Technical Memorandum

To: Valley Branch Watershed District Landlocked Basin Comprehensive Planning Study Project Stakeholders
From: Jennifer Koehler, Cory Anderson, Moges Wagena, and John Hanson
Subject: VBWD Landlocked Basin Flood Mitigation Comprehensive Planning Study —Historical Climate Data Assessment and Proposed Sensitivity Analysis
Date: October 2023
Project: 23821268.00

1.0 Introduction

Valley Branch Watershed District (VBWD) recently experienced record high water levels on several landlocked basins within the watershed because of historic wet conditions from 2014 to 2020. Barr Engineering Co. (Barr) evaluated historical climatic data to help understand conditions that led to widespread flooding within the watershed and to estimate the potential likelihood of increased precipitation and similar ongoing wet conditions. This climatic assessment included statistical evaluation of long-term total annual precipitation data for VBWD.

This memorandum summarizes the assessment approach and results. We discussed this assessment approach with United States Army Corps of Engineers (USACE) staff on January 27, 2023, and this memo reflects further revisions in response to other questions and comments from USACE staff. Barr used the findings of this assessment to inform and evaluate the water level sensitivity of the existing landlocked basins and flood management scenarios included in the VBWD Landlocked Basin Comprehensive Planning Study to identify the risks associated with more total annual precipitation or a wetter period than recently experienced in the VBWD.

2.0 Analysis of Observed Precipitation Data

2.1 Historical Precipitation Data

Our statistical evaluation of long-term total annual precipitation data for VBWD is based on the following:

- Daily precipitation data from the weather station nearest to Township 29 North, Range 21 West from 1891–1939 (http://climateapps.dnr.state.mn.us/mapClim2007/MNlocAPP.asp)
- Hourly precipitation data from the Minneapolis-St. Paul International Airport (MSP) from 1940–2007 (adjusted to match monthly summary data available from the Minnesota Department of Natural Resources [MnDNR] state climatology office)
- Hourly precipitation data from Lake Elmo Airport from 2008 to 2020, augmented by the MSP airport data during the winter months when data was not always available for the Lake Elmo Airport

2.1.1 Total Annual Precipitation Trend Analysis

We analyzed the total annual precipitation depth for different periods using the Mann-Kendall trend test method. This included evaluating the total annual precipitation for the entire period of record (1891–2020) as well as other periods to check for trends in the annual data.

Figure 1 shows the Mann-Kendall trend analysis of total annual precipitation from 1891 to 2020 with a calculated p-value of 0.01. There is statistical evidence of significant trends for $\alpha = 0.05$, where α is a measure of the probability of the null hypothesis being true compared to the acceptable level of uncertainty regarding the true answer. This result indicates an increasing annual precipitation trend for this entire period.

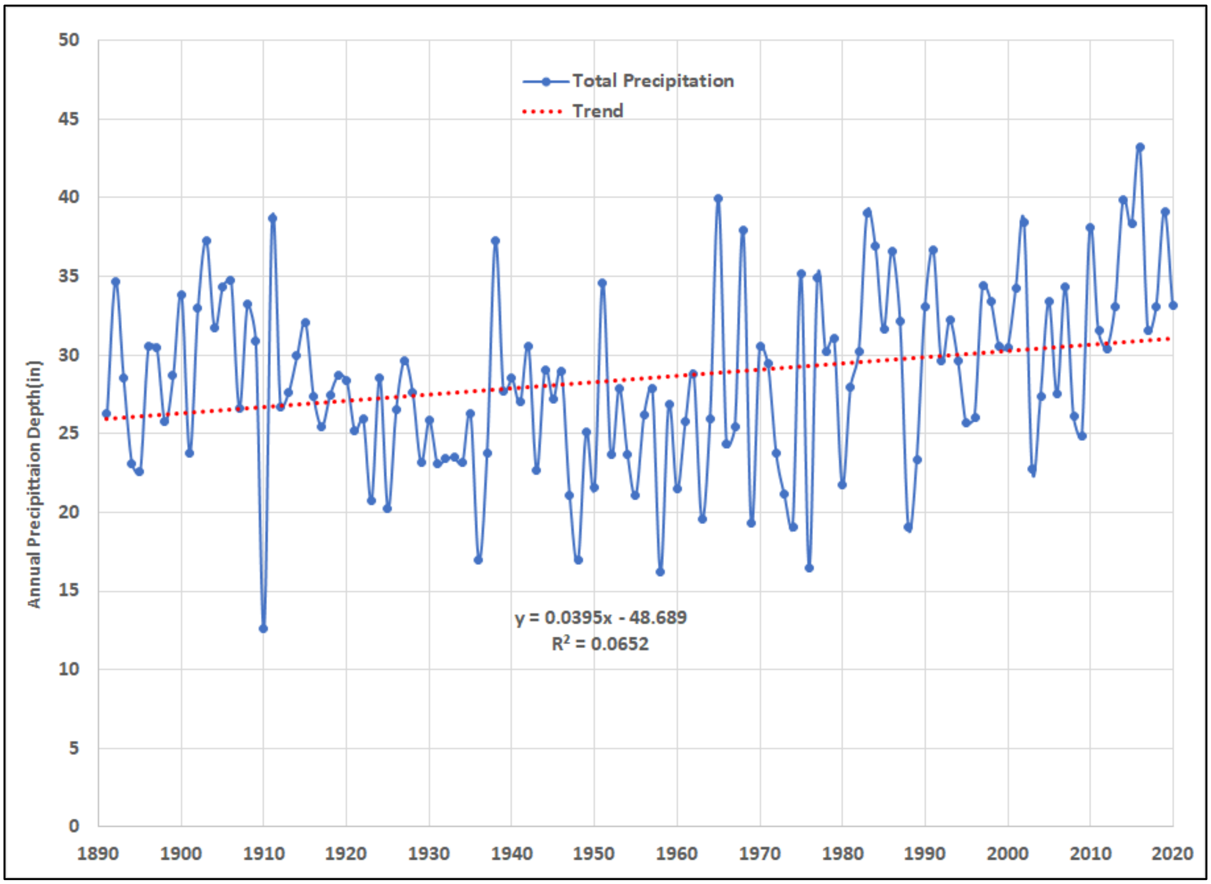

Figure 1 Trend analysis of total annual precipitation data, 1891–2020 (data from the station nearest to T29N, R21W [1891–1939], MSP Airport [1940–2007], and Lake Elmo Airport [2008–2020])

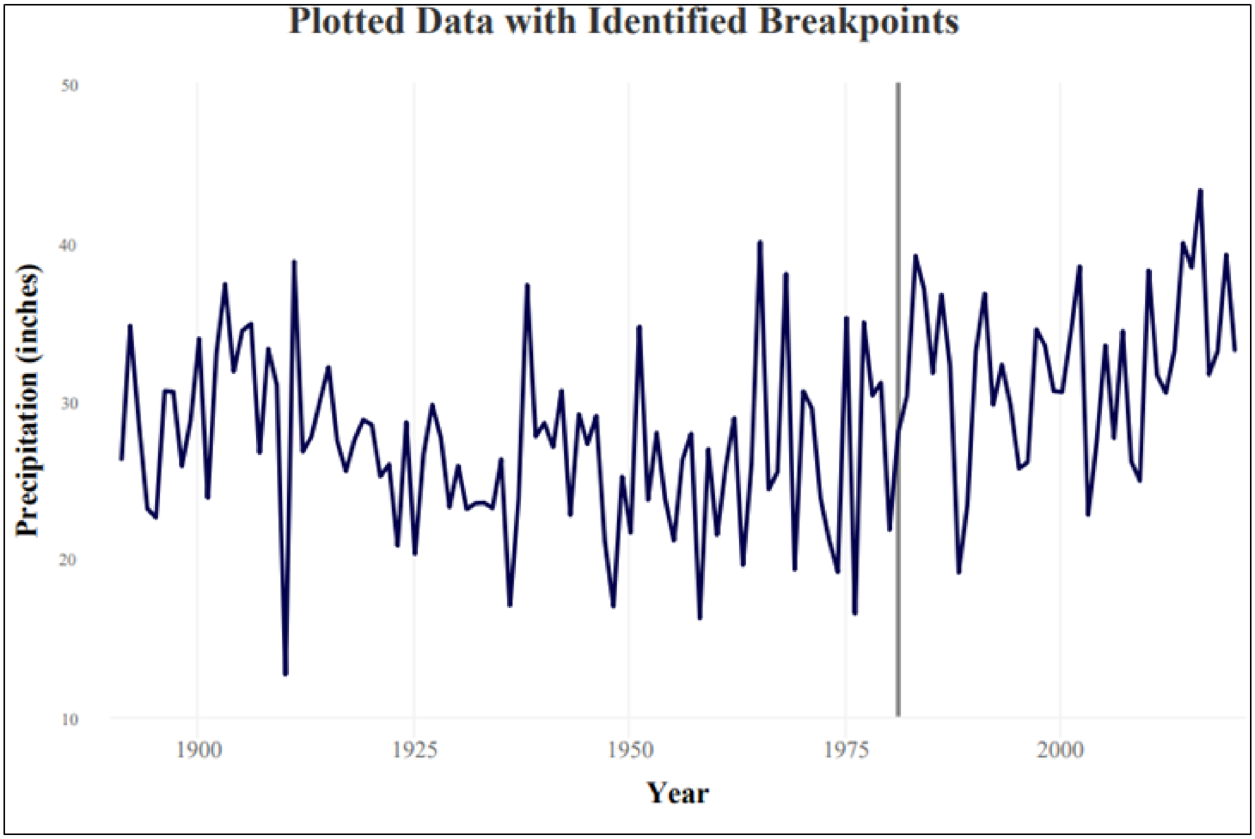

Figure 2 Breakpoint analysis of total annual precipitation data, 1891–2020 (data from the station nearest to T29N, R21W [1891–1939], MSP Airport [1940–2007], and Lake Elmo Airport [2008–2020])

We checked for breakpoints in the data (points in the data that reflect sharp changes in behavior) during the period 1891–2020 (Figure 2) using the USACE Time Series Toolbox (https://climate.sec.usace.army.mil/tst_app/). This analysis shows the presence of a breakpoint starting in the 1980s. We also reviewed autocorrelation for different time lags from 1891 to 2020, and there was autocorrelation among lag times.

However, in our evaluation for different periods (shifting by starting decade to present, e.g., 1901–2020, 1911–2020, 1921–2020), we found there were statistically significant trends for increasing precipitation in the data for nearly all periods until the most recent decades when statistically significant trends were no longer observed as shown in Table 1.

Although there is no trend in the 1981–2020 annual precipitation data, there is autocorrelation among time lags in this time frame, so we used the most recent 30-year period from 1991 to 2020, which has no statistically significant trend with a calculated p-value of 0.08.

This 1991–2020 period coincides with the current climatic "normal" period. The climate "normal" serves as a baseline to compare current weather against an average and as a predictor of conditions in the future and is calculated for a uniform 30-year period (reference (1).) Figure 3 summarizes the total annual precipitation from 1991 to 2020.

Table 1 Summary result for Mann-Kendall trend analysis

Trend Analysis Period	P-value	Trend Exists
1891–2020	0.010407	Yes
1940–2020	0.000013828	Yes
1951–2020	0.0001241	Yes
1961–2020	0.0026087	Yes
1971–2020	0.0084132	Yes
1981–2020	0.14851	**No**
1991–2020	0.083477	**No**

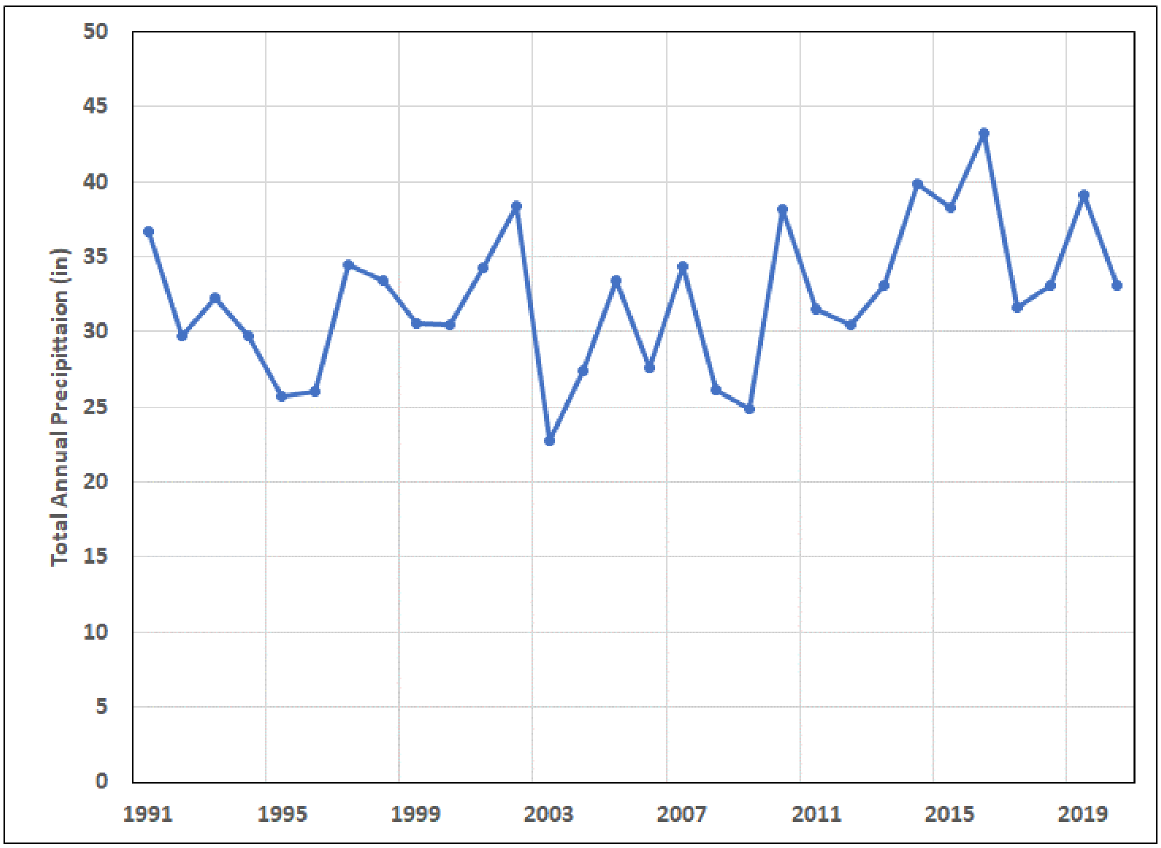

Figure 3 Total annual precipitation data, 1991–2020 (data from MSP Airport [1991–2007] and Lake Elmo Airport [2008–2020])

2.2 Exceedance Probability Analysis (GoldSim Weather Generator Analysis)

The period from 2014 to 2020 was one of the wettest continuous seven-year periods in VBWD history and led to historic high water levels on several landlocked basins and in the VBWD-monitored groundwater wells. As such, we used the most recent 30 years of observed precipitation (1991–2020, based on the analysis above) along with the GoldSim software to estimate the likelihood that the VBWD could experience similar or wetter conditions.

Our approach used the GoldSim Weather Generator (WGEN). WGEN is a stochastic weather generator originally developed in the 1980s in Fortran at the U.S. Department of Agricultural Research Service (reference (1) and (2)) and incorporated into GoldSim software. The WGEN model uses a first-order Markov chain to characterize the occurrence of wet or dry days, and the probability of precipitation on a given day is conditioned on whether there was precipitation on the previous day. We used the WGEN parameter generator to create rainfall parameters needed to run WGEN. In WGEN, the precipitation parameters for a gamma distribution are constant for a given month but vary from month to month.

We generated the rainfall parameters using historical/observed daily precipitation data from MSP and Lake Elmo airport from 1991 to 2020. The WGEN parameter program was used to generate parameters such as the probability of wet days as a function of the previous day being wet or dry, as well as two gamma distribution parameters, alpha and beta (Table 2).

Table 2 Rainfall parameters generated by the WGEN parameter program

Month	pWW[1]	pWD[2]	alpha	beta
January	0.41	0.18	0.64	0.31
February	0.40	0.22	0.71	0.31
March	0.46	0.28	0.69	0.35
April	0.48	0.32	0.77	0.41
May	0.45	0.28	0.78	0.54
June	0.47	0.27	0.68	0.59
July	0.45	0.24	0.72	0.60
August	0.35	0.21	0.66	0.57
September	0.43	0.21	0.61	0.82
October	0.41	0.19	0.57	0.72
November	0.35	0.17	0.70	0.37
December	0.43	0.21	0.76	0.27

[1] Probability of a wet day following a wet day
[2] Probability of a wet day following a dry day

Barr used the first-order Markov chain gamma method in the GoldSim model to generate daily precipitation using the precipitation parameters (Table 2). We ran the model for 110 years for 100 realizations based on the sampling from the most recent 30-year climate period. We also compared the variance of the last 100 years of data to the realizations generated from resampling from the last 30 years (Figure 4). The results show a shift in mean, as expected, but the variance remains similar.

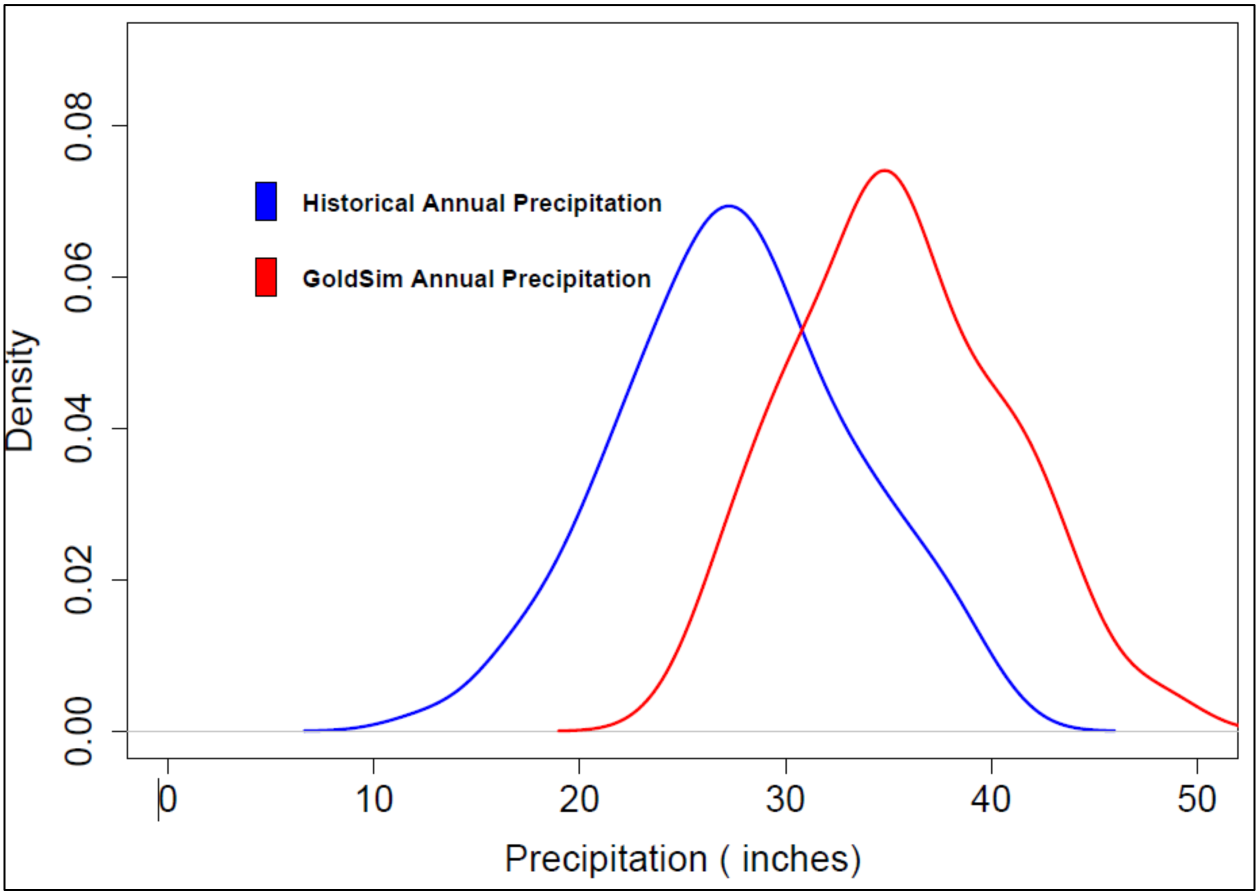

Figure 4 Variance comparison of historical and GoldSim annual precipitation

We then summarized the model-generated daily precipitation values to annual total precipitation and total seven consecutive years of precipitation (similar to the 2014–2020 period). This was completed for all 100 realizations. We selected the seven consecutive year period for consideration for the following reasons:

- The consecutive period from 2014 to 2020 contained several of the wettest years on record for the VBWD area.
- Observed water levels on numerous landlocked basins and in groundwater monitoring wells during that period showed fairly constant increases in water levels, reaching historic high conditions.
- We wanted to select a time period long enough that it fully captured groundwater response to multiple consecutive wet years while not having too many years that could result in averaging out the wet conditions.

Additionally, after USACE feedback, we used the USACE Time Series Toolbox to analyze the annual precipitation from 1991 to 2020. The Time Series Toolbox indicates that in the 30-year climate period, there is a breakpoint after 2013, as shown in Figure 5, where there is more total annual precipitation experienced than other years.

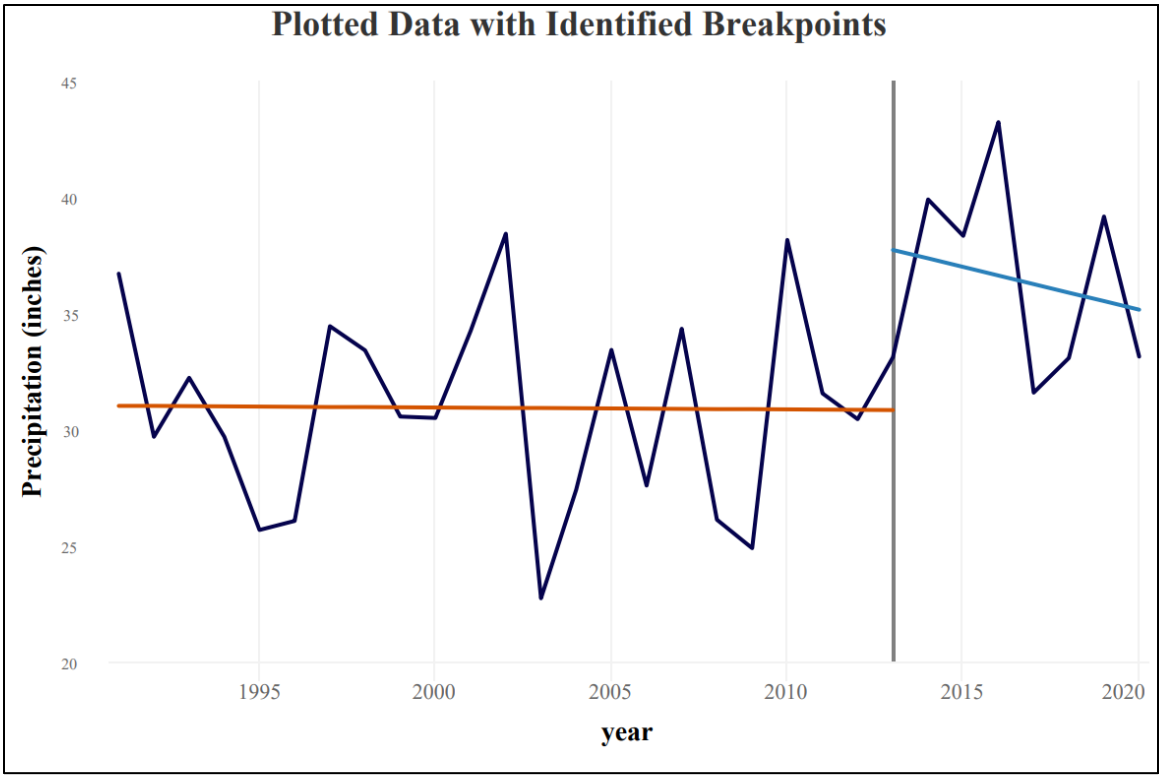

Figure 5 Total annual precipitation data, 1991–2020 (data from MSP Airport [1991–2007] and Lake Elmo Airport [2008–2020]) breakpoint analysis

Based on the historical climate data, Barr wanted to understand how likely it was that the VBWD would have experienced this wet period. The probability of exceedance was determined by comparing the seven consecutive year precipitation totals from all the GoldSim WGEN realizations to the actual total from 2014 to 2020 (258 inches of precipitation over seven consecutive years, an average of 36.9 inches/year).

Figure 6 shows the probability of exceedance of seven consecutive years of total precipitation based on the realizations generated by the GoldSim WGEN. The results indicate that the VBWD could experience a wet period similar to or wetter than the recent seven-year period (2014–2020), with the exceedance probability ranging from 10% to 30%.

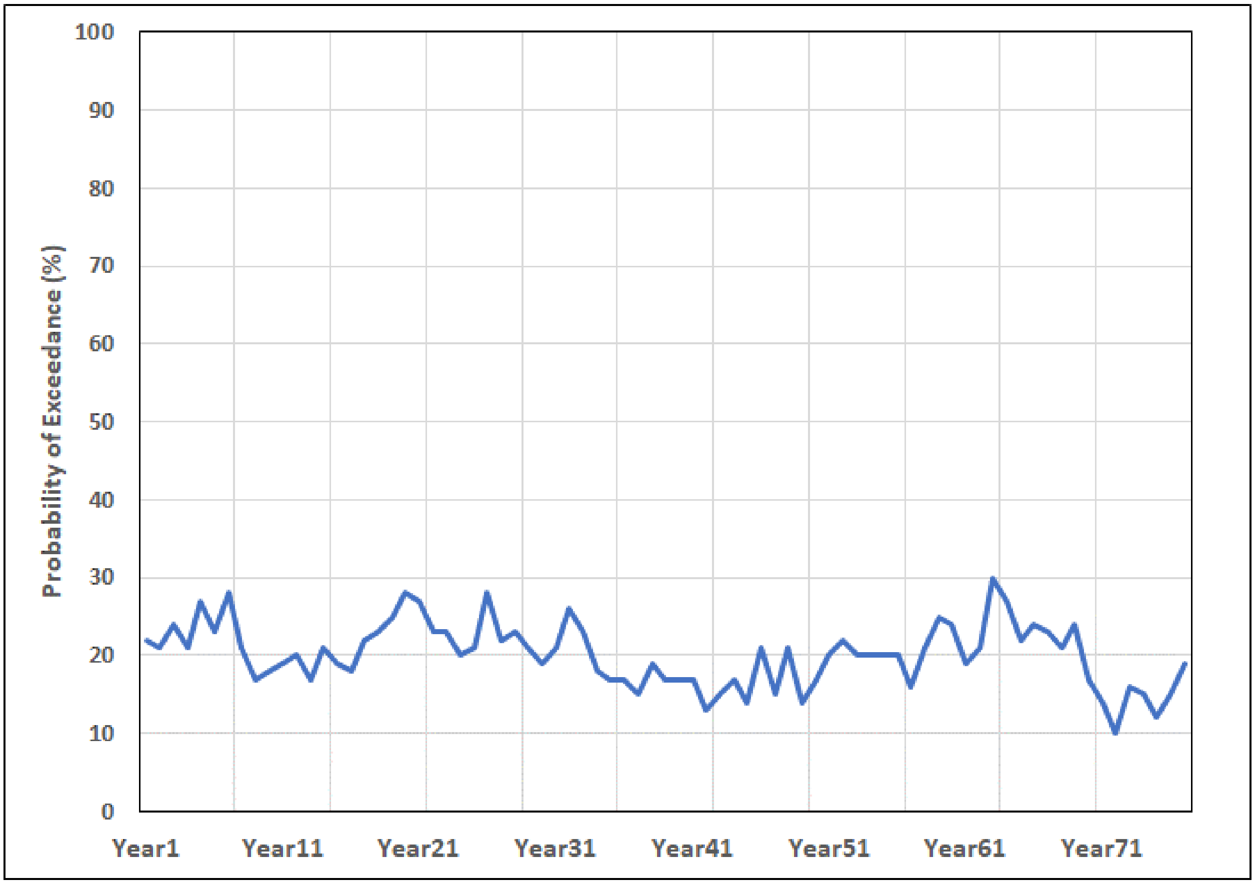

Figure 6 Probability of exceedance of 7-year wettest period (2014–2020) in the future annual precipitation generated by GoldSim

Using the realizations generated by GoldSim WGEN, we summarized and ranked the seven-year total precipitation based on the realizations from wettest to driest. Table 3 compares the observed total precipitation for 2014–2020 to the wet, wetter, and wettest periods based on the GoldSim precipitation realizations. Compared to observed data of the wettest years (2014–2020), the realizations based on the historical precipitation record show that the VBWD could experience as much as 5% to 9% more total precipitation during a seven-year-consecutive period than the watershed experienced from 2014 to 2020 (Table 3).

Table 3 Comparison of 7-year total precipitation of historical and GoldSim WGEN-generated precipitation

Relative Precipitation	7-Year Total Precipitation (in)		Average Annual Precipitation (in/yr)		Percent Increase in Precipitation from Recent Wet Conditions (2014–2020) (%)
	Observed Total Precipitation (2014–2020)	Realizations Based on Recent 30-Year Data (1991–2020)	Observed (2014–2020)	Realizations Based on Recent 30-Year Data (1991–2020)	
Wet	258	255.5	37	36	-1
Wetter	258	270.6	37	39	5
Wettest	258	281.0	37	40	9

2.3 Sensitivity Analysis of VBWD Landlocked Basins' Response to a Wetter Period

GoldSim analysis of the historical climate data indicates that the VBWD could experience a continuous wet condition similar to or even wetter than the conditions experienced from 2014 to 2020 when the watershed experienced extremely high groundwater and surface water conditions.

The USACE conducted a climate assessment in accordance with ECB 2018-14 for the region that suggests the future will be warmer, impacting the distribution of snow and rainfall, as well as increasing the length of the frost-free season. Total annual precipitation, concentrated in heavier precipitation events, will likely increase. Higher temperatures could increase the severity of droughts, evapotranspiration, and soil dryness. Subsequently, the relationship between precipitation and the total runoff entering basins could change and impact groundwater infiltration. See **Appendix 13** for more information on the climate assessment conducted by the USACE.

Although there is some uncertainty as to how future climate change will impact runoff and groundwater flows to the landlocked basins, to help understand the impact of wetter conditions on the landlocked basins in the VBWD, Barr performed a sensitivity analysis of a continuous period of more precipitation on the existing landlocked basins based on the statistical analysis of the historical climate data. This assessment evaluated "without project" and "with project" alternatives.

To inform the sensitivity analysis, Barr used the information summarized in Table 3 above in both the calibrated groundwater modeling (MODFLOW) and the hydrologic and hydraulic (H&H) modeling (XP-SWMM/PC-SWMM) for the VBWD study area. Because of limitations on the type and format of inputs to both the groundwater modeling and the H&H modeling, we scaled the observed hourly precipitation from 2014 to 2020 using the estimated increase in precipitation based on the wettest condition (9% more precipitation) to conduct the sensitivity analysis.

In the groundwater modeling, we used this scaled precipitation to recalculate the watershed runoff to each basin. Additionally, we scaled the recharge to the groundwater as originally estimated by the United States Geological Survey (USGS) Soil Water Balance (SWB) model based on the relationship between the annual precipitation and the recharge to groundwater developed from the calibrated groundwater model run from 2014 to 2020, as shown in Figure 7. Based on the revised inputs and runs of the calibrated groundwater model, we gained a better understanding of the potential impact of increased precipitation on the groundwater conditions in the VBWD study area and generated a revised time series of net groundwater flux at each landlocked basin to be used as an input in the H&H modeling.

We then used the scaled hourly precipitation, along with the revised net groundwater flux, in the H&H modeling to rerun the models continuously for the period from 2014 to 2020 to evaluate the sensitivity of potential water levels in each of the landlocked basins to a wetter period/increased precipitation and the potential impacts to surrounding structures, as compared to the baseline conditions.

Appendix 10 and **Appendix 12** provide additional information on the details related to and results of the climate sensitivity analysis as incorporated into the groundwater and surface water modeling, respectively.

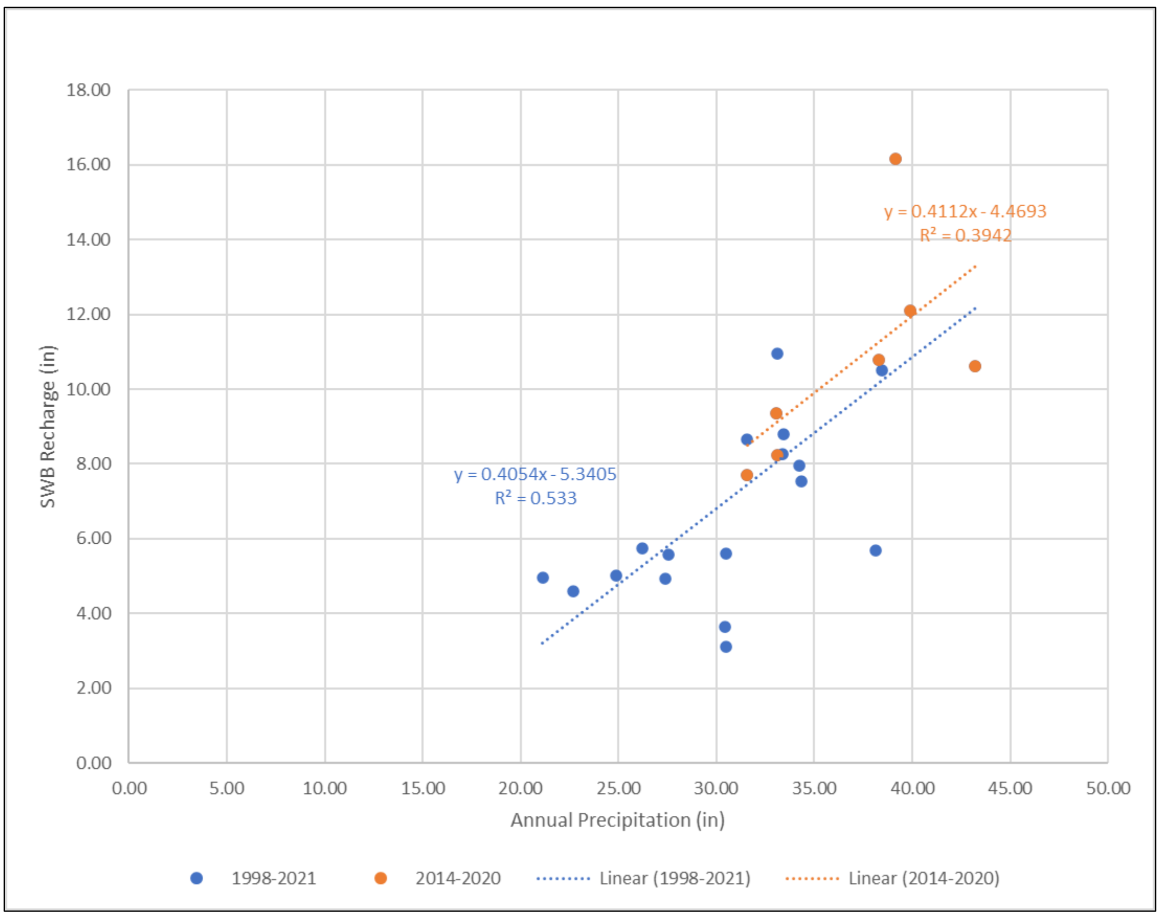

Figure 7 Annual precipitation and soil water balance (SWB) recharge correlation from groundwater model

3.0 References

1. *The Application of WGEN to Simulate Daily Climatic Data for Several Canadian Stations.* **Zhang, Qing, et al.** 1, s.l.: Canadian Water Resources Journal, 2004, Vol. 29. 59–72.

2. *Stochastic Simulation of Daily Precipitation, Temperature, and Solar Radiation.* **Richardson, Clarence W.** 1, s.l.: Water Resources Research, 1981, Vol. 17. 182–190.

3. NCEI generates the official U.S. normals every 10 years in keeping with the needs of our user community and the requirements of the World Meteorological Organization (WMO) and National Weather Service (NWS). The 1991–2020 U.S. Climate Normals are the latest in a series of decadal normals first produced in the 1950s.