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# A Hydrogeologic Evaluation of the Waterloo Area in the Upper Jefferson River Valley, Montana

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A HYDROGEOLOGIC EVALUATION OF THE WATERLOO AREA IN THE UPPER JEFFERSON RIVER VALLEY, MONTANA

by

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## Abstract

The Upper Jefferson River is one of the most dewatered rivers in Montana. The river exists in an intermontane basin filled with sediment transported from the Highland Mountains to the west, the Tobacco Root Mountains to the east, and the Jefferson River from the south. The Upper Jefferson River Valley is highly dependent on the Jefferson River as the main industry in the valley is agriculture. A majority of the valley is irrigated and used to grow crops, and a good portion is also used for cattle grazing. The residents of the Upper Jefferson River Valley use the aquifer as the main source of potable water. The Jefferson River is also widely used for recreation.

This study took place in the Waterloo area of the Upper Jefferson River Valley, approximately 20 miles south of Whitehall, Montana. The Waterloo area provides significant groundwater base flow to the Jefferson River, which is particularly important during the late irrigation season when the river is severely dewatered, and elevated surface-water temperatures occur, creating irrigation water shortages and poor trout habitat. This area contains two spring-fed streams, Willow Springs and Parson's Slough, which discharge to the Jefferson River providing cool water in the late season as well as providing the most important trout spawning habitat in the valley. The area is bordered on both the east and west by irrigation ditches, and about 60% of the study area is irrigated. Tile drains were installed in the study area in close proximity to Parsons Slough causing some concern by neighboring residents.

This study evaluated relationships between surface water, groundwater, and irrigation practices so that water managers and others can make informed management decisions about the Upper Jefferson River. Data was collected via a network of groundwater wells and surface-water sites. Additionally, water-quality samples were taken and an aquifer test was conducted to determine aquifer properties. The field data were analyzed and a groundwater budget was created in order to evaluate the aquifer.

Results of the groundwater budget show that seepage from the irrigation canals and irrigation recharge have the biggest influence on recharge of the aquifer. There is significant groundwater outflow from the aquifer in the spring-fed streams as well as discharge to the Jefferson River. In comparing previous study results to this study's results, there is no evidence of the water table decreasing due to irrigation practice changes or tile drain installation. However, given the amount of recharge irrigation practices contribute to the aquifer, if significant changes were made, they may affect groundwater elevations. Also lining the irrigation ditches would have a significant impact on the aquifer, as the amount of seepage would be greatly reduced.

**Keywords:** hydrogeology, groundwater budget, Waterloo, Jefferson River, Montana

## Dedication

To my loving husband Ted. Without your immense encouragement and support I could not have completed this graduate degree.

## Acknowledgements

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I am grateful to the General Engineering Department for their financial support, without which I could not have begun my graduate degree.

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# 1. Introduction

The Jefferson River is one of the most critically dewatered rivers in Montana, and as such has been subject to numerous closures over the years (JRWC, 2013). Severe dewatering and elevated temperatures typically occur during the irrigation season, causing irrigation water shortages and trout population declines during drought years. By studying the water resources in the Upper Jefferson River valley, more informed decisions can be made toward future development and conservation efforts. It is necessary to understand the interaction between surface water and groundwater in this valley in order to make informed decisions and manage this valuable resource properly.

## 1.1. Background

The Jefferson River begins at the confluence of the Beaverhead, Big Hole and Ruby Rivers near Twin Bridges, Montana. A critical area of the Upper Jefferson River Valley is the Waterloo area. The area, as outlined in Figure 1 below, begins just north of the Parrot Ditch diversion and ends just north of the Jefferson Canal Diversion. The study area is bordered on the east by the Tobacco Root Mountains and on the west by the Highland Mountains.

The major tributary to the Jefferson River within the Waterloo study area is Fish Creek. There are three major irrigation canals which divert water from the Upper Jefferson River: the Parrot Ditch, Jefferson Canal, and Creeklyn Ditch. Other significant water features in the study area include Parson’s Slough and Willow Springs.

The main water use in the Upper Jefferson River Valley is agriculture. The valley is heavily irrigated during the summer months when ranchers are growing and cutting hay. The entire valley is reliant on the aquifer as a source of potable water. There is also an important sport fishing industry in the valley.

The groundwater/surface water interactions in the Waterloo area are complex. There is a balance between the Jefferson River, the alluvial aquifer, natural springs and irrigation practices. Parson's Slough and Willow Springs are naturally occurring spring fed creeks in the Waterloo area. These creeks feed into the Jefferson River. The spring fed creeks are an important source of recharge to the Jefferson River during low flows which are typical during the late summer months when temperatures are high and irrigation is at its peak. The spring fed creeks provide cool groundwater when the river temperatures are warmer during these times. Willow Springs and Parsons Slough also provide a very important trout spawning habitat.

In Parson's Slough recent stream remediation work was done to enhance trout spawning habitat. Tile drains were installed with the purpose of providing more water to the stream. Deeper pools were also constructed in the stream. The drains also serve the purpose of draining excess water from the field they were installed in. The presence of these tile drains has caused some concern among neighboring landowners due to the effect they may have on groundwater levels.

All three major irrigation canals (Creeklyn Ditch, Parrot Ditch, and the Jefferson Canal) are diverted from the Jefferson River either below or in the Waterloo study area. It is believed that irrigation in the area is an important source of recharge, and it becomes increasingly significant during critical low flow periods (typically from July to September; WET, 2006). There are also four ephemeral streams in the study area: Dry Boulder Creek, Beall Creek, Spring Creek, and Mill Creek. These creeks originate in the Tobacco Root Mountains and are diverted for irrigation. On the rare occasion that all the water in the ephemeral creeks is not used, they discharge to the Parrot Ditch.

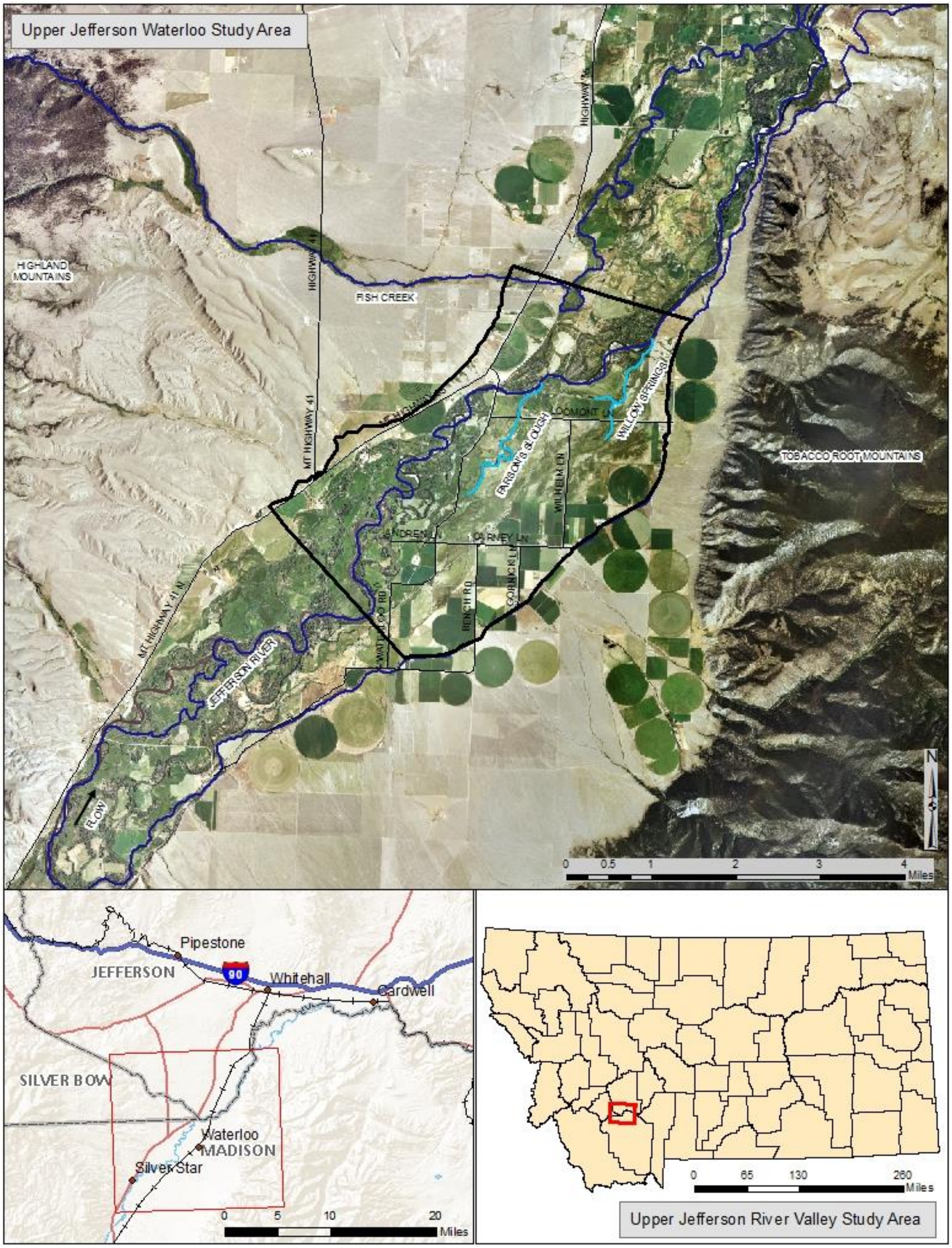


**Figure 1. Waterloo Area Location Map**

## 1.2. Purpose and Scope

The purpose of this project is to better understand the relationship between surface and groundwater with regard to irrigation in the Waterloo area. Since groundwater inputs sustain the Jefferson River during drought years, it is important to understand how changing conditions will affect the hydrogeological system of Waterloo. The spring fed creeks are the largest trout spawning habitat contributing to trout populations in the Jefferson River, making it an important study to the ecological system as well. The main focus of this study was to understand the link between irrigation practices and groundwater, and to determine the effects of the new tile drains.

## 1.3. Study Area Overview

### 1.3.1. Physiography

The Waterloo area is located in southwest Montana in the Upper Jefferson River Valley near Silver Star, approximately 20 miles south of Whitehall and 10 miles north of Twin Bridges. The average annual flow at the Twin Bridges United States Geological Survey (USGS) gaging station 06026500 between 1941 and 2014 was 1,107 cubic feet per second (cfs). The average annual peak flow is 9,467 cfs with the lowest mean monthly flow of 770 cfs in August.

The Waterloo study area is approximately 12 square miles. This area provides significant groundwater base flow to the Jefferson River, which is particularly important during the late irrigation season when the river is severely dewatered, and elevated surface-water temperatures typically occur. The lowest flows typically occur during the month of August with a mean monthly flow of 399 cfs measured at the USGS gaging station 06027600 on the Jefferson River near Parsons Bridge (Silver Star, MT). The lowest recorded monthly flow was in 2006 with a mean monthly flow of only 50.6 cfs. This gaging station lies in the central region of the Waterloo study area.

The two spring fed creeks, Willow Springs and Parsons Slough, are the main source of surface water contribution to the Jefferson River within the Waterloo study area and carry an average of about 20 cfs. The Kurnow Ditch, which is an irrigation ditch blow off used to divert excess water from the Parrot Ditch, also discharges to the Jefferson River in the study area. The Parrot Ditch is the largest irrigation ditch, which runs almost the entire length of the Upper Jefferson Valley. The Parrot Ditch is diverted from the Jefferson River approximately 7 miles south of the southern border of the study area and forms the western boundary of the Waterloo Study area. The Creeklyn Ditch is diverted from the Jefferson River just south of the Parrot diversion near Hell's Canyon and forms the eastern side of the study area. The Jefferson Canal is diverted from the Jefferson River within the study area just upstream of the Parsons Bridge gaging station. The MBMG monitoring site Jefferson River at Silver Star is used as the southern boundary surface water inflow into the study area, with the MBMG monitoring site Jefferson River at Corbett's used for the northern boundary surface water outflow from the study area (Figure 8).

### 1.3.2. Geologic Framework

Understanding the fluvial geomorphology of the valley is an important factor in understanding the groundwater flow in the aquifer. The Upper Jefferson valley is an intermontane basin filled with sediment transported from the Highland Mountains to the west, the Tobacco Root Mountains to the east, and the Jefferson River from the south. The Tobacco Root Range is formed mainly of Precambrian basement rock and a large granite batholith (Alt & Hyndman, 1986). The east side of the valley is covered by middle Pleistocene or younger alluvial fan deposits (Vuke et al., 2004). There is also an alluvial fan on the west side near the mouth of Fish Creek with large boulders believed to be the result of glacial outburst flooding.

The seismically active valley contains numerous faults including the Silver Star Fault and the Waterloo Fault. The thickness of the basin fill over the basement high has been estimated at varying depths ranging from 600 to 3000 meters (Vuke et al., 2004). The depth to the bottom of the Jefferson Basin is estimated to change from sea level near Dry Boulder Canyon over the basement high to 3,000 feet near Hell's Canyon which is north of the horst. The sudden change is attributed to the Silver Star fault, which is a northwest-striking fault bounding the north side of the basement high and down-dropped to the northeast.

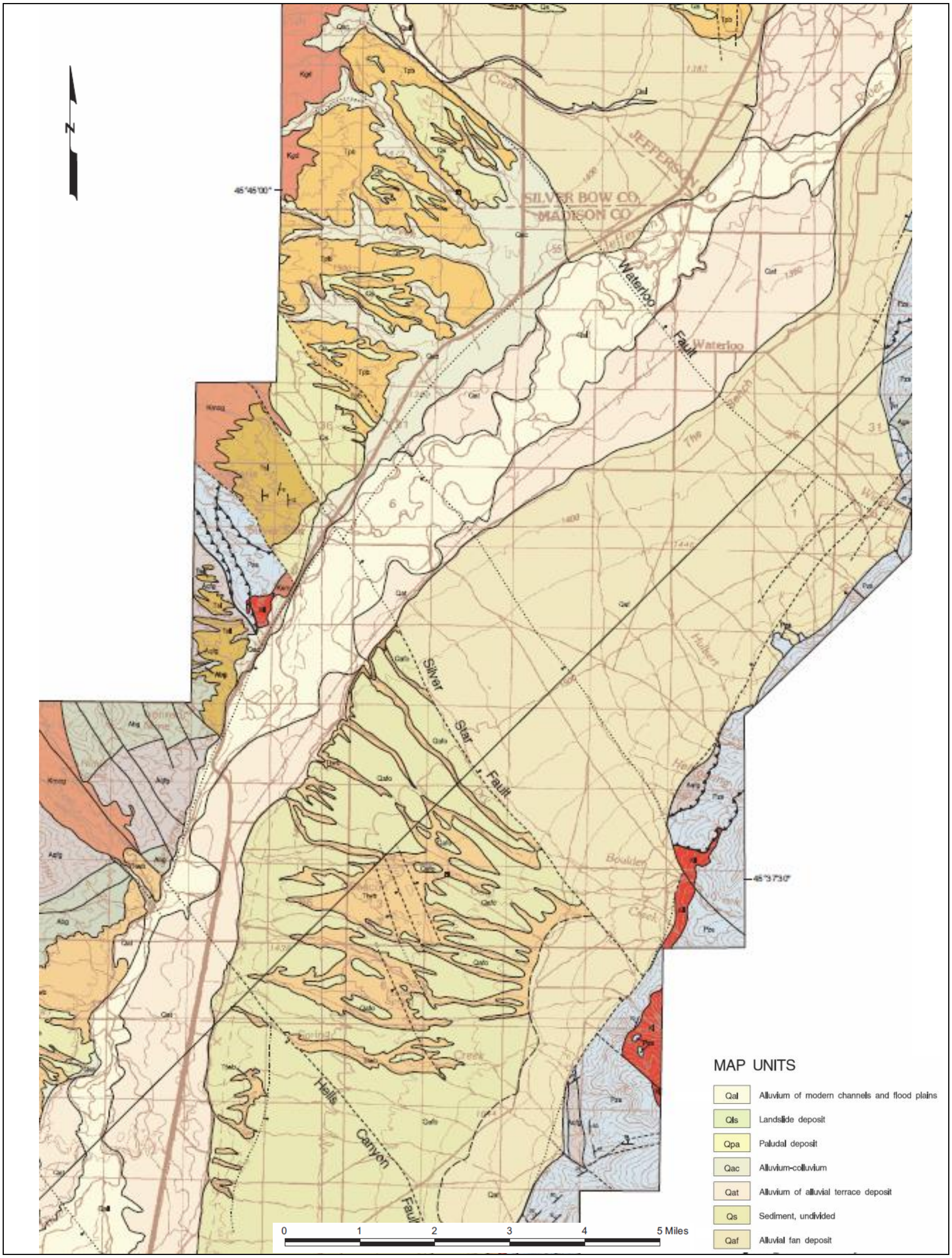


**Figure 2. Geologic Map of the Upper Jefferson Valley (Map from Vuke et al., 2004)**

### 1.3.3. Climate

Two climate stations are located near the study area in the Upper Jefferson valley. AgriMet station JVWM (Jefferson Valley, MT) is located approximately 6.5 miles southwest of Whitehall, Montana (45° 47’ 52”, 112° 09’ 55”) at an elevation of 4,415 feet. National Oceanic and Atmospheric Administration (NOAA) climate station USC00248430 is located near Twin Bridges approximately 12 miles southwest of the Waterloo study area (45° 32’ 49.9194”, -112° 19’ 33.9594”) at an elevation of 4,625 feet.

Additionally, 30 year normal precipitation data were obtained from Oregon State’s Parameter-Elevation Regressions on Independent Slopes Model (PRISM). The current PRISM normal data are calculated from the most recent three full decades, 1981-2010. The average annual precipitation within the Waterloo study area is 10 inches. The wettest month of water year 2014 within the study area was June, with a total of 1.7 inches. The driest month of water year 2014 was November with a total of 0.18 inches (Agrimet station JVWM). The bordering mountains average 18 to 19 inches per year. The Highland mountains to the west receive as much as 32 inches per year while the Tobacco Root Mountains to the east receive as much as 42 inches of precipitation per year.

### 1.3.4. Land Use

The majority of the land, about 60%, within the Waterloo area is used for irrigation and is flood, pivot, or sprinkler irrigated. Alfalfa, hay and natural grass make up the majority of what is grown in the valley. Of the irrigated land, approximately 44% of the area is flood irrigated, and 56% is pivot or sprinkler irrigated. Most of the irrigated fields use surface water (the irrigation ditches) but there are three irrigation wells within the study area that pump water from the aquifer. There are approximately 110 residential wells within the study area according to the GWIC data base. A significant amount of the area is also used for cattle grazing.

# 2. Previous Studies

## 2.1. Water Environmental Technologies

Water Environmental Technologies previously performed a study to define the groundwater/surface water interaction of the Waterloo Area in 2006 (WET, 2006). WET collected data from the end of the irrigation season in 2004 through the irrigation season in 2005. For their data analysis WET organized the data into three seasons: pre-irrigation, mid-irrigation, and late irrigation. A pump test was also completed within the study area to assist in defining geologic properties of the aquifer.

WET used a groundwater monitoring network consisting of 13 private wells and 22 piezometers to collect monthly groundwater elevation data. Water quality data was also collected and analyzed. A surface water network consisting of six surface water sites equipped with a staff gauge and aquarod, as well as five additional sites with staff gauges were used to monitor discharge on the Jefferson River, Parrot Ditch, Willow Springs and Parson's Slough. The ephemeral tributaries (Dry Boulder Creek, Beall Creek, Spring Creek, and Mill Creek) in the Tobacco Root Mountains were also monitored periodically for discharge.

An aquifer test was performed in the alluvial aquifer in the study area in order to determine aquifer properties such as transmissivity and storativity. From the aquifer test data a hydraulic conductivity of 634 feet per day was estimated for the alluvial aquifer, however no data on the aquifer test were made available for this study.

WET collected water quality data from various wells. The samples were analyzed for pH, conductivity, dissolved oxygen and total dissolved solids. Lab analyses were for alkalinity, sulfate, bicarbonate, carbonate, chloride, hardness, nitrogen, calcium, magnesium, potassium, sodium and iron.

WET evaluated their data based on pre-irrigation, mid-irrigation, and late irrigation seasons. Methods used to analyze the data include groundwater elevation and temperature contour maps, precipitation and irrigation timing comparisons, a conceptual water budget, and water quality analysis. From the analysis a conceptual map was created to visualize groundwater and surface water interaction in the Waterloo Area.

Contour maps of groundwater elevations display groundwater flow parallel to the Jefferson River flowing from the southwest to the northeast (downstream). The majority of groundwater discharge to the Jefferson River occurs in the lower reach of the study area where the valley width decreases. Seasonal groundwater elevation fluctuations varied from 21 feet to 1 foot depending on the well location. Contour maps of temperature data in early irrigation season (April) show cooler zones near the Jefferson River, indicating river water flowing into groundwater. During the irrigation season (July) uniform temperatures were seen indicating groundwater and surface water interaction. In the late irrigation season (October) temperatures are well mixed, showing significant impact from irrigation. Temperature data also revealed mountain recharge in cold groundwater coming from the Tobacco Root Mountains. Rising conductivity through the season indicates increasing groundwater contribution to surface water.

WET's surface water budget showed gaining and loosing reaches of the Jefferson River. The river was separated into three separate reaches for the analysis. As the project was developing and flows increased, additional surface water discharge measurements were taken in order to better quantify contributing surface water, however, all potential sources were not quantified.

A major conclusion of the WET study was that changes in irrigation practices in the Waterloo area may not have a desirable outcome. WET concluded that the fields that were flood irrigated provided groundwater recharge to the aquifer, which provides a delayed discharge to the Jefferson River during critical months. If irrigation practices were changed from flood irrigation to sprinkler or pivot irrigation, less water would be stored in the groundwater system and late summer return flows would be less.

Two goals of the study were to improve understanding and management of agriculture and irrigation operations, which would lead to fewer water shortages on the Jefferson River, and prevent any significant upset to the water balance in the area. In order to accomplish these goals WET recommended that the current water management (i.e. drought management plan) stay in place and that new practices be enacted to divert less water while still having an adequate supply of water for irrigation. Among WET's recommendations were also to increase on-site ditch oversight from mid-July to mid-September to reduce ditch spill (more water being taken than needed), and increase monitoring which would shorten the reaction time of needed adjustments and reduce the amount of excess water being diverted.

## 2.2. Seepage Studies

The Montana DNRC conducted a seepage study on the three main irrigation canals in the Jefferson Valley by taking synoptic discharge measurements from 2001 to 2003. The aim of the study was to identify ditch reaches where high levels of seepage occurred with the intent for future research in those stretches.

Synoptic flow measurements were taken on all three ditches at specified distances on two separate occasions. All diversions were shut down prior to the measurements to eliminate these variables. Stretches of significant loss were identified for each irrigation ditch which ranged from 1 to 9.6 cubic feet per second per mile (Amman, 2005).

Van Mullem (2006) completed an irrigation delivery improvement project in the Upper Jefferson River Valley with the intent of increasing flow in the Jefferson River during drought years. This study also expanded on Amman's (2005) seepage investigation. As part of the study, a seepage analysis was done for each of the main irrigation ditches in the Upper Jefferson Valley. Different methods for improving irrigation delivery were then investigated depending on results of the seepage analysis.

Methods used by Van Mullem were synoptic discharge measurements and ponding tests. The ponding test method consists of damming a defined area of the ditch, filling the reach with water and timing how fast water seeps from the ditch. Different methods of analysis were also taken into account to compare the data results. One way data was compared was dividing daily loss rates by the wetted perimeter. However due to inconsistent measurements, the data was also graphed as discharge versus river mile to illustrate the general trend in loss.

Tests on the Creeklyn ditch took place north of Silver Star near the Waterloo area. Two ponding tests were done on the ditch in consecutive years, 2004 and 2005. These showed 0.65 and 0.88 feet lost per day, respectively (Van Mullem, 2006). The increase in loss is possibly due to the use of polyacrylamide (PAM) to treat the ditch in 2004. A ponding test was also done on the Parrot ditch in 2004 near Loomont Road in the Waterloo area that yielded results of 0.43 feet per day. Overall the study showed fairly low seepage rates throughout all the ditches. It was also concluded from the graph data comparisons that seepage is approximately the same throughout the length of the ditch.

# 3. Methods

Groundwater and surface water monitoring was a crucial aspect of this study. Groundwater elevations were monitored in order to examine the water table in the study area and the seasonal changes that occur. Surface water discharge was monitored to quantify the incoming and outgoing flows from the study area, which was essential in determining the groundwater recharge to the Jefferson River within the study area. The MBMG drilled three wells within the study area which were used to conduct an aquifer test which enabled aquifer properties to be estimated. Every well and surface water site was assigned a unique identification number (GWIC ID), and all of the data collected was entered in to the MBMG Groundwater Investigation Center (GWIC) database.

## 3.1. Groundwater Monitoring

The groundwater monitoring network consisted of 36 residential wells and piezometers spread throughout and surrounding the study area. Groundwater elevation data was collected from August 2013 through May 2015 by the MBMG (Table 1). The wells were selected according to hydrogeologic setting, geographic location, and landowner permission. The depth to water (DTW) was measured monthly from a specific measuring point on the top of each well casing using an electronic tape meter. The measuring points were surveyed by professional surveyors contracted by the MBMG. The measuring point elevation was used in addition to the DTW readings to calculate groundwater elevations. Pressure transducers were installed in eight of the wells within the study area. The data loggers recorded pressure and temperature hourly, and were downloaded once a month. The pressure data was corrected using a barometric pressure logger located within the study area and calibrated according to the manual DTW taken at the time the data was downloaded. The hourly data enabled the smaller fluctuations not reflected in monthly measurements to be identified.

**Table I. Monitoring Well Identification, Location and Type**

| Well Name | GWIC ID | Type | Location | Data Type |
|---|---|---|---|---|
| Richard & Pam Smith | 237587 | Residential | Within Study Area | Monthly |
| Harry Townes | 209718 | Residential | Within Study Area | Monthly |
| Willow 1 | 276103 | Piezometer | Within Study Area | Monthly |
| Willow 2 | 276105 | Piezometer | Within Study Area | Monthly |
| Willow 3 | 276106 | Piezometer | Within Study Area | Monthly |
| Willow 4 | 276107 | Piezometer | Within Study Area | Monthly |
| Willow 5 | 276108 | Piezometer | Within Study Area | Monthly |
| Willow 6 | 276127 | Piezometer | Within Study Area | Monthly |
| Willow 7 | 276109 | Piezometer | Within Study Area | Monthly |
| Willow 8 | 276111 | Piezometer | Within Study Area | Monthly |
| Willow 9 | 276285 | Piezometer | Within Study Area | Digital Logger |
| Willow 10 | 276112 | Piezometer | Within Study Area | Monthly |
| Willow Springs Stock Well | 277868 | Stock | Within Study Area | Monthly |
| Laurie & Scott Corbett | 230730 | Residential | Within Study Area | Digital Logger |
| Alex Bauerle | 107080 | Irrigation | Within Study Area | Monthly |
| Phil & Cheryl Mulhulin | 276041 | Residential | Within Study Area | Monthly |
| Bob Pierson | 259547 | Residential | Within Study Area | Monthly |
| Dave Schuit | 276038 | Residential | Within Study Area | Monthly |
| MBMG HA-OW1 | 279258 | Stock | Within Study Area | Digital Logger |
| MBMG HA-OW2 | 279260 | Stock | Within Study Area | Monthly |
| MBMG HA-PW | 279259 | Stock | Within Study Area | Monthly |
| Parson - 2 | 277329 | Piezometer | Within Study Area | Monthly |
| Parson - 3 | 276287 | Piezometer | Within Study Area | Digital Logger |
| Bench- 1 | 276113 | Piezometer | Within Study Area | Digital Logger |
| Bench- 3 | 276114 | Piezometer | Within Study Area | Monthly |
| Jerry & Sharon Engle | 195941 | Residential | Within Study Area | Monthly |
| Lori Armstrong/Dwyer | 261912 | Residential | Within Study Area | Monthly |
| Hunt- 1 | 277080 | Stock | East of Study Area | Monthly |
| Hunt-2 | 107055 | Residential | East of Study Area | Monthly |
| Todd Nelson | 257377 | Residential | Southwest of Study Area | Monthly |
| HCC Ranch (Railroad) | 107330 | Residential | South of Study Area | Monthly |
| MBMG HCC OW1 | 277403 | Stock | South of Study Area | Digital Logger |
| MBMG HCC OW2 | 277404 | Stock | South of Study Area | Monthly |
| MBMG HCC OW3S | 277406 | Stock | South of Study Area | Digital Logger |
| MBMG HCC PW | 277405 | Stock | South of Study Area | Monthly |
| Fish Creek House | 107023 | Residential | Northwest of Study Area | Digital Logger |

## 3.2. Surface Water Monitoring

Surface water monitoring was conducted throughout the study area at various sites along the irrigation ditches and the Jefferson River, as well as the spring fed creeks. In addition to these MBMG sites, data from two USGS sites along the Jefferson River were also used. Data was collected at a total of 16 sites within the study area from April to November 2014 (Figure 3). Staff gauges and stilling wells containing a pressure transducer were installed at each of the sites in order to obtain stage data. The staff gauges were surveyed by the professional surveyors. Discharge measurements were taken biweekly using a Marsh McBirney acoustic Doppler velocity meter where flow conditions allowed. During high flows or in deep cross sections, a SonTek acoustic Doppler river profiler was used. Flow from the Marsh McBirney was calculated by using the measured cross section, depth and velocity readings. Flow is calculated internally by the SonTek river profiler. The flow values along with stage measurements were used to create rating curves at each of the sites. From the rating curves and hourly stage data logged by the transducers, hourly flow was estimated (Appendix B).

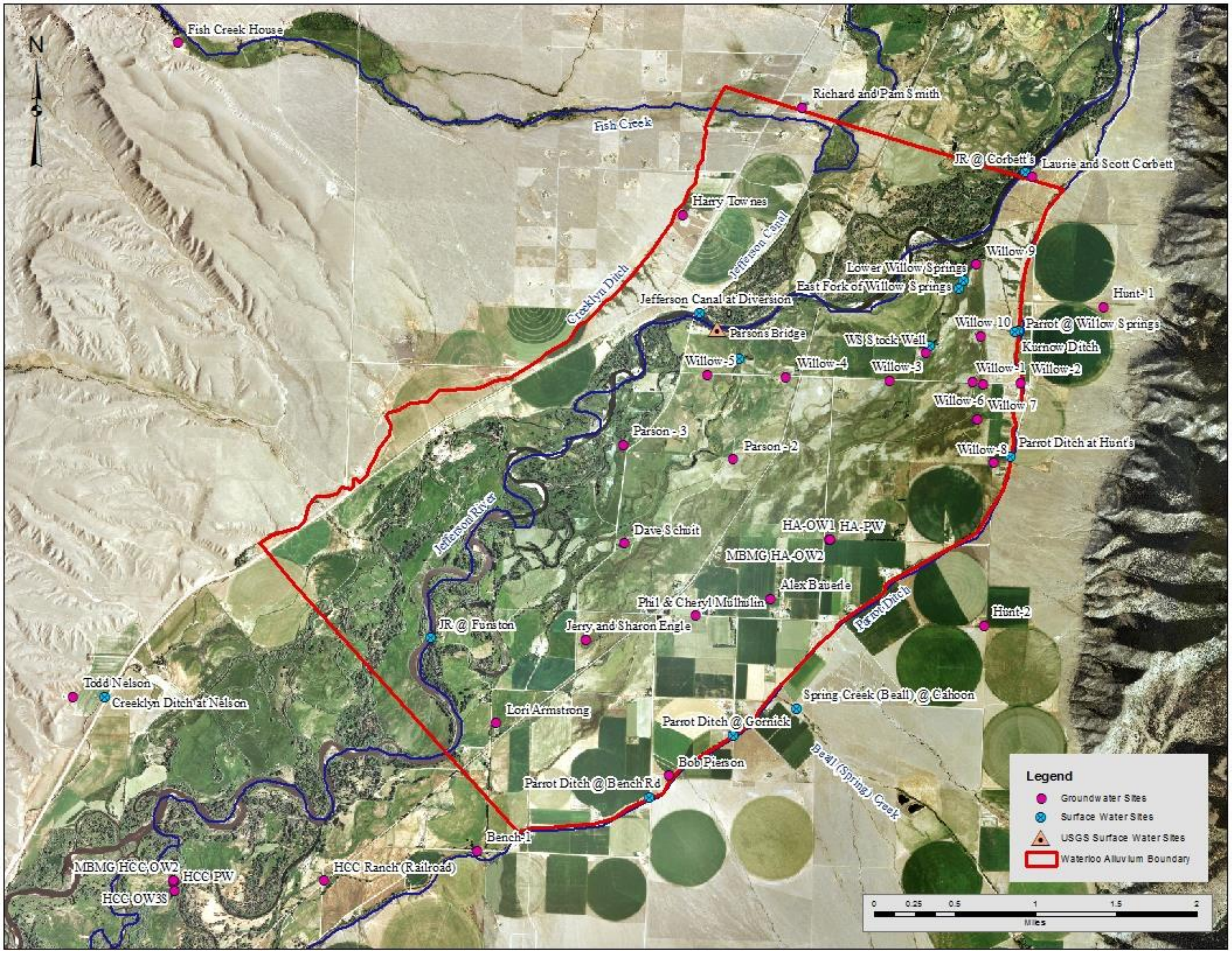


**Figure 3. Groundwater and Surface Water Monitoring Network**

## 3.3. Water Quality

Water quality samples were collected at 10 sites throughout the study area. Data were obtained from three groundwater wells, and seven surface water sites including Parson's Slough, Willow Springs, Parrot Ditch, and the Jefferson River. The sites were sampled periodically throughout the year (August 2014, November 2014, January 2015 and March 2015). A minimum of three well volumes was pumped from the groundwater wells and pH and specific conductivity values were allowed to stabilize before the samples were collected. Grab samples were collected at the surface water sites from the center of the stream. Field temperature, pH and specific conductivity were recorded, and samples were collected following the MBMG standard operating procedure for collecting water quality data. The samples were submitted to the MBMG water quality lab for analysis. Analyses were performed for major ions, trace metals, nutrients and water isotopes (Appendix D).

## 3.4. Aquifer Test

An aquifer test was conducted by the MBMG in March 2015 in the southeast corner of the study area. The test took place in the alluvium at a location determined by hydrogeologic setting and landowner permission. The MBMG drilled three wells at the site, one pumping well (HA PW) and two observation wells (HA OW1 and HA OW2). A step-drawdown test was performed first to determine pumping performance including well loss and pump efficiency. A 72 hour aquifer test was then attempted; however it was terminated after 55 hours due to equipment problems. Well recovery was also monitored. Results of the aquifer test analyzed using Aqtesolv are included in Appendix A.

# 4. Groundwater Budget

The hydrologic system describes the continuous movement of water on, above and below the Earth's surface. Fresh water makes up only a very small percentage (about 3%) of the total water supply on Earth. About 98% of the available fresh water is groundwater (Fetter, 2001). Flow paths of varying length move groundwater through the subsurface, transferring water from areas of recharge to areas of discharge.

The magnitude of the individual components of the hydrologic cycle varies significantly depending on different variables such as the climate and terrain of a region. Therefore, a groundwater budget can be a useful tool in quantifying the different components and estimating components that cannot be easily measured or quantified. There is inherent uncertainty associated with every component of a water budget; however, by combining the different elements reasonable values for each component can be calculated. Using the law of conservation, the total inflows to a system are equal to the total outflows in combination with the change in storage.

$$Inflow = Outflow \pm \Delta S$$

Where $\Delta S$ is change in storage.

A groundwater budget for 2014 was created for this study with the purpose of better quantifying the amount of groundwater recharge to the Jefferson River within the study area. This included considering all of the flows coming in to the study area and all of the flows leaving the study area. By quantifying the inflows and outflows to the aquifer in the Waterloo area we can estimate the amount of groundwater leaving the aquifer and flowing in to the Jefferson River.

Inflows to the aquifer include a groundwater flux from the south boundary, precipitation recharge, irrigation recharge, mountain front recharge, and seepage from the irrigation ditches. The outflows from the aquifer include a groundwater flux out of the north boundary, evapotranspiration, groundwater discharge to the Jefferson River, and spring fed streams (Willow Springs and Parsons Slough). Assuming a steady state, the groundwater budget for the Waterloo area becomes

$$Inflow = Outflow$$

$$P + Darcy\ Flux_{in} + S + MFR + IR = ET + Darcy\ Flux_{out} + SP + JR_{recharge}$$

where P is precipitation recharge, Darcy $Flux_{in}$ is the groundwater flux into the study area, S is ditch seepage, MFR is mountain front recharge, IR is irrigation recharge, ET is evapotranspiration, Darcy $Flux_{out}$ is the groundwater flux out of the study area, SP is groundwater leaving the aquifer as spring fed streams, and $JR_{recharge}$ is groundwater flowing out of the aquifer to the Jefferson River (Figure 4).

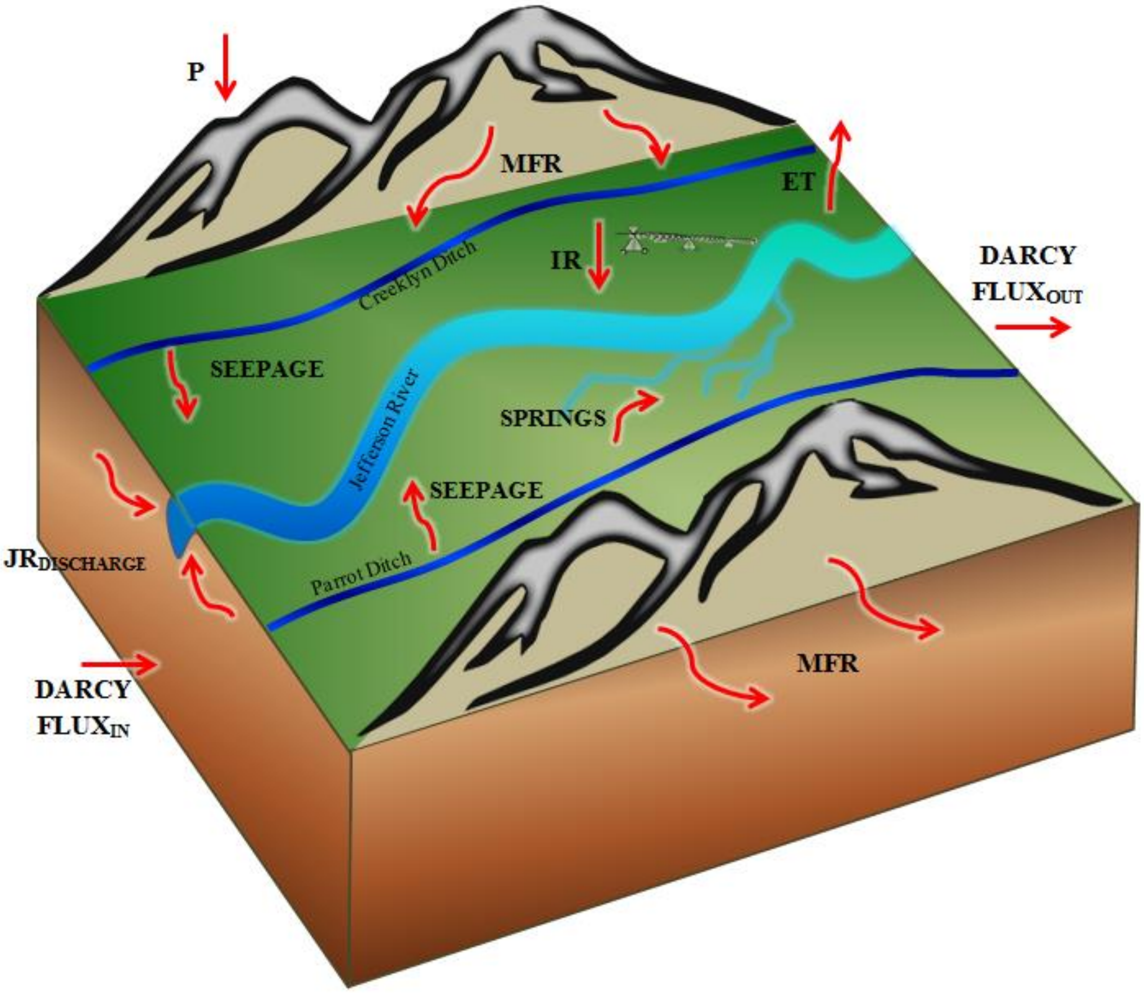


**Figure 4. Conceptual Groundwater Budget of the Waterloo Study Area**

## 4.1. Precipitation

Precipitation, including both rain and snow, is the main source of freshwater in the hydrologic cycle (Winter et al., 1998). However, the distribution of precipitation is highly variable; therefore it is important to collect data from more than one weather station to get an accurate estimate. For a groundwater budget, only the diffuse infiltration, or amount of precipitation that recharges the aquifer, is included. In order to quantify this, evapotranspiration has to be taken into account as well.

Precipitation data was acquired from the PRISM Climate Group, Oregon State University, Parameter-elevation Regressions on Independent Slopes Model (PRISM). PRISM is an analytical model that produces gridded estimates of monthly annual (or 30 year climatological average values) using point data and an underlying grid such as a digital elevation model (DEM). It was developed with the intention to improve climate estimates in mountainous regions where complex variations occur. The model incorporates a conceptual framework that addresses the spatial scale and pattern of orographic processes, making it a good estimate for mountainous terrain (PRISM Climate Group, 2014). The annual average precipitation from the PRISM data ranged from 9.8 to 10.5 inches per year within the study area, with an average of 10 inches per year.

Since precipitation is already taken into account in calculating irrigation recharge (see section 4.6), infiltration from precipitation is only calculated for the non-irrigated areas. A study done by USGS found that the relationship between precipitation and recharge becomes linear when mean annual precipitation exceeds 30 inches, however when precipitation values are less than this most of the infiltrating water is used to replenish soil moisture (Dugan & Peckenpaugh, 1985). This was found to be particularly true for semiarid climates, such as the Waterloo study area. The non-irrigated land in the study area is primarily grass and sagebrush, which have an evapotranspiration rate of about 12 inches per year. With the assumption that only a small percentage of precipitation goes into the ground as recharge due to evapotranspiration, this parameter is negligible to the groundwater budget for this study.

## 4.2. Evapotranspiration

Evapotranspiration in terms of a groundwater budget is important when considering diffuse recharge from precipitation as mentioned earlier, but also important when considering phreatophytes. Phreatophytes are deep rooted plants that pull water from the saturated zone of the aquifer. Since evapotranspiration is already taken into account in irrigated areas when irrigation recharge is calculated, the amount of water the phreatophytes are taking from the aquifer is the main concern for this groundwater budget.

For this study Landscape Fire and Resource Management Planning Tools (LANDFIRE) data was used to evaluate vegetation types in the study area. LANDFIRE is a collaborative program between the wildland fire management bureaus of the U.S. Department of Agricultural Forest Service and U.S. Department of the Interior, which provides landscape scale geo-spatial products.

The LANDFIRE data was used to identify type and quantity of phreatophytes that exist in the alluvial area. The LANDFIRE data revealed that phreatophytes in the study area include aspen, cottonwood and willows. As can be seen in Figure 5 below, they exist primarily in the riparian zone, which is consistent with field observation acres of phreatophytes. A rate of 22 inches per year (Bobst et al., 2014) was used to quantify the amount of ET from these phreatophytes which resulted in total evapotranspiration of about 1,000 acre feet per year.

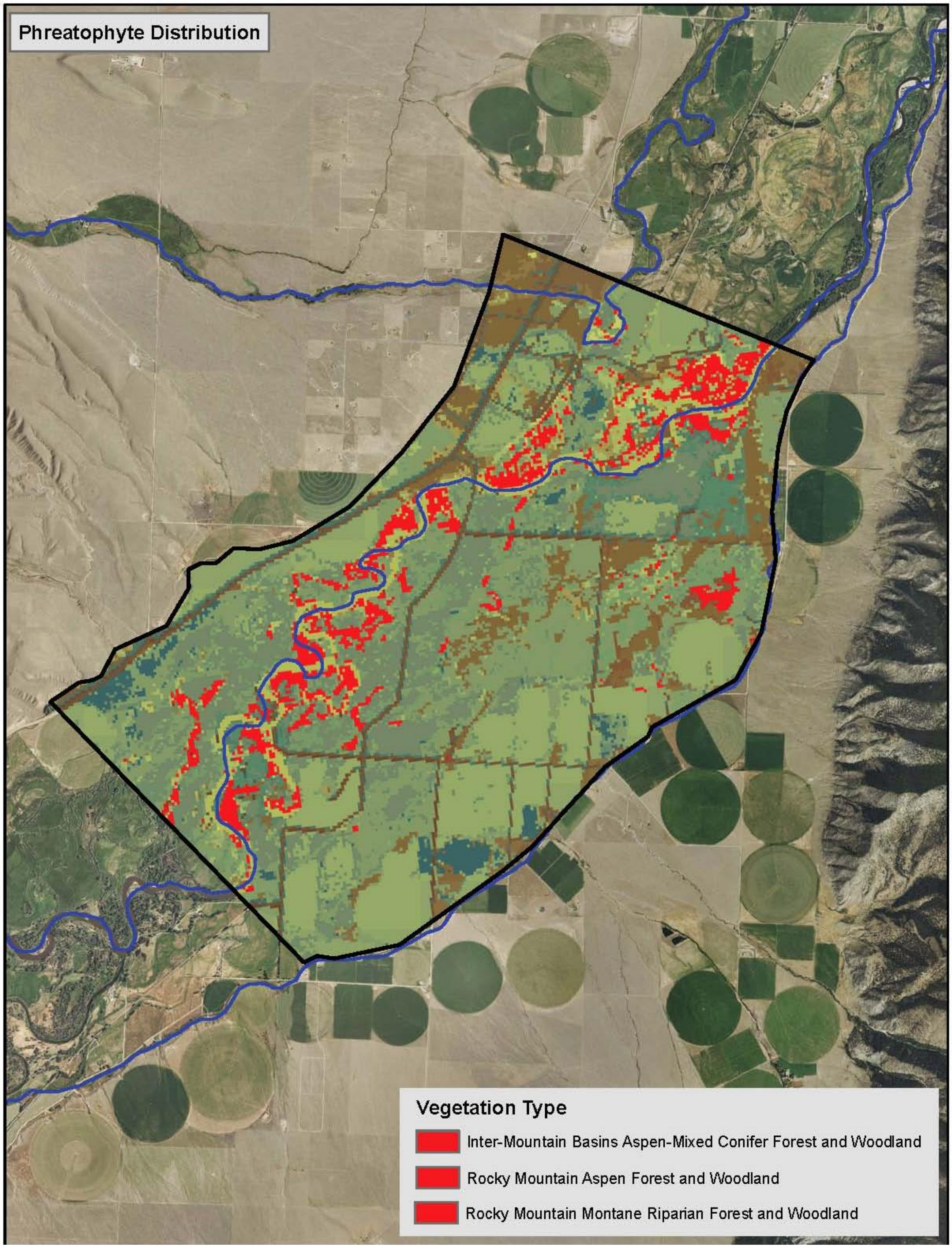


**Figure 5. Phreatophyte Distribution in the Waterloo Area**

## 4.3. Groundwater Flux

Groundwater flux is the amount of groundwater moving horizontally through a specific cross section of the aquifer. The amount of flux can be calculated using Darcy's law (Fetter, 2001):

$$Q = KiA$$

where Q is the total flow (cfs), K is the hudraulic conductivity (ft/s), i is the groundwater gradient (unitless), and A is the cross-sectional area of the aquifer ($ft^2$).

The cross-sectional area of the aquifer depends on the saturated thickness of the aquifer. The aquifer thickness was estimated based on well logs from wells within the study area. The majority of wells in the alluvium were completed around 60 feet below ground surface. An assumed saturated aquifer thickness of 100 feet was used for calculations as that was the depth of the deepest well (MBMG HCC OW1) drilled in the study area.

The cross sectional area was calculated using this assumed aquifer thickness and the measured distance of both the north and south boundary within the alluvium. The geologic map of the study area (Figure 2) reveals that the northern boundary consists of a much narrower cross section than the southern boundary. As such the groundwater flux out of the study area is much smaller than the groundwater flux into the area. The groundwater flux estimates are likely over estimates since the actual geometry of the aquifer is most likely not rectangular. Typically the aquifer is deeper in the middle and shallower on the sides, however, the study area boundary only encompasses the alluvium and as such a rectangular area is sufficient. A cross section near the southern boundary of the study area is shown below.

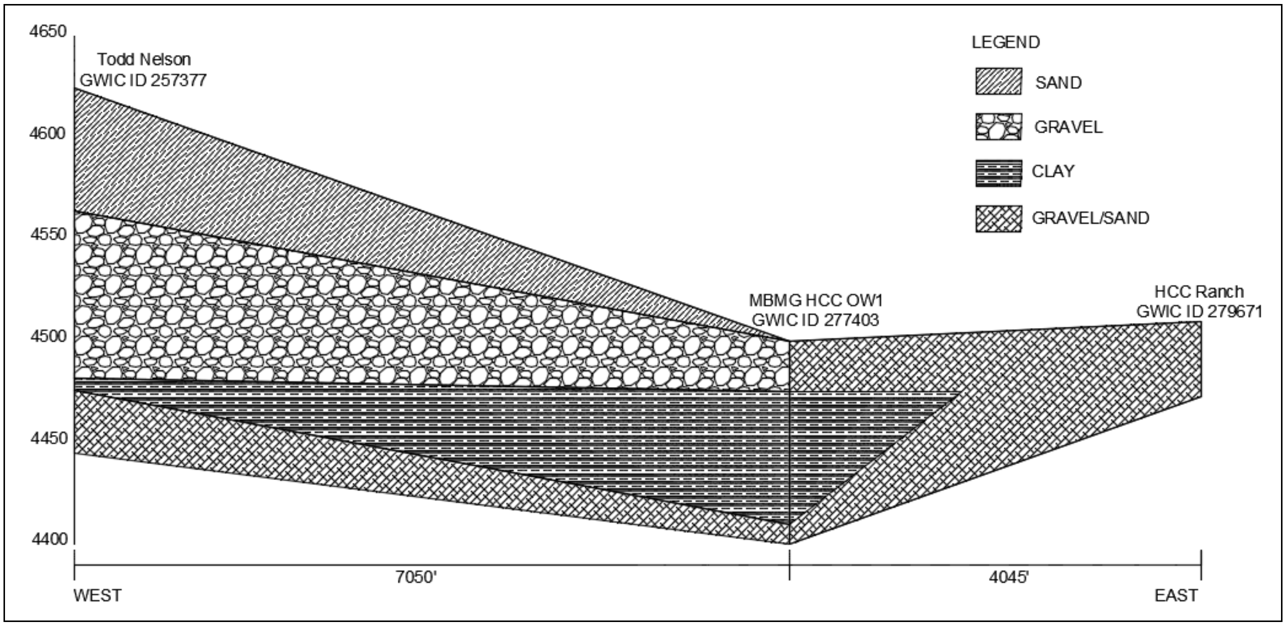


**Figure 6. Geologic Cross Section Near Southern Study Area Boundary**

Hydraulic conductivity was estimated from the aquifer test and well log data. The aquifer test data in the alluvium resulted in a transmissivity value of 110,000 square feet per day using a confined leak aquifer model (Hantush-Jacob) which allowed for the inefficiency of the pumping well to be taken into account. Using the assumed 100 ft saturated thickness the resulting hydraulic conductivity is 1,100 feet per day. This is a reasonable value based on lithology records of the wells showing primarily gravel. The groundwater gradient was calculated using the potentiometric surface created from the static water elevation data collected in 2014. This resulted in a groundwater flux in of 22,364 acre-ft/yr and a groundwater flux out of 13,503 acre-ft/yr.

## 4.4. Mountain-Front Recharge

Mountain-front recharge is generally defined as the contribution of recharge from mountain regions to adjacent basin aquifers. Wilson and Guan 2004 suggest a more specific definition of Mountain Front Recharge as “all water entering the basin aquifer with its source in the mountain block and mount front (zone)." It is particularly important in semi-arid and dry climates due to its significant contribution to the basin aquifer which can be greater than four times the river basin discharge (Wilson & Guan, 2004).

There are many different methods to estimate Mountain-front Recharge. Typical basin-centered methods treat the mountain front as a boundary condition instead of analyzing the actual hydrologic system of the mountain. Mountain-centered methods consider the mountain as a whole and not just as a boundary condition. Mountain-centered methods consider recharge from rainfall, snowmelt, surface runoff, as well as through fractures and faults, along with water returned to the atmosphere through vegetation-controlled evapotranspiration (Wilson & Guan, 2004).

For this study, a mountain-centered water balance method was used to quantify the Mountain-front Recharge contribution. Mountain-front Recharge is pertinent to the groundwater budget as it is a major inflow into the east and west boundaries of the study area. The water balance method assumes that precipitation is the only input in the water budget. Subtracting surface-water runoff and evapotranspiration results in groundwater as the only output. For purposes of this study all surface water runoff exiting both mountain regions is intercepted for irrigation use and never makes it to the basin aquifer. In the event all the water is not intercepted it would discharge to the irrigation canals. Also, assuming a steady state, there is no storage. By making these assumptions the groundwater leaving the mountain front system is equal to the Mountain-front Recharge and can be quantified with the water budget equation below.

$$In = Out \pm \Delta S$$

$$PCP + SW_{in} + GW_{in} = ET + SW_{out} + GW_{out} \pm \Delta S$$

$$PCP - ET = GW_{out}$$

$$GW_{out} = MFR$$

where PCP is precipitation, SW is surface water, GW is groundwater, ET is evapotranspiration, and ΔS is change in storage.

The boundary used to analyze each hydrologic section of the water budget was delineated using topographic maps to determine the divides. It is assumed for this case that the groundwater divides follow the topography of the mountains. Therefore the area used to evaluate precipitation and evapotranspiration was sectioned according to divides near the north and south flux boundaries of the study area and run all the way from the mountain peak to the alluvium boundary of the study area (Figure 7). The resulting areas for the Highland and Tobacco Root Mountains were 39,939 and 28,193 acres, respectively.

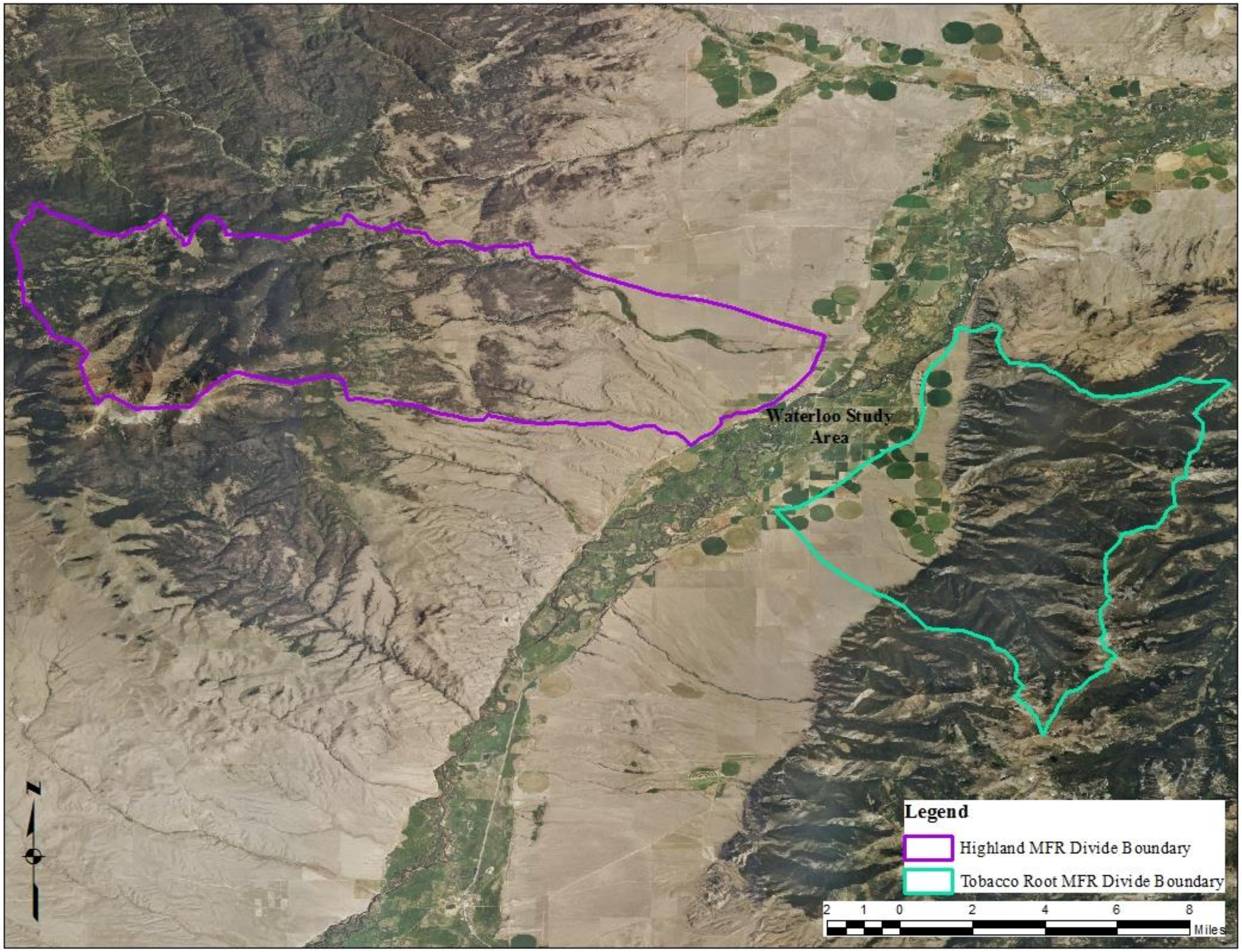


**Figure 7. Divide Boundaries for MFR Estimate (Delineated using topographic maps)**

### 4.4.1. Mountain Peak Precipitation

The 30 year normal data from PRISM was used to estimate the amount of precipitation over the delineated mountain areas contributing to the study area. The 30 year normal data were taken from the time period 1981-2010. Evaluation of the annual average precipitation data for the Highland Mountain region shows a range of 9.95 inches to 32.27 inches, averaging 18.36 inches per year. The Tobacco Root Mountain region shows a range of 10.02 inches to 42.20 inches, averaging 19.02 inches per year. This converted to 61,116 acre-feet of precipitation per year for the Highland Mountains and 44,676 acre-feet of precipitation per year for the Tobacco Root Mountains.

### 4.4.2. Mountain Evapotranspiration

The estimation of evapotranspiration is crucial to the accuracy of the water balance approach, which can be difficult to quantify (Wilson & Guan, 2004). LANDFIRE vegetation data was acquired for the specified mountain regions to determine the amount and variation of different vegetation. Vegetation type was divided according to 11 different categories for which literature values of evapotranspiration rates were used (Johns, 1989). The total area of each type of vegetation was determined and used to calculate total evapotranspiration rates for each mountain region. The evapotranspiration rates ranged from 1.0 foot (shrub/grass lowlands) to 2.2 feet (Whitebark pine) per year. Evapotranspiration estimates totaled 56,674 acre-feet per year and 41,715 acre-feet per year for the Highland Mountains and Tobacco Root Mountains, respectively (Table 2).

**Table II. Vegetation Type and Evapotranspiration Rates**

| Vegetation Group | Highland Mountains | | | Tobacco Root Mountains | | |
|---|---|---|---|---|---|---|
| | Acres | ET Rate (ft/yr) | Acre-ft/yr | Acres | ET Rate (ft/yr) | Acre-ft/yr |
| Upland Sagebrush | 5,350 | 1.1 | 5,885 | 4,593 | 1.1 | 5,053 |
| Douglas Fir | 8,477 | 1.4 | 11,868 | 12,941 | 1.4 | 18,118 |
| Shrub/Grass Lowlands | 9,765 | 1.0 | 9,765 | 2,046 | 1.0 | 2,046 |
| Mixed Evergreen | 8,290 | 1.8 | 14,923 | 3,215 | 1.8 | 5,787 |
| High Xeric Grasses | 2,472 | 1.2 | 2,967 | 343 | 1.2 | 412 |
| Ag lands | 309 | 2.1 | 650 | 1,995 | 2.1 | 4,190 |
| Mesic Meadow | 1,216 | 1.7 | 2,067 | 757 | 1.7 | 1,287 |
| Whitebark Pine | 2,838 | 2.2 | 6,244 | 1,492 | 2.2 | 3,283 |
| Alpine Rangeland, Deciduous Shrubs | 864 | 2.0 | 1,728 | 181 | 2.0 | 361 |
| Developed | 186 | 1.0 | 186 | 206 | 1.0 | 206 |
| Riparian | 170 | 2.3 | 392 | 422 | 2.3 | 971 |
| TOTAL | **39,939** | | **56,674** | **28,193** | | **41,715** |

### 4.4.3. Mountain Front Recharge Estimate

The total mountain front recharge using the water budget approach resulted in 4,443 acre feet per year and 2,961 acre feet per year from the Highland and Tobacco Root Mountains, respectively. This is a high end estimate of the amount of recharge from the mountains. This method does not take surface water runoff, soil moisture retention, or sublimation into account. The surface water runoff is a variable output; there are times it is not completely intercepted for irrigation.

Since snow is the majority of the precipitation that occurs in the alpine region, sublimation may have a significant impact on the water balance of the mountain. Sublimation occurs, in order of decreasing efficiency, due to wind transported snow, intercepted snow, and from the snow pack. In a study done to evaluate the effect of sublimation on a snow mass balance in the Canadian Rocky Mountains, snow mass loss to sublimation as a percentage of cumulative snowfall ranged from 20 to 32% (MacDonald, Pomeroy, & Pietroniro, 2010).

Sublimation was estimated through blowing snow models simulating a transect of hydrological response units (HRU's) along a ridgeline in the Rockies. Of the total snow mass loss 17 to 19% was due to blowing snow.

Numerical modeling of the Boulder River Valley, a region just north of the Upper Jefferson Valley, used the same water budget approach for mountain front recharge. The results of the investigation found the actual mountain front recharge to be about half of the calculated value (Bobst et al., in preperation). Preliminary numerical modeling of the Waterloo area was also done, and the calibration stage of a steady state model showed this same result. Consequently, the calculated values for mountain front recharge were halved for this groundwater budget. The total Mountain-front Recharge was 3,702 acre-ft/year.

## 4.5. Irrigation Ditch Seepage

Accurate seepage estimates were needed for this groundwater budget since irrigation ditches act as the east and west boundaries of the study area. The study area is bordered by the Parrot Ditch on the east and the Creeklyn Ditch on the west. In order to quantify the ditch seepage, a synoptic discharge measuring event was conducted on August 13, 2014 to analyze seepage from the Parrot Ditch. All irrigation pumps drawing from two reaches were turned off at 8am that morning and the measurements were taken consecutively with minimum time in between measurements. Discharge was taken at four sites and seepage was calculated for the two reaches. Results ranged from 3 to 8 cubic feet per second per mile (cfs/mi) for the Parrot Ditch.

Since the synoptic sampling event was only one instance it is not representative of the whole season. To better estimate, seepage hydrographs from surface water monitoring for consecutive sites on both the Parrot and Creeklyn Ditch were analyzed. It is assumed that when the flows at each site are closest in value, minimal pumping occurs and a good estimate of seepage can be calculated. It is recognized, however, that some pumping may still be occurring. During times of minimal loss, flows were compared and the average loss was calculated to be about 2 cfs/mi and 4 cfs/mi for the Creeklyn and Parrot Ditch, respectively (Appendix A). The total seepage was calculated for the approximate 6 months when the irrigation ditches are operating (May – October). These estimates resulted in a total seepage inflow of about 12,800 acre feet per year into the study area from both irrigation ditches.

### 4.6. Irrigation Recharge

Irrigation recharge is the amount of recharge to the aquifer as a result of irrigation. It is dependent on the type of irrigation as well as type of crop being irrigated. The three types of irrigation used in this study area are flood irrigation, pivot irrigation, and sprinkler irrigation. Efficiency ranges for each type of irrigation were determined from the NRCS National Engineering Handbook (2008) and a mid-range was selected: 25% for flood, 65% for sprinkler, and 80% for pivot irrigation. The NRCS Irrigation Water Requirements program (IWR) was used to determine certain parameters used as inputs in the following equation to calculate irrigation recharge:

$$IR = [(NIR/IME + P_{eff}) - ET \times DP_{ex}]$$

where IR is irrigation recharge, NIR is net irrigation requirement, IME is irrigation method application efficiency, $P_{eff}$ is effective precipitation, ET is evapotranspiration and $DP_{ex}$ is the applied water in excess of ET that results in deep percolation. NIR, $P_{eff}$ and ET were estimated from the IWR program.

A weather station in Twin Bridges was selected to use for climate data as it was the closest to the study area. The climate data is used by the program to determine the effective precipitation, and a 30 year normal data set is required. Only weather stations with adequate records can be used.

In an interview conducted with landowner Dean Hunt, irrigation methods and crop types were discussed focusing on the land inside the study area boundary. Crop types within the area include native grass, native alfalfa grass (a 50/50 mix of alfalfa and grass), alfalfa, barley, peas, potatoes, corn, sod and conifer trees (D. Hunt, personal communication, 2014). Approximate irrigation dates and cutting frequency was also discussed. The different crop types were split into four different categories for the purpose of this study: native grass, native alfalfa grass, alfalfa and other. The “other” category encompasses all of the remaining crop types as they have similar irrigation requirements and ET rates, and cover a small percentage of the area in comparison to the other three main crop types. It should be noted that the IR calculations were made using current irrigation type and crop data for 2014.

In addition to crop type and climate data, soil type is also an important input into the IWR program. According to the NRCS Web Soil Survey sandy loam is the predominant soil type within the study area and was selected for the soil type (Appendix A). The value for the $DP_{ex}$ term was based off a study by the Idaho Department of Water Resources (Idaho Department of Water Resources, 2013) which took place in the eastern Snake Plain Aquifer. The variable ranges from 0 to 1 depending on evidence of surface water return flows. For this study $DP_{ex}$ was set to 0.5 for flood irrigated areas and 1 for pivot and sprinkler irrigated areas.

Based on the IWR results the irrigation recharge for each month of the year was estimated. The numbers were then multiplied according to the mid-range average irrigation efficiency values. Tables containing the irrigation recharge values can be found in Appendix A.

Once the areas for each crop and irrigation type were totaled the resulting table was created with the total irrigation recharge estimate for the groundwater budget.

**Table III. Irrigation Recharge**

| Irrigation & Vegetation Type | Area (acres) | IR Rate (ft/yr) | IR (acre-ft/yr) |
|---|---|---|---|
| Pivot (Pasture Grass, Alfalfa Hay, 50/50, Other) | 1,498 | 0.29 | 432 |
| Sprinkler (Pasture Grass, 50/50, Other) | 810 | 0.67 | 539 |
| Sprinkler (Alfalfa Hay) | 214 | 1.67 | 357 |
| Flood (Pasture Grass, Other) | 1,333 | 4.69 | 6,252 |
| Flood (50/50) | 602 | 5.23 | 3,149 |
| Flood (Alfalfa Hay) | 64 | 5.77 | 367 |
| Total | | | 11,096 |

## 4.7. Spring Fed Streams

Willow springs and Parsons Slough both originate within the study area and are groundwater fed springs, essentially groundwater discharging from the aquifer as surface water. In a field visit conducted with landowner Dean Hunt, a house near Willow Springs was toured. The house gets its water from a spring under the house, with the overflow discharging to the stream. Water quality data also shows evidence of these streams being spring fed. In order to quantify this outflow for the groundwater budget, the hydrographs created from field observations were analyzed (Appendix B). The resulting estimate was approximately 22 cfs, or 16,360 acre feet per year.

## 4.8. Groundwater Discharge to the Jefferson River

As stated earlier the Waterloo area is historically identified as the main source of recharge to the Jefferson River, which becomes extremely important in the late summer months when flows are low and temperatures are elevated. Therefore it is important to quantify this for the groundwater budget. A surface water budget analysis was used in order to estimate the recharge.

Since the reach of the Jefferson River between the USGS gaging station at Parsons Bridge and the MBMG site Jefferson River at Corbett's has no major diversions, only additions from Parsons Slough and Willow Springs, it is an ideal stretch of river to analyze for the groundwater recharge in the Waterloo area (Figure 8). The groundwater contribution can be estimated by quantifying the flows coming in to this stretch of river and subtracting the outgoing flows with the following surface water budget equation:

$$Q_{out} = Q_{in} + Q_{gw}$$

$$Q_{gw} = Q_{out} - Q_{in}$$

$$Q_{gw} = Q_{JR@Corbett's} - (Q_{USGS\ Parson's\ Bridge} + Q_{Parson's\ Slough} + Q_{Willow\ Springs} + Q_{Kurnow\ Ditch})$$

where $Q_{gw}$ is the groundwater discharge, and the remaining terms are surface flow at their respective sites. Flows were also analyzed in the southern stretch from the MBMG site Jefferson River at Silver Star to the USGS Parson's Bridge site. The only major diversion known in this stretch is the Jefferson Canal irrigation ditch. The recharge to this stretch of river can be quantified by the following equation:

$$Q_{gw} = Q_{JR@Silver\ Star} - (Q_{USGS\ Parson's\ Bridge} + Q_{Jefferson\ Canal@Diversion})$$


**Figure 8. Surface Water Flows for Estimation of Groundwater Discharge to the Jefferson River**

Using the above equation the groundwater discharge to the Jefferson River was calculated based on the discharge recorded at the surface water monitoring sites. Peak runoff season results in high flows which are not only hard to measure due to field equipment constraints but also make it extremely difficult to distinguish between surface runoff and groundwater recharge. Because of the measurement constraints, the rating curve for Jefferson River at Corbett's has very high uncertainty for high flows. Therefore, the late summer months during low flow (August and September) give the best estimate of actual groundwater discharge.

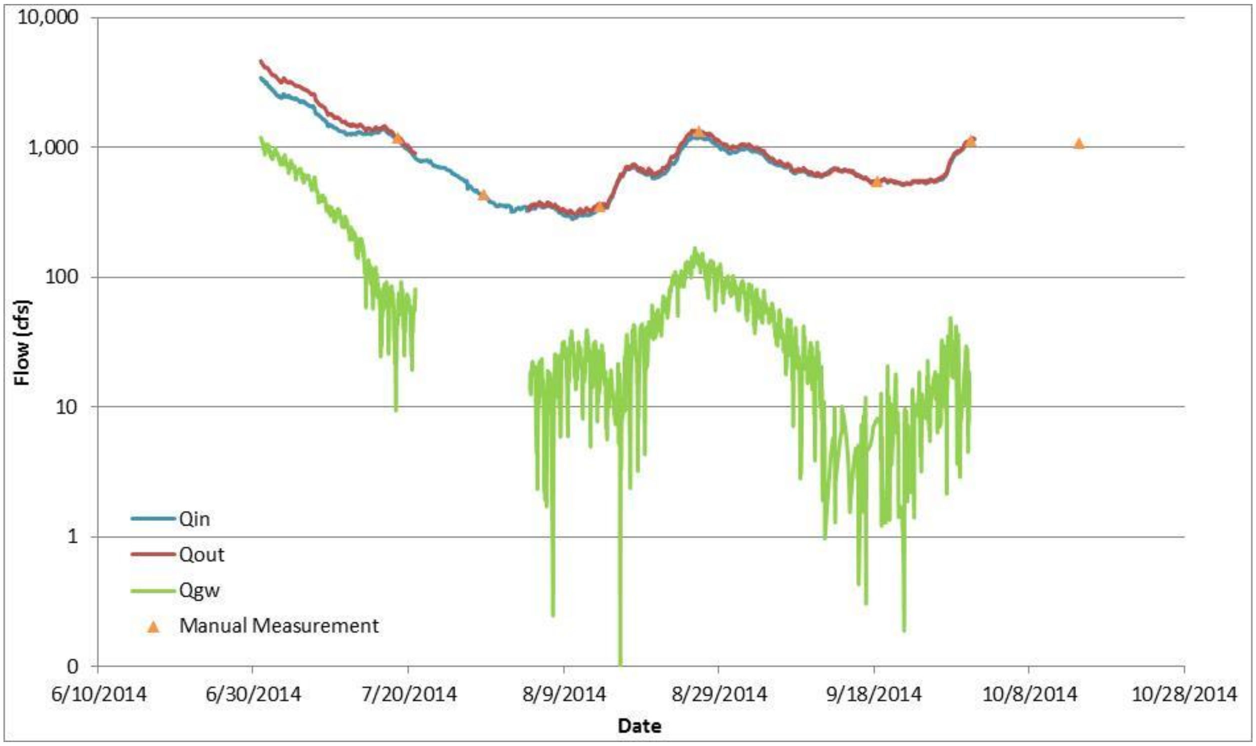


**Figure 9. Hydrograph comparison of Jefferson River at Silver Star and Jefferson River at Parson's Bridge showing direct discharge of groundwater**

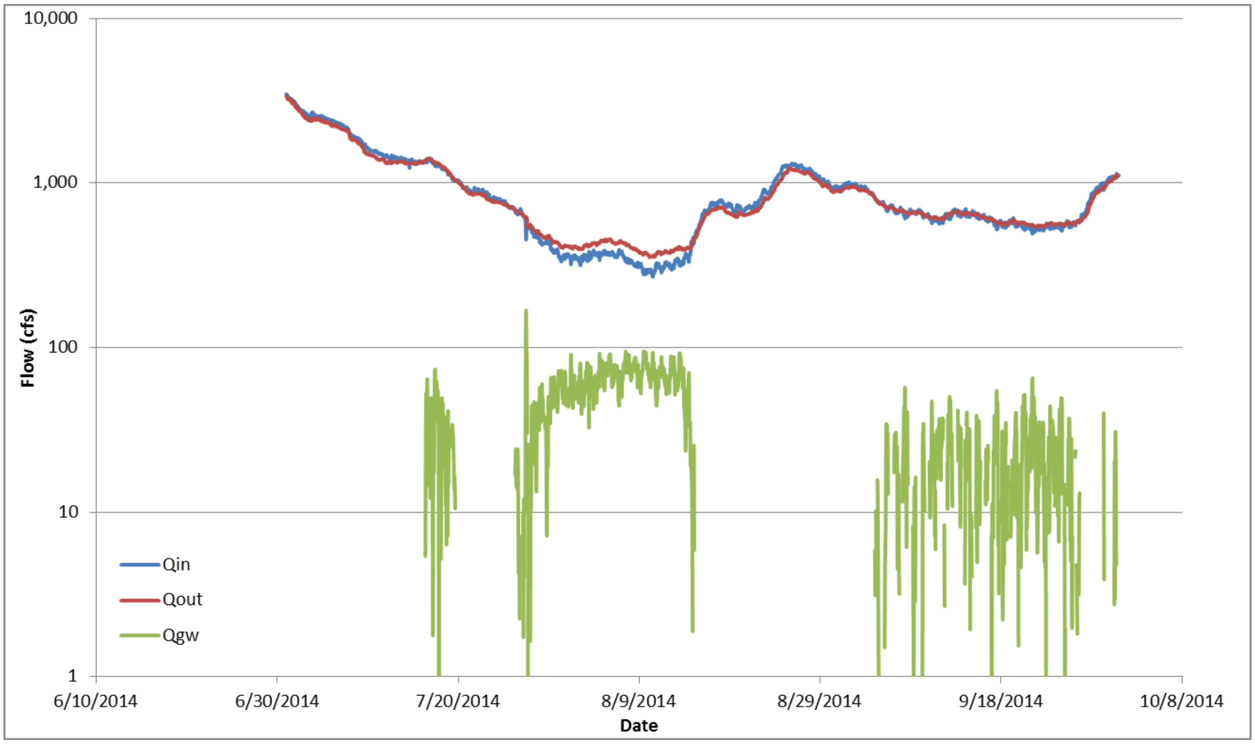


**Figure 10. Hydrograph comparison of Jefferson River at Parson's Bridge and Jefferson River at Corbett's showing direct discharge of groundwater**

The average groundwater discharge to the Jefferson River from Silver Star to Parsons Bridge for 2014 was about 20 cfs, and about 12 cfs in the stretch from Parsons Bridge to the Corbett's. These values equate to 14,779 acre-ft/year and 8,831 acre-ft/year, respectively. The greatest gain occurs at the lowest stage, when the stage increases the river flows into bank storage. The manual measurements for Jefferson River at Corbett's were also plotted on Figure 9, with the highest measured flow at about 1,300 cfs. The highest flow in the hydrograph for Jefferson River at Corbett's was over 3,200, over twice the flow that was measured which is past the acceptable 1.5 factor for extending rating curves (A. Bobst, personal communication, 2015).

# 5. Water Budget Assessment

The final groundwater budget shows that initial estimated inflows to the aquifer totaled 49,991 acre-ft per year and estimated outflows equaled 54,479 acre-ft per year, which comes to about a 4.3% difference (Table 4). The estimated uncertainty for each component of the groundwater budget must also be taken into account. The uncertainty was used to create a range of values for each factor, and with that range a balanced budget can be created. For this study a groundwater budget was estimated for the year 2014, this budget cannot be used as an accurate representation of inflow and outflow of the system for any other year, although it may be similar. Given that any variation in water levels is believed to result from climatic variability, change in storage is believed to be zero. As such, a weighted adjustment was applied to the budget so that it balances.

**Table IV. Groundwater Budget for Waterloo**

| | Initial Estimate (acre-ft/yr) | Uncertainty (%) | Range (acre-ft/yr) | | Adjusted Estimate (acre-ft/yr) |
|---|---|---|---|---|---|
| **$Gw_{in}$** | | | low | high | |
| Darcy $Flux_{in}$ | 22,364 | 10% | 20,128 | 24,601 | 3,371 |
| MFR | 3,702 | 10% | 3,332 | 4,072 | 3,869 |
| Seepage | 12,829 | 5% | 12,187 | 13,470 | 13,406 |
| IR | 11,096 | 5% | 10,541 | 11,651 | 11,595 |
| *TOTAL IN* | 49,991 | | | | 52,241 |
| $Gw_{out}$ | | | | | |
| Darcy $Flux_{out}$ | 13,503 | 10% | 12,153 | 14,853 | 12,963 |
| Spring Fed Streams | 16,365 | 5% | 15,547 | 17,183 | 15,670 |
| ET | 1,002 | 10% | 902 | 1,102 | 957 |
| $Jr_{recharge}$ | 23,609 | 10% | 21,248 | 25,970 | 22,653 |
| *TOTAL OUT* | 54,479 | | | | 52,242 |

Due to a number of limitations in estimating the groundwater budget, it is important to note the uncertainty of this evaluation. In an ideal steady state situation the percent error would be zero: all flow into the system would equal the flow out of the system. However, there is no such thing in the real world as true steady state. Averaging the flows and fluxes throughout an entire year helps to estimate the steady state, but there is never a time that the aquifer is at a true steady state.

There are many different variables which affect the inflows and outflows to the aquifer. For instance, historical climate change will affect the budget. 2014 had near normal precipitation and temperatures. In 2005 during the WET study the valley experienced a drought year with less precipitation and higher temperatures than normal. There were also limits to the amount and type of groundwater and surface water monitoring that could be accomplished. Ideally data would be collected for more than one year. Other constraints included budget, access, acquiring landowner permission, and equipment limitations. Measuring surface water discharge during high flows was extremely difficult at both the south and north boundary sites on the Jefferson River (Jefferson River at Funston and Jefferson River at Corbett's). Therefore the rating curves at both of these sites have high uncertainty during high flows.

There is also uncertainty in assuming a homogenous hydraulic conductivity in the aquifer across the entire study area. The aquifer test that was conducted is only an accurate representation of the hydraulic conductivity in the area the wells are located. The uncertainty of the Darcy flux strongly relies on the saturated thickness. In order to accurately estimate the saturated thickness of the aquifer, a deeper well would be needed to identify the true saturated layer. A breakdown of the percentages of the inflows and outflows can be seen in Figure 11 below.

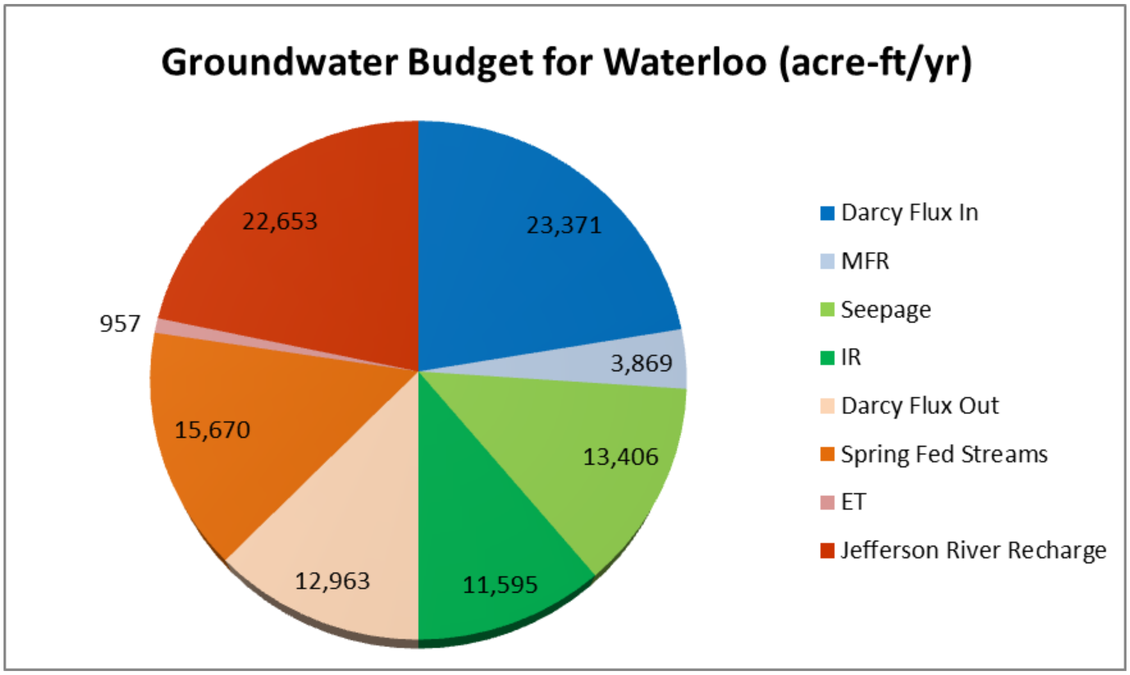


**Figure 11. Groundwater Budget for Waterloo**

The major sources of inflow (aside from the darcy flux) are seepage and irrigation recharge. This is not surprising given that almost the entire area is irrigated land and the east and west borders of the area are irrigation ditches carrying over 200 cubic feet per second of water at times. The major outflows are groundwater discharge to the Jefferson River and the spring fed streams that originate within the study area.

## 5.1. WET – MBMG SWE Comparison

Groundwater elevations from the WET study in 2005 were compared to groundwater elevations collected from the same wells by the MBMG in 2014. Graphs of all of the well comparisons can be found in Appendix C. It is important to note that these comparisons only show the difference between the water elevations in the year the data was collected, and are dependent on many different variables. Water level elevations change as the inflows and outflows of the water budget change throughout time. Although there are limitations, these graphs do provide important information of the water table trends in the Waterloo aquifer and some conclusions can still be drawn.

In evaluating the graph comparisons it is apparent that the water table in 2014 was at a higher elevation than the water table in 2005. The main reason for this is most likely that 2005 was considered a "drought" year with significantly lower flows in the Jefferson River compared to 2014 data. However, the general trend of the water table, steadily decreasing during the winter months and peaking May – June, then decreasing again throughout the rest of the year, has remained the same. There is no evidence to support the presumption that the water table in the Waterloo area is decreasing.

## 5.2. Irrigation Practice Change Evaluation

As irrigation recharge makes up about 22% of the inflows in the groundwater budget, irrigation practice changes have the potential to impact groundwater levels. As WET presumed from their study, flood irrigation early in the season is an important source of recharge to the Jefferson River in the late summer months. Although many of the fields in the area are still currently flood irrigated, a field just south of Loomont Road was converted from flood to pivot irrigation sometime after 2005. Two of the wells monitored by the MBMG are in close proximity to the field. Looking at these two graph comparisons there is no evidence to support the fact that switching this field from flood to pivot irrigation caused less recharge to the aquifer. Since this is an area where groundwater discharge occurs it could be that it is not sensitive to these changes, while practices in recharge areas would cause more of a change.

However, flood irrigation requires approximately three times the amount of water as sprinkler or pivot irrigation. Although changing one field from flood to pivot irrigation seemingly had no impact, if all fields were switched the impact may be significant enough to noticeably alter the groundwater budget.

In a predictive scenario analysis, the irrigation recharge was recalculated to visualize the effect of changing irrigation practices. The fields that are currently flood irrigated were calculated as if they were changed to pivot irrigation. The resulting irrigation recharge value was calculated to be 1,904 acre feet per year. This is a drastic reduction, over 80%, in irrigation recharge as opposed to the current calculated value of 11,096 acre feet per year. Although it is not typical, due to size and expense, that all fields would be converted to pivot, it is the most conservative prediction of how the groundwater budget could be altered by changing irrigation practice.

## 5.3. Ditch Lining Evaluation

As seepage makes up approximately 26% of the inflows of the groundwater budget, it has the potential to have a major impact on the Waterloo aquifer. It is widely known that lining ditch canals will result in water conservation, as less water is required to be diverted from the river with reduced seepage. Conversely, from an aquifer standpoint, lining the ditch canals could have an adverse effect on aquifer recharge. Without seepage from the irrigation canals recharging the aquifer, it is likely that not as much recharge to the Jefferson River would occur later in the summer when it is most needed.

## 5.4. Tile Drain Effect

The tile drains that were installed in the Waterloo area have caused some concern among neighboring residents. The major concern is that the presence of these tile drains is causing the water table to lower in that area. Two wells were monitored (Shuit and Parson 2) in close proximity to where the tile drains were installed. There is no evidence to support the presumption that the water table has been lowered in this area. Although no evidence was seen in the water elevations of these wells, some quick calculations can be made to support this theory.

Freeze and Cherry wrote in relation to developing tunnels that if groundwater inflows could be predicted it was possible to design an adequate drainage system. They theorized that tunnels essentially acted as drains. With a known hydraulic conductivity the rate of groundwater inflow per unit length of tunnel can be calculated from a quantitative analysis of the net flow (Freeze & Cherry, 1979). Using this approach, an estimated flow from the tile drains can be made.

Agricultural subsurface drains are installed depending on field topography and soil permeability. Typical depths range from 3 to 4 feet (Wright & Sands, 2001) with more permeable soil at deeper depths. In order to serve their purpose and discharge to Parson's Slough, the drains would also have to be fairly shallow. Drain material and diameter are dependent on how much water is required to drain. Although exact dimensions and placement of the tile drains in the Waterloo area is unknown, with assumptions, an estimate can be made of the amount of water being drained. Using an approximate depth of 4 feet and aquifer characteristics from the aquifer test a cumulative transient inflow per unit length of drain after a specified time can be determined. From the calculation, approximately 23 square feet of water per linear foot of drain would be drained after one year. If there were 3,000 linear feet of tile drains this would equate to about 5 acre-ft/year after 10 years, which, in comparison to the water budget, is extremely small.

To estimate the effect of the tile drains on nearby wells the Theis method was used. When aquifer properties are known a Theis curve can be used to estimate hydraulic head drawdown in a well at a specified distance and time in a confined aquifer. Using this method and the aquifer properties from the aquifer test a time-drawdown curve for a radius of 100 feet from the tile drains was developed.

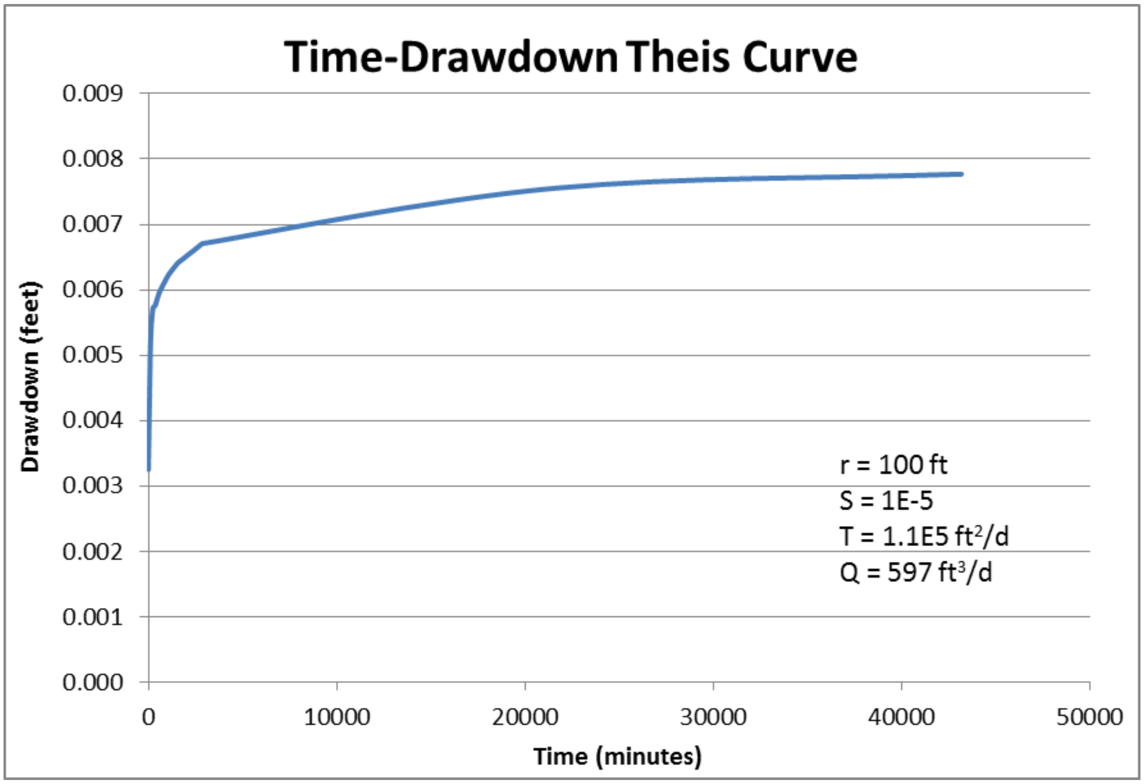


**Figure 12. Time-drawdown Theis Curve for Tile Drain Influence Prediction**

The tile drains likely have little to no influence on neighboring wells, as drawdown even after one month is extremely insignificant at less than 0.01 feet. The drawdown was calculated as if the tile drains were a pumping well at the edge of the field. Since the closest neighboring well is greater than 100 feet from the field where the tile drains are installed, it is not likely neighboring wells will see any effect from the tile drains.

## 5.5. Water Quality Evaluation

Four sampling events were performed during the duration of this study in August 2014, November 2014, January 2015, and March 2015. Piper diagrams were created in order to analyze the results of the sampling events (Appendix D). The predominant water type in both surface water and groundwater samples is calcium-bicarbonate. Since there is only subtle change in the marker placement from the different sampling dates, it is hard to determine if there are different sources of water in each location. However, it is apparent that the Hunt-1 well is a different water type, magnesium-bicarbonate, and from a different source. This result is expected as it is in the alluvial fan at the base of the Tobacco Root Mountains, likely strongly influenced by mountain front recharge.

The total dissolved solids (TDS) ranged from 235.34 mg/l in the west fork of Willow Springs and 360.67 mg/l in Parsons Slough. A simple comparison of the lab specific conductivity results from each sampling event is a good indicator of how water composition changes throughout the season. For example, there is little change in the Hunt-1 or Willow Springs Stock wells, indicating that not much change occurs in the composition of the water. However, in all three sites in Willow Springs, the specific conductivity values decrease steadily after the irrigation season. This could be an indication of irrigation recharge or seepage.

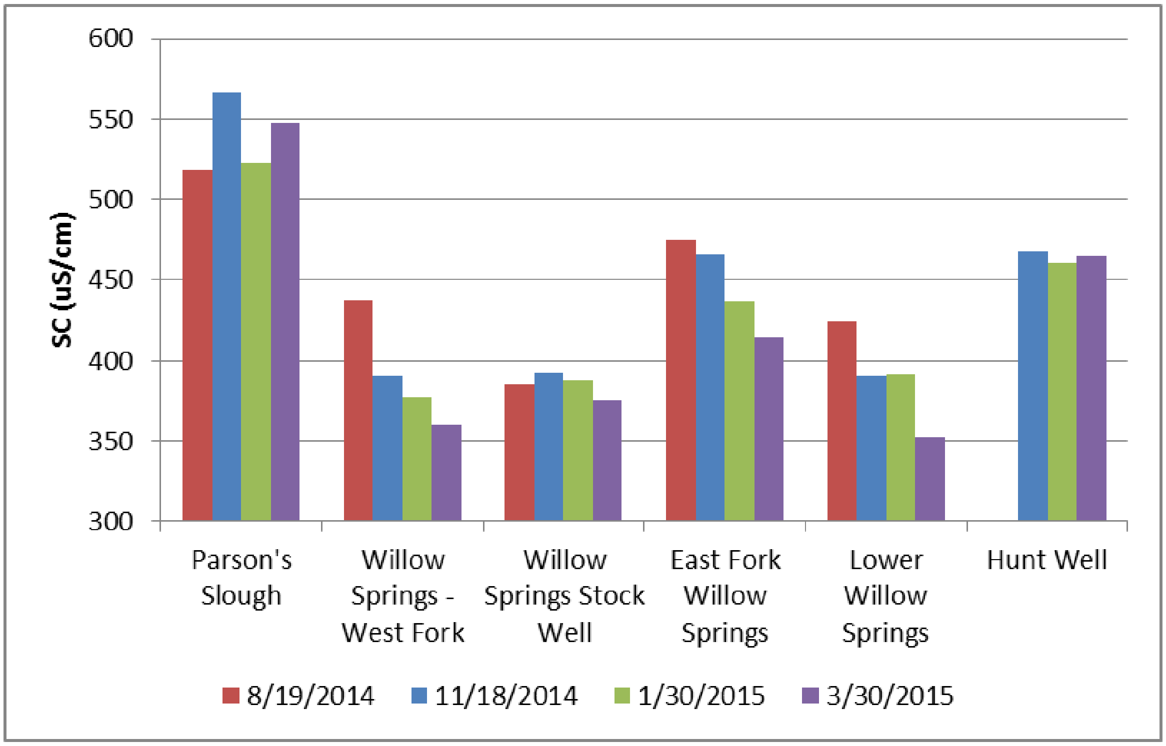


**Figure 13. Seasonal Specific Conductivity Measurements of Sites within the Waterloo Area**

# 6. Conclusion

There are many factors that could alter the water table and cause significant changes to groundwater flow in the Waterloo area. The biggest factors affecting the groundwater budget in the Waterloo study area are irrigation ditch seepage, irrigation recharge, and groundwater discharge to the Jefferson River. As such, lining the irrigation ditches could cause significant impact as seepage would be greatly reduced. In addition, major changes to the type of irrigation could also have a significant impact.

There is no evidence of a decline in water levels within the past 9 years to the aquifer. With continual change both in irrigation practices and climate changes are possible, however, more detailed groundwater modeling will be needed to predict the magnitude of the effects. From the groundwater budget, it is evident that seepage and irrigation recharge have the biggest impact on the inflows to the aquifer, and therefore these factors have the potential to make a large impact on the groundwater system. Continued water conservation efforts and monitoring are recommended for the welfare of the Jefferson River.

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# Appendix A: Groundwater Budget Data, Graphs & Charts

## MOUNTAIN FRONT RECHARGE:

**Table A-1. Highland Mountain Vegetation Distribution and ET**

| Vegetation Group | Area (Acres) | Evapotranspiration Rate (ft/yr) | ET (Acre-ft/yr) |
|---|---|---|---|
| Upland Sagebrush | 5350 | 1.1 | 5885 |
| Douglas Fir | 8477 | 1.4 | 11868 |
| Shrub/Grass Lowlands | 9765 | 1.0 | 9765 |
| Mixed Evergreen | 8290 | 1.8 | 14923 |
| High Xeric Grasses | 2472 | 1.2 | 2967 |
| Ag lands | 309 | 2.1 | 650 |
| Mesic Meadow | 1216 | 1.7 | 2067 |
| Whitebark Pine | 2838 | 2.2 | 6244 |
| Alpine Rangeland, Deciduous Shrubs | 864 | 2.0 | 1728 |
| Developed | 186 | 1.0 | 186 |
| Riparian | 170 | 2.3 | 392 |
| TOTAL | **39939** | | **56674** |

**Table A-2. Tobacco Root Mountain Vegetation Distribution and ET**

| Vegetation Group | Area (Acres) | Evapotranspiration Rate (ft/yr) | ET (Acre-ft/yr) |
|---|---|---|---|
| Upland Sagebrush | 4593 | 1.1 | 5053 |
| Douglas Fir | 12941 | 1.4 | 18118 |
| Shrub/Grass Lowlands | 2046 | 1.0 | 2046 |
| Mixed Evergreen | 3215 | 1.8 | 5787 |
| High Xeric Grasses | 343 | 1.2 | 412 |
| Ag lands | 1995 | 2.1 | 4190 |
| Mesic Meadow | 757 | 1.7 | 1287 |
| Whitebark Pine | 1492 | 2.2 | 3283 |
| Alpine Rangeland, Deciduous Shrubs | 181 | 2.0 | 361 |
| Developed | 206 | 1.0 | 206 |
| Riparian | 422 | 2.3 | 971 |
| TOTAL | **28193** | | **41715** |

**Table A-3. Precipitation in the Highland and Tobacco Root Mountains**

| Precipitation | Highland Mountains | Tobacco Root Mountains |
|---|---|---|
| Minimum (in/yr) | 9.95 | 10.02 |
| Maximum (in/yr) | 32.27 | 42.20 |
| Average (in/yr) | 18.36 | 19.02 |
| Area (acres) | 39,939 | 28,193 |
| Total Precipitation (acre-ft/yr) | 61,106 | 44,686 |

**SEEPAGE:**


**Figure A-1. Parrot Ditch Seepage Hydrograph**

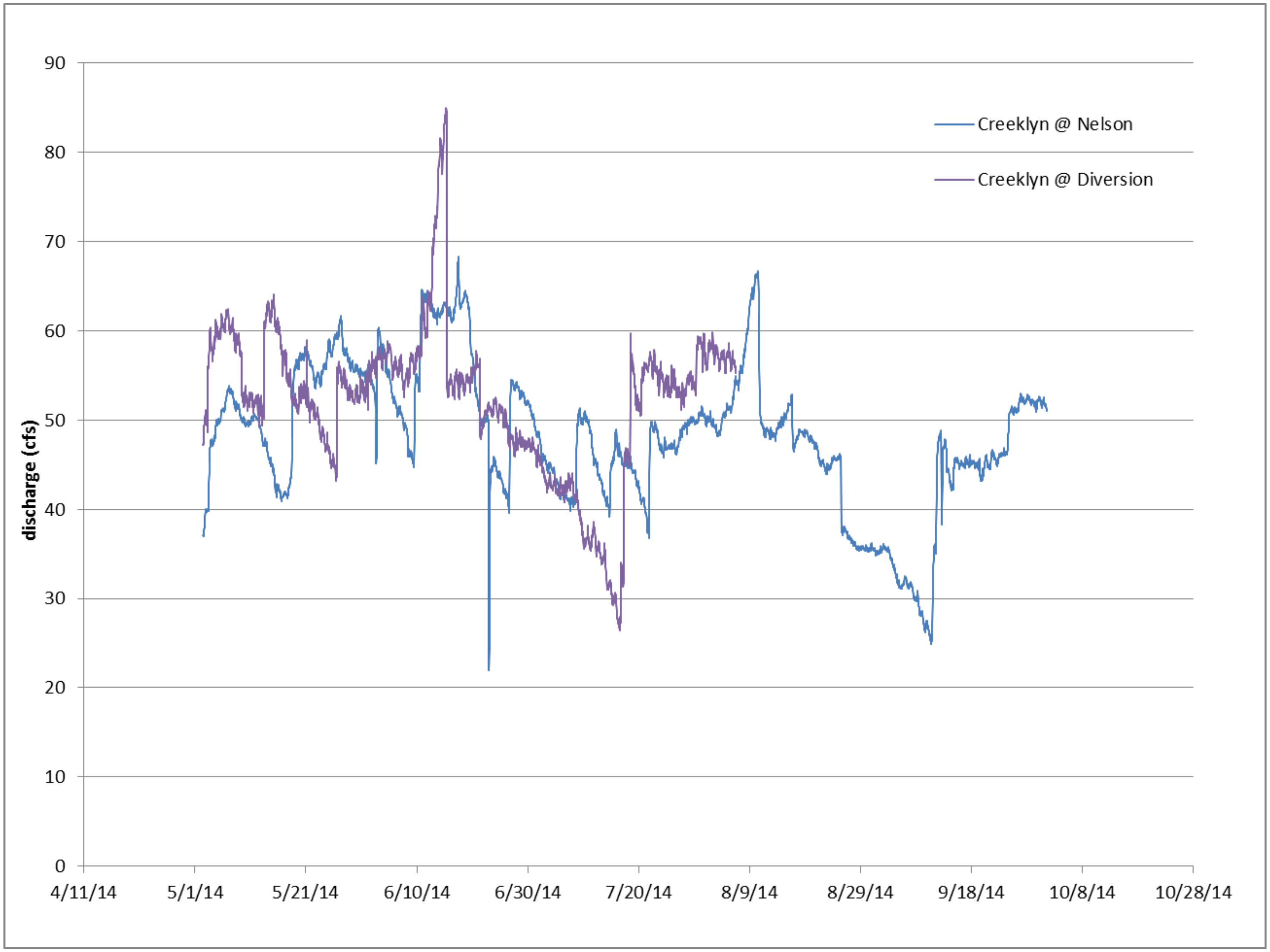



**Figure A-2. Creeklyn Ditch Seepage Hydrograph**

**IRRIGATION RECHARGE:**

**Table A-4.1. IWR Outputs for Pasture Grass**

| Irrigation Method | Flood | | | Sprinkler | | | Pivot | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Mid-range | Max | Min | Mid-range | Max | Min | Mid-range | Max |
| Application Efficiency | 35% | 25% | 15% | 75% | 65% | 60% | 85% | 80% | 70% |
| | inches | inches | inches | inches | inches | inches | inches | inches | inches |
| January | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| February | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| March | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 2.48 | 3.60 | 6.21 | 0.00 | 0.03 | 0.15 | -0.33 | -0.26 | -0.08 |
| June | 8.98 | 13.11 | 22.74 | 1.20 | 1.94 | 2.41 | 0.64 | 0.90 | 1.55 |
| July | 12.25 | 18.02 | 31.49 | 1.68 | 2.72 | 3.37 | 0.89 | 1.26 | 2.16 |
| August | 10.38 | 15.28 | 26.69 | 1.43 | 2.30 | 2.85 | 0.76 | 1.07 | 1.83 |
| September | 4.24 | 6.27 | 11.02 | 0.15 | 0.52 | 0.75 | -0.13 | 0.00 | 0.32 |
| October | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| November | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Annual** | 38.33 | 56.28 | 98.14 | 4.47 | 7.51 | 9.53 | 1.83 | 2.99 | 5.79 |

**Table A-4.2. IWR Outputs for Alfalfa Hay**

| Irrigation Method | Flood | | | Sprinkler | | | Pivot | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Mid-range | Max | Min | Mid-range | Max | Min | Mid-range | Max |
| Application Efficiency | 35% | 25% | 15% | 75% | 65% | 60% | 85% | 80% | 70% |
| | inches | inches | inches | inches | inches | inches | inches | inches | inches |
| January | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| February | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| March | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 3.56 | 5.21 | 9.05 | -0.03 | 0.27 | 0.45 | -0.26 | -0.15 | 0.11 |
| June | 11.22 | 16.45 | 28.63 | 4.26 | 5.20 | 5.78 | 0.76 | 1.09 | 1.91 |
| July | 14.86 | 21.92 | 38.37 | 5.46 | 6.73 | 7.52 | 1.04 | 1.49 | 2.59 |
| August | 12.28 | 18.10 | 31.67 | 4.52 | 5.57 | 6.22 | 0.87 | 1.24 | 2.15 |
| September | 5.13 | 7.60 | 13.36 | 1.84 | 2.28 | 2.56 | -0.07 | 0.09 | 0.48 |
| October | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| November | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Annual** | 47.05 | 69.26 | 121.07 | 16.05 | 20.03 | 22.52 | 2.34 | 3.77 | 7.24 |

**Table A-4.3. IWR Outputs for Natural Grass (50/50 Alfalfa and Grass)**

| Irrigation Method | Flood | | | Sprinkler | | | Pivot | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Mid-range | Max | Min | Mid-range | Max | Min | Mid-range | Max |
| Application Efficiency | 35% | 25% | 15% | 75% | 65% | 60% | 85% | 80% | 70% |
| | inches | inches | inches | inches | inches | inches | inches | inches | inches |
| January | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| February | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| March | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 3.02 | 4.40 | 7.63 | -0.10 | 0.15 | 0.30 | -0.29 | -0.20 | 0.01 |
| June | 10.10 | 14.78 | 25.68 | 1.34 | 2.18 | 2.70 | 0.70 | 1.00 | 1.73 |
| July | 13.56 | 19.97 | 34.93 | 1.85 | 3.00 | 3.72 | 0.96 | 1.38 | 2.38 |
| August | 11.33 | 16.69 | 29.18 | 1.55 | 2.51 | 3.11 | 0.81 | 1.16 | 1.99 |
| September | 4.68 | 6.93 | 12.19 | 0.21 | 0.62 | 0.87 | -0.10 | 0.05 | 0.40 |
| October | 0 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| November | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Annual** | 42.69 | 62.77 | 109.61 | 4.84 | 8.44 | 10.70 | 2.08 | 3.38 | 6.51 |

**Table A-4.4. IWR Outputs for Other (Including barley, corn, & oats)**

| Irrigation Method | Flood | | | Sprinkler | | | Pivot | | |
|---|---|---|---|---|---|---|---|---|---|
| | Min | Mid-range | Max | Min | Mid-range | Max | Min | Mid-range | Max |
| Application Efficiency | 35% | 25% | 15% | 75% | 65% | 60% | 85% | 80% | 70% |
| | inches | inches | inches | inches | inches | inches | inches | inches | inches |
| January | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| February | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| March | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| April | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| May | 0.21 | 0.21 | 0.21 | -0.42 | -0.42 | -0.42 | -0.42 | -0.42 | -0.42 |
| June | 8.37 | 12.20 | 21.14 | 1.09 | 1.78 | 2.21 | 0.57 | 0.82 | 1.41 |
| July | 16.04 | 23.67 | 41.46 | 2.15 | 3.52 | 4.38 | 1.11 | 1.60 | 2.79 |
| August | 11.72 | 17.26 | 30.19 | 1.59 | 2.59 | 3.21 | 0.83 | 1.19 | 2.06 |
| September | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 | 0.52 |
| October | 0.00 | 0 | 0 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| November | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| December | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Annual** | 36.85 | 53.86 | 93.53 | 4.95 | 8.00 | 9.90 | 2.61 | 3.71 | 6.36 |

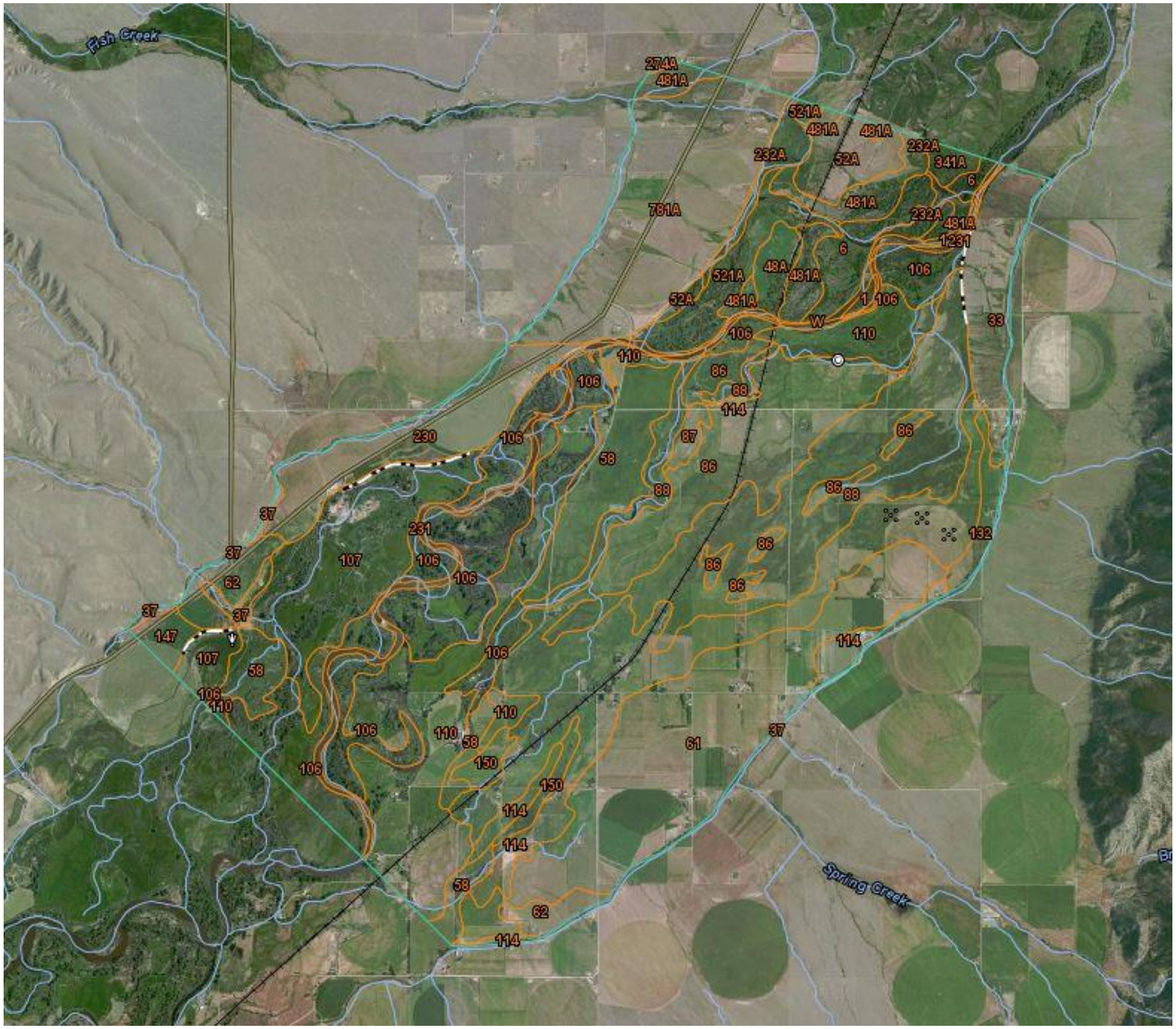
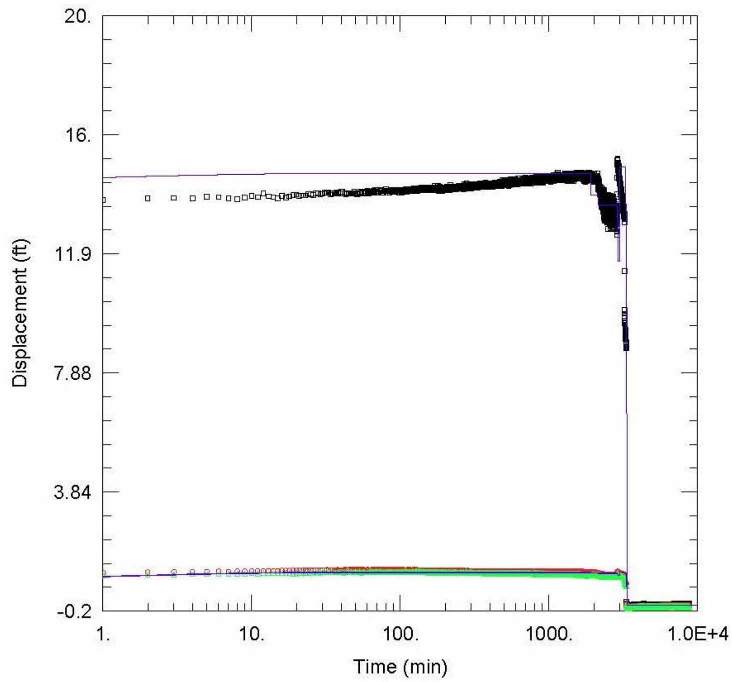



**Figure A-3. NRCS Web Soil Survey Soil Type Map (Soil types listed on pg 61)**

**Table A-5. NRCS Web Soil Survey Soil Types for Waterloo**

| Jefferson County Area and Part of Silver Bow County, Montana (MT627) | | | |
|---|---|---|---|
| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
| 1 | Riverwash | 11.6 | 0.10% |
| 6 | Wetsand, Cardwell, and Clunton soils, 0 to 8 percent slopes, channeled | 119.9 | 1.50% |
| 48A | Riverrun sandy loam, 0 to 2 percent slopes | 53.5 | 0.70% |
| 52A | Ryell loam, 0 to 2 percent slopes | 120.7 | 1.50% |
| 232A | Clunton-Wetsand-Bonebasin complex, 0 to 2 percent slopes | 90.7 | 1.20% |
| 274A | Bronec complex, 0 to 2 percent slopes | 6.2 | 0.10% |
| 341A | Pieriver-Cardwell-Riverrun loams, 0 to 2 percent slopes | 26.9 | 0.30% |
| 481A | Riverrun gravelly sandy loam, 0 to 2 percent slopes | 203 | 2.60% |
| 521A | Cardwell-Riverrun complex, 0 to 2 percent slopes | 153.4 | 1.90% |
| 781A | Vendome sandy loam, 0 to 8 percent slopes | 618.5 | 7.90% |
| W | Water | 36.2 | 0.50% |
| | Subtotals for Soil Survey Area | 1,440.4 | 18.30% |
| Madison County Area, Montana (MT636) | | | |
| Map Unit Symbol | Map Unit Name | Acres in AOI | Percent of AOI |
| 33 | Crago gravelly loam, cool, 0 to 8 percent slopes | 201.1 | 2.60% |
| 37 | Crago-Scravo complex, cool, 15 to 45 percent slopes | 39.3 | 0.50% |
| 58 | Havre loam, cool, 0 to 2 percent slopes | 381.6 | 4.80% |
| 61 | Kalsted sandy loam, 0 to 2 percent slopes | 837.1 | 10.60% |
| 62 | Kalsted sandy loam, 2 to 8 percent slopes | 126.8 | 1.60% |
| 86 | Neen silty clay loam, 0 to 2 percent slopes | 1,201.6 | 15.30% |
| 87 | Neen silty clay loam, drained, 0 to 2 percent slopes | 26.9 | 0.30% |
| 88 | Neen silty clay loam, wet, 0 to 2 percent slopes | 794.5 | 10.10% |
| 106 | Rivra, cool-Fluvaquents complex, 0 to 2 percent slopes | 857.2 | 10.90% |
| 107 | Rivra-Ryell-Havre complex, cool, 0 to 2 percent slopes | 480.1 | 6.10% |
| 110 | Ryell-Rivra complex, cool, 0 to 2 percent slopes | 744.3 | 9.40% |
| 114 | Scravo sandy loam, cool, 2 to 8 percent slopes | 161.8 | 2.10% |
| 132 | Thess loam, cool, 2 to 8 percent slopes | 51.7 | 0.70% |
| 143 | Trudau loam, 2 to 8 percent slopes | 1.5 | 0.00% |
| 147 | Varney clay loam, 2 to 8 percent slopes | 52.9 | 0.70% |
| 150 | Villy silty clay loam, cool, 0 to 2 percent slopes | 63.8 | 0.80% |
| 217 | Bronec-Amesha complex, 2 to 8 percent slopes | 0.5 | 0.00% |
| 230 | Vendome sandy loam, 0 to 8 percent slopes | 290.6 | 3.70% |
| 231 | Water | 123.9 | 1.60% |
| | Subtotals for Soil Survey Area | 6,437.1 | 81.70% |
| | Totals for Area of Interest | 7,877.5 | 100.00% |

## AQUIFER TEST RESULTS:




HUNTA AQUIFER TEST

Data Set: M:\...\HuntA_CR_all_Leaky.aqt
Date: 04/03/15 Time: 15:04:27

PROJECT INFORMATION

Company: MBMG
Client: HuntA
Project: BWIPUJ
Location: Upper Jefferson
Test Well: PW
Test Date: 2/24/15

AQUIFER DATA

Saturated Thickness: 100. ft
Anisotropy Ratio (Kz/Kr): 0.1
Aquitard Thickness (b'): 1. ft
Aquitard Thickness (b"): 1. ft

WELL DATA

Pumping Wells

| Well Name | X (ft) | Y (ft) |
|---|---|---|
| PW | 0 | 0 |

Observation Wells

| Well Name | X (ft) | Y (ft) |
|---|---|---|
| □ PW | 0 | 0 |
| ○ OW1 | -1.112 | 22.767 |
| △ OW2 | -21.792 | 2.695 |

SOLUTION

Aquifer Model: Leaky
Solution Method: Hantush-Jacob

$T = 1.1E{+}5\ ft^2/day$
$1/B = 8.55E{-}5\ ft^{-1}$
$C = 0.00012\ min^2/ft^5$

$S = 1.0E{-}5$
$Sw = 2.02$
$P = 2.78$

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min

$s(t) = 0.06485Q + 0.00012Q^{2.78}$
W.E. = 31.53% (Q from last step)

**Figure A-4. MBMG HA1 Aquifer Test Results for Leaky Hantush-Jacob Model (Bobst, personal communication, 2015)**

# Appendix B: Surface Water Hydrographs

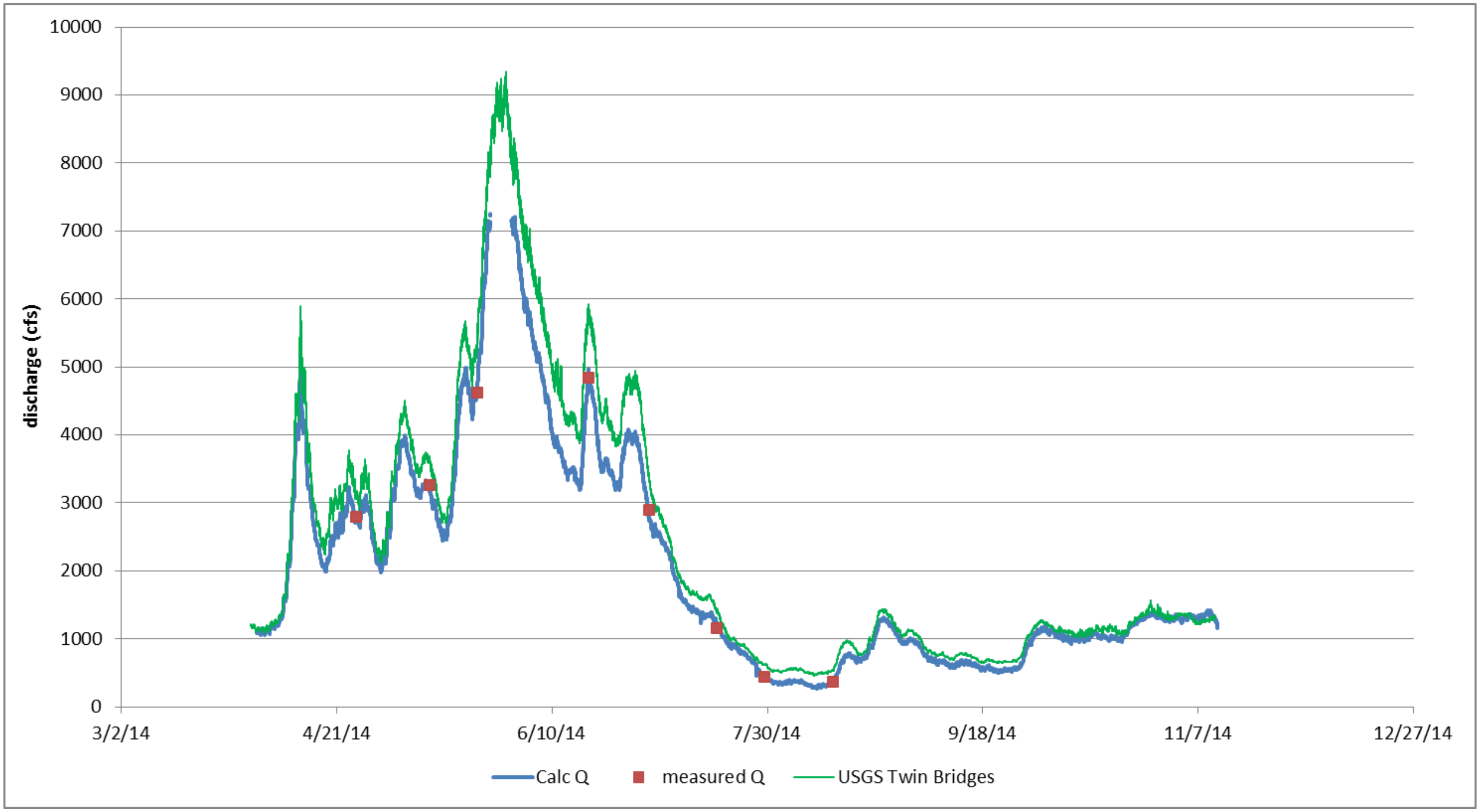



**Figure B-1. Surface Water Hydrograph of Calculated Flow and Manual Measurements at Jefferson River at Silver Star and USGS Twin Bridges Flow**

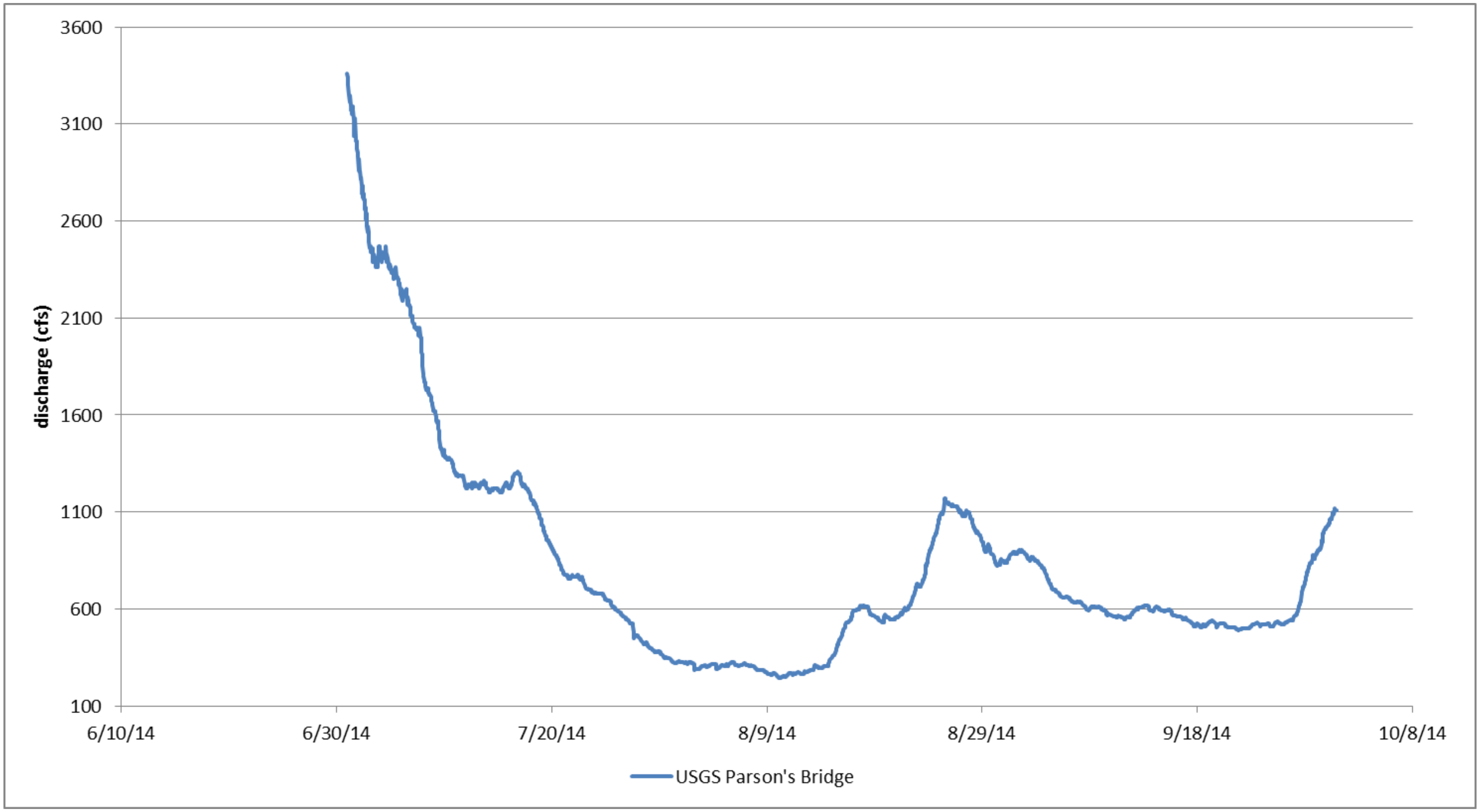



**Figure B-2. Surface Water Hydrograph of Jefferson River at USGS Parson’s Bridge**

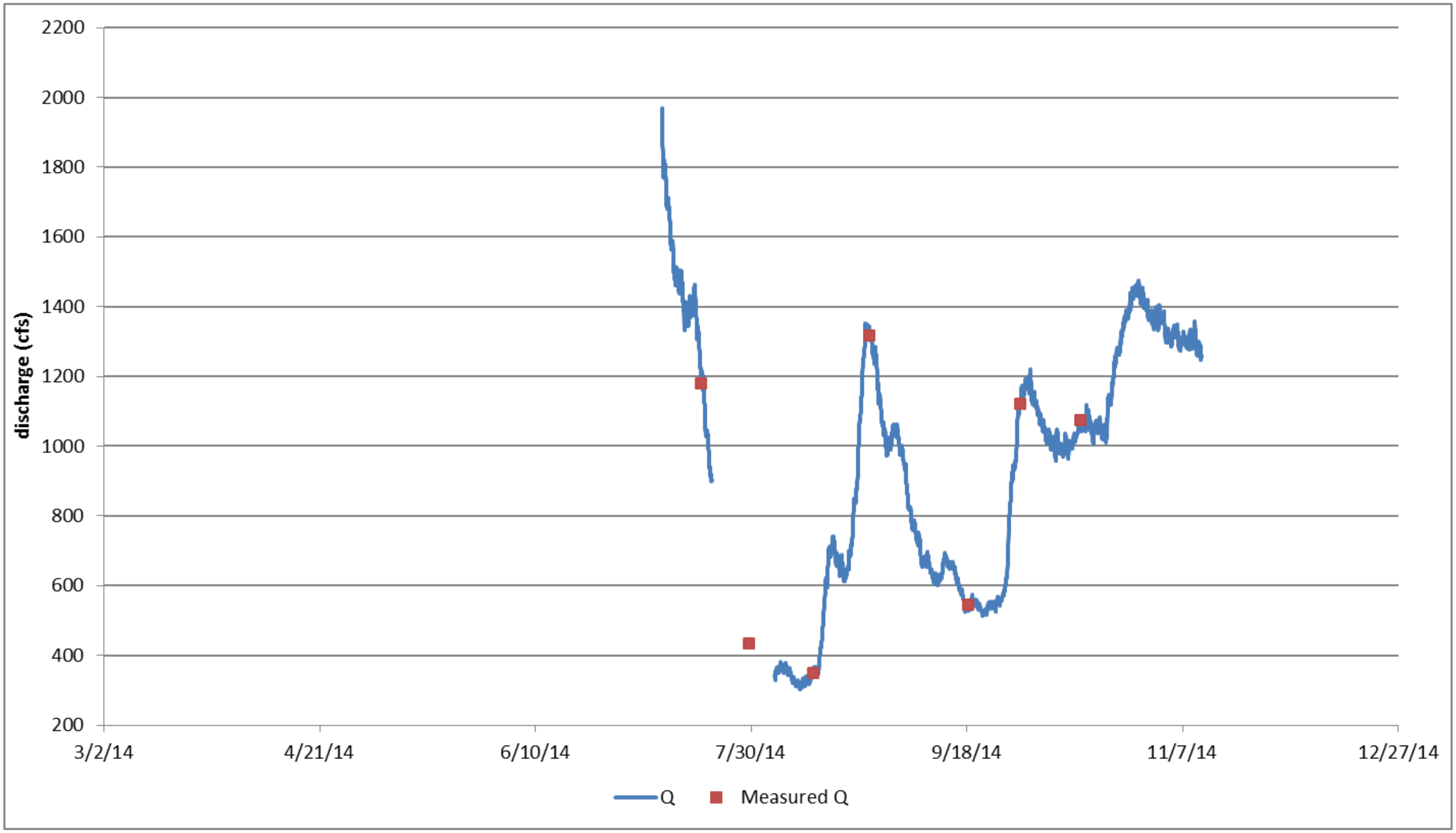



**Figure B-3. Surface Water Hydrograph of Jefferson River at Corbett's**

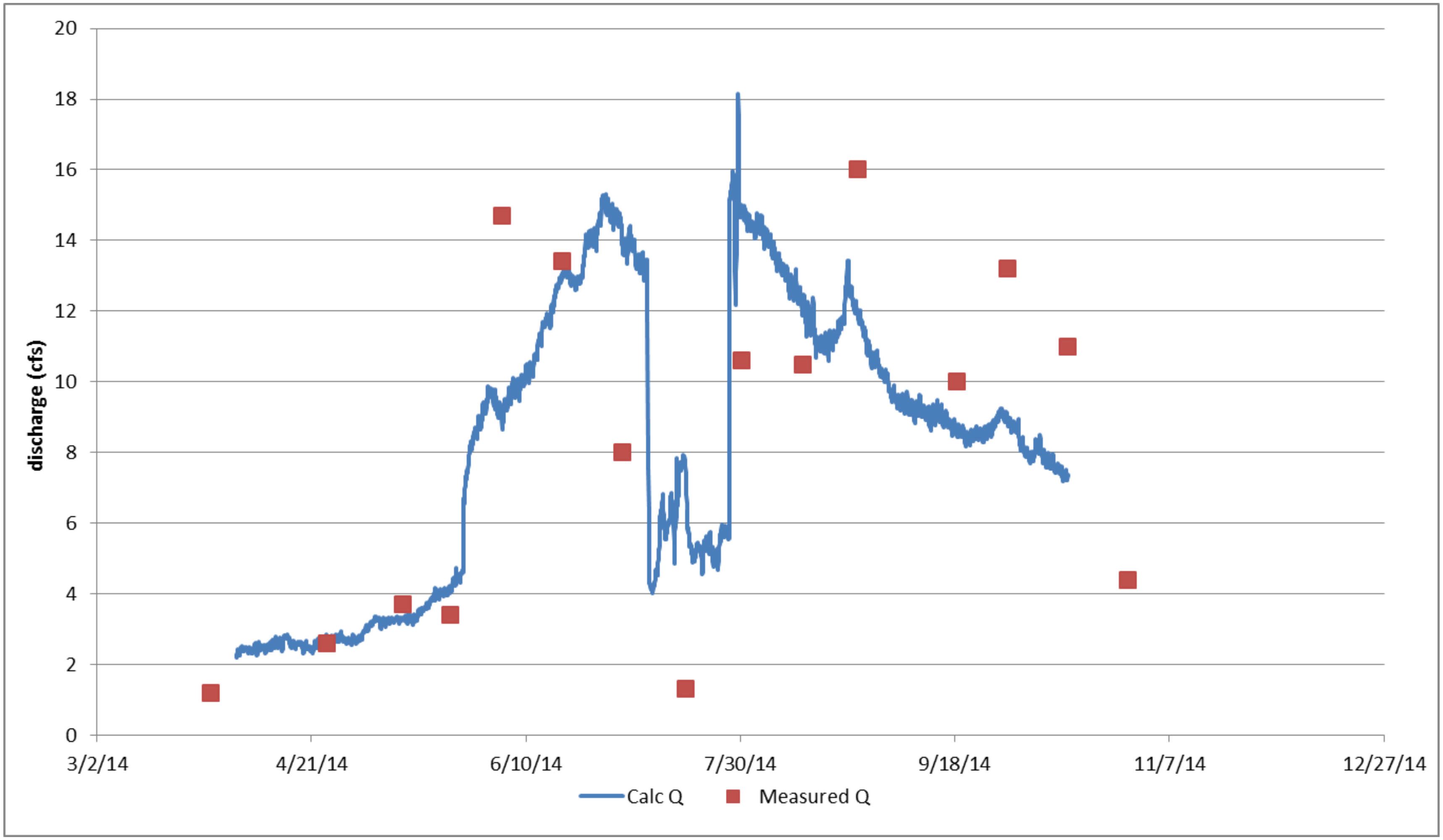



**Figure B-4. Surface Water Hydrograph of Parson's Slough at Loomont Road**

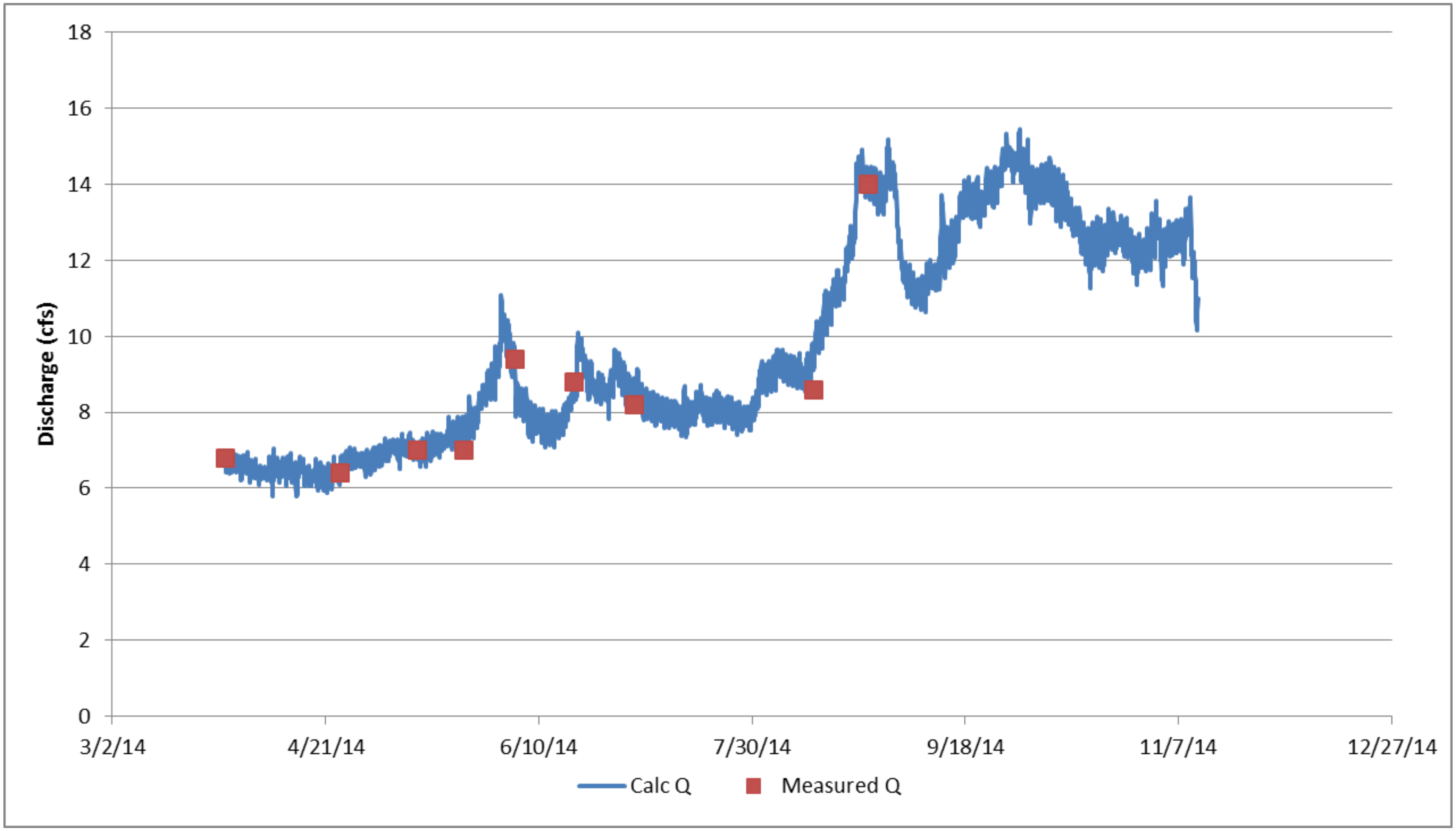



**Figure B-5. Surface Water Hydrograph of West Fork of Willow Springs**

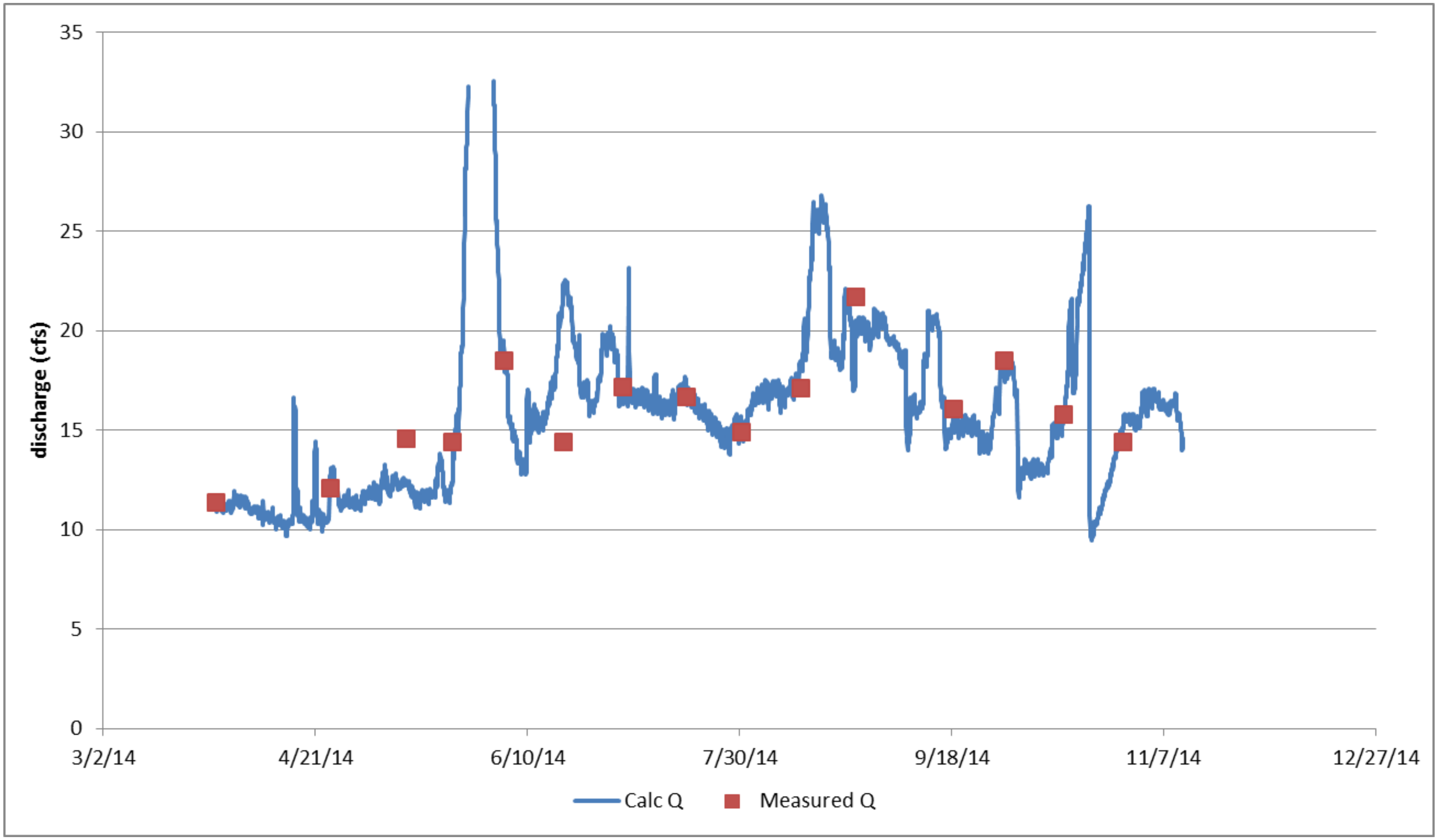



**Figure B-6. Surface Water Hydrograph of Lower Willow Springs**

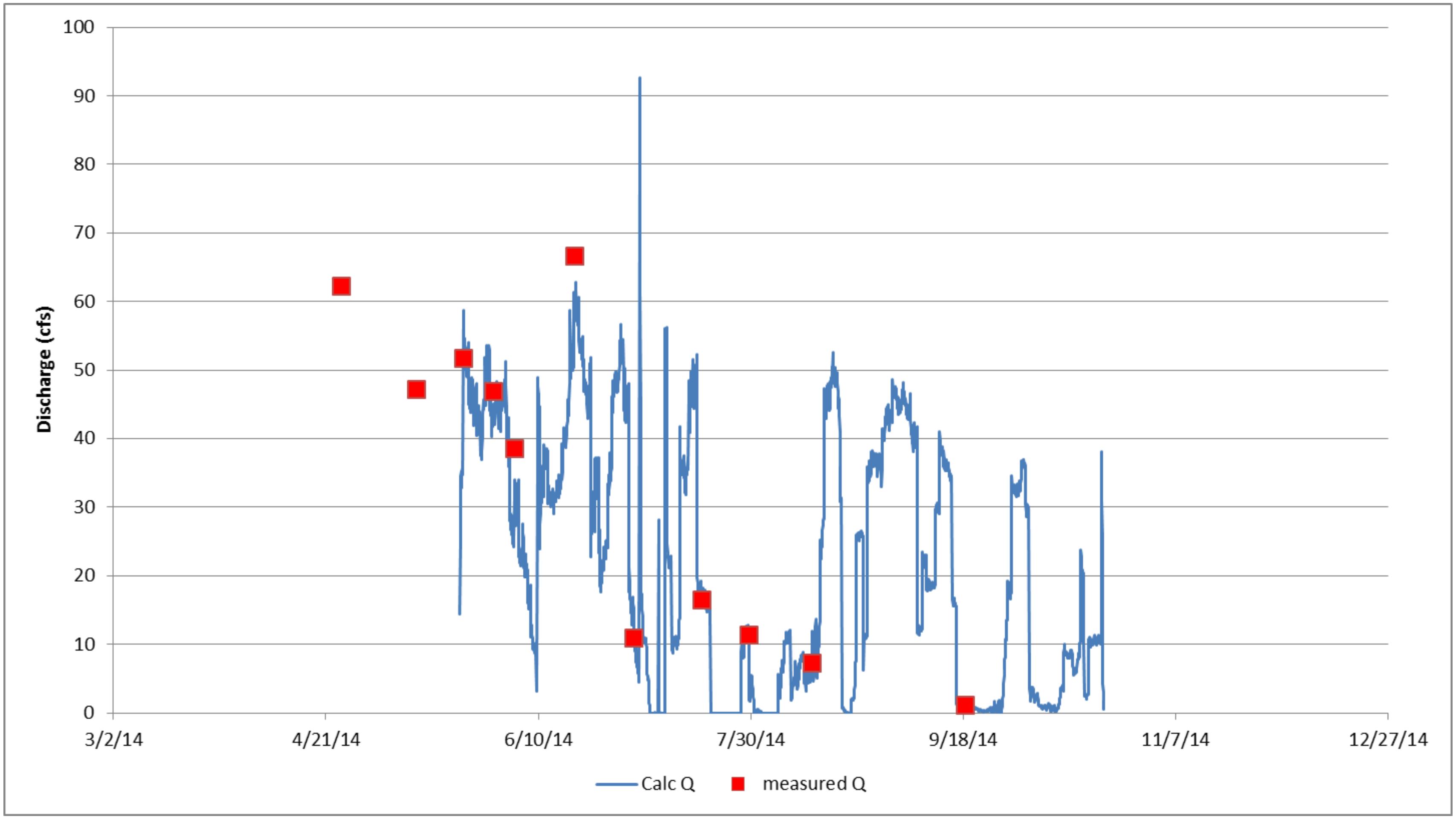



**Figure B-7. Surface Water Hydrograph of Kurnow Ditch (Parrot Ditch Blowoff)**

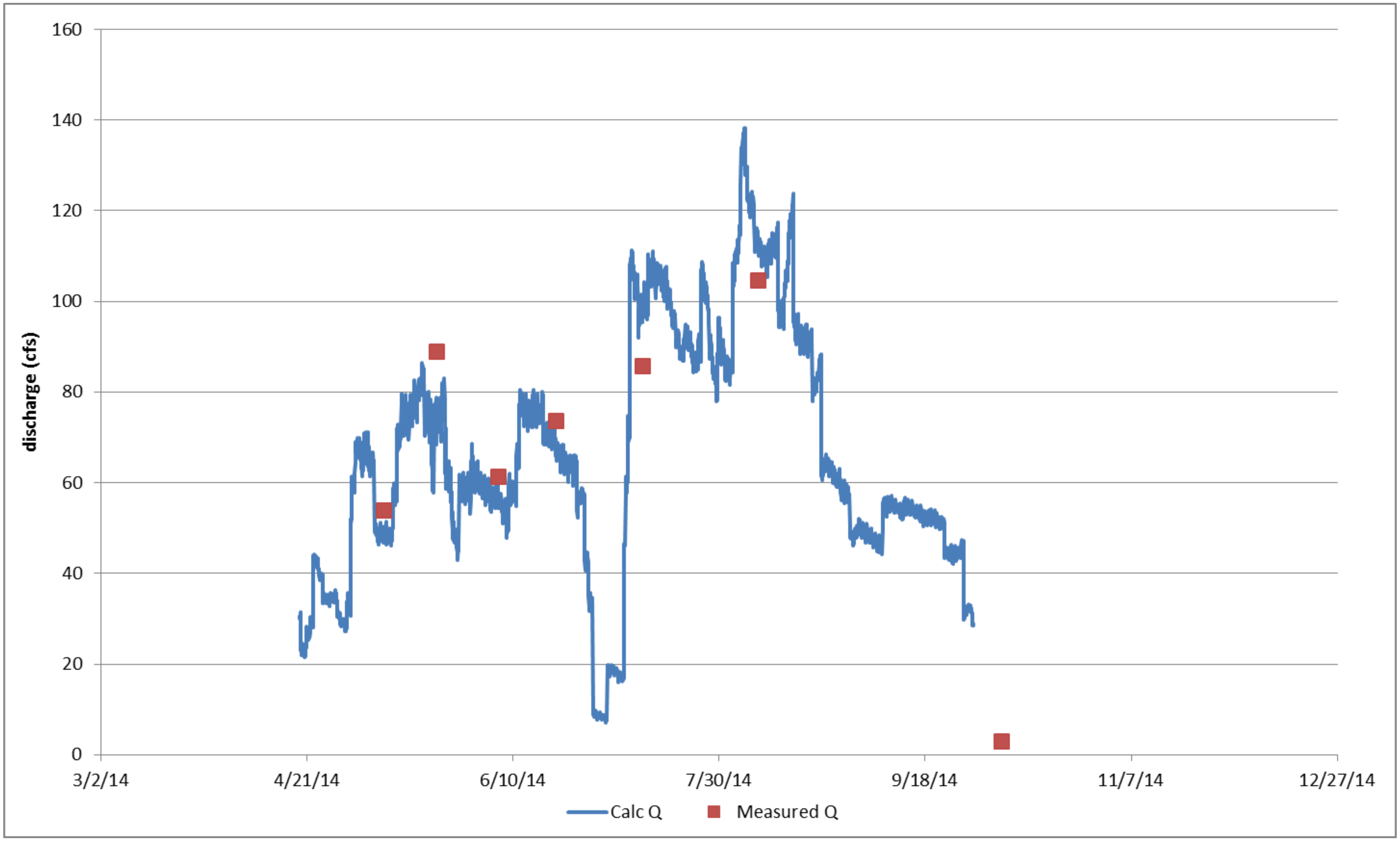



**Figure B-8. Surface Water Hydrograph of Jefferson Canal at Diversion**

## Appendix C: Static Water Elevations (MBMG – WET Comparison)


**Figure C-1. Static Water Elevations for Willow 1**

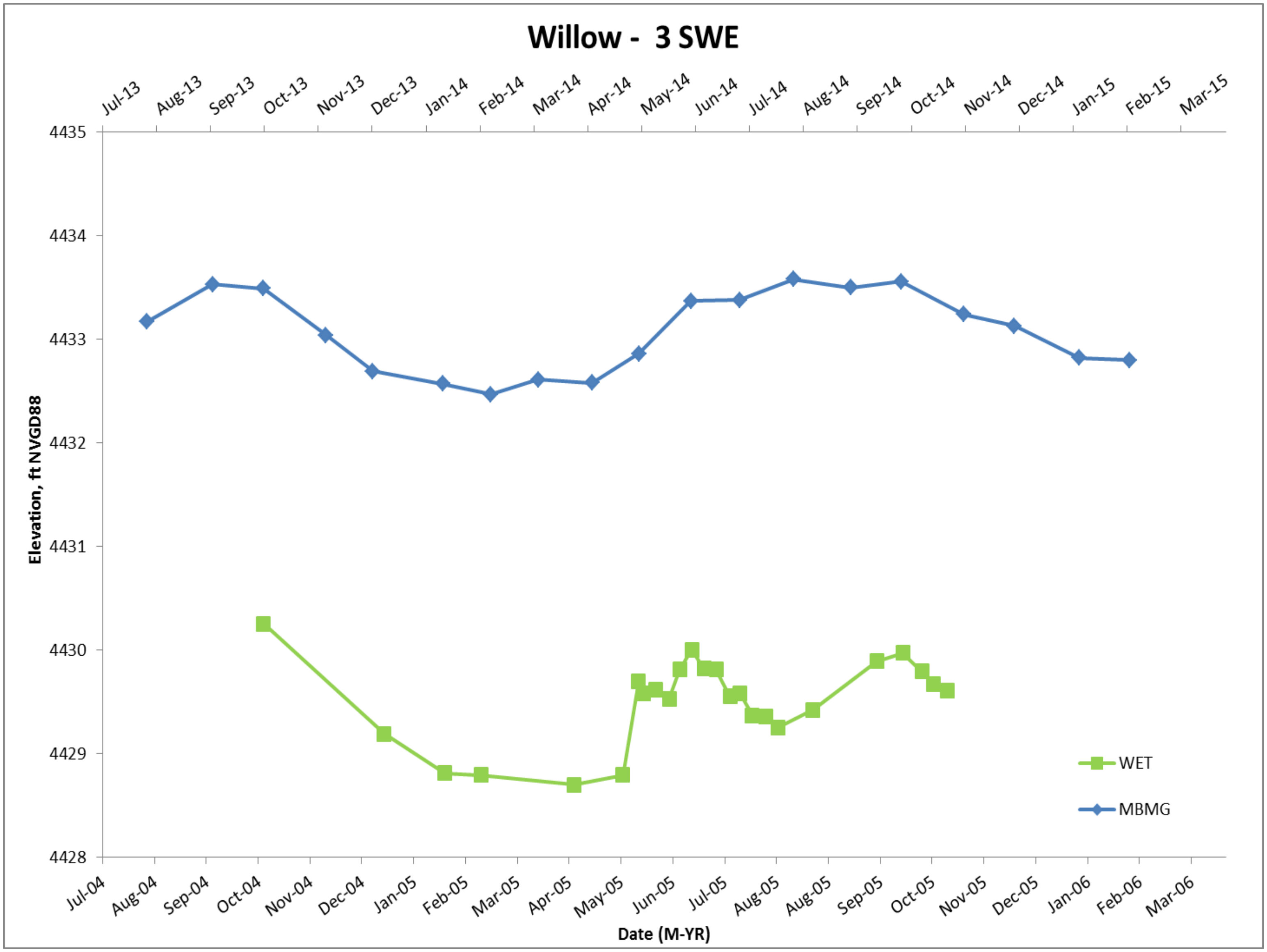



**Figure C-2. Static Water Elevations for Willow 3**

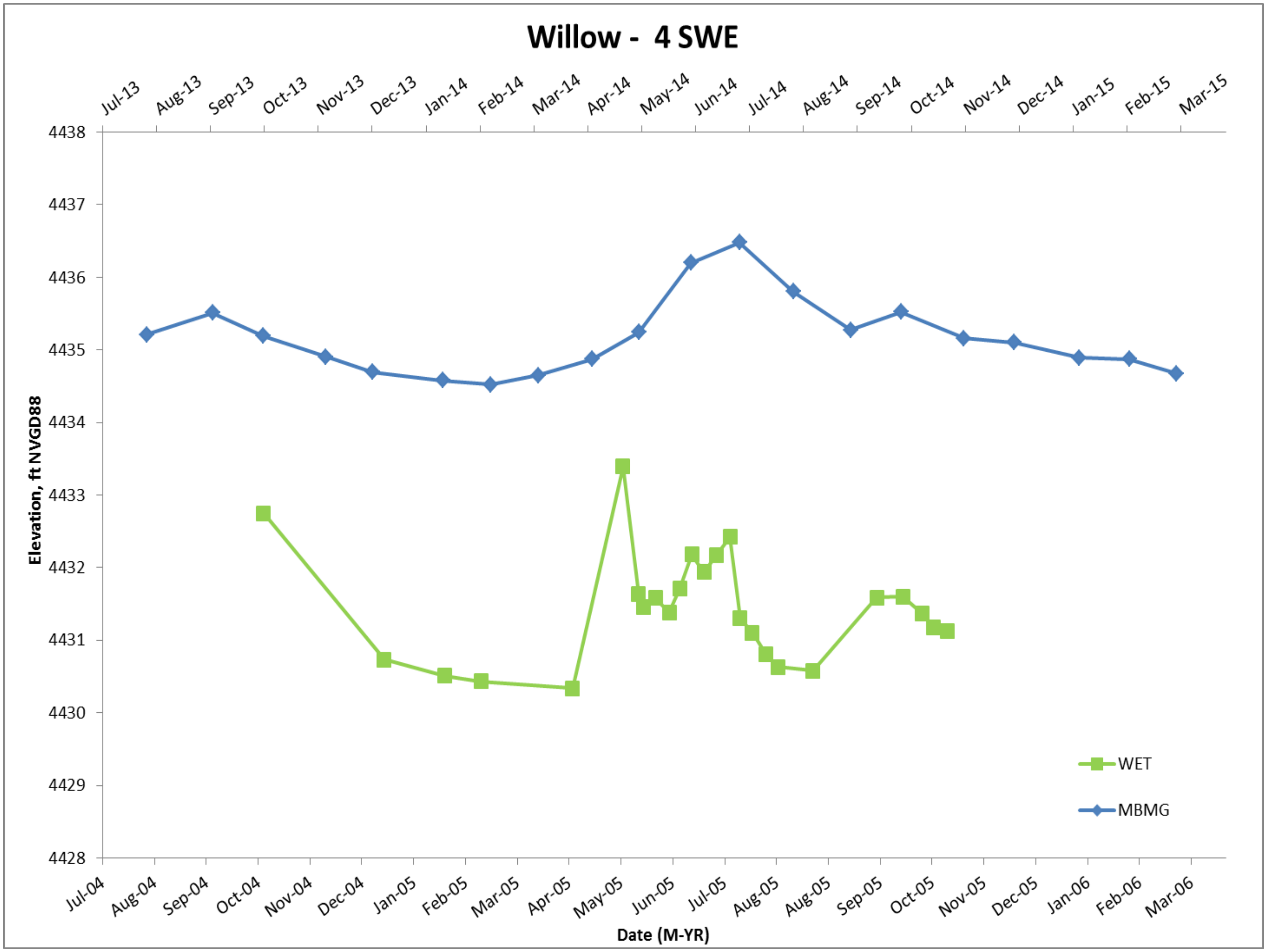



**Figure C-3. Static Water Elevations for Willow 4**

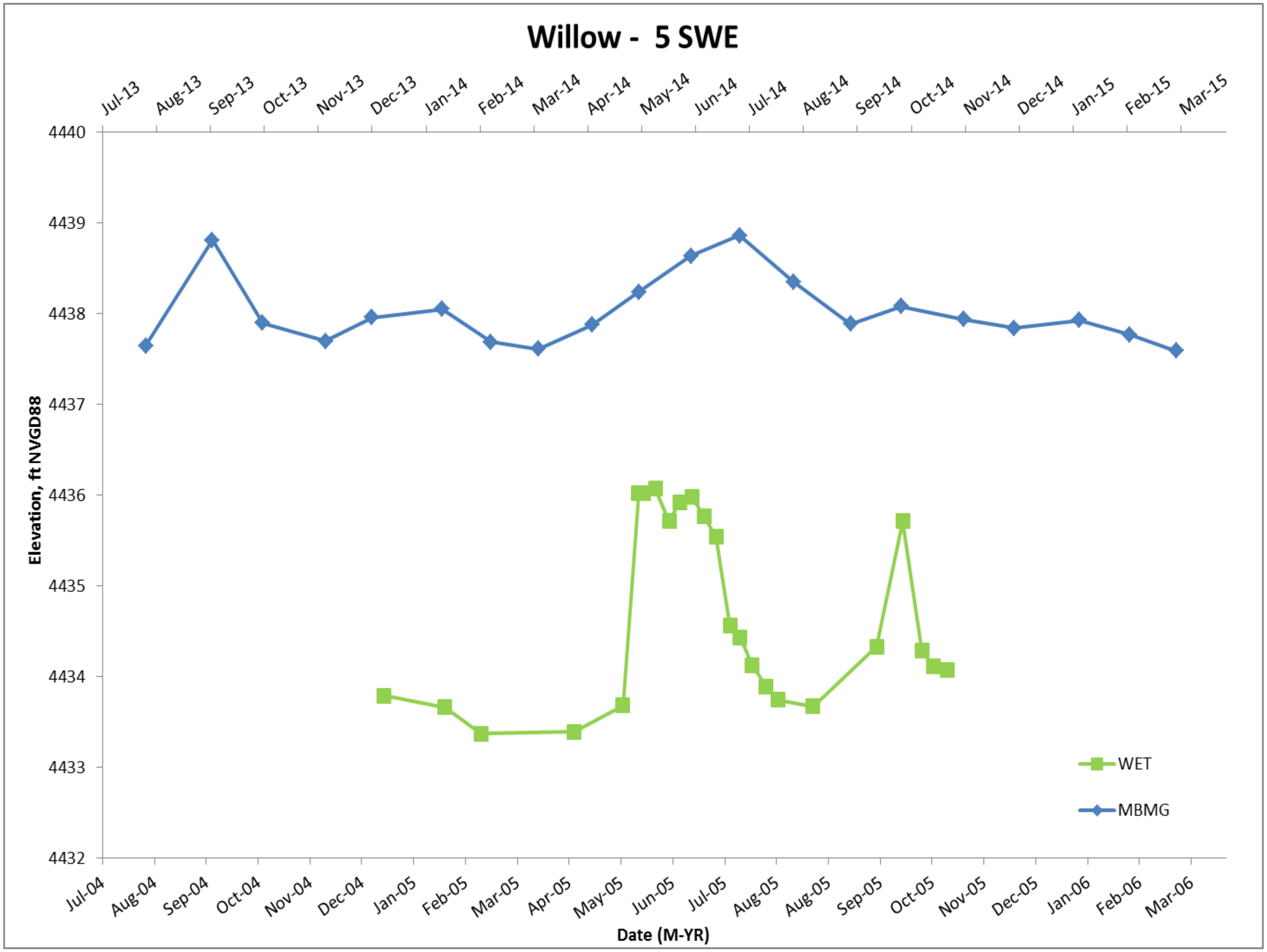



**Figure C-4. Static Water Elevations for Willow 5**

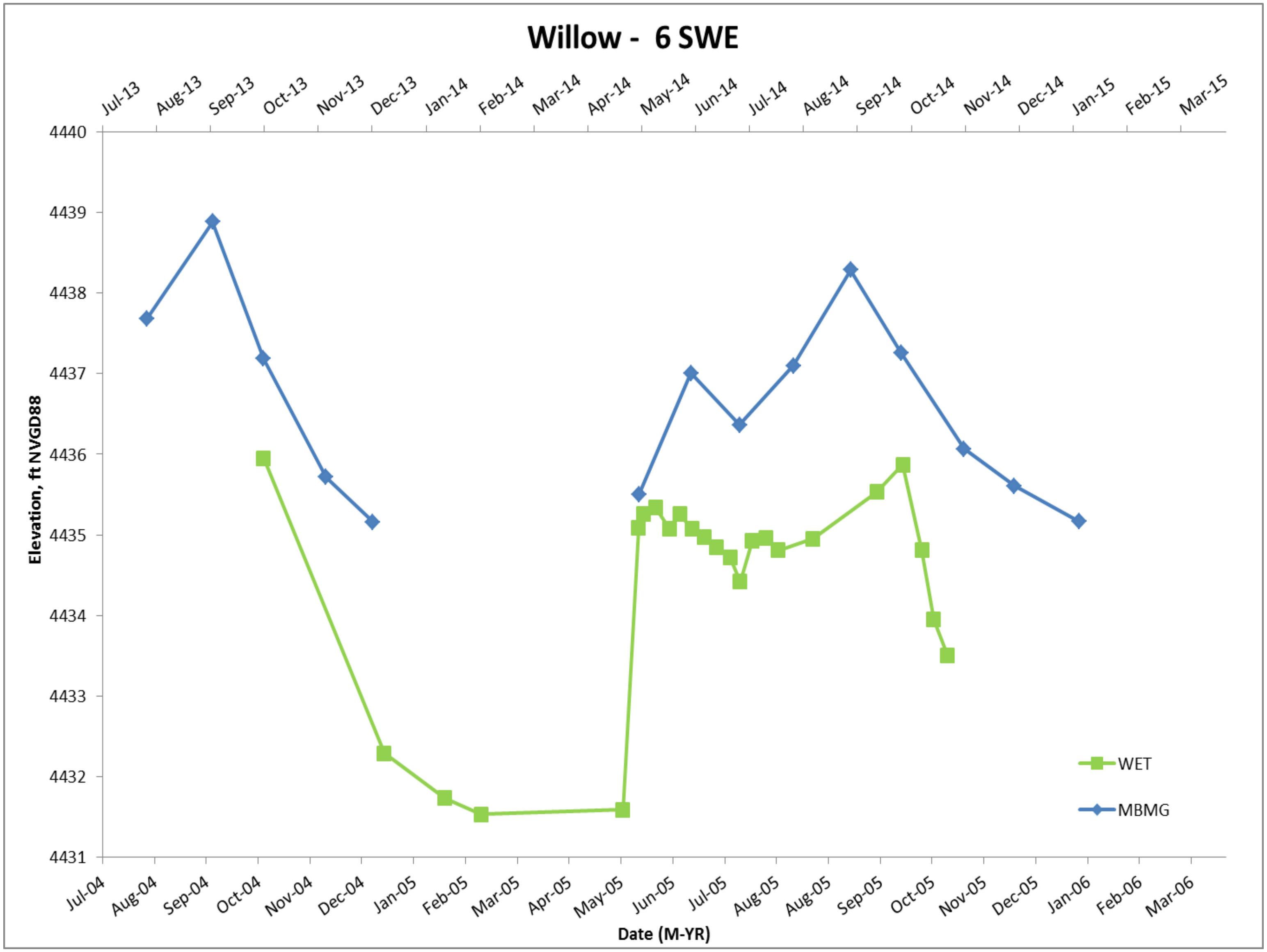



**Figure C-5. Static Water Elevations for Willow 6**


**Figure C-6. Static Water Elevations for Willow 7**

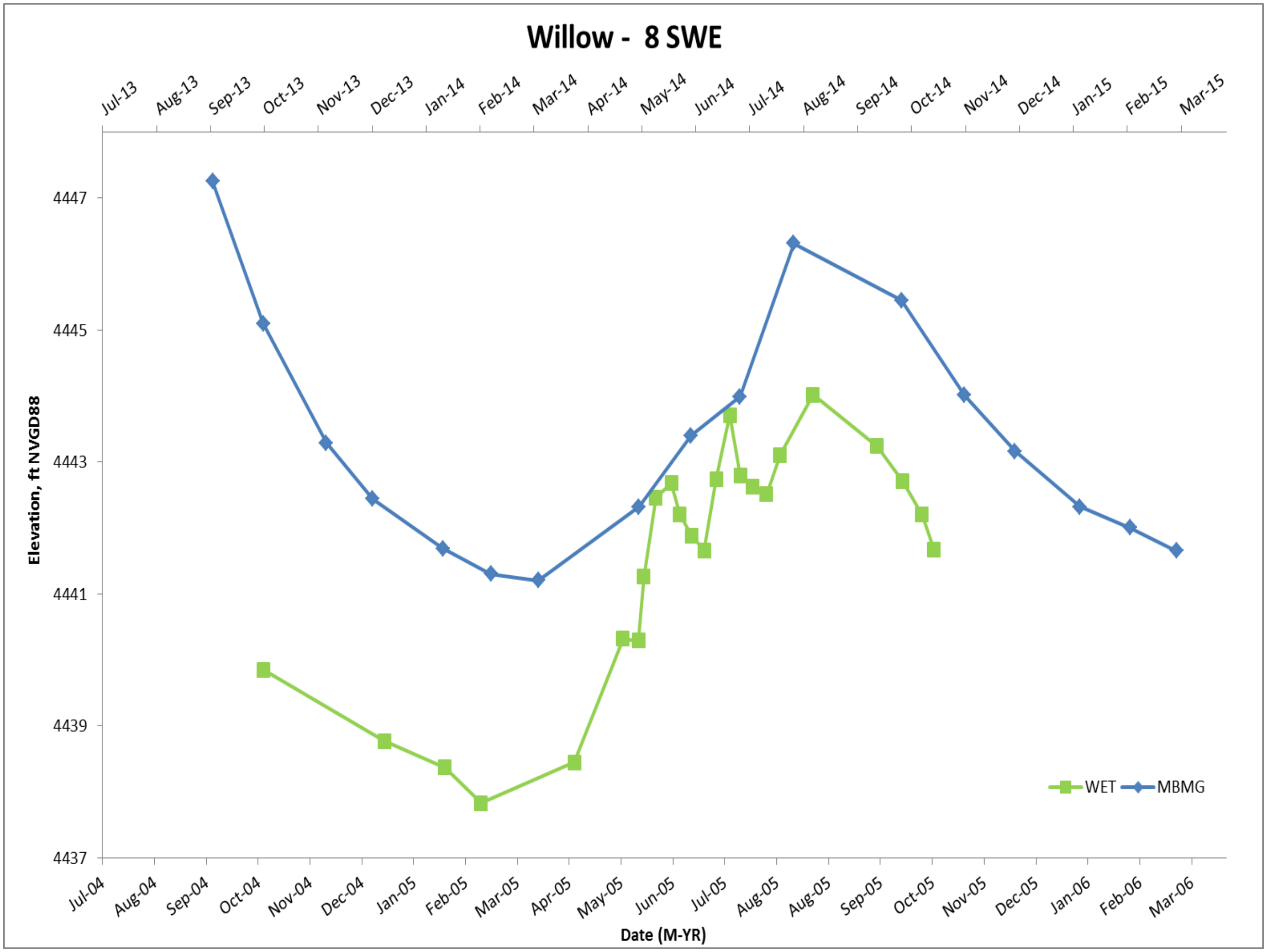



**Figure C-7. Static Water Elevations for Willow 8**

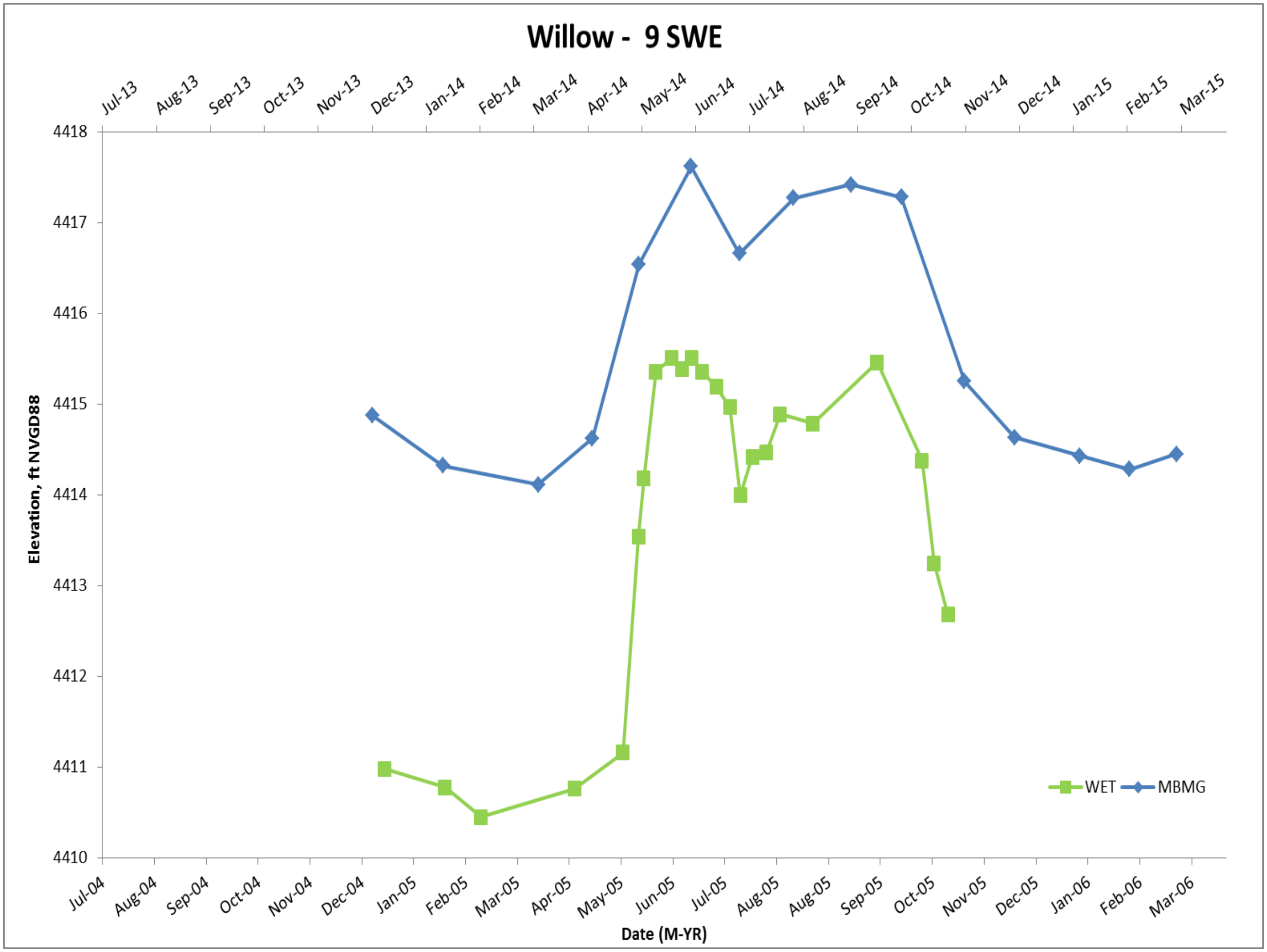



**Figure C-8. Static Water Elevations for Willow 9**

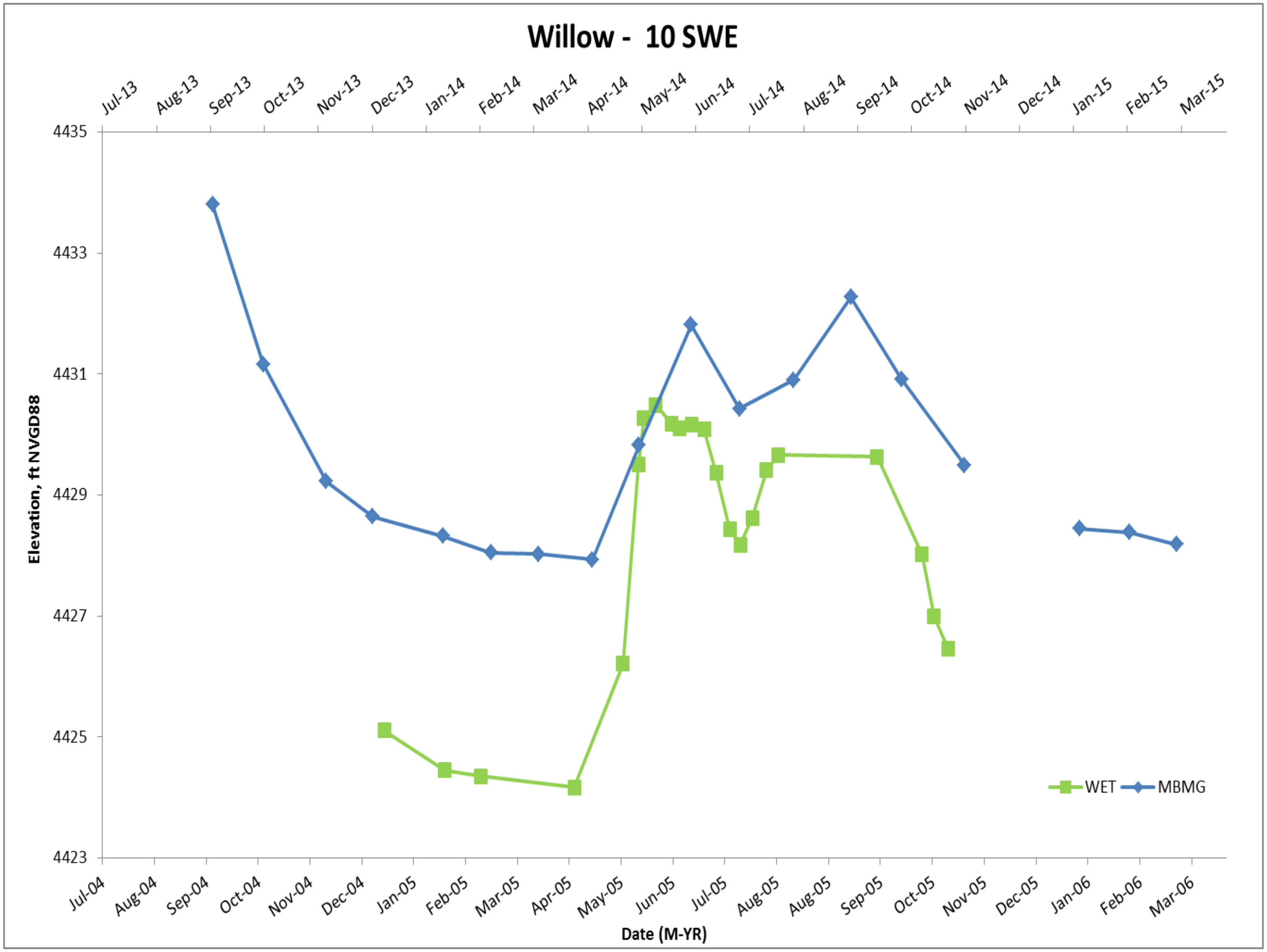



**Figure C-9. Static Water Elevations for Willow 10**

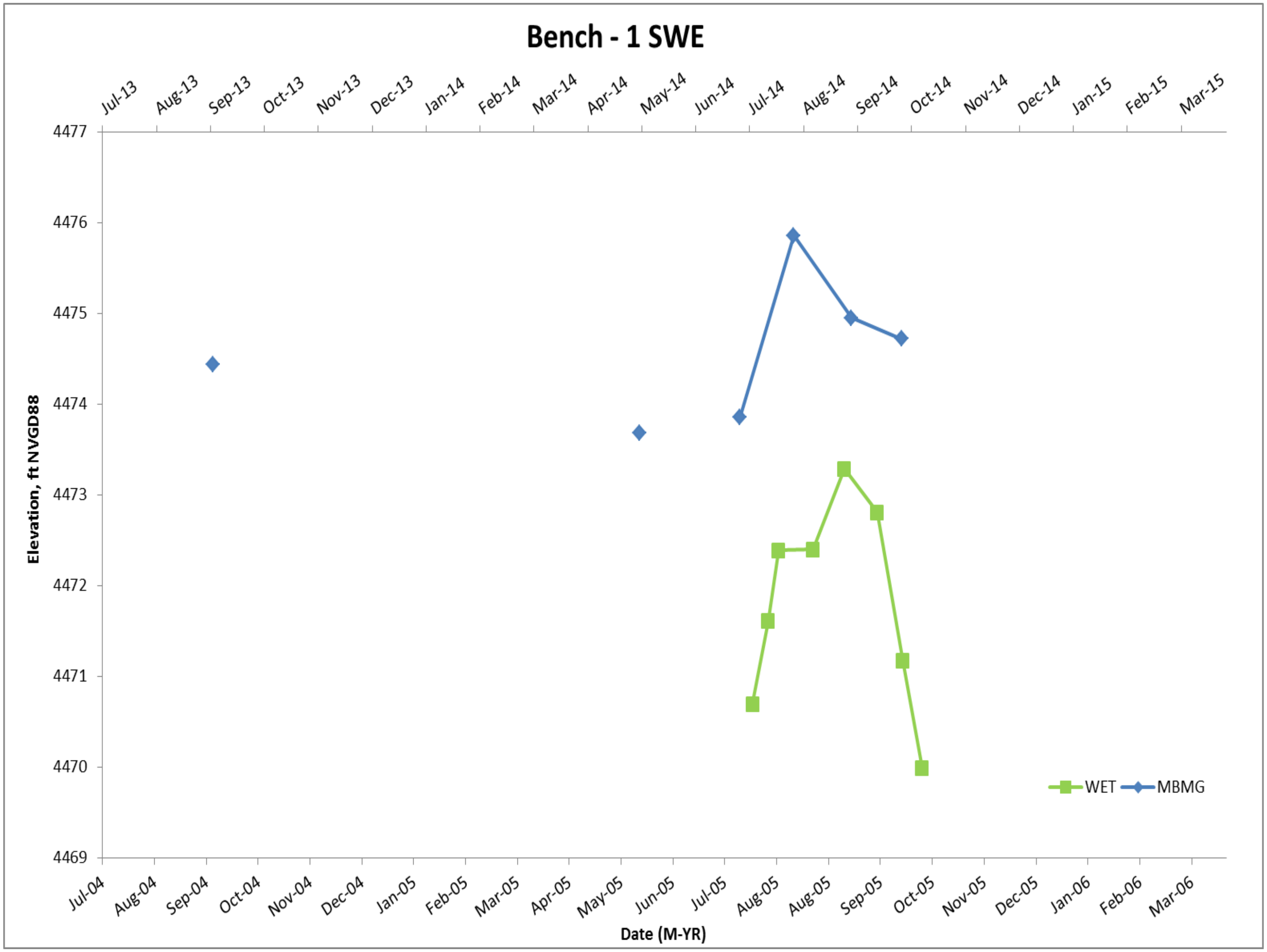



**Figure C-10. Static Water Elevations for Bench 1**

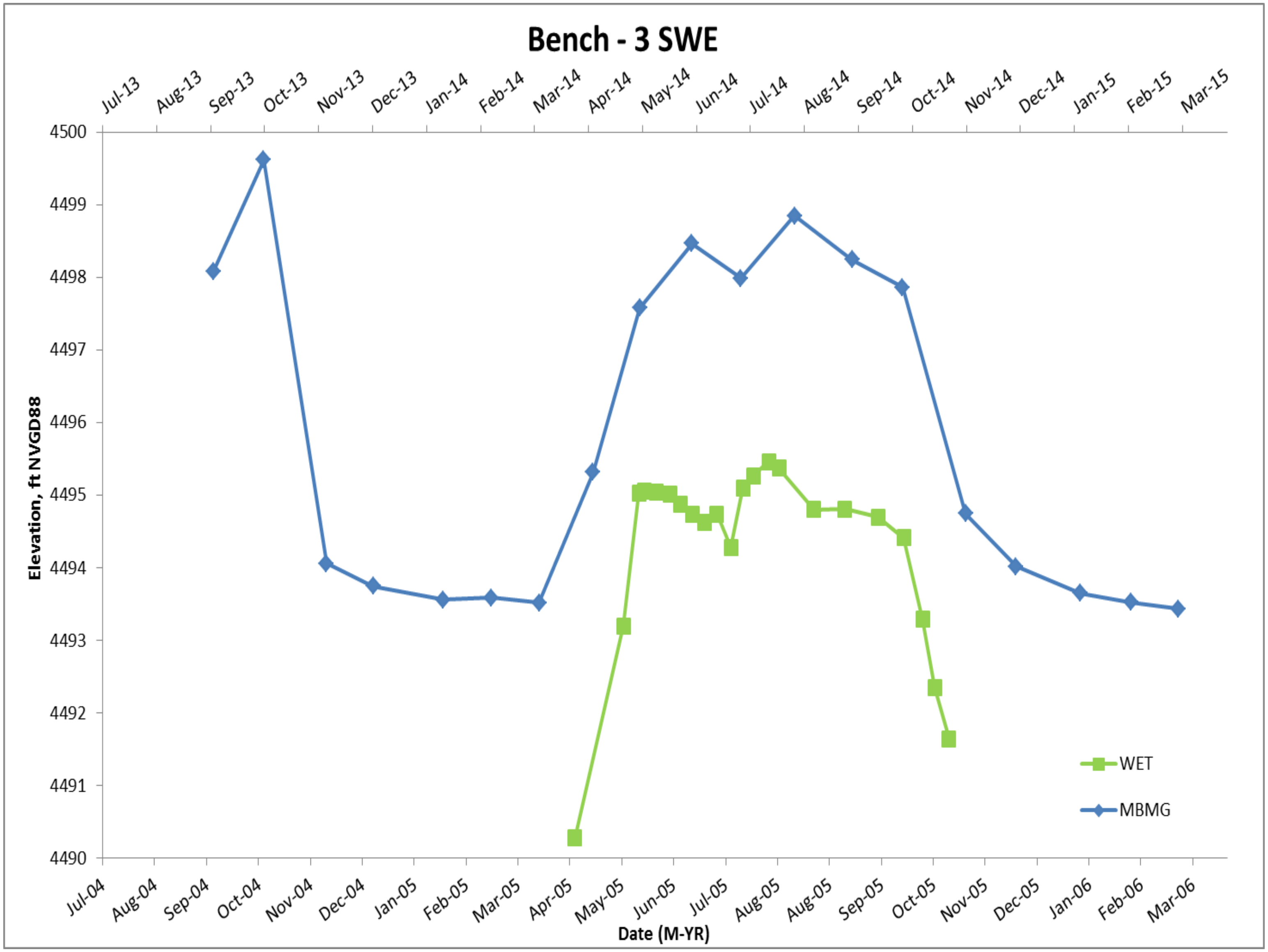



**Figure C-11. Static Water Elevations for Bench 3**

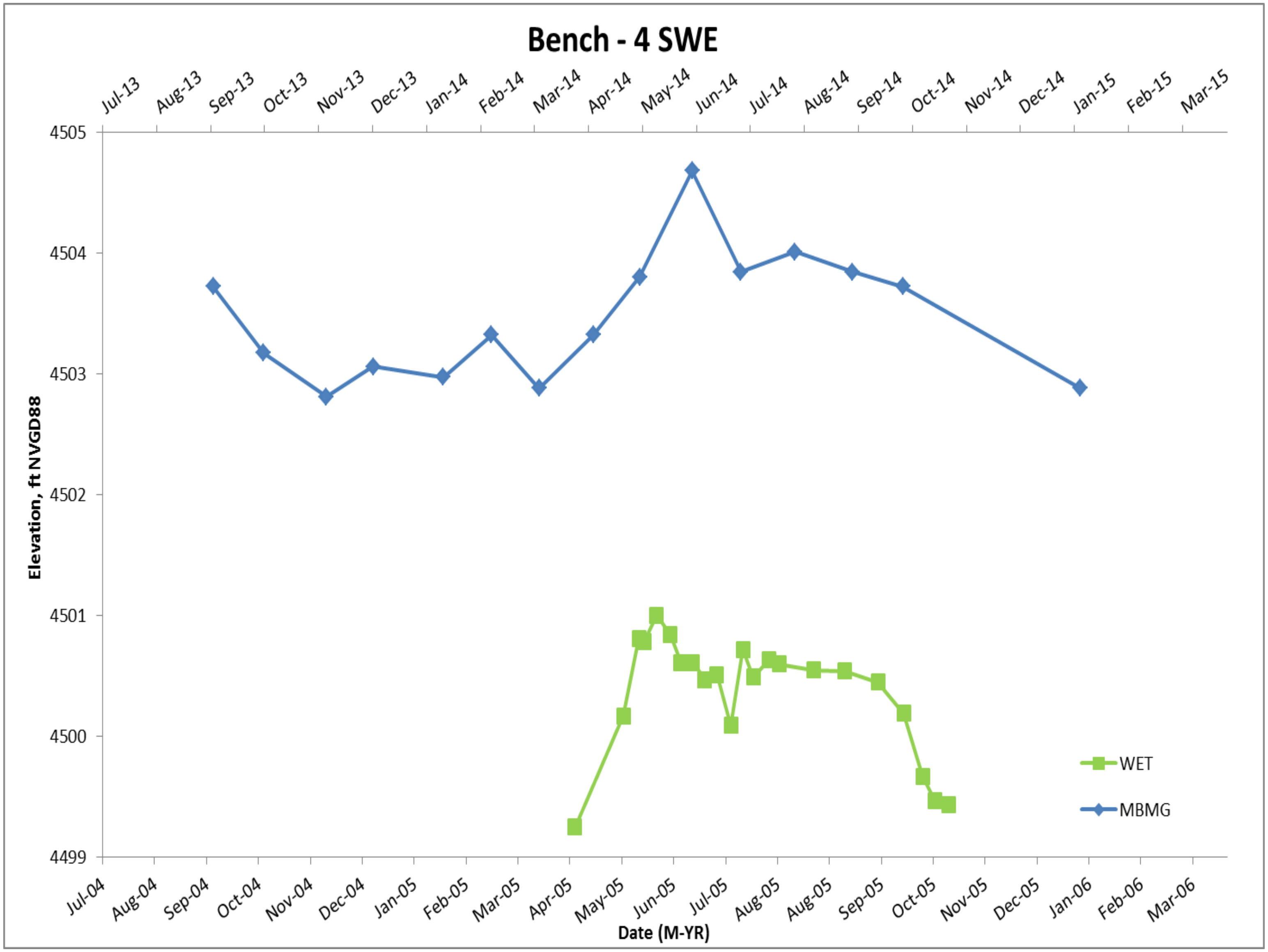



**Figure C-12. Static Water Elevations for Bench 4**

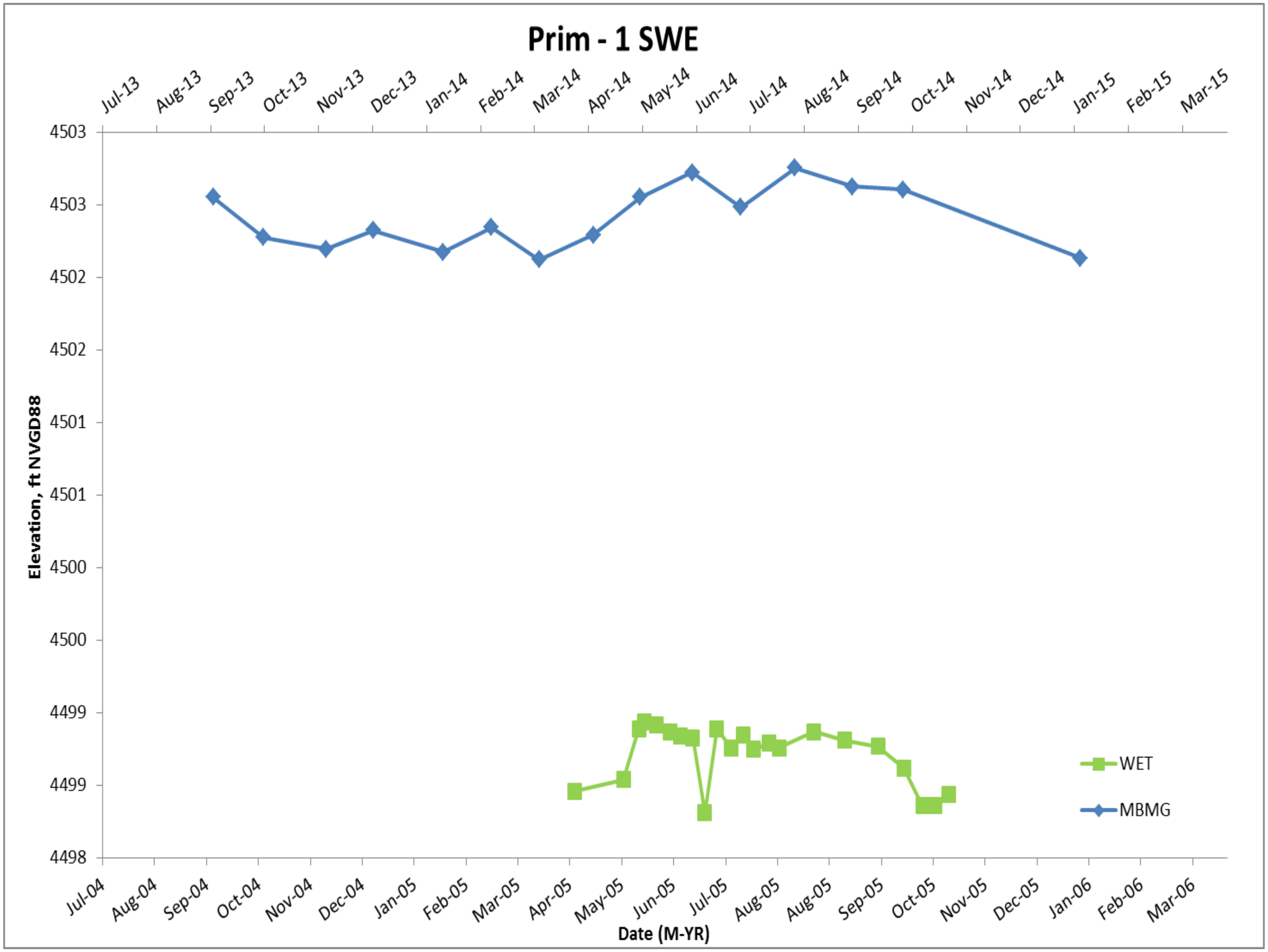



**Figure C-13. Static Water Elevations for Prim 1**

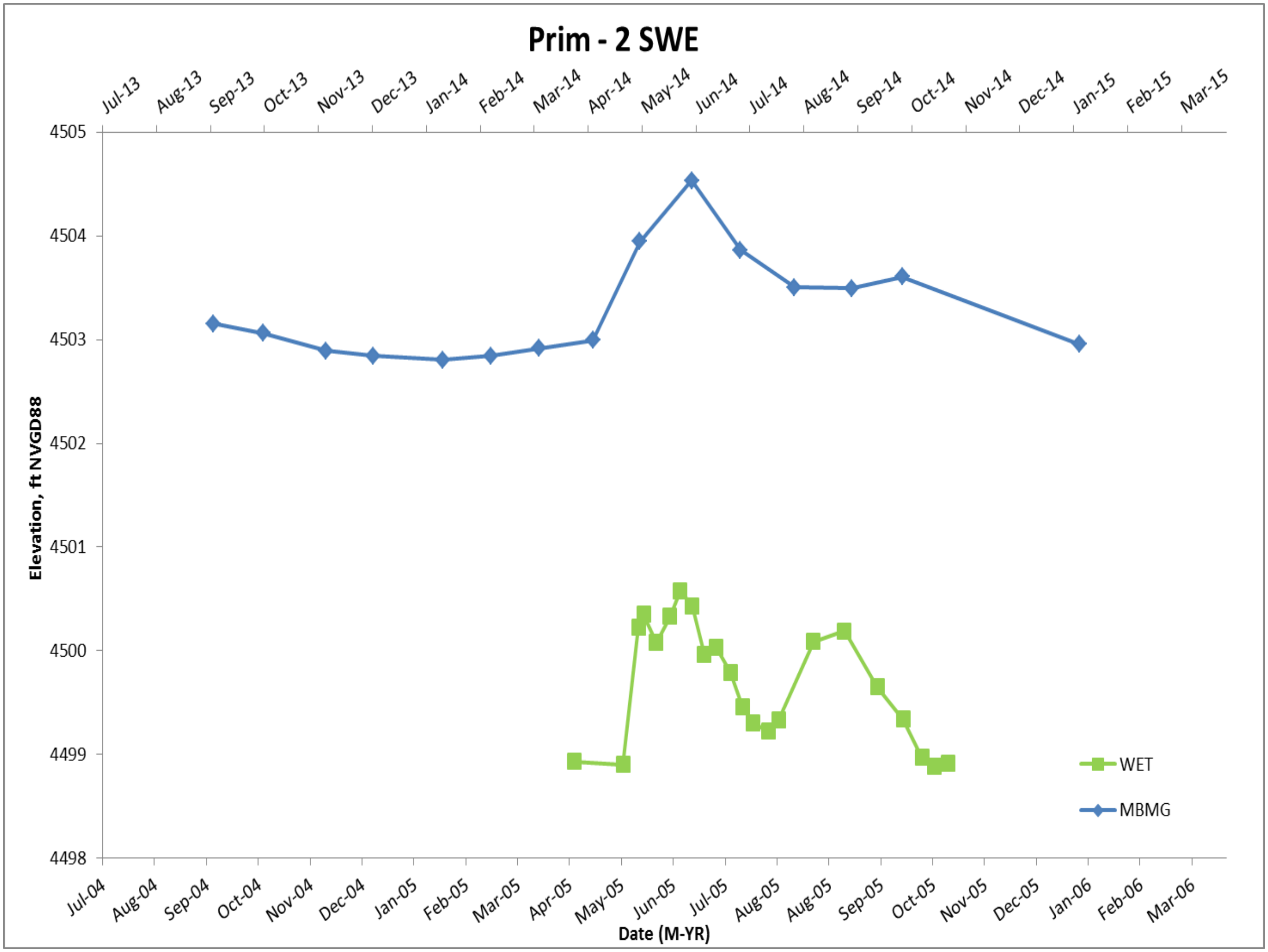



**Figure C-14. Static Water Elevations for Prim 2**

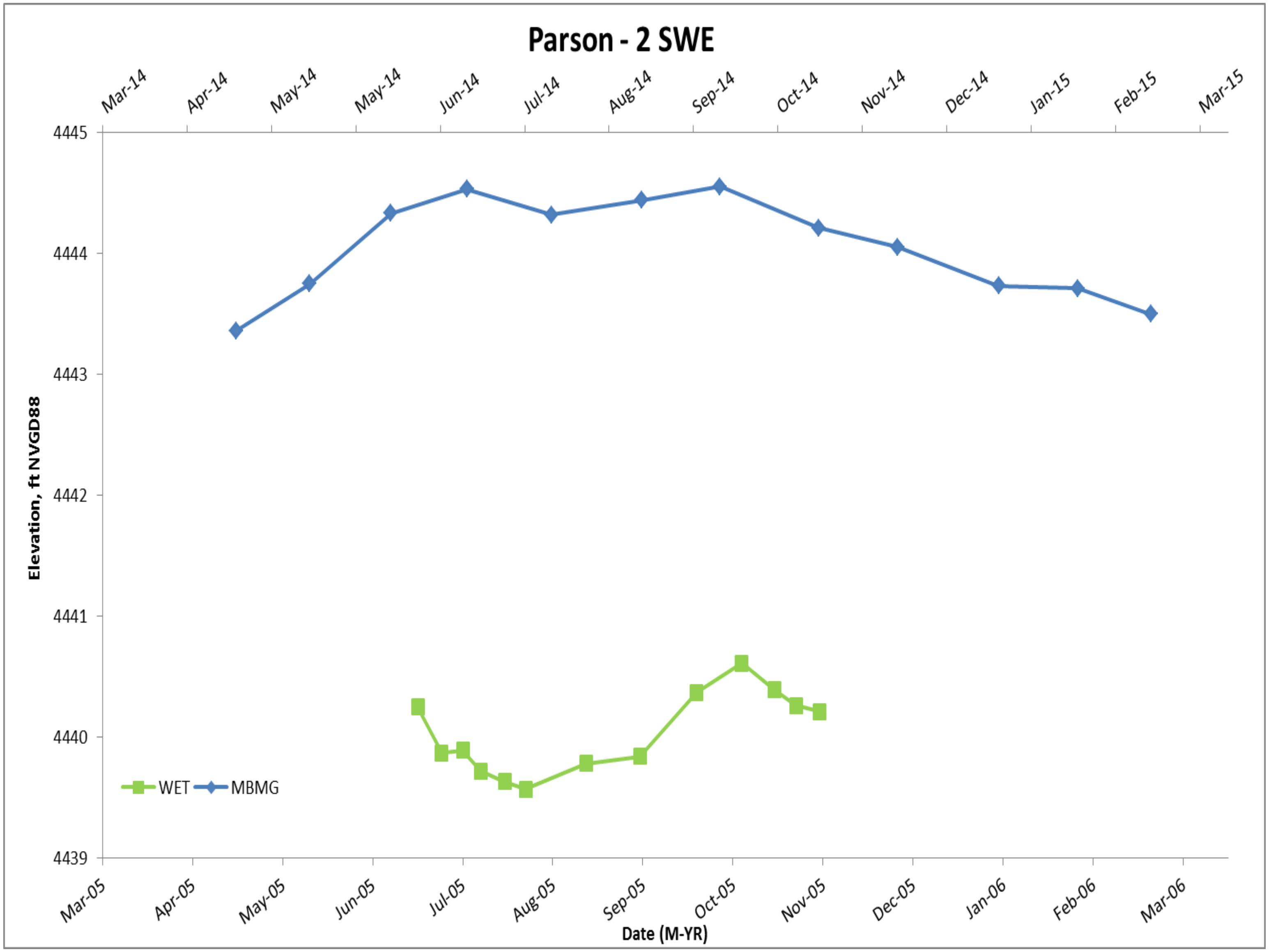



**Figure C-15. Static Water Elevations for Parson 2**

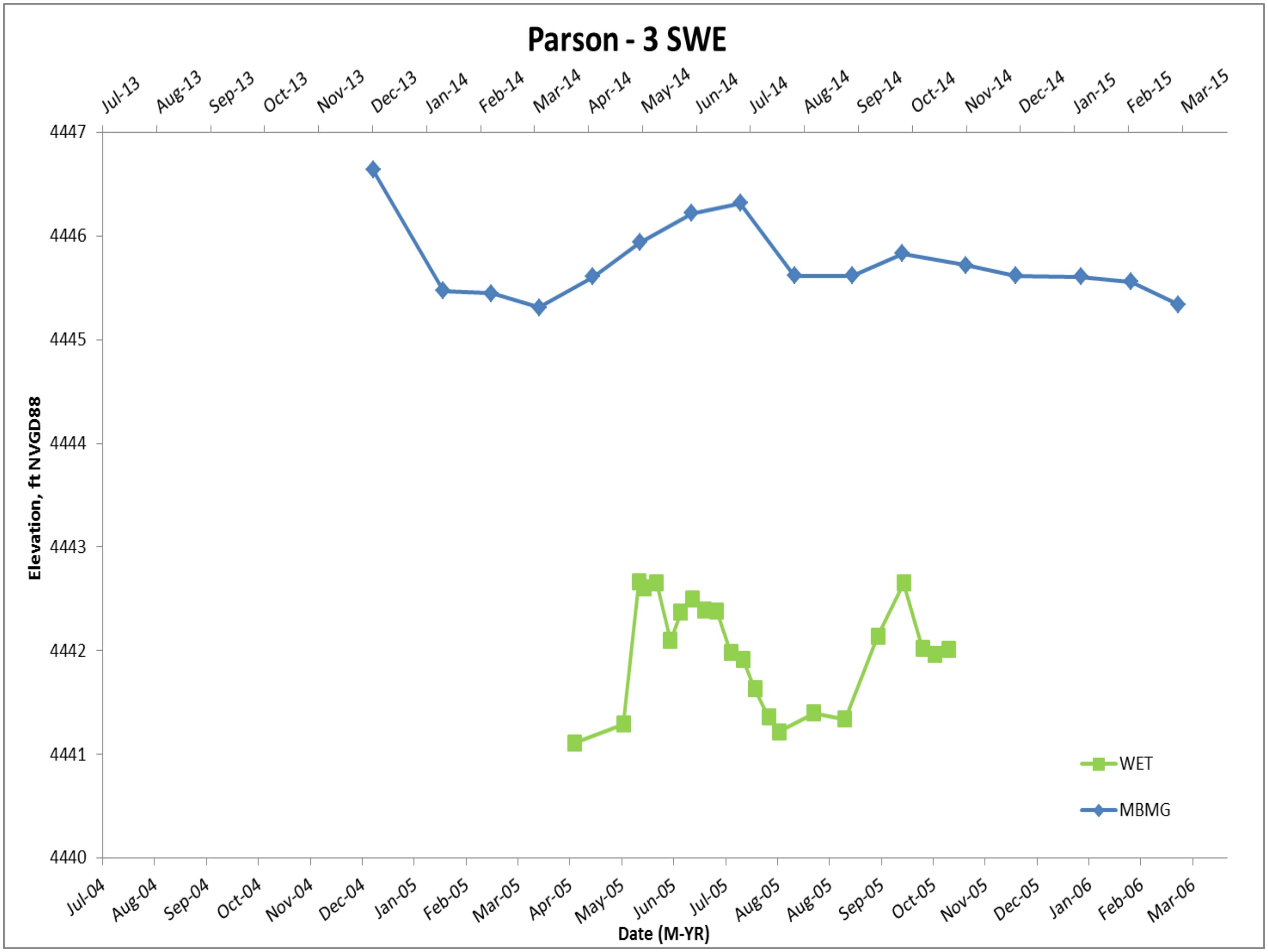



**Figure C-16. Static Water Elevations for Parson 3**

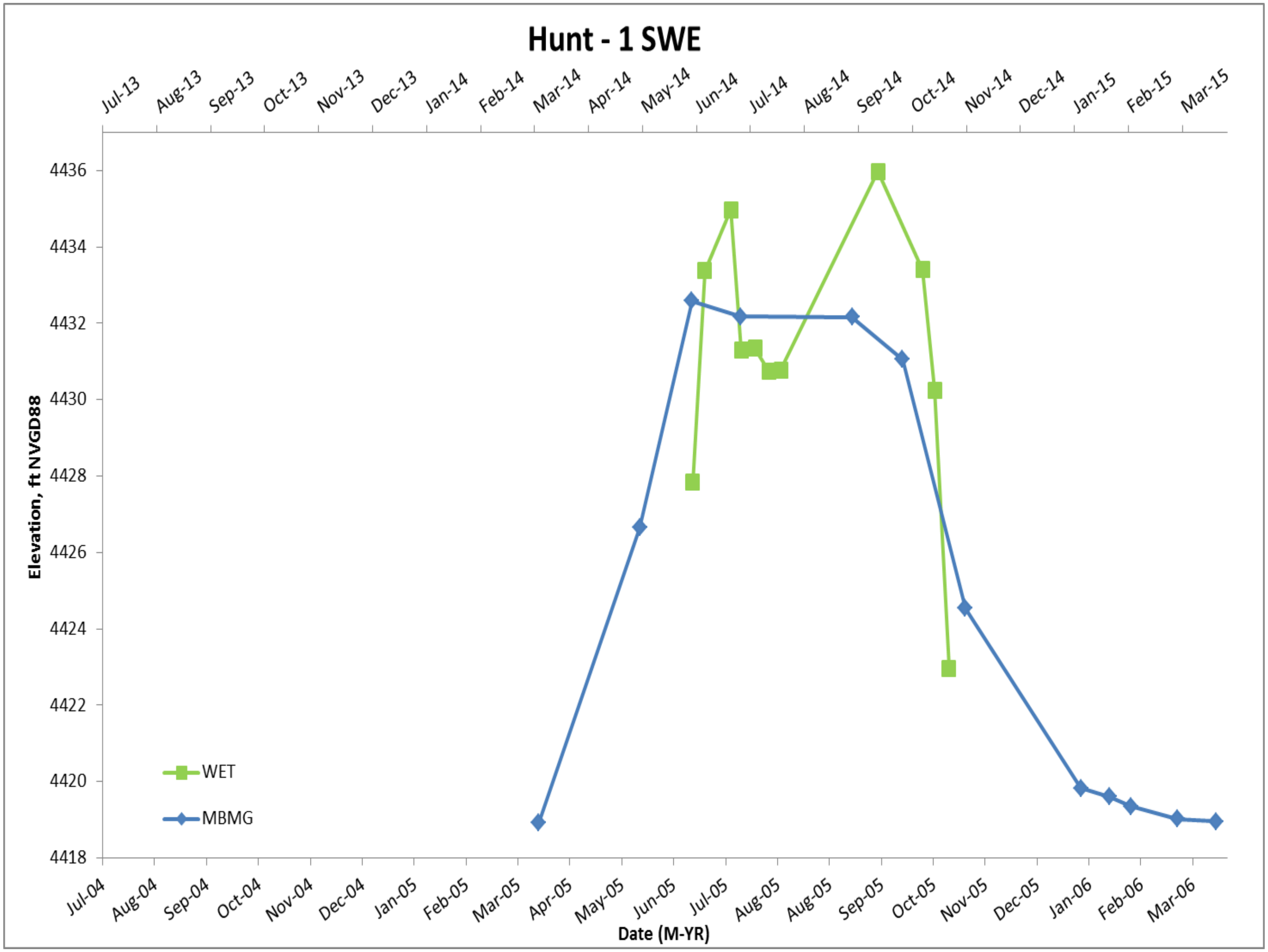



**Figure C-17. Static Water Elevations for Hunt 1**

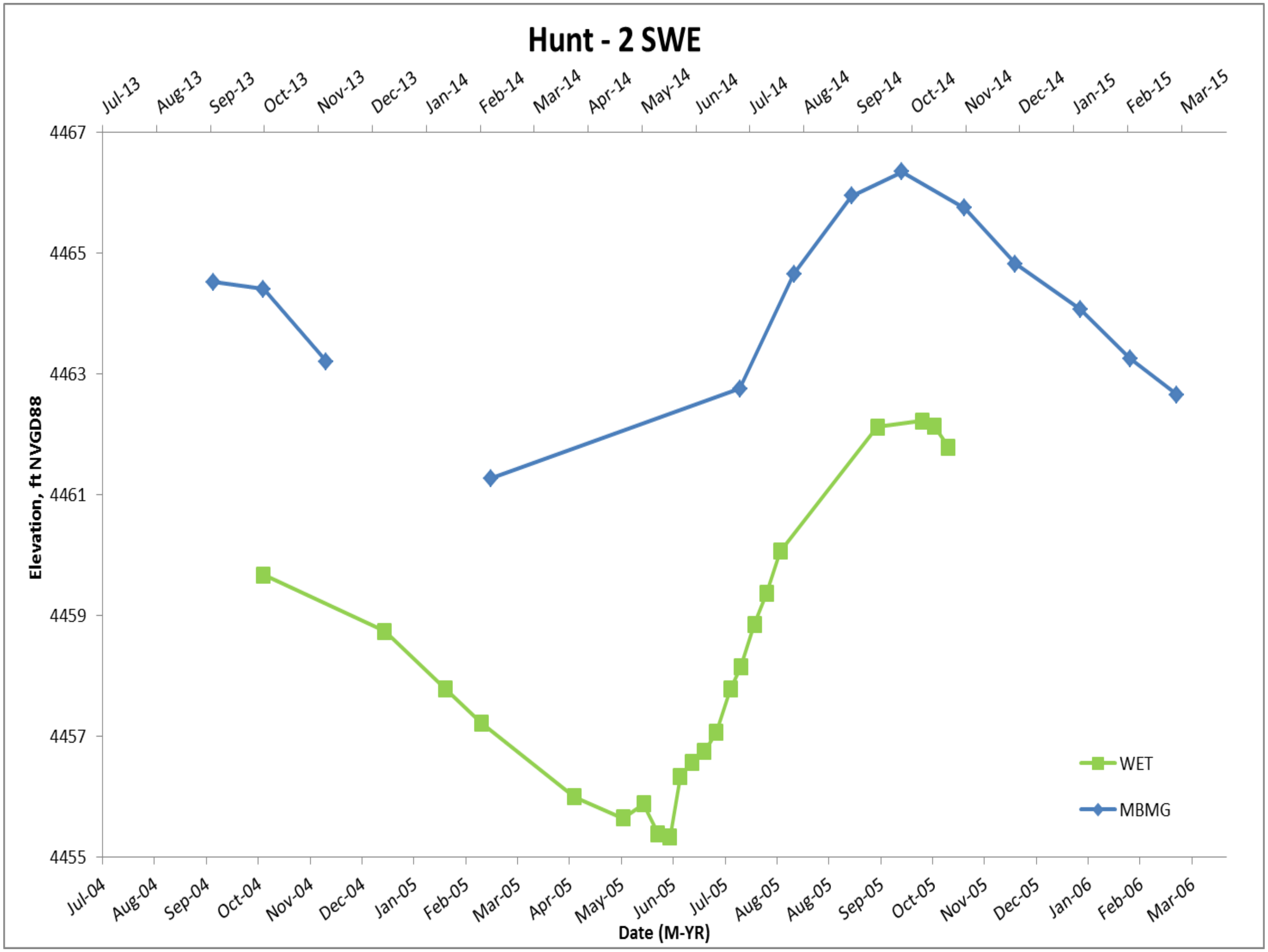



**Figure C-18. Static Water Elevations for Hunt 2**

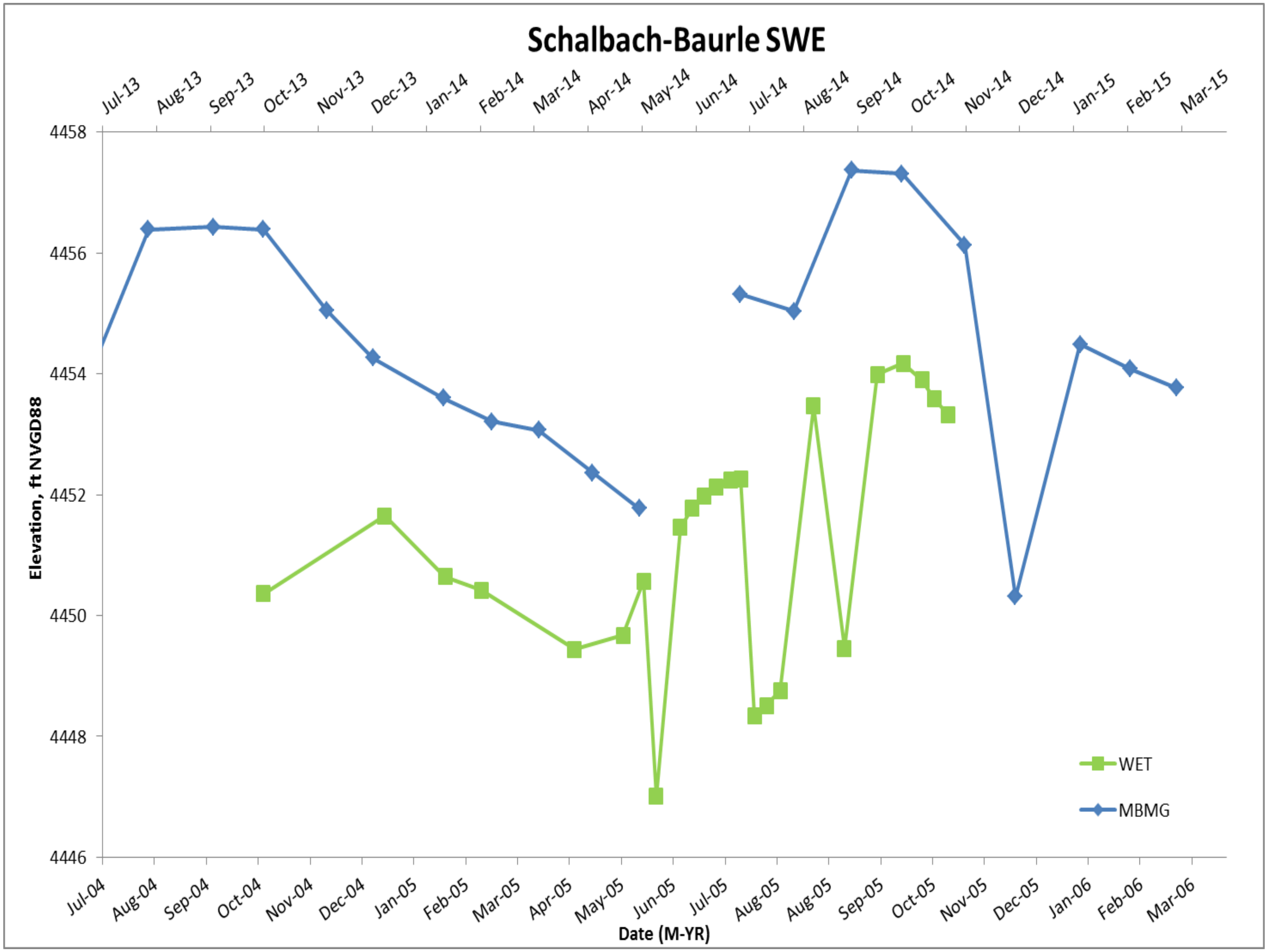



**Figure C-19. Static Water Elevations for Schalbach-Baurle**

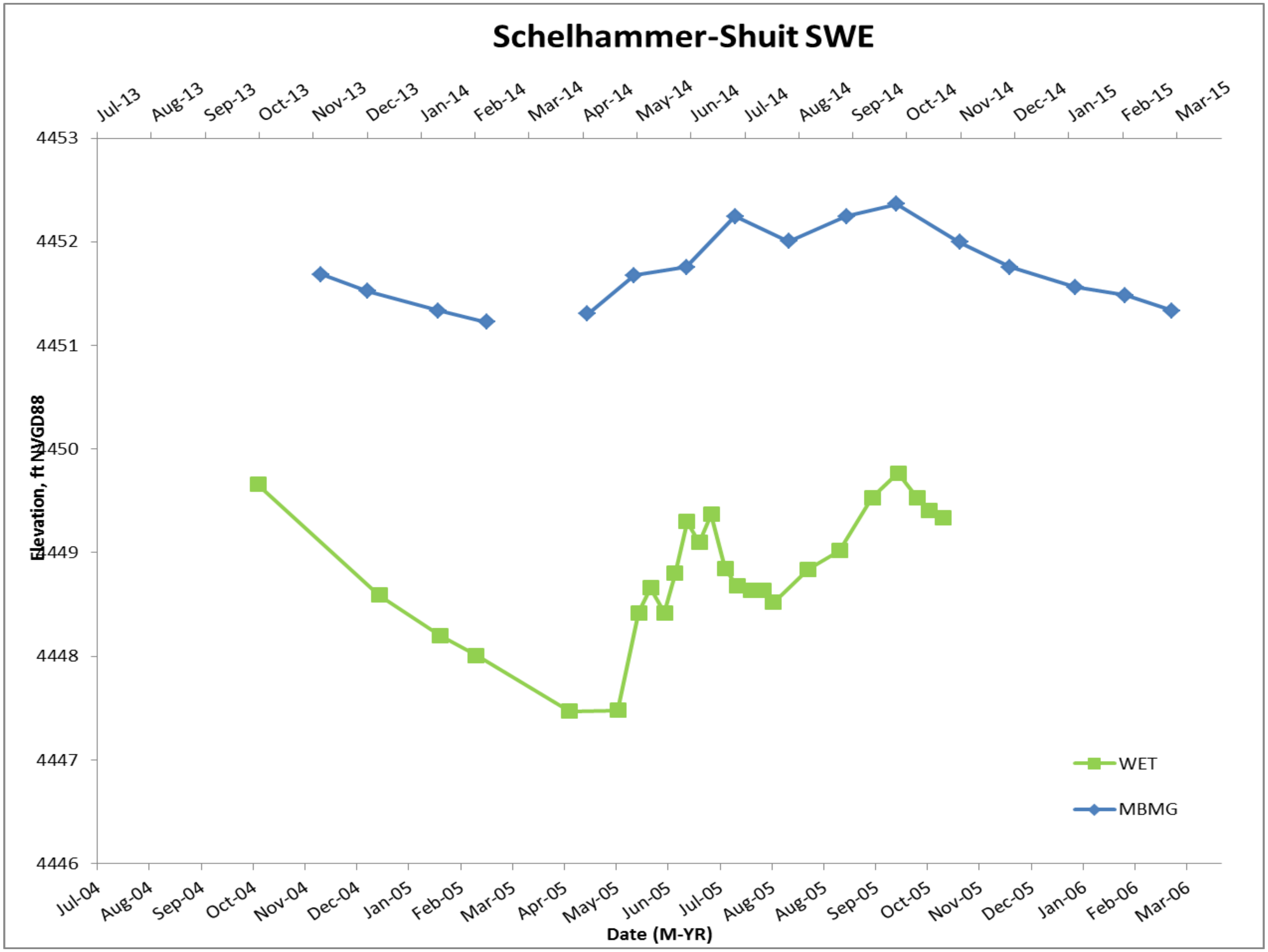



**Figure C-20. Static Water Elevations for Schelhammer-Shuit**

## Appendix D: Water Quality Data and Piper Diagrams

**Table D-1: Major Ion Water Quality Data**

| Site | Date | Lab pH | Lab SC | Ca (mg/l) | Mg (mg/l) | Na (mg/l) | K (mg/l) | SiO2 (mg/l) | HCO3 (mg/l) | SO4 (mg/l) | Cl (mg/l) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Parson's Slough at Loomont Rd | 8/19/2014 | 8.18 | 518.39 | 69.03 | 20.00 | 19.11 | 3.51 | 18.01 | 277.36 | 64.58 | 11.34 |
| | 11/18/2014 | 7.35 | 566.41 | 73.55 | 21.71 | 22.28 | 3.03 | 17.69 | 283.44 | 70.88 | 12.12 |
| | 1/30/2015 | 7.51 | 522.65 | 72.43 | 20.48 | 19.79 | 3.19 | 16.83 | 267.58 | 68.46 | 12.10 |
| | 3/30/2015 | 7.48 | 547.43 | 69.97 | 20.67 | 19.03 | 9.15 | 16.21 | 270.98 | 65.09 | 16.72 |
| West Fork of Willow Springs | 8/19/2014 | 8.12 | 437.76 | 54.84 | 19.81 | 14.64 | 3.21 | 14.66 | 245.11 | 45.74 | 7.59 |
| | 11/18/2014 | 7.82 | 390.80 | 47.19 | 18.06 | 13.42 | 2.97 | 13.26 | 219.66 | 37.44 | 5.62 |
| | 1/30/2015 | 8.01 | 377.04 | 46.66 | 16.72 | 11.25 | 4.69 | 12.22 | 209.28 | 33.04 | 7.19 |
| | 3/30/2015 | 8.18 | 354.12 | 44.82 | 16.44 | 10.61 | 2.96 | 11.23 | 200.44 | 32.18 | 4.96 |
| | 3/30/2015 | 8.21 | 360.40 | 45.41 | 16.69 | 10.58 | 3.02 | 11.36 | 200.18 | 31.30 | 4.80 |
| Lower Willow Springs | 8/19/2014 | 8.30 | 424.63 | 52.68 | 19.89 | 14.53 | 3.52 | 15.68 | 238.19 | 44.09 | 7.56 |
| | 11/18/2014 | 8.22 | 390.14 | 46.97 | 18.33 | 14.20 | 3.20 | 14.24 | 216.50 | 38.02 | 6.82 |
| | 11/18/2014 | 8.03 | 415.19 | 47.10 | 18.64 | 14.32 | 3.17 | 13.85 | 231.47 | 37.98 | 5.78 |
| | 1/30/2015 | 8.23 | 391.03 | 46.43 | 17.39 | 12.69 | 10.38 | 12.75 | 202.63 | 35.04 | 11.20 |
| | 3/30/2015 | 8.29 | 352.25 | 44.22 | 16.47 | 11.24 | 3.11 | 11.47 | 195.97 | 32.77 | 5.12 |
| East Fork of Willow Springs | 8/19/2014 | 8.24 | 474.98 | 55.12 | 23.13 | 17.27 | 4.70 | 18.34 | 262.82 | 48.05 | 8.04 |
| | 11/18/2014 | 8.13 | 465.86 | 53.17 | 23.43 | 17.00 | 4.70 | 16.92 | 256.31 | 50.44 | 8.26 |
| | 1/30/2015 | 8.12 | 436.29 | 50.96 | 23.14 | 16.64 | 5.33 | 16.13 | 240.02 | 46.84 | 8.62 |
| | 3/30/2015 | 8.20 | 414.70 | 47.22 | 22.17 | 15.52 | 4.92 | 14.18 | 227.87 | 43.68 | 7.40 |
| Willow Springs Stock Well | 8/19/2014 | 7.86 | 385.02 | 47.18 | 16.30 | 11.37 | 2.98 | 14.31 | 215.70 | 32.72 | 5.44 |
| | 11/18/2014 | 7.72 | 392.12 | 48.74 | 17.64 | 13.41 | 3.06 | 13.92 | 219.18 | 33.85 | 5.21 |
| | 1/30/2015 | 7.82 | 387.75 | 48.09 | 16.68 | 12.12 | 3.00 | 14.44 | 215.67 | 33.24 | 5.20 |
| | 3/30/2015 | 7.85 | 375.38 | 46.41 | 16.10 | 11.42 | 3.76 | 14.07 | 211.54 | 31.34 | 5.27 |
| Hunt-1 Well | 11/18/2014 | 7.81 | 467.94 | 47.13 | 30.59 | 6.14 | 1.33 | 10.45 | 189.16 | 46.71 | 39.29 |
| | 1/30/2015 | 7.85 | 460.67 | 47.33 | 30.85 | 6.00 | 1.25 | 10.29 | 190.03 | 46.60 | 39.71 |
| | 3/30/2015 | 7.90 | 465.04 | 46.79 | 30.17 | 5.72 | 1.64 | 10.52 | 188.61 | 44.05 | 37.69 |

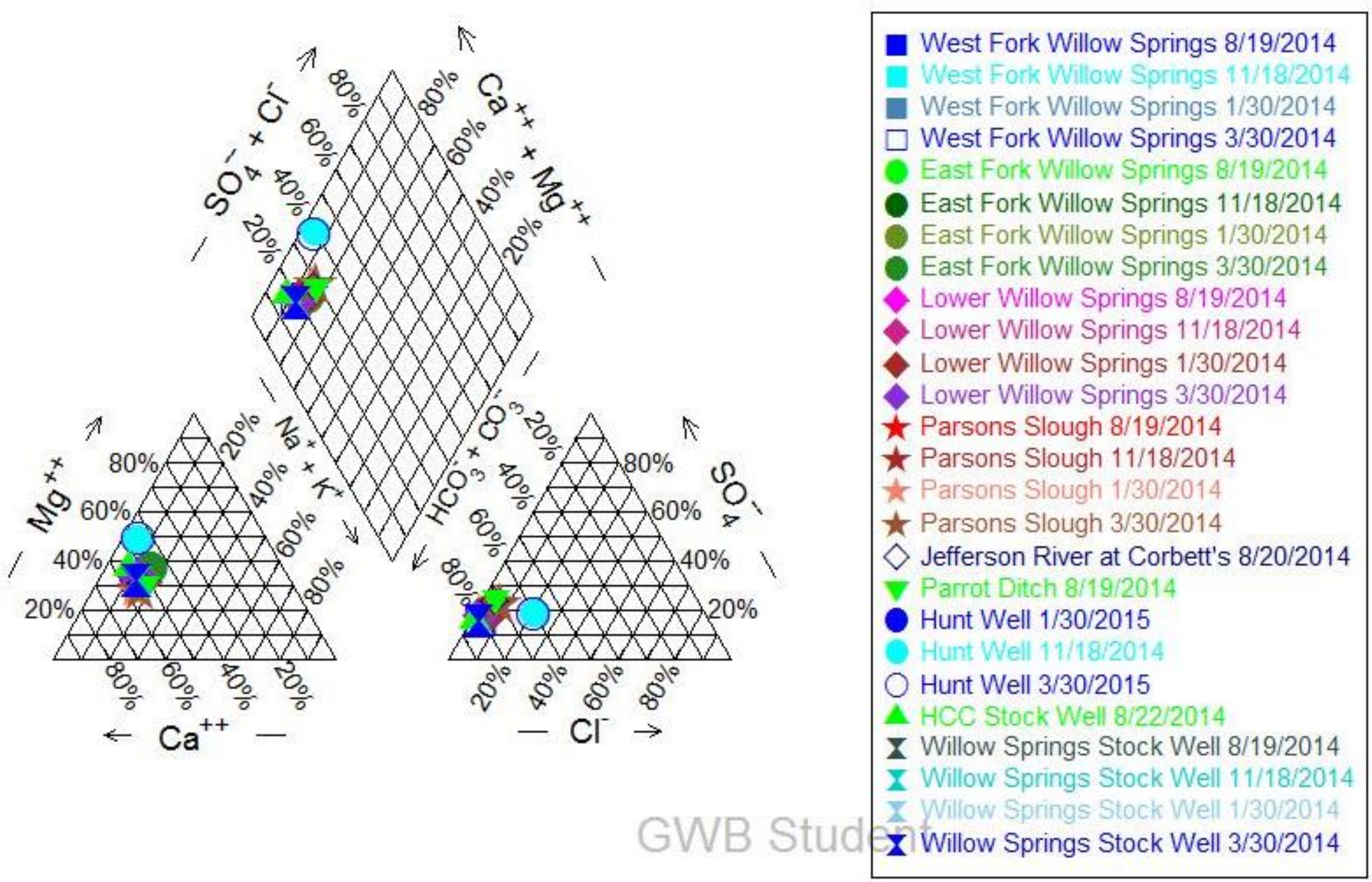



**Figure D-1. Piper Diagram of all Sites Sampled**

## SIGNATURE PAGE

This is to certify that the thesis prepared by Nicole Brancheau entitled "A Hydrogeologic Evaluation of the Waterloo Area in the Upper Jefferson River Valley, Montana" has been examined and approved for acceptance by the Department of General Engineering, Montana Tech of The University of Montana, on this 1st day of May, 2015.

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