US Army Corps
of Engineers ®
St. Paul District

Appendix 13:
Valley Branch Watershed District Qualitative Climate Change Assessment

U.S. Army Corps of Engineers
St. Paul District

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1.0 Purpose

The purpose of this analysis is to provide past (observed) and potential future (projected) climate benefits, vulnerabilities, and impacts specific to project operations. Long-term, natural fluctuations in climate or anthropogenic driven climate change can alter regional precipitation, temperature, hydrology patterns, and ecosystem functions. This climate change assessment provides qualitative information on how hydrometeorological variables have changed in the observed records and how they may respond to climate change in the future. Specifically, this assessment focuses on potential climate impacts to the flood risk management business line in the Valley Branch Watershed District (VBWD) in Minnesota.

The *VBWD Landlocked Basin Flood Mitigation Comprehensive Planning Study* evaluates the cost-benefit of water level management options such as pumps, gravity drainage, and property acquisition for nine landlocked lakes and ponds. In recent years, wet conditions have resulted in high groundwater conditions and record high surface water levels, causing flooding of roads, homes, and septic systems. Relevant climate variables for this study include precipitation, temperature as a primary driver of evapotranspiration, and groundwater recharge. This climate assessment includes evaluation of the without project conditions and two alternatives for high water level management.

2.0 Motivation

USACE projects, programs, missions, and operations can accommodate the range of natural climate variability over their operating life. Recent scientific evidence shows that in some locations relevant to USACE operations, climate change has shifted the climatological baseline about which natural climate variability occurs and may also be changing the range of that variability. Therefore, assumptions of stationary climatic baselines and a fixed range of natural variability, as captured in the historic hydrologic record, may no longer be appropriate for long-term projections of risk for USACE business lines and needs to be investigated.

Climate change impacts on the hydrology of the study area are investigated according to the requirements in the USACE Engineering Construction Bulletin (ECB) 2018-14, *Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs and Projects* (USACE, 2020), as well as USACE Engineering Technical Letter (ETL) 1100-2-3 *Guidance for Detection of Nonstationarities in Annual Maximum Discharges* (USACE, 2017). This analysis uses an evidence-based approach to make a qualitative assessment of climate change impacts in Valley Branch watershed.

3.0 Project Background

The VBWD covers approximately 70 square miles within Washington and Ramsey counties in southeastern Minnesota. There are a series of lakes in the northwest and to the southeast Valley

Branch, a creek which drains into the St. Croix River. The area primarily consists of landlocked basins, which historically have flooded. In 1987, the Project 1007 flood control system was constructed and provides a network of stormwater pipes, open channels, catch basins, and two dams to direct flow from the Lake DeMontreville, Olson, and Jane (also called Tri-Lakes) area to the St. Croix River (VBWD, 2017). Following the implementation of Project 1007, there were still numerous landlocked basins remaining in the VBWD. At that time, flooding was not a major issue at these basins. However, in recent years, many of the landlocked basins have experienced high-water and flooding conditions. It is located in the Hydrologic Unit Code 'HUC' 0703 watershed. HUC 0703 lies within the larger Upper Mississippi Region (HUC 07); this is indicated by the purple outline in Figure 3-1. The VBWD is shaded in grey in Figure 3-1.

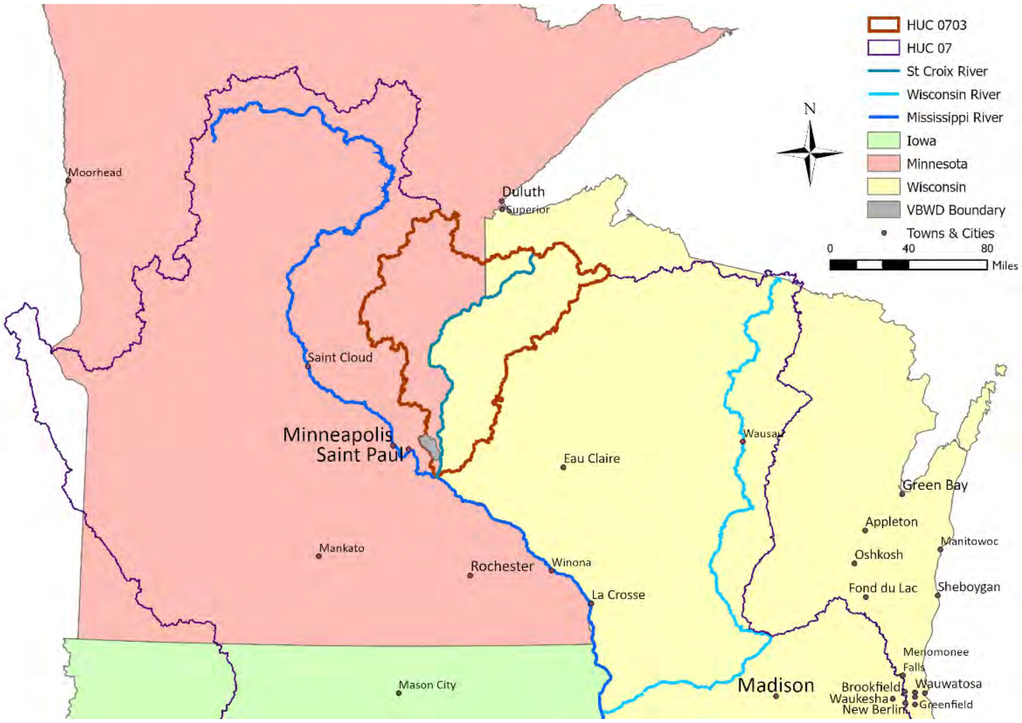


Figure 3-1: Project Location and Watershed Map

4.0 Literature Review

The literature review summarizes peer reviewed science regarding both natural and human driven climate trends in the region which encompass the VBWD. The focus is on summarizing trends identified within observed temperature, precipitation, and streamflow records, as well as providing an indication of future climate conditions based on the outputs from Global and Regional Climate/Circulation Models (GCMs & RCMs). Observed precipitation, temperature, and hydrology data available over the past century have been extensively studied on regional and national scales.

For projected climates, GCMs are used in combination with different greenhouse gas emission scenarios to project future temperature and precipitation conditions. Those projected temperature and precipitation results can be transformed to regional and local scales (a process called downscaling) for use as inputs in hydrologic models (Graham et al., 2007). Uncertainty is inherent to climate modeling due to the large scale of the models and the many variables needed to create projections of temperature and precipitation (USGCRP, 2017). Plus, hydrologic models introduce an additional layer of uncertainty. However, these methods represent the best available science to make projections about hydroclimatic variables. Many researchers use multiple GCMs and hydrologic models in their studies in order to understand how various assumptions impact results (Gleckler et al., 2008).

4.1 Temperature

Based on observed temperature records, the annual average air temperature between 1986-2016 for the Midwest increased by 1.26°F from the 1901-1960 annual average temperature (USGCRP, 2017). Increased temperatures can accelerate snowmelt and lengthen the frost-free season (Carelton and Hsiang 2019; Liu, Goodrick, and Stanturf 2013; Woodward, Perkins, and Brown 2010). Many studies indicate a change in the seasonality in the region marked by increasing winter temperatures and early spring melt (Schwartz et al., 2013; Wang et al., 2009; Westby et al., 2013; Wolter et al., 2015). Warmer winter temperatures have cause reduced ice cover and earlier ice-outs dates causing an early start and longer duration of spring mixing and summer stratification (Frankson et al., 2022; Pilla & Williamson, 2022; Runkle et al., 2022).

In Minnesota, winter has warmed 13 times faster than summer, and nights have warmed 55% faster than days since 1970. The frequencies of -35ºF and -25ºF readings in northern and southern Minnesota, respectively, have fallen by up to 90%. The minimum temperature for Minnesota during the winter months of December-February has increased 0.49ºF per decade since the 1890's (MN DNR, 2019). Decreases in annual maximum temperatures in the summer are observed across the upper Midwest (USACE, 2015) and could be due to the impact of greenhouse gases on cloud cover (Karl et al., 1991).

Although climate conditions will vary from year to year, in Minnesota observed increases in temperature are projected to continue throughout the 21st century. GCM projections for the Midwest show a statistically significant increase in both annual average temperature and the number of extreme heat days over the next century (Vavrus & Behnke, 2014). There is a high degree of uncertainty associated with temperature estimates in large part due to the use of GCMs, the natural variability of temperature, and greenhouse gas emissions assumptions. Regardless of emission scenario applied, unprecedented warming is projected for Minnesota by the end of the 21st century (Frankson, Kunkel, Stevens, et al., 2017).

4.2 Precipitation

On a national scale, the fourth National Climate Assessment (NCA4) concluded that average annual precipitation has increased approximately 4% over the 1901–2015 period (USGCRP, 2017). Average annual precipitation in the Midwest region has increased by 5% to 15% from the first half of the last century (1901–1960) as compared to present day (1986–2015). The amount of rain falling in extreme rain events (1% Annual Exceedance Probability (AEP) Storm Events), has increased by 42% from 1958 to 2016 (USGCRP, 2018). According to the MN DNR, on average, Minnesota has become 3.4 inches wetter between 1895 and 2017 (MN DNR, 2019). Between 1895 and 2014, the wettest five year period is 1982-1986 (Frankson, Kunkel, Stevens, et al., 2017). Not only is Minnesota receiving more precipitation, but high intensity, 1-inch and 3-inch rains, have become more common. The volume of the heaviest annual rainfall has increased (Frankson, Kunkel, Stevens, et al., 2017; MN DNR, 2019). Similarly, an investigation of hourly data at Minneapolis-St. Paul International Airport (MSP) showed increasing trends in both magnitude and frequency from 1948-2019 with strong nonstationarities detected in the 1970s (USACE, 2021).

A MN DNR analysis, based on data collected by the National Centers for Environmental Information (NCEI), also indicates that annual average precipitation in Minnesota is projected to increase; with increases most likely occurring in the winter and spring (MN DNR, 2019; NCEI, 2020). Since winter and spring precipitation are important to flood risk, projected increases in precipitation are important for future planning. Precipitation increases of more than 10% are projected in the winter and the spring for HUC 07 from 2070–2099 relative to 1976–2015. However, in the summer and the fall, projected precipitation amounts are not expected to significantly change. A northward shift in the rain–snow transition zone in the central and eastern United States is projected by end of the 21st century shortening the snow dominated cold season in this area (Ning & Bradley, 2015; USGCRP, 2017).

4.3 Hydrology

Observed hydrologic trends are strongly influenced by precipitation, temperature, and other factors such as land use and land cover in a region, dynamics of groundwater-surface water interaction, drainage patterns, channel geomorphology, and regulation. In the Upper Mississippi Region, multiple studies have identified increasing trends in the observed annual average streamflow (Mauget, 2004; Novotny & Stefan, 2007; Small et al., 2006) and in the observed annual mean/median baseflow (Juckem et al., 2008; Xu et al., 2013). Annual peaks have increased in the spring and summer (Novotny & Stefan, 2007). Seasonally, the studies have reported increasing annual minimum 7-day low flows in the fall (Small et al., 2006) and annual average 7-day low flows in the fall and winter (Novotny & Stefan, 2007). Increases in the 7-day low flows have continued to increase through today (US EPA, 2021).

There is little to no consensus in the literature regarding changes in projected, future streamflow in the Upper Mississippi Region (USACE, 2015). With the anticipated increase in precipitation intensity, the frequency and intensity of floods could also increase (Frankson, Kunkel, & Champion, 2017), but corresponding changes in evapotranspiration could dampen the impacts. A recent study of the St. Croix River using four climate projections with representative concentration pathways (RCP) 4.5 and 8.5 showed increasing flow across all simulations (Yang et al., 2019); however, for the 2030 planning horizon under the A2 emission scenario, a different study found no change in average annual total runoff on the St. Croix near the VBWD (Mishra et al., 2010).

4.4 Groundwater

The landlocked lakes within the VBWD are connected to a shallow unconfined aquifer that is not a source of regional drinking water. These groundwater levels are likely to be impacted by a changing precipitation and temperature since groundwater levels have established relationships with precipitation and evapotranspiration at multiple spatial and temporal scales (Amanambu et al., 2020). For example, in Clearwater County, Minnesota, the closed basin of Long Lost Lake saw increased water levels starting in 1990, but by 2003 water levels started to decline. A study of precipitation and temperature fluctuations over the 20th century showed that the 2001 water levels followed primarily natural and historically normal meteorological trends (Christensen & Bergman, 2005).

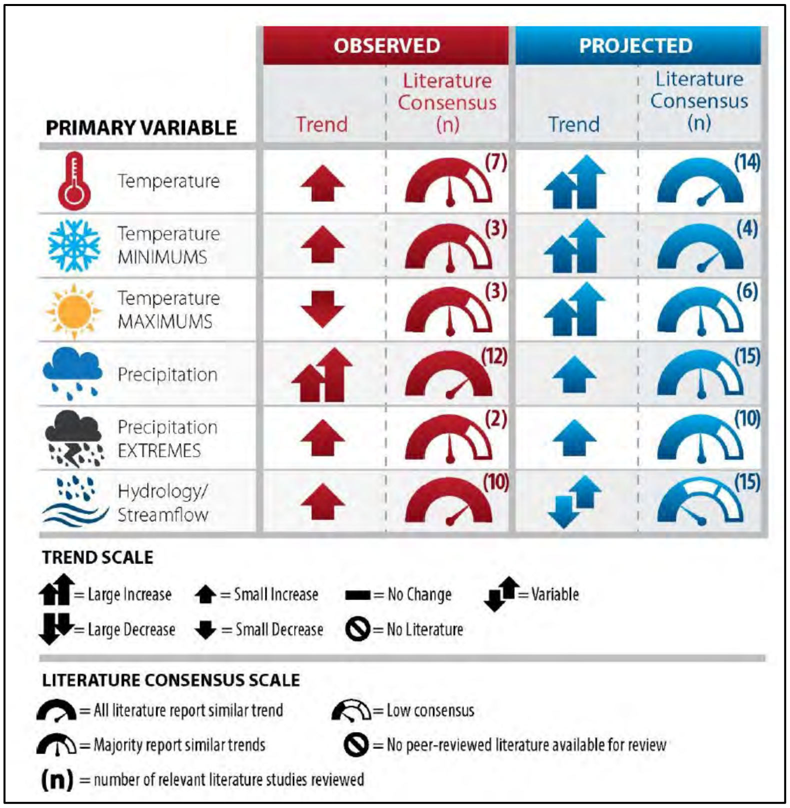
In 2021, Hanson et al. investigated future climate projections using six different climate models in the Northern Highlands Lake District of Wisconsin and Michigan and similar to other studies found generally wetter winters, but uncertain summers (Person et al., 2007). The impact of future climate on lake hydrology was more pronounced for seepage lakes. Unlike drainage lakes, which have surface water inputs to buffer climate changes, seepage lakes are more sensitive to changes in precipitation and/or evaporation because they have no surface inlet or outlet (Hanson et al., 2021). Analysis of paleo (mid-Holocene) lake sediment data and creation of a surface-groundwater model demonstrated that lake level fluctuations in the Crow Wing watershed in Minnesota corresponds to short term climate forcing, soil permeability, and surface water connectivity. Lakes with low permeability soils and/or no surface water outlet tended to see more dramatic changes in their water levels (Person et al., 2007).

Groundwater recharge is influenced by the type, amount, and intensity of precipitation. Snowmelt is able to recharge groundwater more effectively than rainfall. The reduction of snowpack due to rising winter temperatures could lower the recharge (Amanambu et al., 2020). However, shallower frost depths could increase the duration for conditions favorable to groundwater recharge, rather than runoff, despite the reduced snowpack. A study of the state of Minnesota using five statistically downscaled climate models showed that the Central Hardwood Forests area, where the Valley Branch is located, is likely to see lower recharge (Anurag & Ng, 2022). In a study of Black Earth Creek in Wisconsin, the USGS used 13 dynamically downscaled climate models and three future emission scenarios to concluded that groundwater levels will likely be more dependent on fall and winter recharge rather than the snowmelt pulse and that groundwater recharge is likely to decrease due the increase in evapotranspiration (Hunt et al., 2016).

Similarly, simulated infiltration rates for the Twin Cities Metropolitan Area using Bias-Correction Constructed Analogues downscaled global climate model projections in a Soil Water Balance model were estimated to be lower than the infiltration rates based on observed data from 2010-2019. However, the combination of the downscaling method and comparison to a particularly wet observed period suggests that the lower infiltration results are in part due to the simulation choices and additional investigation is needed of further determine the drivers of lower infiltration rates (Christianson, 2020). Projecting future groundwater levels is difficult due to the uncertainty created by the GCMs, downscaling, hydrologic, and groundwater modeling (Amanambu et al., 2020).

4.5 Summary

Within the literature reviewed, there is strong evidence through consensus that temperature, precipitation, and streamflow have increased over the observed period of record within the Upper Mississippi Region HUC 07. Projections of future climate show strong consensus on increases in future temperature, and moderate consensus on increases in precipitation. There is little to no consensus related to trends in projections of future streamflow. Groundwater recharge will be impacted by changes in temperature, precipitation, and streamflow. Slightly more studies suggest lower recharge rates in the future; however, groundwater recharge projections have considerable uncertainty due to the large number of variables impacting recharge rates. The 2015 USACE *Civil Works Technical Report CWTS-2015-13* provides a visual summary of the trends in observed and projected hydrometeorological variables, and this is presented Figure 4-1, below.



PRIMARY VARIABLE	OBSERVED		PROJECTED	
	Trend	Literature Consensus (n)	Trend	Literature Consensus (n)
Temperature	⬆	(7)	⬆⬆	(14)
Temperature MINIMUMS	⬆	(3)	⬆⬆	(4)
Temperature MAXIMUMS	⬇	(3)	⬆⬆	(6)
Precipitation	⬆⬆	(12)	⬆	(15)
Precipitation EXTREMES	⬆	(2)	⬆	(10)
Hydrology/ Streamflow	⬆	(10)	⬇⬆	(15)

TREND SCALE

⬆⬆ = Large Increase
⬆ = Small Increase
▬ = No Change
⬇⬆ = Variable
⬇⬇ = Large Decrease
⬇ = Small Decrease
⊘ = No Literature

LITERATURE CONSENSUS SCALE

= All literature report similar trend
= Low consensus
= Majority report similar trends
⊘ = No peer-reviewed literature available for review
(n) = number of relevant literature studies reviewed

Figure 4-1: Summary matrix for the Upper Mississippi River Region 07

5.0 Nonstationarity Detection and Trend Analysis

ECB 2018-14, *Guidance for Incorporating Climate Change Impacts into Inland Hydrology in Civil Works Studies, Designs, and Projects* (USACE, 2020) as well as USACE ETL 1110-2-3, *Detection of Nonstationarities in Annual Maximum Discharges* (USACE, 2017) are followed to analyze observed precipitation, temperature, and surface water elevations relevant to this project. A series of statistical nonstationarity tests look for abrupt changes and smooth transitions in the statistical properties of observed datasets. Changes in a dataset's statistical properties may negate the assumption of stationarity (i.e., represent nonstationarity) in the sample. With no long-term groundwater data in the VBWD, maximum 1-Day precipitation, accumulated precipitation, maximum daily temperature, and minimum daily temperature are analyzed over the past 100 years of record as indicators of change to groundwater recharge. Available lake level, groundwater, and streamflow information from within the watershed is presented for awareness and should be updated as additional years of data is collected.

Changes in the statistical properties of streamflow records can be driven by the effects of anthropogenic climate change, long-term natural fluctuations in climate, changes in water management, changes to land use, changes in land cover, changes in channel geomorphology, etc. Nonstationarity detection in itself does not attribute the shifts in statistical properties detected to a particular driver. Under USACE (2018) guidance, the stationarity of records is assessed by applying 12 statistical tests to an observed record. Ten of these tests look for an abrupt change, while two smooth tests look for a gradual change over time (USACE 2018). USACE has developed the Time Series Toolbox (TST) to apply these tests. The TST also allows the user to evaluate the datasets of interest for linear and monotonic trends using the t-Test, Spearman Test and the Mann-Kendall Test. When evaluating datasets for the presence of linear trends or applying the selected monotonic trend tests, p-values below 0.05 provide a reasonable basis for statistical significance and allow the user to assume that some driver (outside of randomness) is causing a change.

5.1 Meteorological Variables

Daily meteorological data used for this study is collected from the NOAA National Centers for Environmental Information (NCEI) Global Historical Climatology Network (GHCN). Data from the following gages are downloaded from the NCEI database and averaged across all the stations to create a single representative record. The following gages are used:

1. River Falls, WI (USC00477226): October 1921 - November 2021
2. Minneapolis St. Paul International Airport (USW00014922): October 1921 - November 2021
3. Stillwater 1 SE, MN (USC00218037): October 1921 - January 2006
4. Vadnais Lake, MN (USC00218477) January 1982 – October 2021
5. Hastings, MN (USC00213567): October 1921 - November 2021

Precipitation data, as published by the NCEI is available as daily, cumulative precipitation (NCEI, 2020). Since missing data can have substantial impacts on cumulative precipitation totals, gaps in the daily record are filled in by averaging across the stations where data is available. Missing temperature data that remains is estimated with linear interpolation. Interpolation is only applied if the gap in the daily minimum or maximum temperature record is less than five days. Missing precipitation data is not interpolated and left as Not Applicable (NA). If there are still large periods with missing data, the record is truncated.

In computing the annual timeseries, if more than five days remain missing within a season for a given year, the maximum or minimum depending on the variable is not reported for that year. Similarly, years with more than 31 days missing or more than five days missing in impactful seasons are not reported. In this dataset, 25 days of precipitation data cannot be estimated in August 1926. Therefore, no precipitation variables are reported for the summer or water year in 1926. The water year is not reported since a significant amount of precipitation typically falls in the summer. Table 5-1 shows the results of the trend and nonstationarity analyses. A strong nonstationarity is one that demonstrates consensus, robustness and an operationally-significant increase or decrease in the sample mean and/or variance. Consensus requires change points identified by two or more tests targeting the same statistical properties (e.g., mean or standard deviation) while robustness requires two of more tests of difference statistical properties as defined in ETL 1100-2-3.

Table 5-1: Summary of Meteorological Trends and Nonstationarities

	HUC-4	Period of Record Analyzed	Trends in Period of Record	Strong NSD	Statistical Shift	Subsets Analyzed	Subsets Trends
1 DAY MAX PRECIP	Annual-WY	1922-2021 (MISSING 1926)	NONE	NONE	NA	NA	NA
	Winter	1922-2021	NONE	NONE	NA	NA	NA
	Spring	1922-2021	NONE	NONE	NA	NA	NA
	Summer	1922-2021 (MISSING 1926)	NONE	NONE	NA	NA	NA
	Fall	1922-2021	NONE	1942	M: ↓ 0.5in	1922-1942	NONE
						1943-2021	**NONE**
TOTAL PRECIP	Annual-WY	1922-2021 (MISSING 1926)	⬆	1982	M: ↑ 2in	1922-1982	NONE
						1983-2021	**NONE**
	Winter	1922-2021	NONE	NONE	NA	NA	NA
	Spring	1922-2021	⬆	NONE	NA	NA	NA
	Summer	1922-2021 (MISSING 1926)	⬆	NONE	NA	NA	NA
	Fall	1922-2021	NONE	NONE	NA	NA	NA
TMAX	Annual-WY	1922-2021	⬇	1991	M: ↓ 2°F	1922-1991	NONE
						1992-2021	**NONE**
	Winter	1922-2021	NONE	NONE	NA	NA	NA
	Spring	1922-2021	NONE	NONE	NA	NA	NA
	Summer	1922-2021	⬇	1991	M: ↓ 2°F	1922-1991	NONE
						1992-2021	**NONE**
	Fall	1922-2021	⬇	1962	M: ↓ 3°F	1992-1962	NONE
						1963-2021	**NONE**
TMIN	Annual-WY	1922-2021	⬆	1937	M: ↑ 7 °F	1922-1937	NONE
						1938-2021	POSITIVE
				1985	M: ↑ 6°F	1922-1985	NONE
						1986-2021	**NONE**
	Winter	1922-2021	⬆	1937	SD: ↓ 2.3°F, M: ↑ 6°F	1922-1937	NONE
						1938-2021	POSITIVE
				1997	M: ↑ 5°F	1922-1997	POSITIVE
						1998-2021	**NONE**
	Spring	1922-2021	⬆	NONE	NA	NA	NA

	HUC-4	Period of Record Analyzed	Trends in Period of Record	Strong NSD	Statistical Shift	Subsets Analyzed	Subsets Trends
	Summer	1922-2021	⬆	1937	M: ↑ 6°F	1922-1937	NONE
						1938-2021	POSITIVE
				2004	M: ↑ 6°F	1922-2004	POSITIVE
						2005-2021	**NONE**
	Fall	1922-2021	⬆	1997	M: ↑ 8.4°F	1922-1997	NONE
						1998-2021	**NONE**

Statistical shifts reported for standard deviation (SD) and mean (M)
Water Year: Oct 1 to Sept 30
Seasons: Winter (Dec, Jan, Feb), Spring (Mar, Apr, May), Summer (Jun, July, Aug), & Fall (Sept, Oct, Nov)

Figure 5-1 shows strong nonstationarity in 1982 where the mean of accumulated precipitation increased from 31 inches to 33 inches per water year. Similarly, the total precipitation is increasing within the spring and summer (Figure 5-2) at a rate of approximately 2 and 4 inches per century respectively, and there are no strong nonstationarities in either season as shown in Table 5-1. There are not statistically significant trends in the maximum 1-day precipitation, suggesting that 1-day storms have not changed dramatically over the past century.

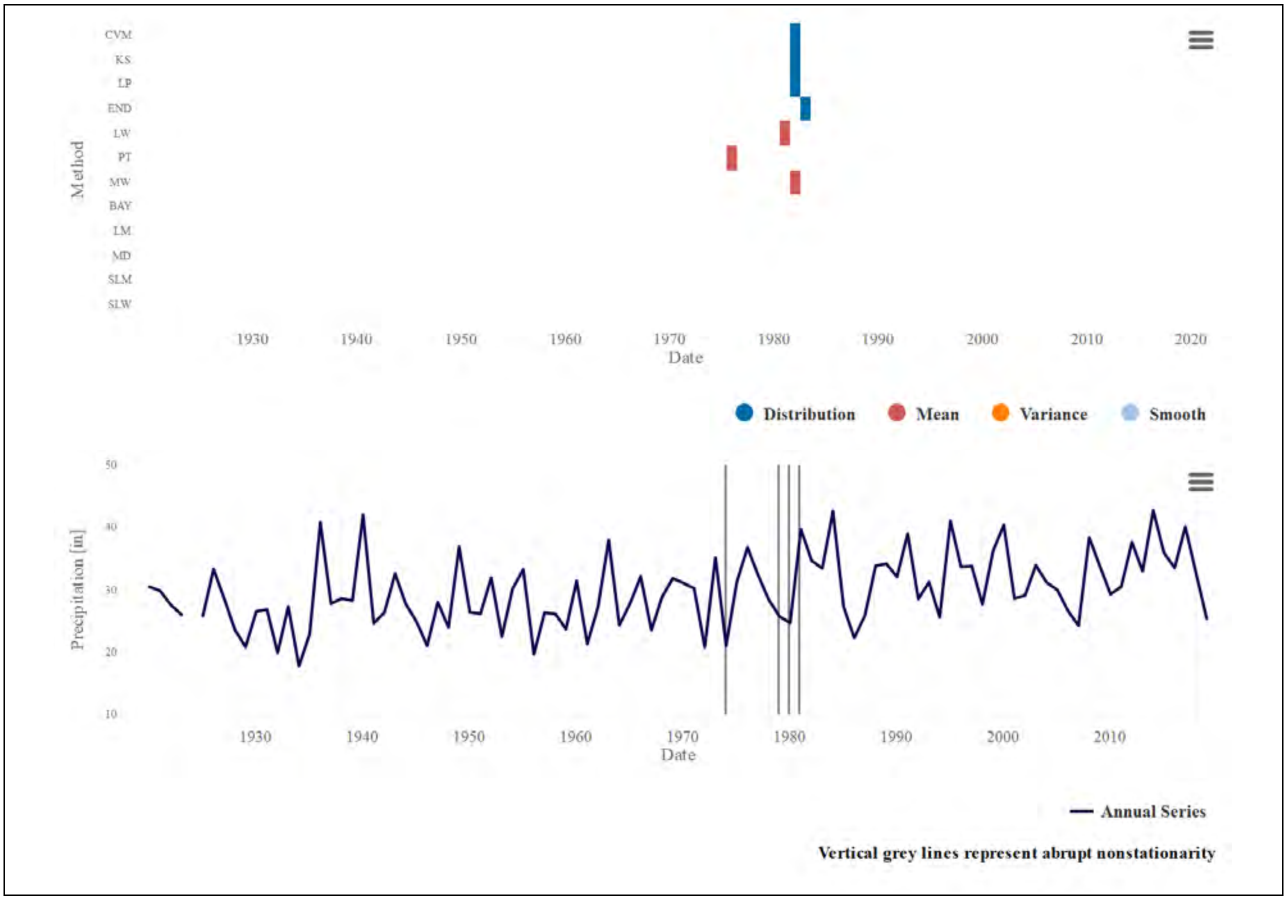


Figure 5-1: Annual Accumulated Preciptation: 1922-2021

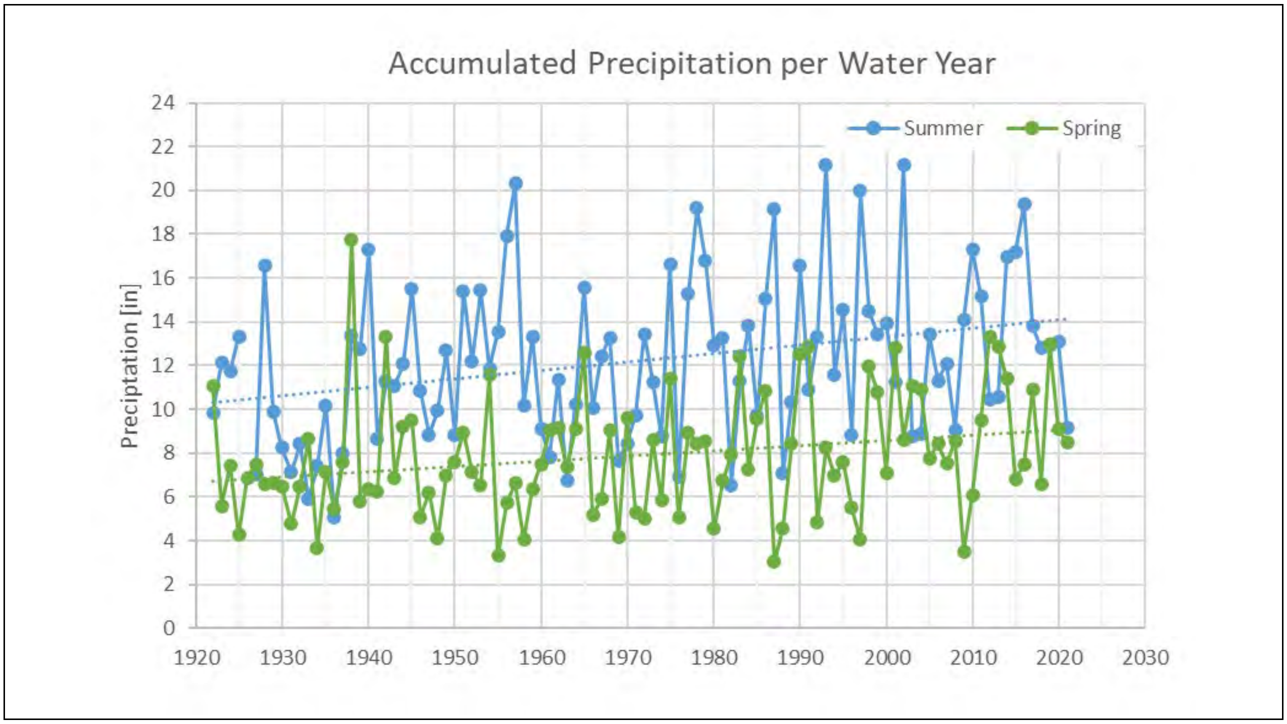


Figure 5-2: Spring and Summer Accumulated Preciptation: 1922-2021

Maximum temperatures are decreasing in the summer and fall across the period of record. There is evidence of a strong nonstationarity in 1991 for the summer and 1962 for the fall, showing a decrease in the mean annual maximum temperature in the more recent periods. Figure 5-3 shows the maximum temperatures for each water year across the period of record.

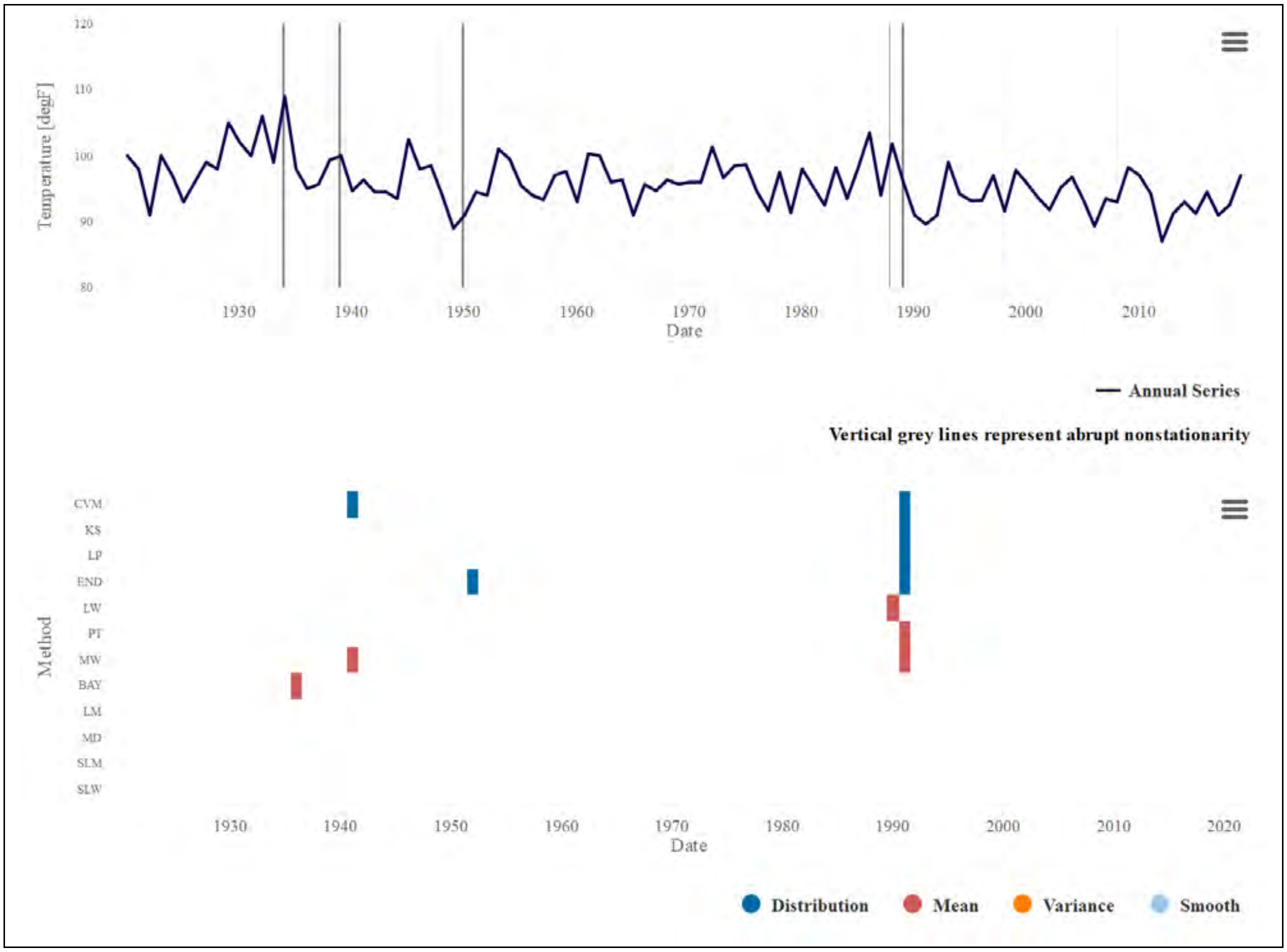


Figure 5-3: Annual Maximum Temperatures: 1922-2021

Minimum temperature is increasing across the water year and all four seasons for the period of record (See Figure 5-4). As shown in Table 5-1, there are strong nonstationarities in the late 1930s and in the late 1990s/early 2000s with abrupt increases in the mean minimum temperatures by more than 5°F. Both these periods are associated with extreme droughts connected with La Nina-like conditions, and in the case of the 1930s the drought was exacerbated by vegetation loss and available soil dust (Cook et al., 2009; Seager, 2007). There are no statistically significant trends in the most recent time periods except in the spring. Minimum temperature in the spring is increasing at rate of approximately 1°F per decade. Winter minimum temperature increased at a similar rate until 1997, but the trend did not continue. Similarly, the summer minimum temperatures increase at a rate of approximately 0.7°F per decade from 1922 to 2004.

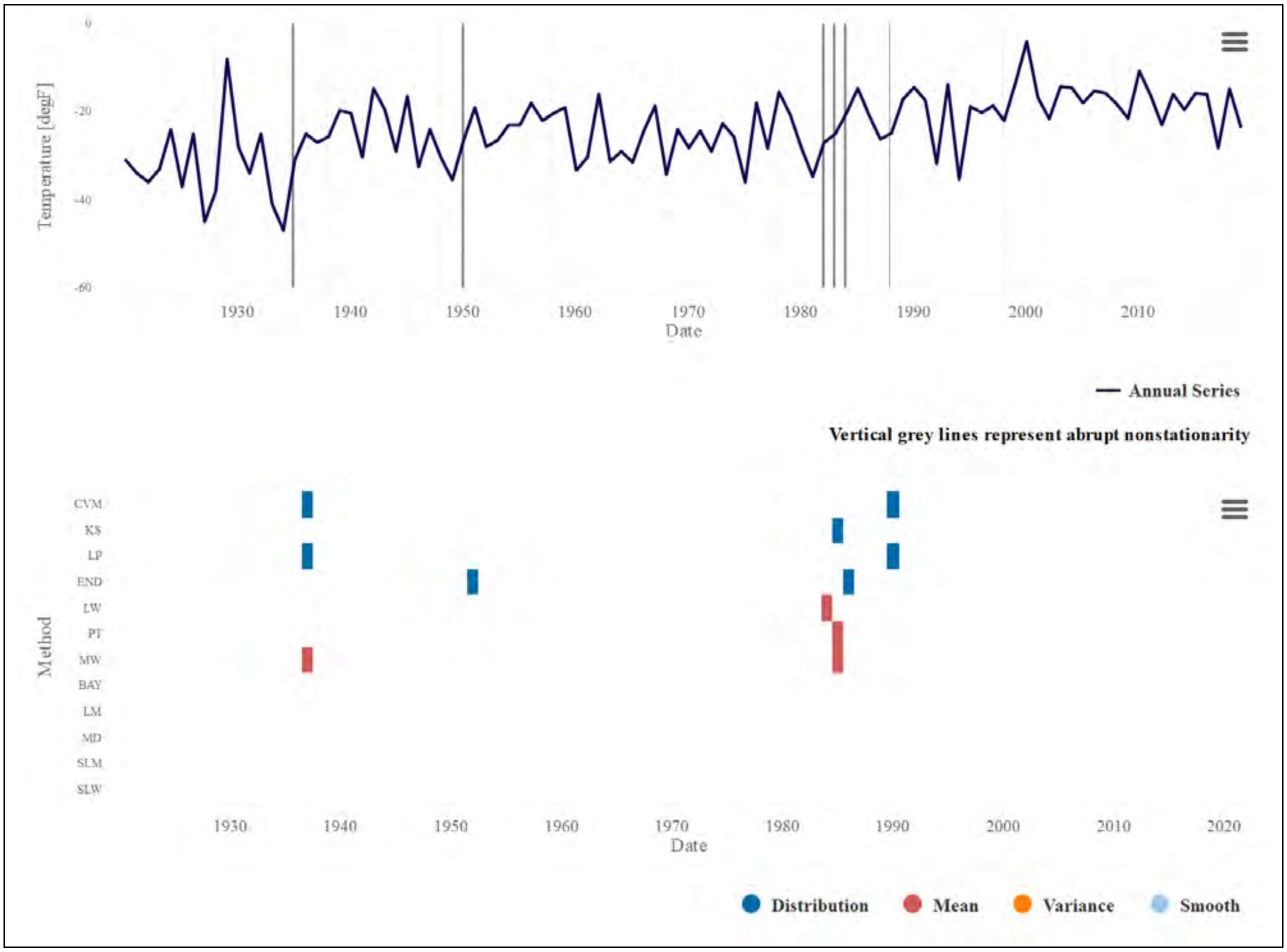


Figure 5-4: Annual Minimum Temperatures: 1922-2021

5.2 Hydrology

5.2.1 Lake Water Levels

As mentioned previously, Project 1007 was completed in the late 1980s to reduce flood risk to homes in the VBWD. A combination of pipes, manholes, dams, and open channels direct water from the lakes to the St. Croix River. The project lowered the discharge invert elevation and prevents extreme lake levels. Lakes in connection with Project 1007 have been routinely monitored by the VBWD and have data extending back to the mid-1970s. The effect of the Project 1007 is apparent. Lakes outside of the Project 1007, including many of the landlocked basins included in the study, have data from the mid to late 1990s until the present. However, many of these basins are not part of the VBWD routine lake level monitoring program and the data are sporadically collected throughout the year, making statistical analyses challenging. To maintain seasonal consistency the data is filtered into Spring (March, April, and May), Summer (June, July, and August), and Fall (September, October, and November). The maximum value for each year is extracted to create an annual time series for each season.

Including the lakes impacted by Project 1007, twenty of the lakes within the VBWD have observed water surface elevation data. Of those which are not impacted by Project 1007, Lake McDonald has the longest record extending from 1986 to present (excluding 1987-1988, 1990-1992, 2011). Figure 5-5 shows the maximum water surface level for each season across the observed record.

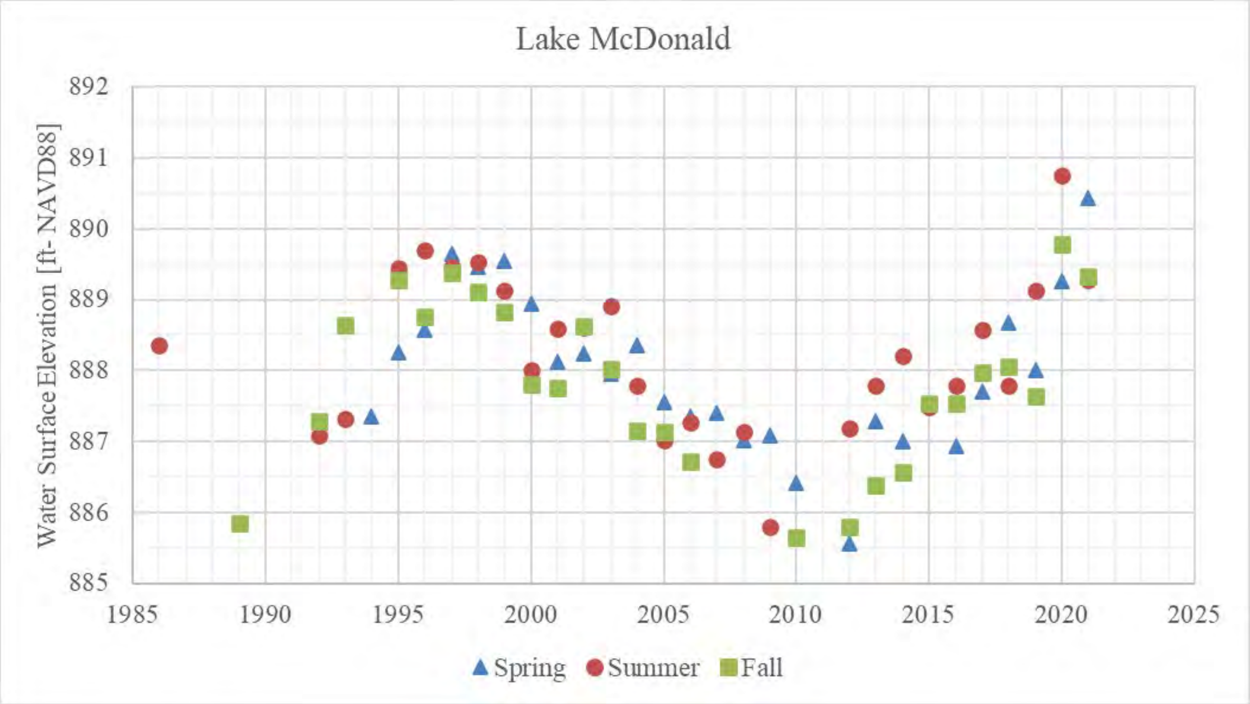


Figure 5-5: Seasonal Water Surface Elevations for Lake McDonald

A trend analysis is completed for the Spring and Summer. There was not enough data to analyze the Fall; therefore, the frost-free period of April to October was analyzed. As shown in Table 5-2, no statistically significant trends are evident in the data and there is not enough data to look for nonstationarities.

Table 5-2: Lake McDonald Water Surface Elevation Trends

Season	POR	Trend
Spring	1992-2021, excluding 2011	NONE
Summer	1995-2021, excluding 2011	NONE
Frost Free	1992-2021, excluding 2011	NONE

Connected lakes in the western portion of the watershed, Lake Olson and Lake DeMontreville have the longest record extending back to 1960. Project 1007 dropped the lake outlet elevation 1.4 feet in July 1987 and is considered prior knowledge of a nonstationarity. The data is filtered to the approximate frost-free season (April-Oct), and the maximum is extracted for each year to create an annual time series. The water surface elevations, analyzed from 1965 to 2021 (excluding 1979), do not show a statistically significant trend. As expected, the analysis shows a strong nonstationarity in 1987 when Project 1007 became operational. The water surface elevation shows a considerable shift in standard deviation dropping from approximately 1ft from 1.8ft between 1969-1987 to 0.78ft between 1991-2021. Figure 5-6 shows the data plotted over time. The grey lines represent nonstationarities detected. The heat map in the bottom portion of the figure shows the strongest nonstationarity in the variance of the annual seasonal maximum in 1987 as indicated by the year with highest number of statistically significant tests. A statistically significant increasing trend is detected between 1988-2021, suggesting that the lake level has risen slightly over the past 30 years. However, analyzing the data from 1992-2021, no trends are detected; thus, the trend is very sensitive to the data directly following the installment of Project 1007. Continued observation of lake levels into the future will provide more insight into whether this trend is stable over time and this analysis should be updated when such data is available.

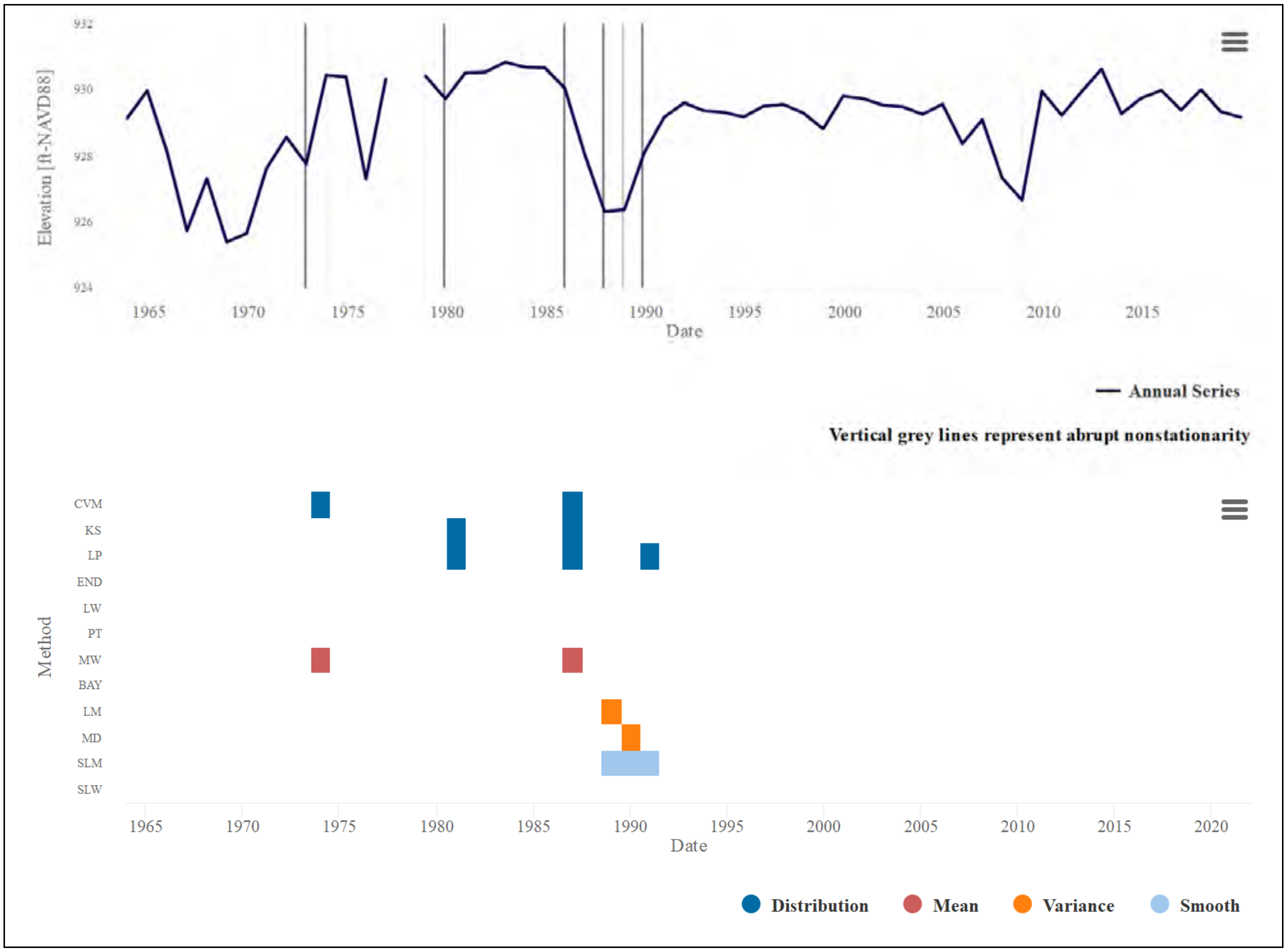


Figure 5-6: Lake Olson & Lake DeMontreville Water Surface Elevation Nonstationarity Analysis

5.2.2 Groundwater Wells

Similar to the lake water surface elevations, groundwater elevations were taken occasionally over the past 20 years at various locations within the VBWD. While this was enough data to look for trends, it was not enough to detect nonstationarities. The observations were not filtered by season due to limited data; instead, the data is filtered to the frost-free period (April to October). The maximum values are selected for each year to create the time series analyzed. Three groundwater monitoring wells are selected and plotted due to their length of record and lack of impact from Project 1007 as shown in Figure 5-7. Only monitoring well 18 at Baytown had enough continuous data to be analyzed for trends and no statistically significant trends are identified. However, the p-values for the t-test and Spearman Rank Order test are barely above the threshold of 0.05 and the Mann-Kendall returned a p-value less than 0.05. As additional data is collected this analysis should be repeated.

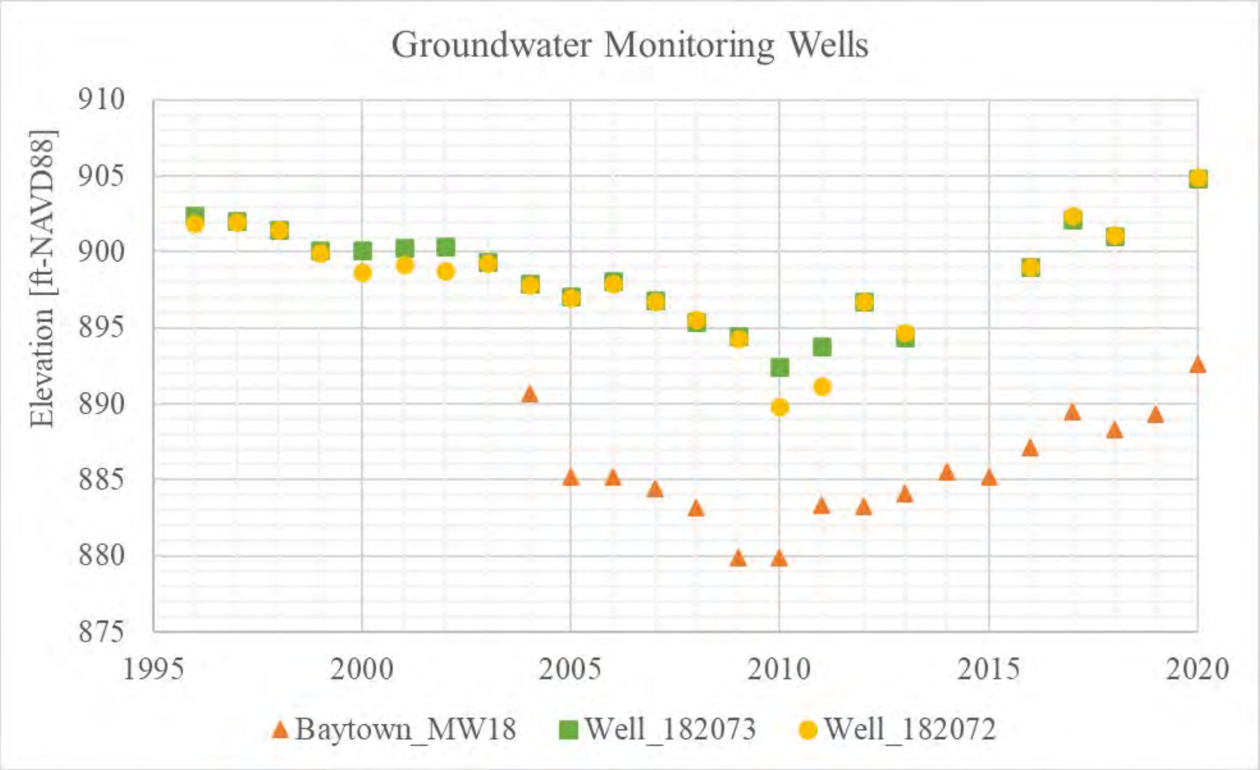


Figure 5-7: Groundwater Elevations

5.2.3 Valley Creek

Valley Creek is a small tributary of the St. Croix River and has drainage area is less than 15 square miles. It lies within Valley Branch Watershed District but does not include flows from Project 1007. There are no statistically significant trends in the maximum annual or seasonal peak flows from 1999-2020 for Valley Creek.

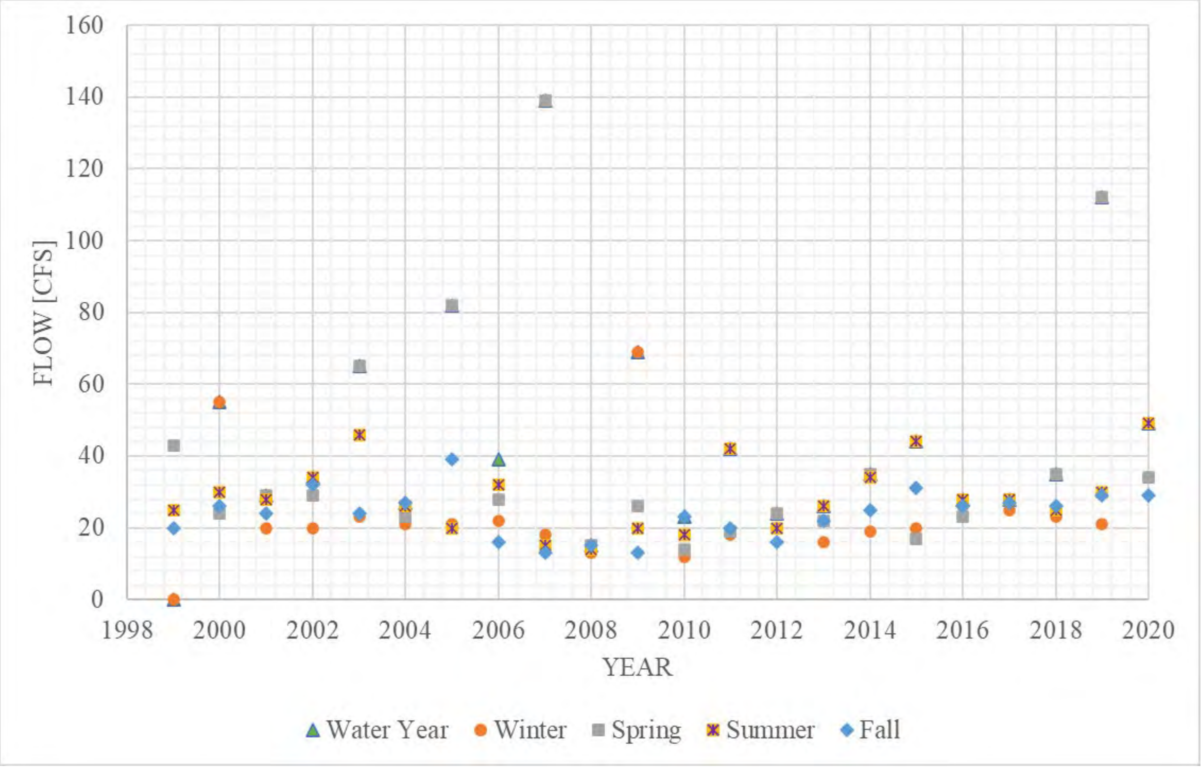


Figure 5-8: Valley Creek Maximum Flows

6.0 Projected Hydrology and Vulnerability

To understand potential future conditions, USACE developed several tools to project future streamflow and assess vulnerability to climate change at a regional scale up to water year 2099. These tools are used to investigate projected changes to basin hydrology in response to climate change. HUC 0703, the St. Croix shown in Figure 3-1, encompasses the VBWD and is used for this assessment.

6.1 USACE Climate Hydrology Assessment

The USACE Climate Hydrology Assessment Tool (CHAT) is used to investigate potential future trends in streamflow for the St. Croix (HUC 0703) up to water year 2099. The CHAT uses output from Global Climate Model (GCM) simulations from the Coupled Model Intercomparison Project, Phase 5 (CMIP5). CMIP5 GCM meteorological data outputs are statistically downscaled to a spatial scale relevant to water resources decision-making using the Localized Constructed Analogs (LOCA) method (Pierce et al., 2014).

Meteorological outputs are translated into a hydrologic response using a Variable Infiltration Capacity (VIC) macroscale hydrology model (Liang et al., 1994). This model represents unregulated and largely uncalibrated areal hydrology across the continental United States (CONUS). Areal runoff from VIC was routed through the stream network using mizuRoute (Mizukami et al., 2016). The range of results is indicative of the uncertainty associated with projected, climate changed hydrology. Sources of uncertainty include GCM boundary conditions, emission trajectory selected, model uncertainty (meteorologic & hydrologic) and the uncertainty associated with the selected downscaling technique.

Future, climate changed hydrology is based on the outputs of 64 different GCMs run using RCPs 4.5 and 8.5. Future projections for 2006 to 2099 are compared to modeled, historic period outputs for 1950 through 2005. For the historic simulation period, meteorological conditions are also derived from GCM outputs, but greenhouse gas emissions are assumed to be equivalent to reconstructed, historic levels. The CHAT tool evaluates whether there is evidence of a statistically significant trend in the mean of the 64 simulated timeseries for both the historic simulation period (i.e., water years 1951-2005) and the projected future simulation period (i.e., water years 2006-2099).

As a critical variable to groundwater recharge, projected precipitation, as represented by the annual maximum 1-Day and the annual accumulation, is analyzed through 2099 for the 8-digit HUC 07030005, Lower St. Croix where VBWD is located. Figure 6-1 shows statistically significant increasing trends in the annual maximum 1-Day precipitation for both the RCP 4.5 (p-value = 0.0119) and RCP 8.5 scenario (p-value = <2.2E-6). In the more extreme RCP8.5 scenario, annual maximum precipitation increases at approximately 0.3 inches per century. Figure 6-2 shows the statistically increasing trend for the Annual Accumulated Precipitation for both the RCP 4.5 (p-value = 8.4E-4) and RCP 8.5 scenario (p-value = <2.2E-6). In RCP 8.5, accumulated precipitation is expected to increase 3.4 inches per century. There is a similar increasing trend in the annual maximum 3-day precipitation.

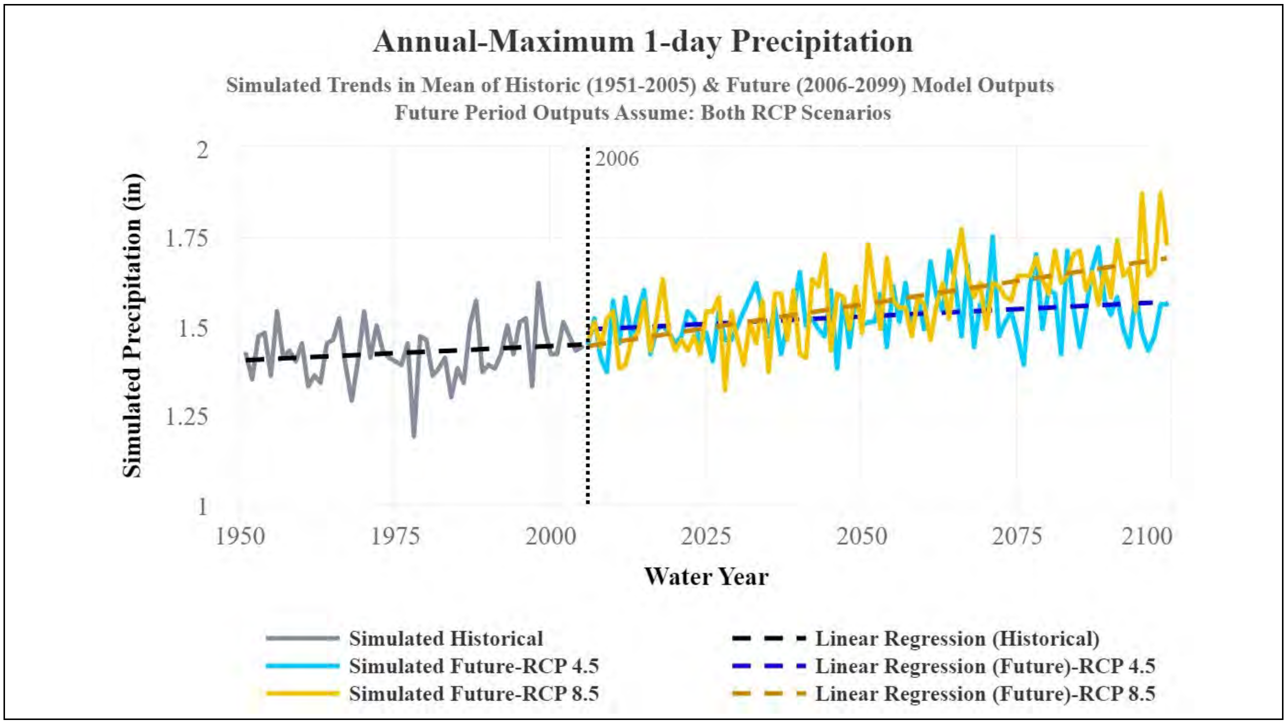


Figure 6-1: Projected Annual Maximum 1-day Precipitation for HUC 07030005

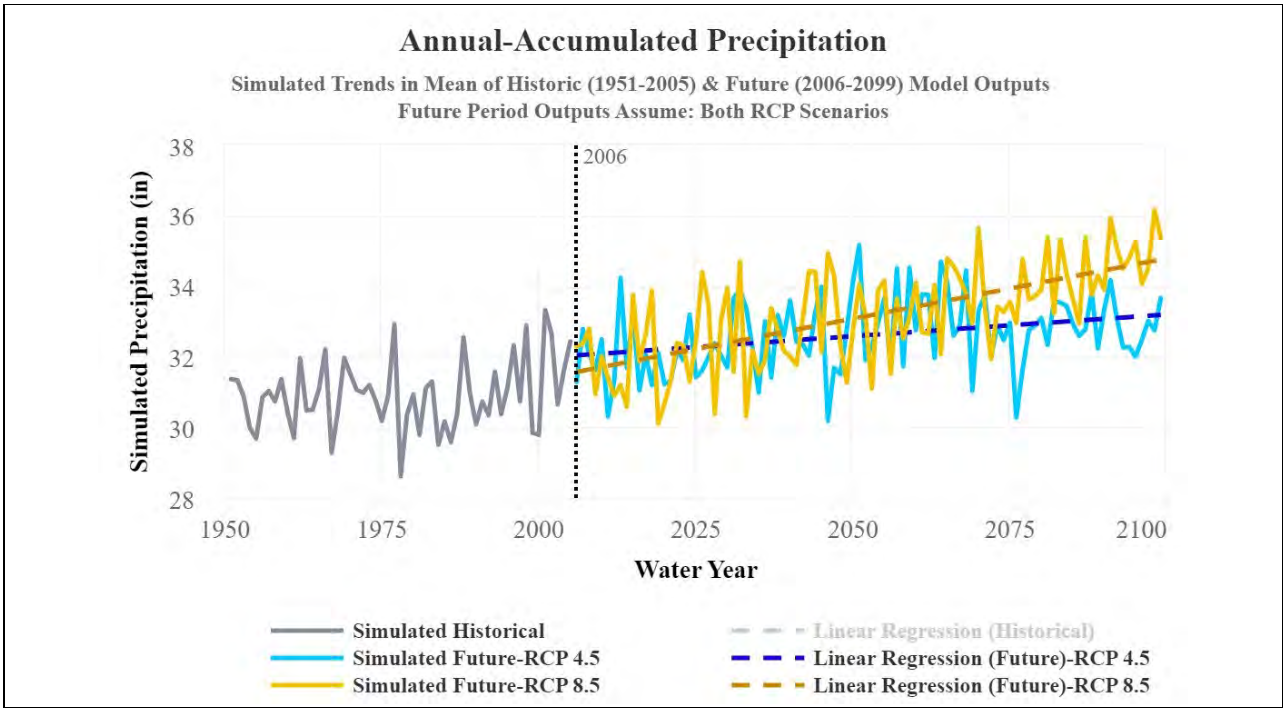


Figure 6-2: Trends in Annual Accumulated Precipitation for HUC 07030005

6.2 Vulnerability Assessment

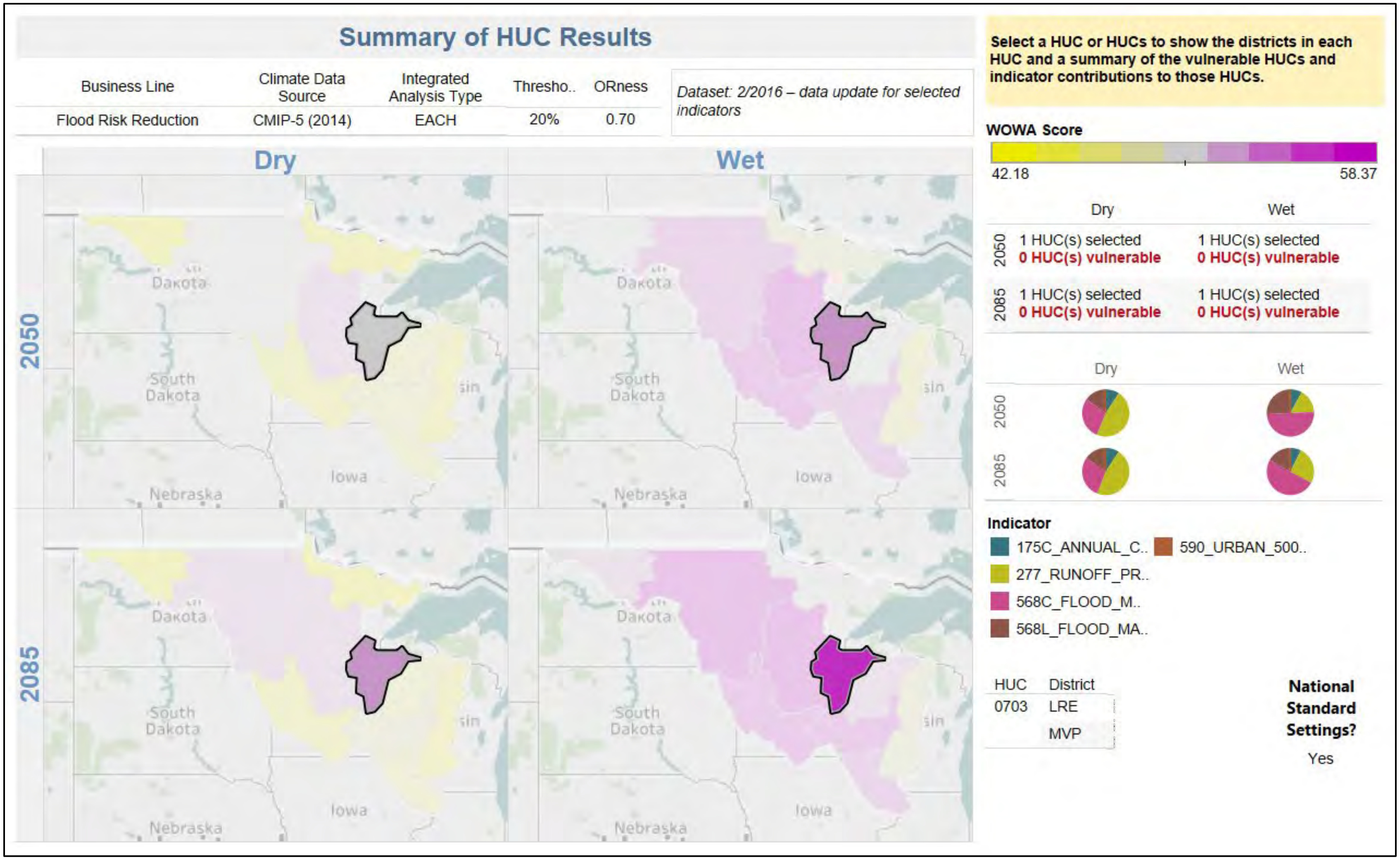
The USACE Watershed Climate Vulnerability Assessment (VA) Tool completes a screening level, climate change assessment of vulnerability by comparing a selected watershed to all 4-digit HUC watersheds in the CONUS. This tool is used to assess the relative vulnerability of a specific USACE business line within a watershed to projected climate change impacts. Vulnerability is measured using the Weighted Order Weighted Average (WOWA) method to compute a composite vulnerability score for each business line, time period (2050 or 2085, 30-year epoch), and scenario (wet or dry). Each WOWA score is based on a set of standardized indicator variables which reflect stressors related to climate, demographic changes, ecological changes, and other factors (USACE, 2016).

For this study, the Flood Risk Reduction (FRR) business line is analyzed with the tool’s default, National Standard Settings. Indicators used to compute the FRR WOWA score include: the acres of urban area within the 500-year floodplain, the coefficient of variation in cumulative annual flow, runoff elasticity (ratio of streamflow runoff change to precipitation change), and two indicators of flood magnification (indicator of how much high flows are projected to change over time), one of which includes contributions from upstream watersheds and the other focused only on the change in flood frequency within the watershed of interest. Figure 6-3 and Table 6-1 display the vulnerability scores for the St. Croix (HUC 0703) watershed for the Flood Risk Reduction business line.

The St Croix is not considered vulnerable under any scenario. The dominant indicator contributing 50% to the St. Croix’s FRR vulnerability score is Flood Magnification in the wet scenarios and is Runoff Elasticity in the dry scenarios. To provide absolute context to the watersheds’ vulnerability, the cumulative flood magnification is projected to be above one in the wet scenarios. Watersheds with flood magnification above one should anticipate higher flood flows in the future. Within the VA tool, flood flows are defined as the monthly flow magnitude that is exceeded 10% of the time (USACE, 2016). For the dry scenarios, runoff elasticity is estimated to be 2.8 and 2.9 for 2050 and 2085, respectively. This means that for every 1% monthly increase in precipitation, runoff is projected to increase by 2.8 and 2.9%, respectively.

Table 6-1: Flood Risk Reduction Vulnerability Scores for HUC 0703

HUC 4 Watershed	**Flood Risk Reduction Vulnerability Score (WOWA)**			
	2050		2085	
	WET	DRY	WET	DRY
St. Croix (0703)	52.46	50.71	56.18	51.78



Summary of HUC Results

Business Line	Climate Data Source	Integrated Analysis Type	Thresho..	ORness
Flood Risk Reduction	CMIP-5 (2014)	EACH	20%	0.70

Dataset: 2/2016 – data update for selected indicators

Select a HUC or HUCs to show the districts in each HUC and a summary of the vulnerable HUCs and indicator contributions to those HUCs.

WOWA Score

42.18 58.37

	Dry	Wet
2050	1 HUC(s) selected **0 HUC(s) vulnerable**	1 HUC(s) selected **0 HUC(s) vulnerable**
2085	1 HUC(s) selected **0 HUC(s) vulnerable**	1 HUC(s) selected **0 HUC(s) vulnerable**

Indicator

- ■ 175C_ANNUAL_C..
- ■ 590_URBAN_500..
- ■ 277_RUNOFF_PR..
- ■ 568C_FLOOD_M..
- ■ 568L_FLOOD_MA..

HUC	District
0703	LRE
	MVP

National Standard Settings?

Yes

Figure 6-3: Projected Vulnerability for Flood Risk Reduction in HUC 0703

7.0 Conclusion: Qualitative Residual Risks due to Climate Change

The goal of this project is to provide high water management recommendations to the VBWD to reduce the impact of flooding on numerous landlocked basins. In the literature reviewed, a warmer and wetter climate is expected in the future. However, the literature did not contain much consistency on how the hydrology or groundwater levels within the project area is likely to change. Trend and nonstationarity analyses of the historic temperature, precipitation, lake and groundwater wells showed the following:

- Minimum temperature has increased. In the winter, this can cause less ice cover and snowfall accumulation. Increases in lake surface temperature and reductions in ice cover duration could modify the start and duration of spring mixing and summer stratification and accelerate evaporation.
- Accumulated precipitation has increased particularly in the spring and summer. This could alter groundwater recharge rates depending on the type, amount, and intensity.
- Available water levels for Lake McDonald do not have statistically significant trend. Water levels on Lake Olson and Lake DeMontreville, clearly demonstrate the influence of Project 1007.
- There is not enough groundwater monitoring well data to understand long term trends, and the occasional data from the past 20 years does not show statistically significant trends.

Future climate projections expect that the VBWD will see increased accumulated precipitation and 1-day annual maximum precipitation. Previous regional and global studies have shown that changes in the type, amount, and intensity of precipitation can impact groundwater recharge, although the direction and magnitude of the change remains an area of active research (Amanambu et al., 2020; Crosbie et al., 2013). The USACE VA Tool indicates that Flood Risk Reduction in the St. Croix (HUC 0703) is not highly vulnerable to the impacts of climate change relative to other watersheds in the CONUS. This vulnerability is based on increasing flood flows and runoff elasticity in the future without project condition.

Table 7-1 indicates potential residual risks for this project due to climate change along with a qualitative rating of how likely those residual risks are to occur. The project is considering two types of projects as well as future without project alternative. The alternatives' features include gravity outlets, pumping and/or, acquisition of adjacent properties. The qualitative likelihood considers the likelihood and uncertainty of the climate change trigger and the harm occurring. The project features considered for this project are conservatively designed based on high groundwater and precipitation conditions and should be resilient to climate change triggers. Furthermore as seen in this climate assessment, there is considerable uncertainty in how the changes in precipitation and temperature will impact groundwater recharge and lake levels.

Current evidence points to lower recharge rates within the project area due to increases in evapotranspiration and to larger fluctuation in lake levels with more intense storms.

Table 7-1: Residual Risks to Project Features due to Climate Change

Project Feature	Climate Change Trigger	Environmental Hazard	Harm	Qualitative Likelihood Rating	Justification
Future without Project	Increased annual precipitation, intense storms and high groundwater	Multiyear periods of high-water surface water levels.	High water levels can flood homes and septic systems more frequently.	Unlikely	Natural climate variability has shown that this scenario is possible; however, it is unlikely that climate change will increase the likelihood of high groundwater due to the increase in ET.
Gravity Drainage Infrastructure and/or Pumping	Increased annual precipitation, intense storms and high groundwater	Prolonged high-water levels	Gravity drainage/pumping is undersized and will not be able to lower lake levels within designed draw down period	Unlikely	It's unlikely because the drainage system and/or pumps are sized based on a conservative estimate of current conditions such that the system should be able restore lake levels with design draw down period
Acquisition of property	Increased annual precipitation, intense storms and high groundwater	Larger flooded area due to high water surface elevation	Higher water levels could flood additional properties	Unlikely	It's unlikely because the acquired property was based on water levels reaching the low opening or basement floor during a conservative estimate of today's conditions.

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