size in hectares, the minimum saturated hydraulic conductivity (Ksat) value for the dominant soil type, the maximum Ksat value, the average Ksat value, and the percent imperviousness for the minor watershed.

A threshold of hydrologic resiliency needed to be established to properly analyze the data and the statistical tests. It was determined that the threshold for regression was an R-squared value of 0.2 and a p-value of 0.05. In other words, to be statistically significant a specific regression had to have both an R-squared value greater than 0.2 and a p-value below 0.05. It should be noted that this threshold is specific to wetlands that are located within sand and gravel like the Anoka Sand Plain. It would be inappropriate and inaccurate to apply this threshold to wetlands in other geologic settings.

3. Results

3.1 Individual Wetland Trends

The water level for each wetland was analyzed using regressions and transformed data. No significant trend was found within the water level data alone. To further round out the analysis, precipitation, pan evaporation and temperature were added to the regressions. We anticipated finding some correlation, however, none of the regression models satisfactorily described the data.

Our goal was for the *R*-squared values to be at least 0.2 or higher. A very low *R*-squared value can be expected because wetlands are a natural system that are impacted by many different parameters, some of which cannot be measured. The highest *R*-squared for each wetland was from the model that included water level and all three additional parameters. Given this, the highest *R*-squared was 0.17 for wetlands 6 and 8. The remaining wetlands had *R*-squared values ranging from 0.01 to 0.14 (Table 1).

It was found that precipitation and pan evaporation had the greatest impact on water level in every wetland. Although this relationship was established, there was not a statistically significant difference over time. This leads to the conclusion that the wetlands have not passed a hydrologic threshold of resiliency.

3.2 Flashiness and Imperviousness

Flashiness of the study site wetlands was found to be very low, ranging from 0.018 to 0.118 (Table 2). Interestingly, the flashiness of the wetland 1 varied greatly from the middle well location (well 1b) to the edge well location (well 1a), suggesting some littoral water exchange.

Analysis of flashiness and imperviousness did not reveal any relationship. Based on this study, the percent imperviousness of the minor watershed has no impact on the flashiness of water level change in the wetland. This was found to be true across all of the wetlands in the study. We suspected that over time impervious surface would have increased enough to cross a threshold of wetland water level response; it did not.

3.3 K-Means and Wetland Relationships

The k-means analysis found that the wetlands fell into two groups: cluster 1, and cluster 2 (Fig. 4). Generally, the wetlands were located within a same or similar sized watershed. Cluster 1 included wetlands 1, 2 and 3. Cluster 2 included wetlands 4, 5, 6, 7 and 8. Notably, cluster 1 had lower sample variance and lower imperviousness in the minor watershed. However, wetland 1 and wetland 2 could be included in cluster 2 based on spatial location plotted in Fig. 1.

Table 1 *R*-squared and *p*-values for the best-fit model which includes water level, precipitation, pan evaporation, and temperature.

Wetland	*R*-squared	*p*-value
1a	0.05	0.33
1b	0.09	0.99
2	0.01	0.07
3a	0.05	0.02
3b	0.03	0.28
4	0.07	0.09
5	0.09	0.15
6	0.17	0.07
7	0.14	0.01
8	0.17	0.81

Table 2 Descriptive statistics for all wetland sites, include sample variance, minor watershed area, wetland size, average Ksat, percent imperviousness of the minor watershed, and the average flashiness.

Wetland	Sample variance	Minor watershed area (acres)	Wetland size (acres)	Average Ksat (inches per hour)	% Imperviousness of minor watershed	Average flashiness
1a	110.6	14,962	1	3.965	60%	0.032
1b	121.7	14,962	1	3.965	60%	0.118
2	198.0	24,162	5.9	3.1	7%	0.025
3a	178.6	14,962	9.6	3.965	60%	0.035
3b	272.0	14,962	9.6	3.1	60%	0.037
4	50.8	11,113	10	3.1	42%	0.018
5	132.0	10,342	0.5	1.1	20%	0.033
6	190.5	3,637	0.5	3.965	20%	0.050
7	153.3	3,591	0.8	13	10%	0.025
8	154.2	6,596	1.9	3.1	14%	0.032

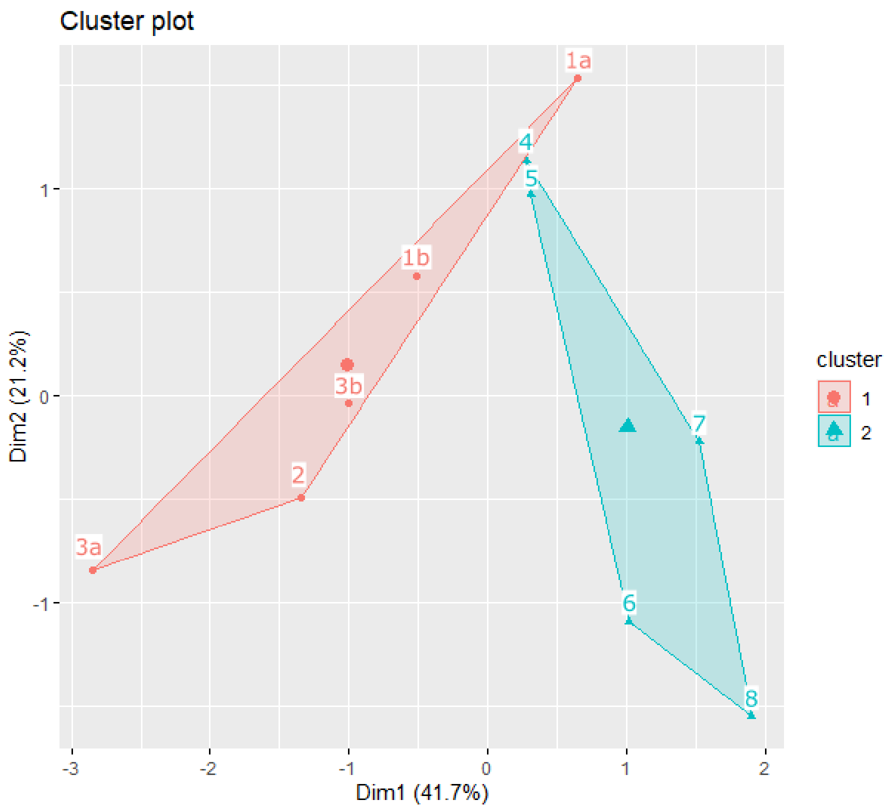

Fig. 4 K-means analysis which found two clusters. Cluster 1 included wetlands 1, 2 and 3. Cluster 2 included wetlands 4, 5, 6, 7 and 8.

4. Discussion

4.1 Statistical Findings

Based on the findings, wetlands in the ASP have not passed a threshold of resiliency and still have the ability to buffer an increase in precipitation. Although the relationship between water level and precipitation is established, there are some parameters that may be missing that would normally be included in a water balance equation. Missing parameters might include groundwater flow, evapotranspiration (as opposed to pan evaporation), and surface water flow out of the wetlands. While this study did not consider the impact of groundwater on these wetlands, it is highly probable that the study wetlands are primarily groundwater fed due to the geology of the area. To further expand on this study, the ACD could focus on groundwater and attempt to complete the water budget analysis. If these wetlands are more dependent on groundwater, it could explain why they have not crossed the threshold of resiliency, as groundwater tends to be more stable and less flashy over time.

Another aspect that could be impacting the wetlands is seasonality. An example of this would be that in the ASP, the highest groundwater infiltration happens in the spring. Groundwater could help buffer the changes in precipitation over a season and make the wetlands more resilient. Installing three or four monitoring wells around each wetland could aid further study into the impacts of seasonality.

In addition to gathering more robust data, the threshold that was defined for the study could also be changed. These wetlands are natural systems that can be hard to quantify and ascribe to statistical models. The threshold established for this study was an *R*-squared of 0.2 and a *p*-value of 0.05. Although the *R*-squared value accounts for a natural system and is relatively low, the *p*-value could be changed to 0.1. This would be appropriate for wetlands in this study.

4.2 Monitoring Network Changes and DIY Sensors

The ACD has a well-established monitoring network that has gathered an incredible amount of data and is an integral resource. Their effort is commendable. There were two main issues with the data used in this study; namely, that only a small number of sites that could be compared because of constraining factors and that the impact of groundwater was not accounted for. To solve these issues the ACD could add wetland sites with varied hydrogeomorphic conditions and sites that do not have controlled hydrology. In addition, the installation of monitoring wells would account for groundwater flow in and out of the wetland, as explained in the above section. Given the expense and that the ACD does not have unlimited funding or time, there may be other appropriate options for filling in missing data.

Similar to the ACDs funding and time constraints, not all government agencies or private entities have the ability to build such a widespread monitoring network. Although the goal for some entities is to fill in the data gaps by gathering more wetland hydrology data, they may not feel it is actually attainable. In these situations, there are three routes that could be taken; hand collecting data, using data loggers, or using DIY (Do It Yourself) solutions. Hand collecting data is a great option, but you lose some nuance of the data since a person cannot collect data every four hours around the clock, and it is incredibly time intensive. At best an employee would need to collect a water level reading every day or week and especially after precipitation events. Using data loggers is the ideal solution as the instruments are pre-built, coded correctly, and have support from the company for issues or battery changes. The main issue is the price, which ranges, depending on the brand and the options, from \$500 to \$1,000 per data logger. If funding is the constraining factor, pre-built data loggers would not be an option. The third option is a DIY solution, like MayFly or Adafruit data loggers. These are environmental sensors that can be built and coded to suit specific needs and come as a fully programmable microprocessor board with options to add on specific environmental sensors, including a pressure transducer to read water levels. These microprocessor boards range from \$20 to \$120, depending on the brand with additional environmental sensors ranging from \$100 to \$300. In addition to providing an affordable and customizable option, these DIY sensors also have incredible crowd-sourced support with open-source software. There are websites like EnviroDIY from Stroud Water Research Center, with forums and a wealth of information in addition to copy-and-paste coding to help with DIY environmental sensors. The major drawback of a DIY solution is the precipitous learning curve. DIY solutions require the drive to learn, or background knowledge in, the assembly of microprocessors and their accessories, along with custom coding. While the time commitment may be great up front, once the sensors are built and programmed their functionality compares favorably with pre-built data loggers. In many situations DIY sensors could be the best solution, effectively balancing funds, and time.

5. Conclusion

Overall, it is important to maintain long-term monitoring networks so that the impact of a changing climate and changing landscape can be analyzed. Wetlands are an important part of the ecosystem and can help buffer these changes. For the ASP, although the wetlands have not shown a significant impact from precipitation and impervious surfaces, they could be more impacted in the future. To further this study, the ACD monitoring network should be maintained and expanded to include different wetland types and different hydrogeomorphic conditions. These wetlands are an ecological version of the “Canary in the Coal Mine”. Someday either an increase in precipitation or imperviousness may cross a critical threshold and sound an alarm for ACD to make management changes. Our recommendation to ACD is to add more shallow monitoring wells to track both water quantity and quality.

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