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Montana Bureau of Mines and Geology Report of Investigation 28

HYDROGEOLOGIC INVESTIGATION OF THE UPPER JEFFERSON VALLEY, MONTANA—INTERPRETIVE REPORT

Andrew L. Bobst and Ali F. Gebril

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Ground Water Investigation Program

Cover photo: Andy Bobst, August 2013.

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Montana Bureau of Mines and Geology

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PREFACE

The Ground Water Investigation Program (GWIP) at the Montana Bureau of Mines and Geology (MBMG) investigates areas prioritized by the Ground-Water Assessment Steering Committee (2-15-1523 MCA) based on current and anticipated growth of industry, housing and commercial activity, or changing irrigation practices. Additional program information and project-ranking details are available at: http://www.mbmg.mtech.edu (Ground Water Investigation Program).

The final products of the Upper Jefferson Valley study include:

- This **Interpretive Report** that presents data, addresses questions, offers interpretations, and summarizes project results.
- **Groundwater Modeling Reports** that document the groundwater flow models (Gebril and Bobst, 2020, 2021). Models were developed to evaluate the potential hydrologic effects from changes in irrigation practices in the Waterloo area, and potential impacts to surface water due to increased groundwater development in the Whitehall area.
- An **Aquifer Test Report** (Bobst and Gebril, 2020) that documents the field procedures, data, and analysis for five aquifer tests conducted for this study.
- A Montana Tech Master’s Thesis (Brancheau, 2015) was completed in association with this study. The thesis focused on development of a water budget for the Waterloo area.
- MBMG’s Groundwater Information Center (GWIC) online database (http://mbmggwic.mtech.edu/) provides a permanent archive for the data from this study.

ABSTRACT

The Jefferson River, a major tributary to the Missouri River, flows through the Upper Jefferson River Valley in southwestern Montana. Low-flow conditions on the Jefferson during the late summer threaten ecological conditions that support aquatic life. This study focused on (1) the potential for changes in irrigation practices near Waterloo to reduce groundwater discharge to Parson's Slough, Willow Springs, and the Jefferson River; and (2) the potential for increased groundwater use related to residential development and reductions in irrigation recharge near Whitehall to reduce groundwater discharge to the Jefferson River and the Jefferson Slough. The Montana Bureau of Mines and Geology (MBMG) conducted groundwater and surface-water monitoring, and these data were used to aid in understanding the groundwater system, and to develop groundwater models for the Waterloo and Whitehall areas.

The Waterloo groundwater model was developed to evaluate the potential effects of changes in irrigation practices. Scenarios were developed for different combinations of lining canals, and changing fields from flood to pivot irrigation. The results showed that if diversion rates were unchanged, August flows in the Jefferson River could be reduced by up to 30 cfs (a 4.3% reduction in mean August flows) as a result of lining all irrigation canals and changing all fields from flood irrigation to pivot. Of this 30 cfs maximum reduction, about 17 cfs was due to lining irrigation canals and 13 cfs was due to the change in irrigation methods.

The Whitehall groundwater model was used to evaluate effects from groundwater use at residential subdivisions at various locations. Scenarios differed by pre-development land use, hydrogeologic setting, and the density of wells. A 23-home subdivision in a previously irrigated area caused the greatest simulated change in surface-water flows, because this resulted in reduced groundwater recharge, and increased groundwater withdrawals. This scenario resulted in an 8.4 acre-ft reduction in groundwater discharge to streams in August. This represents a 0.02% reduction in mean August stream flow in the Jefferson River, which is much smaller than could be quantified based on field measurements. These results show that changes in land use that reduce groundwater recharge, such as converting irrigated fields to other uses, can impart larger reductions in groundwater discharge to streams than the effects of additional wells.

Late summer flows in the Jefferson River can be enhanced by long-term projects to maintain or increase groundwater storage in shallow aquifers. The locations of such projects must be selected with consideration of the permeability of the aquifer, so that the groundwater is stored for long enough to increase discharge to surface water during the late summer. For shallow aquifer storage mechanisms to be effective, groundwater recharge (such as canal leakage and irrigation recharge) should be maintained or increased while stream flows are high, and irrigation efficiency should be emphasized when stream flows are low.

INTRODUCTION

Background

The Upper Jefferson watershed, located in southwestern Montana, encompasses 261 mi^2 (fig. 1). The Jefferson River is formed from the confluence of the Beaverhead, Big Hole, and Ruby Rivers near Twin Bridges, Montana. The Jefferson River flows to the north and east, and joins the Madison and Gallatin Rivers near Three Forks, Montana, to form the Missouri River (fig. 1).

The Upper Jefferson River is classified as "chronically dewatered" (MFWP, 2012). Low late summer stream flow has been a longstanding problem (Missouri River Basin Commission, 1981). Low flows in the late summer are likely due to a combination of the natural annual snowmelt and precipitation cycles (figs. 2, 3), and irrigation diversions. The Montana Fish Wildlife and Parks (MFWP) closes the Upper Jefferson to fishing more than any other river in Montana (JRWC, 2010). Trout populations decline during drought cycles, and recover during years of normal to above-normal flows (MFWP, 2012).

During low flows in the late summer, water temperatures in the Jefferson River approach 27^{o}C (80^{o}F; MFWP, 2012). The Montana Department of Environmental Quality (MDEQ) developed a Total Maximum Daily Load (TMDL) and Water Quality Improvement document for temperature in the Jefferson River (MDEQ, 2014). They found that stream dewatering and a lack of shade caused temperature impairment. This work concluded that groundwater discharges and inflow from spring-fed tributaries near Willow Springs in the late summer aid in reducing in-stream temperatures, and that some of this groundwater is derived from early season irrigation recharge.

In response to low late summer stream flows, stakeholders from various interest groups developed a drought management plan for the Upper Jefferson River in 2000. The plan provides a protocol to leave enough water in the river to allow for fish passage over shallow riffle areas (JRWC, 2013), and specifies a minimum flow of at least 50 cfs at the USGS station at Parson's Bridge (USGS 06027600; below the Jefferson/Fish Creek Canal diversion and above the inflow from Parson's Slough; fig. 4), when the flow at the gage near Twin Bridges (USGS 06026500; fig. 4) is above 250 cfs. When the Twin Bridges gage is below 250 cfs, the goal is to have at least 20% of the Twin Bridges flow at the Parson's Bridge gage. The drought management plan includes triggers based on both water temperature and stream flow, which cause voluntary and mandatory limits on fishing, and encourage voluntary reductions in irrigation diversions.

Occasional measurements at the Parson's Bridge site (fig. 4) prior to 2006 show that stream flow dipped as low as 4 cfs in 1988, and fell below 20 cfs in 1992 and 1994. The USGS established a station at this site in 2006, and has measured stream flow from at least July to September every year since. Low flows typically occur in August, and mean August flow has varied from 40.5 (2016) to 1,275 (2011) cfs. The lowest mean daily flow at this site since 2006 was 19.9 cfs in August 2016.

Immediately downstream of the USGS gage at Parson's Bridge (06027600), Parson's Slough and Willow Springs flow into the Jefferson River (fig. 4). These perennial streams are groundwater fed, and they provide important spawning habitat for brown and rainbow trout (MFWP, 2012). During the late summer these streams contribute relatively cool (~12^{o}C) water to the Jefferson River (WET, 2006, 2010a,b; MDEQ, 2014). Groundwater also discharges directly to the Jefferson River along the reach near the mouths of Parson's Slough and Willow Springs.

Canal leakage and infiltrated irrigation water provide groundwater recharge in the Waterloo area (WET, 2006). Therefore, changes in irrigation management practices that would reduce recharge, such as lining canals or changing from flood to pivot irrigation, have the potential to decrease late summer groundwater discharge to Parson's Slough, Willow Springs, and the Jefferson River.

The Jefferson River is a closed basin for new water rights (MT DNRC, 2016). Thus, new residential developments rely on individual domestic wells that are exempt from DNRC's formal permitting process (JRWC, 2010). "Exempt wells" withdraw water at less than 35 gallons per minute (gpm) and less than 10 acre-ft per year [MCA §85-2-306(3)]. The potential for additional groundwater withdrawals to reduce surface-water availability in the Jefferson Slough and the Jefferson River is a concern for many area residents and river users.

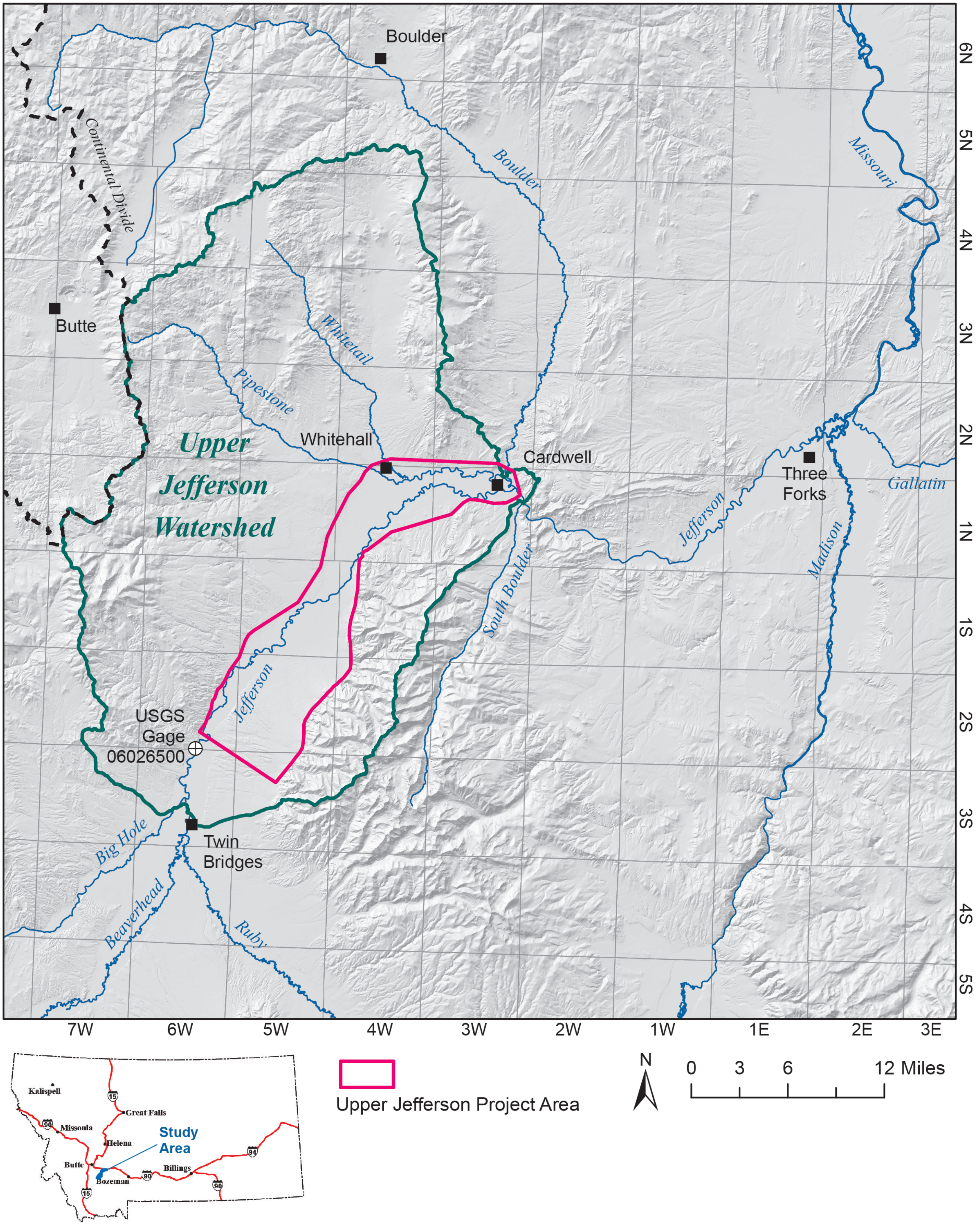


Figure 1. The Upper Jefferson project area is located in southwest Montana along the alluvial floodplain and adjacent benches of the Jefferson River, generally between Twin Bridges and Cardwell.

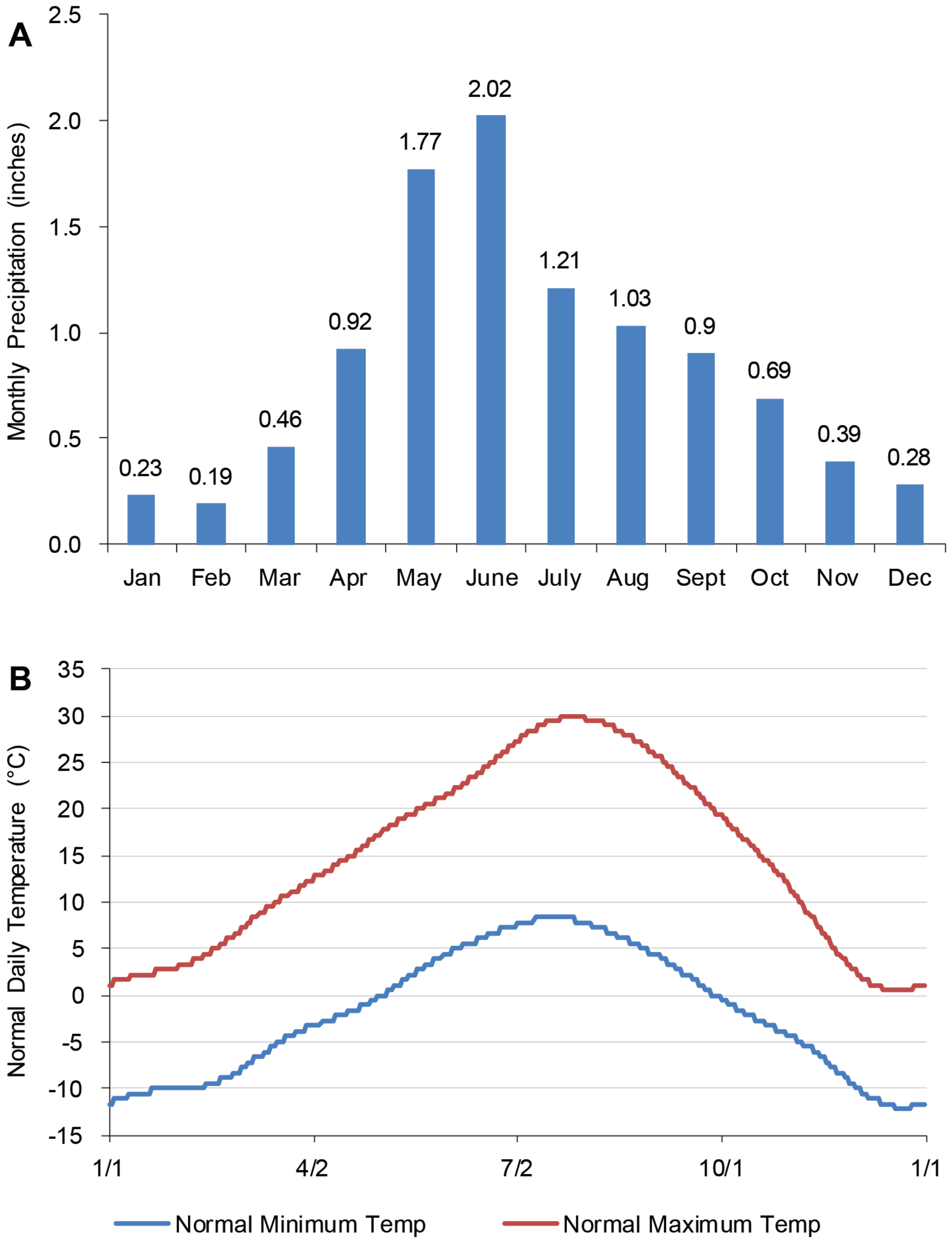


Figure 2. Climate normal data from Twin Bridges, period of record 1981–2010 (NOAA, 2011). The normal annual precipitation is 10.1 in.

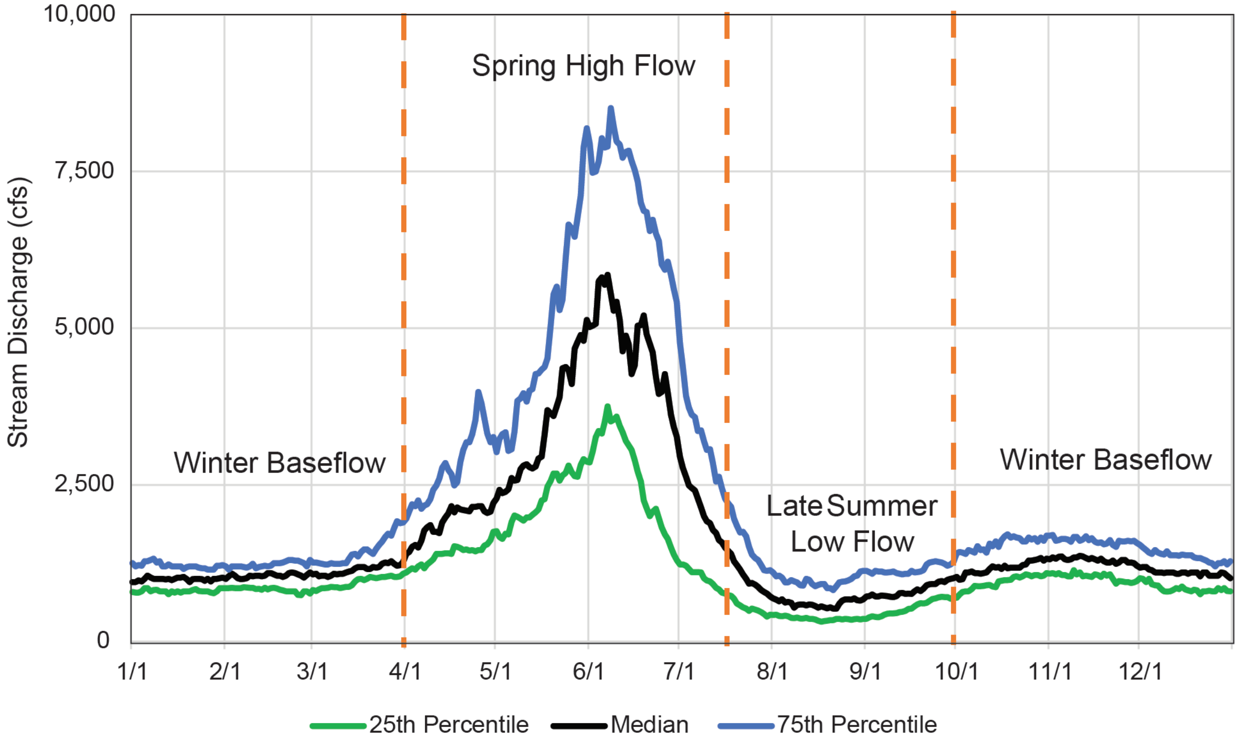


Figure 3. Flows on the Jefferson River near Twin Bridges, at USGS gage 06026500, period of record 1940–2019. The median daily baseflow in the winter averages 1,127 cfs; high flows occur in the spring and early summer due to snowmelt and spring rains. Irrigation diversions and evapotranspiration contribute to low flows in the late summer. The lowest flows occur in mid-August, when the interquartile range extends from 342 to 821 cfs (median = 528 cfs).

Purpose and Scope

The Upper Jefferson groundwater investigation, carried out by the Montana Bureau of Mines and Geology's (MBMG) Ground Water Investigation Program (GWIP), focused on two issues. The first was the potential for changes in irrigation practices in the Waterloo area to reduce the amount and timing of groundwater discharge to Parson's Slough, Willow Springs, and the Jefferson River. The second was the potential for increased groundwater withdrawals and changes in land use associated with residential development in the Whitehall area to reduce groundwater discharge to the Jefferson River and the Jefferson Slough.

We used geologic information, groundwater and surface-water monitoring, aquifer tests, and water-quality sampling to characterize the hydrogeologic setting, and to aid in understanding groundwater flows and groundwater/surface-water interactions. This study provides technical information for groundwater management, and a hydrogeologic framework within which site-specific issues can be considered. Hydrogeologists may use the numerical models from this study to evaluate the effects that would result from various management strategies.

Location

The Upper Jefferson Valley groundwater investigation covered 107 mi^2 in the valley bottom and adjacent benches from the junction of Hells Canyon with the Jefferson River to the upstream end of the Jefferson Canyon (fig. 5). The area is bounded by the Tobacco Root Mountains, the Highland Mountains, and Bull Mountain (fig. 5). This study area includes portions of Jefferson, Madison, and Silver Bow Counties, Montana.

The Waterloo and Whitehall areas were investigated in greater detail (fig. 6). The Waterloo subarea includes the area between the Creeklyn and Parrot irrigation canals, including the areas drained by Parson's Slough and Willow Springs. The Whitehall subarea covers the floodplain and adjacent benches near Whitehall. The Jefferson and Parrot Canals run along the west and south sides of the Whitehall subarea, respectively.

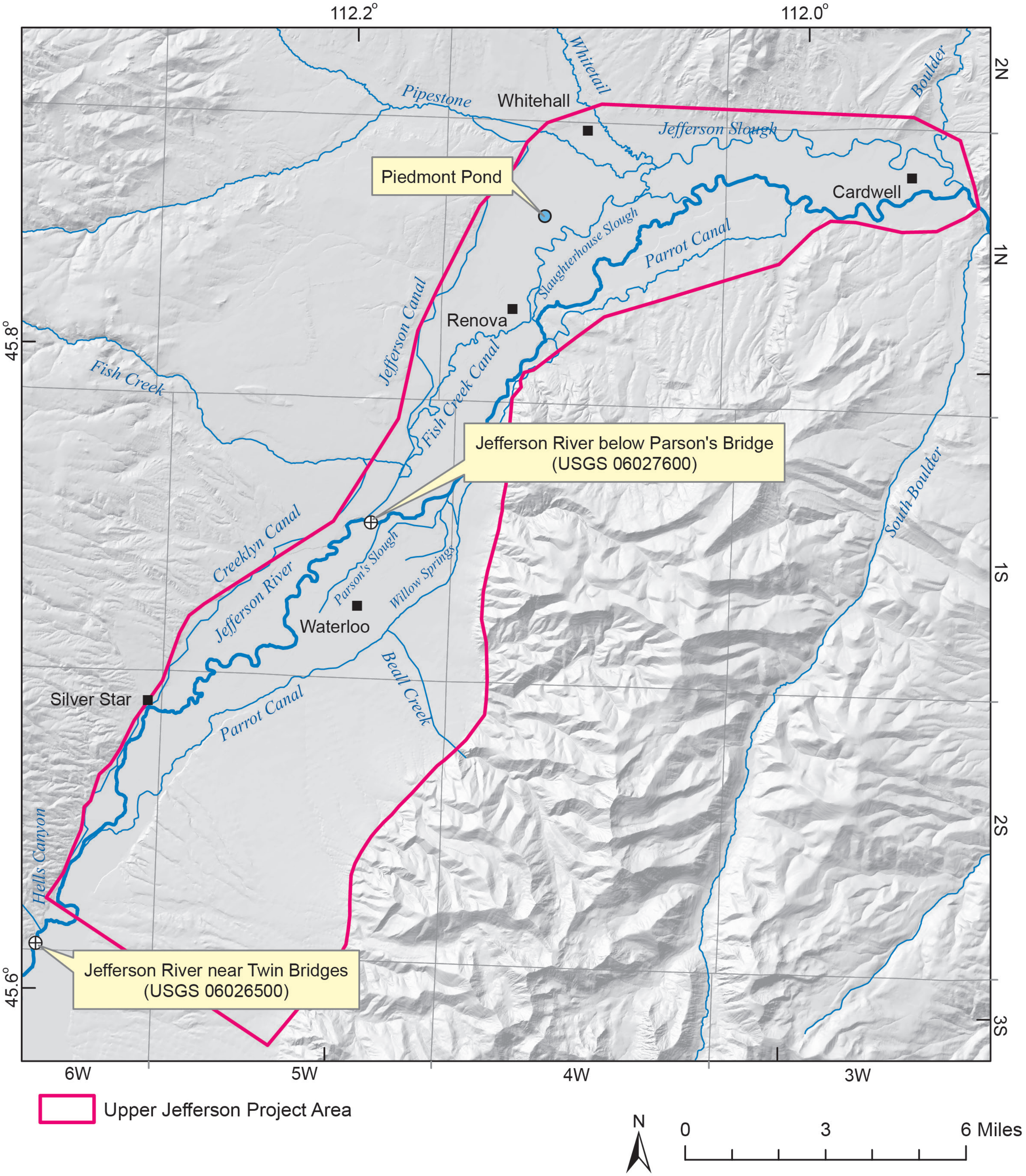


Figure 4. The Jefferson River is diverted into a network of canals and sloughs. The main tributaries include Fish Creek, Pipestone Creek, Whitetail Creek, and the Boulder River. The Jefferson and Slaughterhouse Sloughs are secondary channels to the rivers' main-stem.

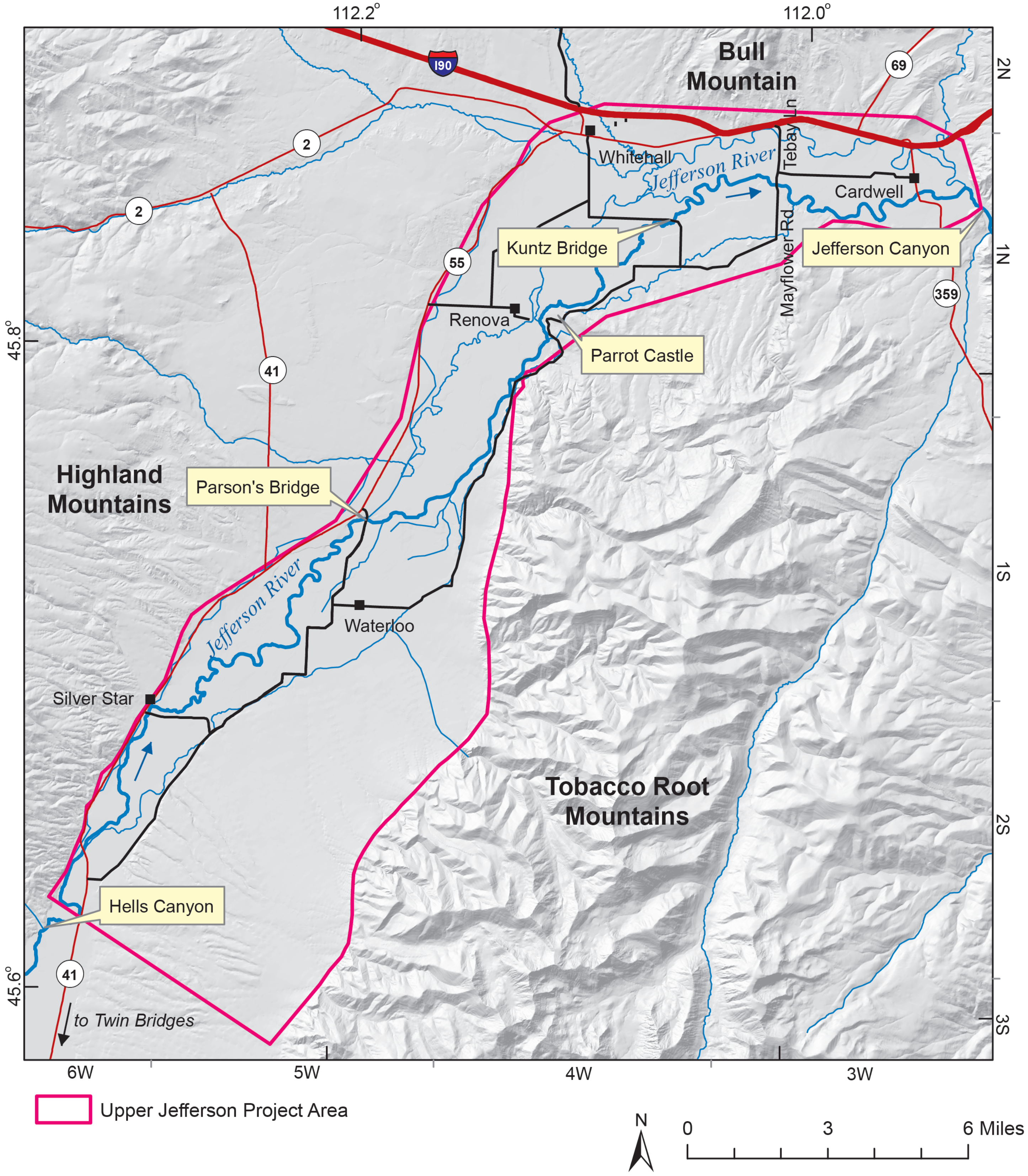


Figure 5. The Upper Jefferson Groundwater Investigation evaluated the hydrogeology of the alluvium and adjacent benches of the Jefferson River from Hells Canyon to the upstream end of the Jefferson Canyon (near Cardwell). This area includes the towns of Silver Star, Whitehall, and Cardwell.

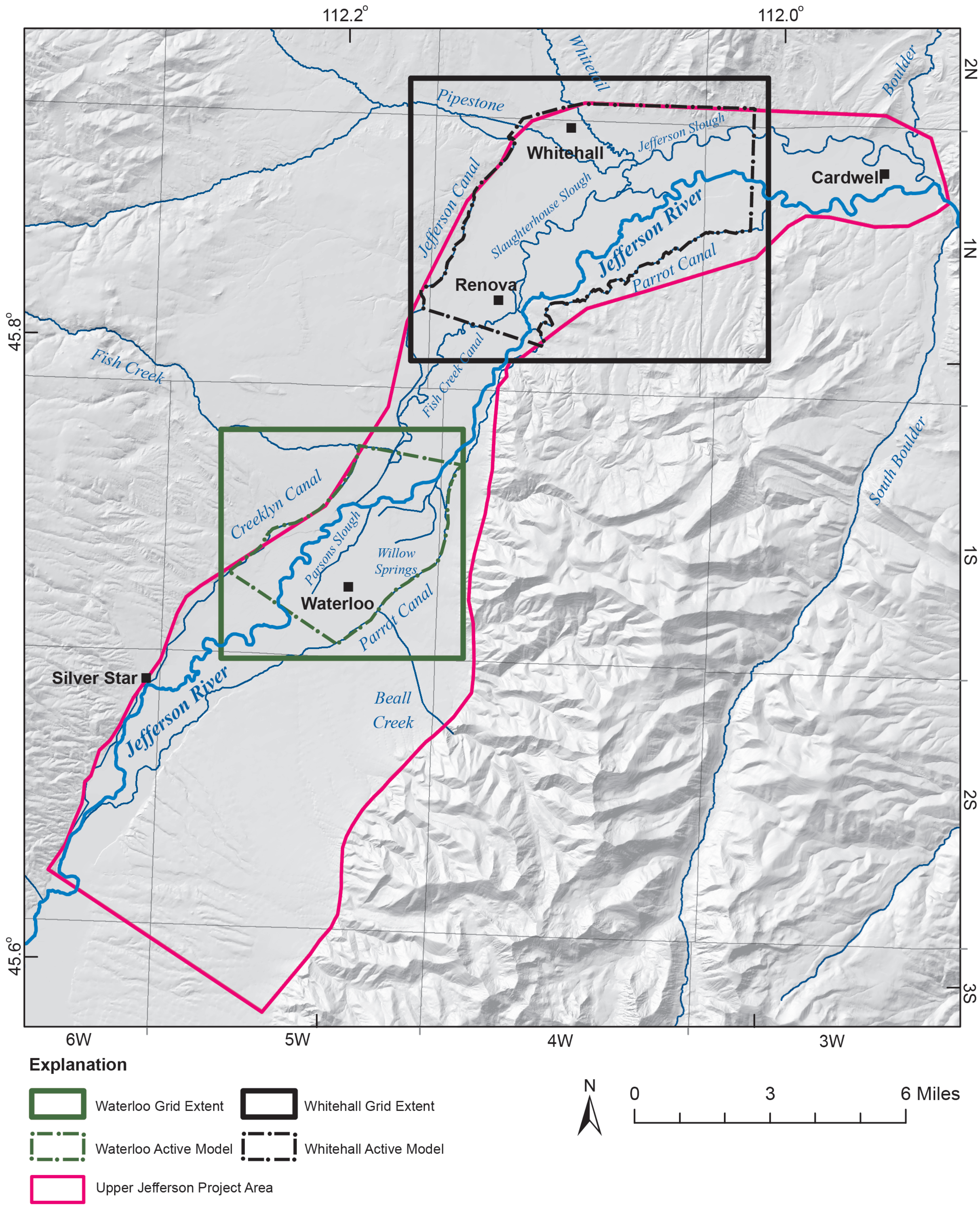


Figure 6. Numerical groundwater flow models were developed for the Waterloo and Whitehall areas. The active portion of the model domain extends 11.7 mi^2 for the Waterloo model, and 24.2 mi^2 for the Whitehall model.

Physiography

The portion of the Upper Jefferson River Valley from Twin Bridges to Whitehall is a north–northeast-trending intermontane basin (fig. 7). From Whitehall to Cardwell the valley trends east–west. Throughout the valley alluvial fans extend from the mountain fronts to the alluvial floodplain. Elevations within the study area range from 4,277 ft where the Jefferson River flows into the Jefferson Canyon to about 5,900 ft on the highest alluvial fans.

Climate

The Jefferson Valley has cold winters and mild summers. Climate normal values for Twin Bridges, based on data from 1981 to 2010 (NOAA, 2011; fig. 2), show that precipitation is the greatest in June, with an average of 2.0 in, and the lowest in February, with an average of 0.2 in. December is the coldest month, with a mean monthly temperature of -5.2°C (23°F). July is the warmest month, with a mean monthly temperature of 18.4°C (65°F). Twin Bridges receives an average of 10.1 in of precipitation per year with a large amount of interannual variability (fig. 8). Annual precipitation totals were below average during the monitoring period for this study, at 9.0, 9.4, and 8.1 in. in 2013, 2014, and 2015, respectively.

The SNOWTEL site closest to the study area is Albrio Lake (station 916; elevation 8,300 ft-amsl) in the Tobacco Root Mountains. This station received an average of 38 in of precipitation (rain plus snow water equivalent) per year from 1997 to 2017. Annual precipitation amounts were close to average during this study, at 41, 43 and 36 in. in 2013, 2014, and 2015, respectively.

Geographically distributed 30-yr normal annual precipitation estimates (1981–2010; PRISM, 2012; Daly and others, 2008) within the study area range from less than 10 in in the southern portion of the valley bottom to about 14 in on the higher benches. The PRISM estimates show 10–12 in per year of precipitation in the valley, up to 33 in per year in the Highland Mountains, and up to 50 in per year in the Tobacco Root Mountains.

Vegetation

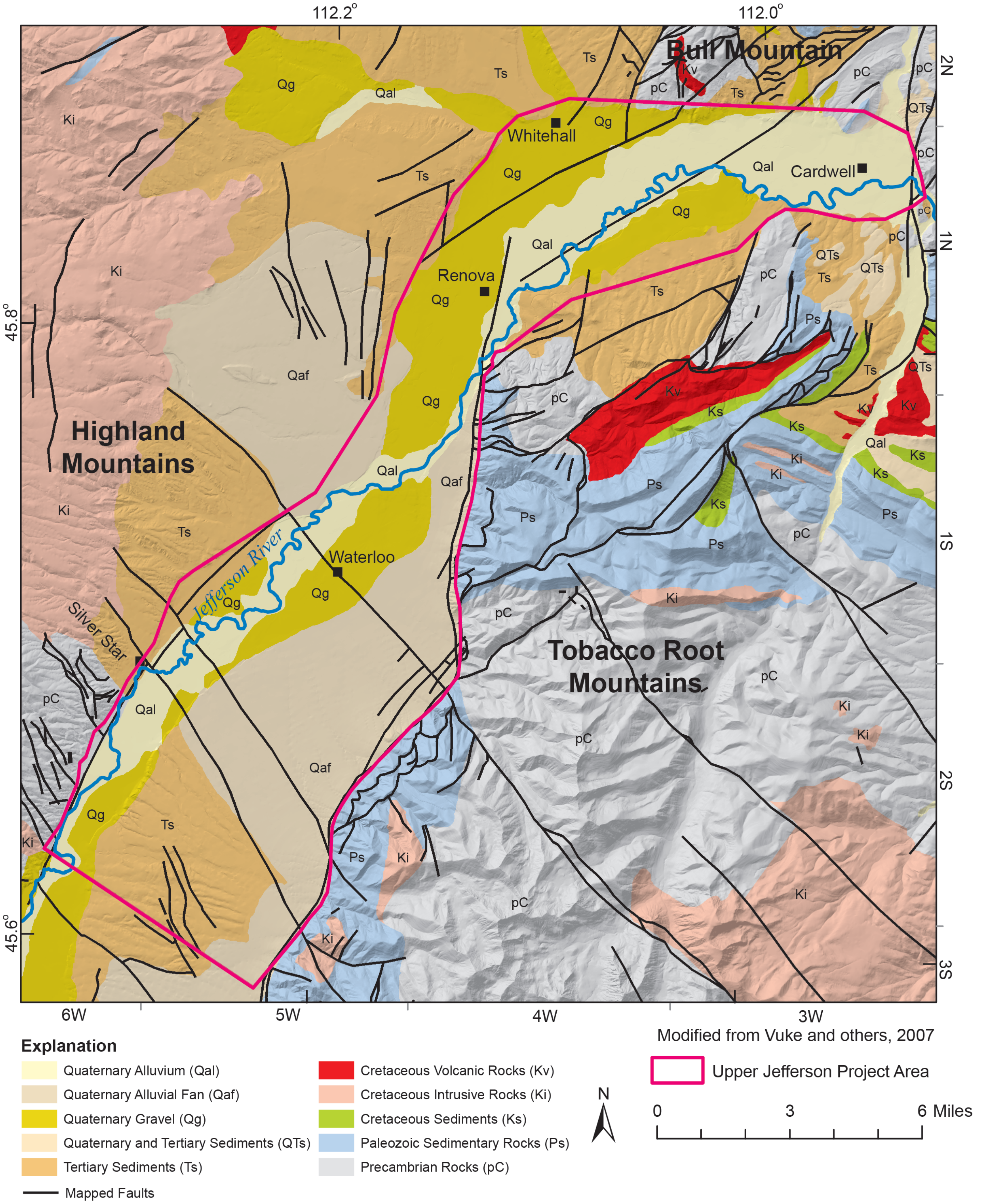
Vegetation within the study area consists of both native and cropped species. Alfalfa and grass hay are the primary crops, and cropland comprises 25% of land cover in the study area (USGS, 2010). Native willow, cottonwood, aspen, and wetland grasses are common along the Jefferson River and some tributaries. These phreatophytes grow where their roots can access shallow groundwater. Riparian plants cover 5% of the study area. Native upland vegetation is primarily shrubs (44% of the area) and grasses (19% of the area). Other land covers include developed areas (3%), conifer forest (2%), and open water (2%). Conifer forests, composed primarily of ponderosa pine, Douglas fir, lodgepole pine, Engleman spruce, and whitebark pine, cover the adjacent mountain blocks.

Geologic Setting

Geologic maps for the Jefferson Valley have been produced by Vuke and others (2004) and Vuke (2006; fig. 7). These maps provide a geologic framework for the study area, showing the surficial extent of the different geologic units, the locations of known or inferred faults, and geologic cross sections.

The bedrock on the west side of the Upper Jefferson Valley is dominated by plutonic rocks associated with the Cretaceous Boulder Batholith (Ki in fig. 7), and Precambrian rocks (pC; primarily gneiss). The Tobacco Root Mountains along the east side of the valley are dominated by Precambrian rocks (pC), but also include Paleozoic sedimentary clastic and carbonate rocks (Ps), Cretaceous intrusive rocks (Ki), and Cretaceous volcanic rocks (Kv). The Bull Mountains bound the northern part of the Upper Jefferson Valley, and the area draining to the valley is mainly composed of Precambrian rocks (pC) and Cretaceous volcanic rocks (Kv).

The valley is asymmetrical, with west-dipping faults on the east side, and smaller east-dipping faults on the west side of the valley (Vuke and others, 2004). Faults also cross-cut the basin (Hanneman and Wideman, 1991; Ruppel, 1993; Kendy and Tresch, 1996; Vuke and others, 2004). Fine-grained Tertiary Renova Formation sediments were deposited in the valley in the Eocene, Oligocene, and Miocene epochs of the Tertiary period (Vuke and others, 2004). In the late Tertiary (middle Miocene), Basin and Range style extension caused tilting and erosion of the Renova Formation, and a change in the basin-fill deposits to the more coarse-grained Sixmile Creek Formation (Vuke and others, 2004). In many areas these Tertiary sediments have been locally overlain by Quaternary deposits.



Modified from Vuke and others, 2007

Figure 7. The study area is underlain by Quaternary and Tertiary sediments. The adjacent mountains are composed of igneous, sedimentary, and metamorphic rocks ranging in age from Archean to Tertiary.

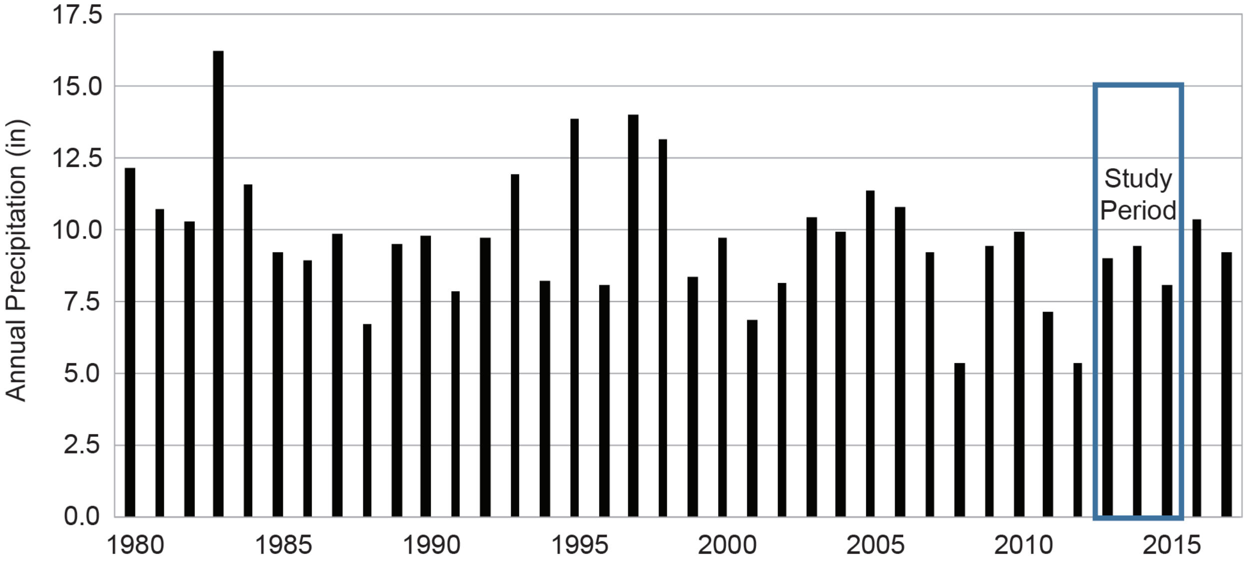


Figure 8. Annual precipitation in Twin Bridges (from https://climate.umt.edu/). During this study (2013, 2014, 2015) precipitation was below the 1981–2010 normal of 10.1 in, with values of 9.0, 9.4, and 8.1 in in these years.

Quaternary sediments consist of alluvial fan, alluvial terrace, colluvial, and alluvial deposits (Vuke and others, 2004). Alluvial fan deposits are composed of a poorly sorted mix of gravel, sand, silt, clay, and ash beds. Alluvial terrace deposits are thin (~5 ft) and composed of gravel, sand, silt, and clay. The colluvium is generally less than 30 ft thick, and is dominantly composed of sand, silt, and clay. The alluvium is a mixture of gravel, sand, silt, and clay deposited by modern rivers and streams and is typically less than 40 ft thick (Nobel and others, 1982; Vuke and others, 2004). The contact between the Quaternary sediments and the Sixmile Creek Formation can be difficult to discern in boreholes where both are coarse-grained (Kuenzi and Fields, 1971; Ruppel, 1993; Kendy and Tresch, 1996).

Hydrogeologic Setting

Hydrogeologic summaries of the Upper Jefferson area were developed by Noble and others (1982) and Kendy and Tresch (1996). These studies show that the north–south-trending part of the valley, from Twin Bridges to Whitehall, results from faulting along the mountain fronts (fig. 7). The valley bottom in this area is underlain by up to 6,000 ft of unconsolidated Tertiary sediments (Renova and Sixmile Creek Formations) and Quaternary alluvium, with the greatest thickness occurring near Waterloo. In the east–west-trending part of the valley, from Whitehall to Cardwell, the unconsolidated materials are thinner, with a reported thickness near Cardwell of 850 ft (Nobel and other, 1982). Most of the wells in the valley are completed in the Quaternary alluvium, which typically produces 50–100 gpm; however, some wells near Waterloo are reported to produce up to 1,000 gpm. The alluvium is typically less than 100 ft thick. Wells located on benches are typically completed in the Tertiary Renova sediments and produce about 10–15 gpm. Groundwater in this area is generally a good quality calcium-bicarbonate type water (Ca-HCO_3), with total dissolved solids (TDS) concentrations less than 500 mg/L.

Kendy and Tresch (1996) presented a qualitative groundwater budget for the area. They found that groundwater generally flows from the uplands to the floodplain, and then flows parallel to the Jefferson River. The basin-fill aquifers of the Jefferson Valley receive their water from precipitation and snowmelt, surplus irrigation water, irrigation canal leakage, subsurface flow from the adjacent bedrock, infiltration of tributary streams, and groundwater inflow from upgradient alluvium. Outflow from the area aquifers includes evapotranspiration (ET); pumping from wells; groundwater discharge to springs, seeps, irrigation drains, and streams; and groundwater outflow through the Jefferson River alluvium.

Water and Environmental Technologies (WET), LLC conducted a groundwater study of the Waterloo area (WET, 2006) that included measurement of groundwater levels, stream flows, canal flows, and an aquifer test. WET found that decreased canal losses and converting from flood to pivot irrigation could decrease the amount of water diverted from the river in the late summer. However, these measures would also decrease the amount of groundwater recharge throughout the entire irrigation season, resulting in less groundwater discharge to surface waters in the late summer. WET found that the net effect on late summer flows in the Jefferson River was unclear; however, such changes in irrigation practices would likely cause a decrease in groundwater recharge, with a subsequent reduction in late summer groundwater discharge that sustains flows in Parson's Slough and Willow Springs.

Surface-Water Network

The Jefferson River, the major surface-water feature flowing through the Upper Jefferson Valley (fig. 4), flows from the south to the northeast. Upstream from the study area, Lima Reservoir and the Clark Canyon Reservoir provide surface-water storage in the Beaverhead River drainage, and the Ruby Reservoir stores surface water on the Ruby River. When the Government Land Office surveyed this area in 1880, the Jefferson River followed what is now the Slaughterhouse Slough, and then split into the Jefferson Slough (Left Branch) and the lower portion of Slaughterhouse Slough (Right Branch; Confluence Consulting and Applied Geomorphology, 2014). Due to this historical alignment, the boundary between Jefferson and Madison Counties follows the Slaughterhouse Slough. A major avulsion occurred after 1880, which moved the mainstem of the channel to its current location on the south side of the valley.

Major tributaries to the Jefferson River within the study area are Fish Creek, Beall Creek, Pipestone Creek, Whitetail Creek, and the Boulder River. The South Boulder River flows into the Jefferson River approximately 0.75 mi downstream of the study area. Many ephemeral to intermittent streams flow out of the mountains and typically infiltrate into the alluvial fans, or are intercepted by irrigation canals, before reaching the Jefferson River. Several groundwater-fed tributaries to the Jefferson River begin and end within the floodplain, and most appear to be ancestral channels of the Jefferson River. These include Parson's Slough, Willow Springs, the lower portion of Fish Creek (the Fish Creek Canal), Slaughterhouse Slough, and the Jefferson Slough.

The USGS has monitored flows in the Jefferson River near Twin Bridges (USGS station 06026500; figs. 3, 4) intermittently from 1940 to present. Median daily discharge ranges from 528 to 5,850 cfs. Winter baseflow conditions extend from October through March. Higher flows occur during the spring when snowmelt occurs and precipitation is highest (fig. 3). Flows in the Jefferson River are at their lowest from late July through September (fig. 3).

The Creeklyn Canal begins near the south end of the study area where water is diverted from the Jefferson River upstream of the Highway 41 bridge (figs. 4, 5). The Creeklyn Canal is primarily used to irrigate land north of Silver Star. Any unused "tail water" from the canal flows into Fish Creek.

The Parrot Canal also begins in the southern portion of the study area, with a diversion from the Jefferson River downstream of the Creeklyn Canal diversion (fig. 4). The Parrot Canal feeds the All Nations Ditch near Silver Star, and provides irrigation water for the Waterloo area and the Parrot Bench. The Parrot Canal runs for 26 mi, and any tail water flows to the Jefferson River downstream of Mayflower Road (figs. 4, 5). Beall Creek and other Tobacco Root Mountain tributaries flow into the Parrot Canal during high flows. These tributaries have little or no flow during most of the year. Several "blowouts" along the canal allow excess water to discharge back to the Jefferson River, so that the canal's capacity is not exceeded.

The Jefferson/Fish Creek Canal diversion from the Jefferson River is immediately downstream of Parson's Bridge, but upstream of the USGS gage (figs. 4, 5). This canal flows north from the diversion until it reaches Fish Creek. A diversion from the canal just south of Fish Creek feeds the Fish Creek Canal (the lower portion of Fish Creek). The remainder of the water feeds the Jefferson Canal. Flow from Fish Creek, entering from the west, including any tail water from the Creeklyn Canal, flows into the Jefferson Canal. Any tail water from the Jefferson Canal flows into Pipestone Creek, and tail water from the Fish Creek Canal flows into the Slaughterhouse Slough.

The Slaughterhouse Slough is primarily fed by a diversion from the Jefferson River near Parrot Castle (figs. 4, 5). Water is diverted from the Slaughterhouse Slough to feed the Jefferson Slough, and Slaughterhouse Slough tail water discharges back to the Jefferson River between Kuntz Road and Mayflower Road (figs. 4, 5).

The Jefferson Slough begins with diversion of water from Slaughterhouse Slough, and is then supplemented with inflows from Pipestone Creek, including any Jefferson Canal tail water, Whitetail Creek, and the Boulder River. The Jefferson Slough discharges to the Jefferson River downstream of Cardwell (figs. 4, 5).

Piedmont Pond is a constructed pond that was excavated in the Piedmont wetlands area south of Whitehall (fig. 4). This pond was constructed by FWP as a youth fishing pond. Groundwater in this area is shallow, and efflorescent salts (likely calcite) are commonly observed at the surface due to the evaporation of groundwater rising to the surface via capillary action through the fine textured soils.

Water Infrastructure

Infrastructure related to crop irrigation includes irrigation canals, irrigated fields, irrigation wells (fig. 9), and drain tiles. Other infrastructure includes domestic wells and septic systems.

There are about 200 mi of irrigation canals (MT DNRC, 2007), and 15,000 irrigated acres [Montana Department of Revenue (MT DOR), 2012] within the study area. Water is applied to fields by pivot (45% of the acreage), flood (35%), and sprinkler (20%) systems (fig. 9). Most irrigation water is obtained from the Jefferson River, with smaller amounts diverted from Pipestone Creek, Whitetail Creek, Beall Creek, and the Boulder River (figs. 4, 9). Groundwater is also used for irrigation, with 40 irrigation wells in the study area (MBMG, 2016; table 1). Irrigation occurs along the floodplains of streams, and on the adjacent benches. Canals recharge aquifers through leakage. Irrigated fields provide recharge when water is applied in excess of crop demand. Drain tiles have been installed in some fields to promote rapid groundwater drainage to surface waters.

Table 1. Well uses based on GWIC (MBMG, 2016)

Well Type	Number of Wells
Irrigation	40
Domestic	569
Livestock	61
Monitoring	28
Public Water Supply	12
Unused	10
Commercial	2
Fire Protection	1
Industrial	1
TOTAL	724

The Montana DNRC measured canal leakage rates along portions of the Parrot, Creeklyn, and Jefferson/Fish Creek Canals between 2001 and 2003, with a focus on the reaches believed to have the highest loss rates (Ammon, 2005). This work showed overall canal leakage rates from 2.1 to 3.5 cfs/mi on the Parrot Canal; from 2.4 to 2.7 cfs/mi on the Creeklyn Canal; and from 0.9 to 1.1 cfs on the Jefferson/Fish Creek Canal. These measurements were made as synoptic events; all diversions from the evaluated canal reaches were shut off for at least 24 h before the synoptic runs.

An investigation of canal leakage rates and evaluation of approaches to increasing flow in the Jefferson River during droughts was completed by Van Mullem (2006). Synoptic discharge measurements and ponding tests indicated that canal leakage rates ranged from about 1 to 3 cfs/mi, with the higher rates occurring at higher canal stages.

Non-irrigation water infrastructure in the study area is primarily related to domestic uses. There are 684 non-irrigation wells within the study area (fig. 9, table 1), including 569 domestic wells. Septic systems serve homes outside of city service areas, and they infiltrate wastewater to the groundwater system.

METHODS

Data Management

Data collected for the Upper Jefferson investigation are archived in the MBMG's Ground Water Information Center (GWIC) database. Accessible online at http://mbmggwic.mtech.edu/, GWIC includes information on well completions, groundwater levels, water chemistry, aquifer tests, and other data. The sites monitored for this study, with GWIC ID numbers, are listed in appendices A and B. The data for this study can also be accessed through the relevant project page within the GWIP section of the MBMG website (mbmg.mtech.edu).

Monitoring and Sampling

For this report, monitoring locations are denoted by the well or surface-water site numbers on figures 10 and 11 (e.g., well 12 or site 34). These numbers are used throughout this report, and are also included in appendices A and B.

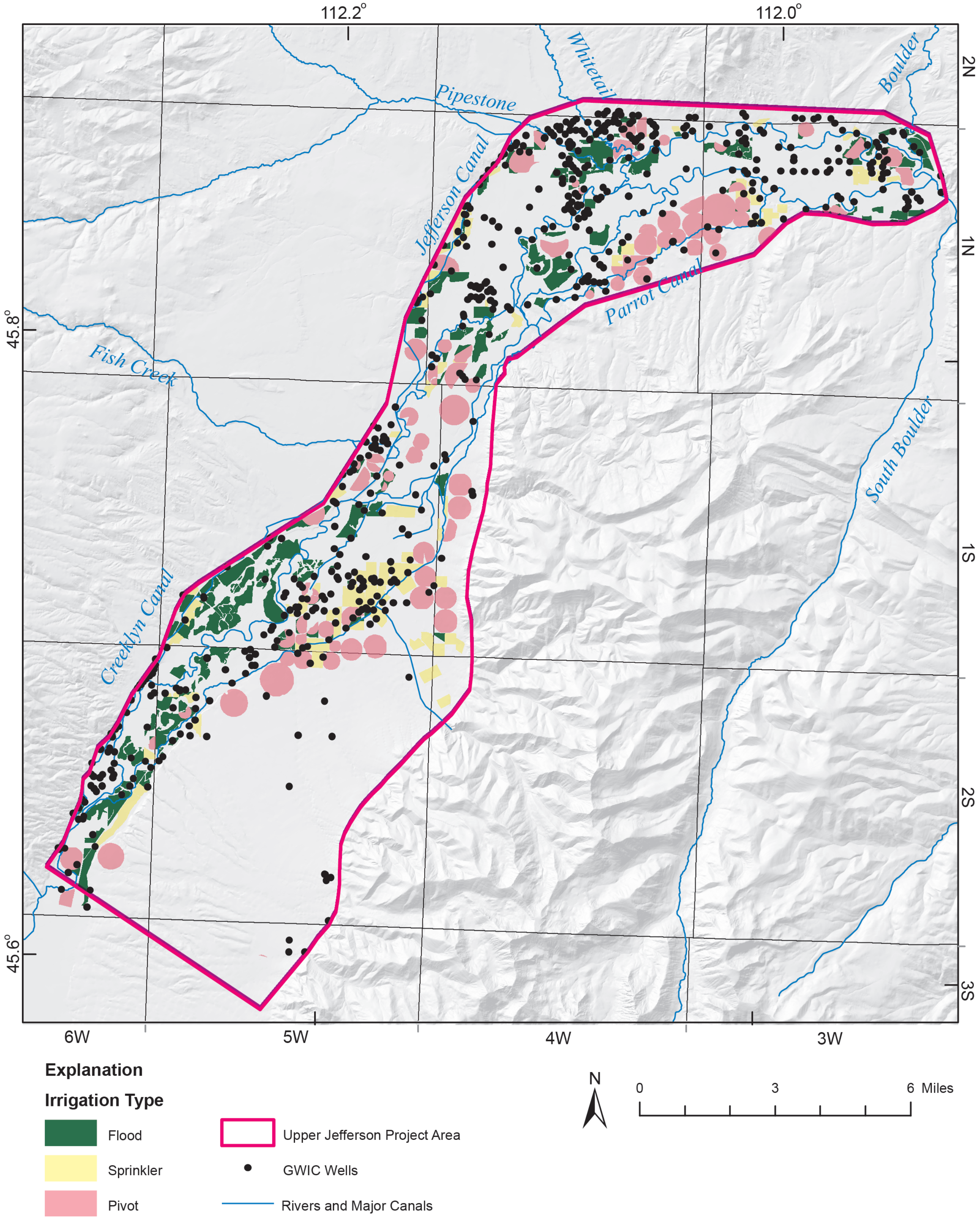


Figure 9. Irrigation canals, irrigated fields, and wells affect the movement of water through the Upper Jefferson Valley.

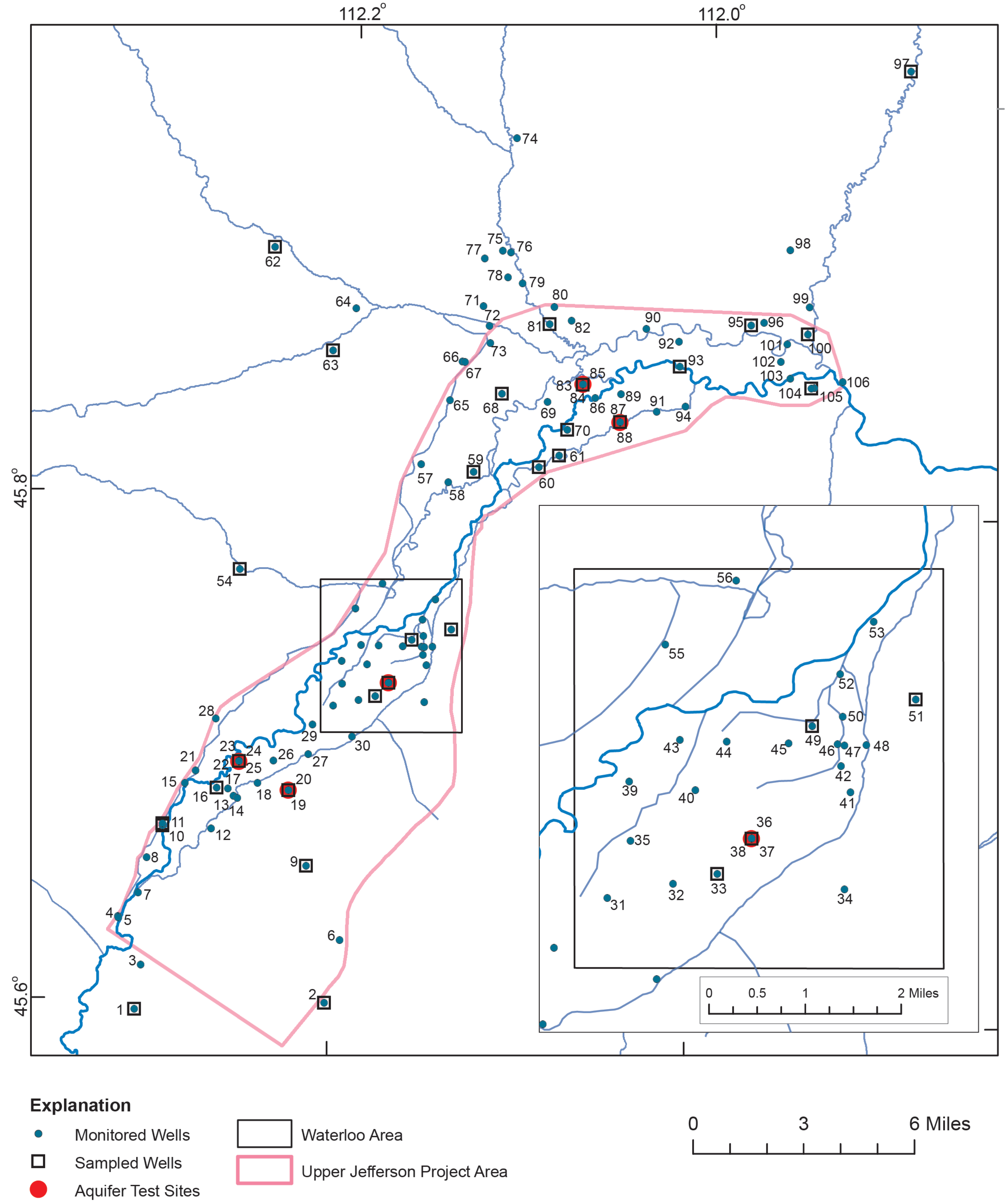


Figure 10. Groundwater-level data from 106 wells were used for this study. Groundwater-quality samples were collected from 11 of these wells, and aquifer tests were conducted at five sites. Water-quality samples were collected during each of the aquifer tests. The inset map shows wells near Waterloo. See appendix A for GWIC ID numbers and additional site information.

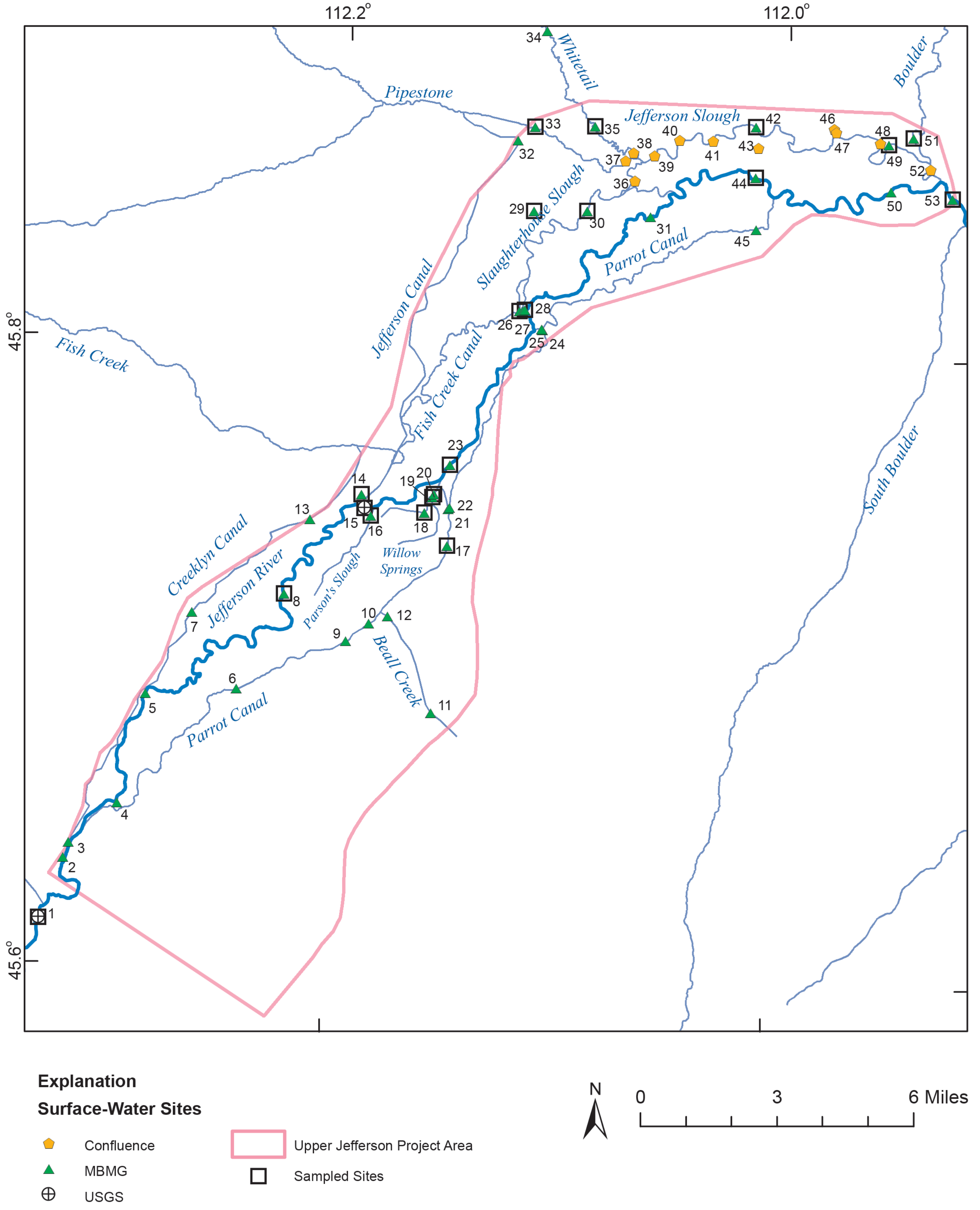


Figure 11. Surface waters were monitored at 53 sites by the MBMG, the USGS, and Confluence Consulting. The MBMG collected water quality at 19 of these sites (black dots, plotted behind the other symbols). See appendix B for GWIC ID numbers and additional site information.

Groundwater

A monitoring network of 106 wells was established to obtain water-level and water-quality information (fig. 10, appendix A). The network included 17 dedicated monitoring wells installed during a prior investigation by WET (2006), and 20 dedicated monitoring wells installed during this study. The rest of the monitoring network consisted of domestic or stock water wells. Fifty-three of the wells were monitored prior to this study by MBMG's Ground Water Assessment Program and by WET (appendix A). Although groundwater levels were measured in domestic and stock wells under non-pumping conditions, some measurements may have been somewhat lower than static due to recent use.

Well selection for the network was based on hydrogeologic setting, geographic location, historical groundwater information, and well owner permission. Measuring points marked on each well casing were surveyed and static groundwater levels were measured monthly. Monitoring occurred from July 2013 until May 2015; however, the period of record for each well depended on when permission to monitor was obtained. Monitoring began at 49 wells in July 2013, and 89 wells were included by the end of March 2014. Most of the wells added after March 2014 were installed for this study. Twenty-four wells were equipped with pressure transducers that provided hourly records of water level and temperature.

Seventeen groundwater-quality samples were collected from 11 wells (fig. 10, appendix A). Sampled sites were selected based on location and well completion, with a focus on sampling that would aid in understanding groundwater/surface-water interactions. All samples were collected and handled according to MBMG standard sampling procedures and all samples were analyzed by the MBMG analytical lab (Timmer, 2020). Specific conductance, pH, and temperature were measured in the field. An unfiltered unpreserved sample was analyzed for specific conductance, pH, and alkalinity in the lab. Filtered samples were analyzed for major ions, trace elements, nutrients, and water isotopes ($\delta^{18}O$ and δD). Six well samples were collected between August 19 and 22, 2014, as part of a synoptic groundwater/surface-water sampling event (wells 9, 49, 54, 68, and 93; fig. 10). Two wells (49 and 51; fig. 10) in the Waterloo area were sampled on November 18, 2014, January 30, 2015, and March 30, 2015, in conjunction with surface-water sampling, to evaluate seasonal changes in water chemistry. Five samples were collected during aquifer tests in February and March 2015 (wells 19, 22, 37, 84, and 88). Data presented in this report also include results from 25 samples collected from 17 wells in the study area during past MBMG studies (fig. 10; appendix A).

Surface Water

Surface-water data presented in this report were collected at 53 sites (fig. 11, appendix B). Most of the surface-water sites included stilling wells and staff gages outfitted with recording pressure transducers to collect hourly stage and temperature readings during the ice-free period. The USGS sites recorded values every 15 min, although the Parson's Bridge site (site 15) was only operational from July through September each year. Four of the sites operated by Confluence Consulting included only temperature monitoring. At MBMG sites, staff gages were surveyed, and discharge and stage were measured approximately every 2 weeks during the ice-free period of 2014 to develop rating curves. The rating curves were used in conjunction with the recorded stage measurements to calculate hourly discharge for the ice-free periods.

Thirty-four surface-water-quality samples were collected at 19 of the surface-water sites (fig. 11, appendix B). All samples were collected, handled, and analyzed using the same methods as the groundwater samples (Timmer, 2020). Twenty of these samples were collected between August 19 and 22, 2014. The other 14 samples (including 2 duplicate samples) were collected from sites 16, 18, 19, and 20, near Waterloo, on November 18, 2014, January 30, 2015, and March 30, 2015, to evaluate seasonal changes in water chemistry.

Canal Leakage

Sixteen of the surface-water sites were located on irrigation canals. The difference in discharge between consecutive stations was used to estimate the net loss between those stations; however, all diversions were not measured, so it is assumed that most (but not all) of the estimated net loss includes diversions. Assuming that the soils beneath a canal have reached field capacity, the canal leakage rate will be a function of canal stage (Wooding, 1968). Therefore, the leakage to discharge relationship was estimated based on the lowest net loss rate (presumably when diversions were not occurring) over a range of stages. These results were also compared to previous leakage studies conducted under conditions of no diversions (Ammon, 2005; Van Mullem, 2006).

Hydrogeologic Units

Surficial geologic maps (Vuke and others, 2004; Vuke, 2006) and lithologic descriptions from water-well logs (GWIC) were used to develop a three-dimensional model of the distribution of hydrogeologic units (HGUs) in the Upper Jefferson study area. This model was developed using Aquaveo's GMS software (v. 10.0). The land surface in the model was defined using a 1/3 arc-second (~10 m) digital elevation model (DEM; USGS, 2012). Within the study area, 1,247 wells and boreholes were rated based on the quality of their location information. A "good" rating was assigned to sites with survey or global positioning systems (GPS) information (239 wells; GWIC project code BWIPUJLITH1). Sites located in a parcel with cadastral ownership information matching the name of the well, or located to a 2.5-acre parcel by the township-range-section (TRS) method were classified as "moderate" (348 wells; BWIPUJLITH2). All other sites (660 wells; BWIPUJLITH3) were rated as poor. Records used in the model were restricted to the good and moderate location categories. Where wells were located in close proximity, preference was given to deeper wells and those with more detailed lithologic descriptions; this resulted in a subsurface model based on 349 well records.

Hydrogeologic Units (HGUs)

The lithologic information reported on drillers' well logs was evaluated and assigned to one of four HGUs. The four HGUs are bedrock, Renova Formation, bench sediments, and alluvium (table 2). Each of these units is used as an aquifer within the study area, but they have differing aquifer properties.

Aquifer Tests

Bobst and Gebril (2020) report on five aquifer tests conducted during this study to estimate hydraulic conductivity and storativity of the alluvium and the Renova Formation (fig. 10).

Groundwater/Surface-Water Interactions

Surface and groundwater monitoring data were analyzed in four ways. These were: (1) comparing hourly stream flows from the upstream and downstream ends of a reach; (2) comparing water temperatures from the upstream and downstream ends of a reach; (3) comparing time-series groundwater and surface-water elevations at specific points; and (4) comparing time-series groundwater and surface-water temperatures at specific points. We attempted to use geochemical signatures to help identify gaining reaches and to quantify the magnitude of those gains; however, the major ion chemistry of alluvial water and surface waters was similar, and these data did not provide a reliable indicator of groundwater baseflow to streams. The isotopic compositions of different water sources did provide some information. The different methods used in this analysis are difficult to interpret independently, in part because some measure processes along a reach while others are based on point measurements. We used these methods in combination to characterize groundwater/surface-water interactions along reaches throughout the study area (appendix C). Since several methods were used in combination, we summarized the results for each reach. A preponderance of the data was used to classify each reach as gaining, slightly gaining, neutral, slightly losing, or losing. For gaining and losing reaches all of the available methods

Table 2. General hydrostratigraphy.

Geologic Age	Geologic Unit*	Hydrogeologic Units
Quaternary	Alluvium (Qal)	Alluvium
	Alluvial Terrace and Colluvium (Qg)	Bench Sediments
	Alluival Fan (Qaf)	
Tertiary	Sixmile Creek Formation (Ts)	
	Renova Formation (Ts)	Renova Formation
Mesozoic, Paleozoic and Precambrian	Bedrock (Kv, Ki, Ps, and pC)	Bedrock

*Figure 7 illustrates geologic setting.

indicated a net gain or loss all of the time. For slightly gaining and losing reaches most methods indicated net gains or losses most of the time. Reaches were assigned as neutral when they did not show clear gaining or losing behavior.

Numerical Models

Numerical groundwater flow models were developed for the Waterloo and Whitehall areas using the United States Geological Survey's (USGS) MODFLOW code (Harbaugh and others, 2000; Harbaugh, 2005; fig. 6). Reports for each model provide documentation on groundwater budgets, model construction, calibration, and applications (Gebril and Bobst, 2020, 2021), with a brief summary presented here.

Waterloo Model

The Waterloo model (Gebril and Bobst, 2021) simulates potential changes in irrigation practices and related effects to groundwater discharge to Parson's Slough, Willow Springs, and the Jefferson River. This single-layer model represents shallow alluvial sediments under unconfined conditions. A steady-state version of the Waterloo model was calibrated to observed groundwater levels in April 2015 (before irrigation began), and water levels reported by drillers in well completion reports. A transient version of the model was calibrated to conditions from July 2013 to October 2015 and simulates time-dependent stresses, including seasonal irrigation activities, groundwater pumping, and changes in river stage.

Whitehall Model

The Whitehall model (Gebril and Bobst, 2020) simulates increased groundwater development via exempt wells and changes in land use, and related effects on groundwater discharge to the Jefferson River and the Jefferson Slough. The model was based on groundwater and surface-water monitoring data collected during this study (2013–2015). Layer 1 of the two-layer model generally represents alluvium and bench sediments, and Layer 2 generally represents the Renova Formation. The steady-state model incorporates spatially variable hydraulic conductivity and was calibrated to average groundwater levels. A transient version of the model was calibrated to conditions from April 2013 to December 2015. Time-dependent stresses included variations in surface-water flows, groundwater pumping rates, canal leakage, irrigation recharge, and evapotranspiration.

RESULTS

Hydrostratigraphy and Aquifer Properties

The subsurface hydrogeologic model was used to develop 687 cross sections that establish the extent and thickness of HGUs across the study area (figs. 12, 13). This geometry informed the development of water budgets and numerical groundwater flow models (Gebril and Bobst, 2020, 2021). The general geometry of the HGUs and their relationships are discussed below. All of these units are used as aquifers within the study area; groundwater levels in the different HGUs are similar, and aquifer tests show that confining layers are often leaky. Therefore, we view these HGUs as parts of a single system, with the HGUs having differing hydrogeologic properties.

Bedrock

Bedrock underlies the Tertiary and Quaternary sediments, and outcrops along the edges of the study area (figs. 7, 13). Many of these rocks have been fractured, folded, and faulted due to several episodes of tectonism in the area (McDonald and others, 2012). The bedrock has a relatively low primary permeability, but the fractures provide for some secondary permeability. The hydraulic conductivity (K) of fractured bedrock units typically ranges from about 0.2 to 5 ft/d (Heath, 1983). Reported well yields in this study area from the bedrock are typically less than 10 gpm (Noble and others, 1982; Kendy and Tresch, 1996; MBMG, 2016). The Jefferson Canyon at the downstream end of the study area features a narrow bedrock canyon, with bedrock outcropping along the banks of the Jefferson River. Within the canyon bedrock likely extends to near the streambed elevation.

Renova Formation

Renova Formation sediments underlie the bench sediments and the alluvium in most of the study area (fig. 13). The Renova Formation HGU is mainly composed of mudstone and siltstone; however, there are regionally discontinuous sand and gravel lenses. The sand and gravel layers are typically confined to semi-confined. Reported well yields from the Renova sand and gravel layers are about 10–15 gpm.

Four aquifer tests were conducted in the Renova Formation HGU for this study (table 3; Bobst and Gebril, 2020). A leaky-confined model provided the best

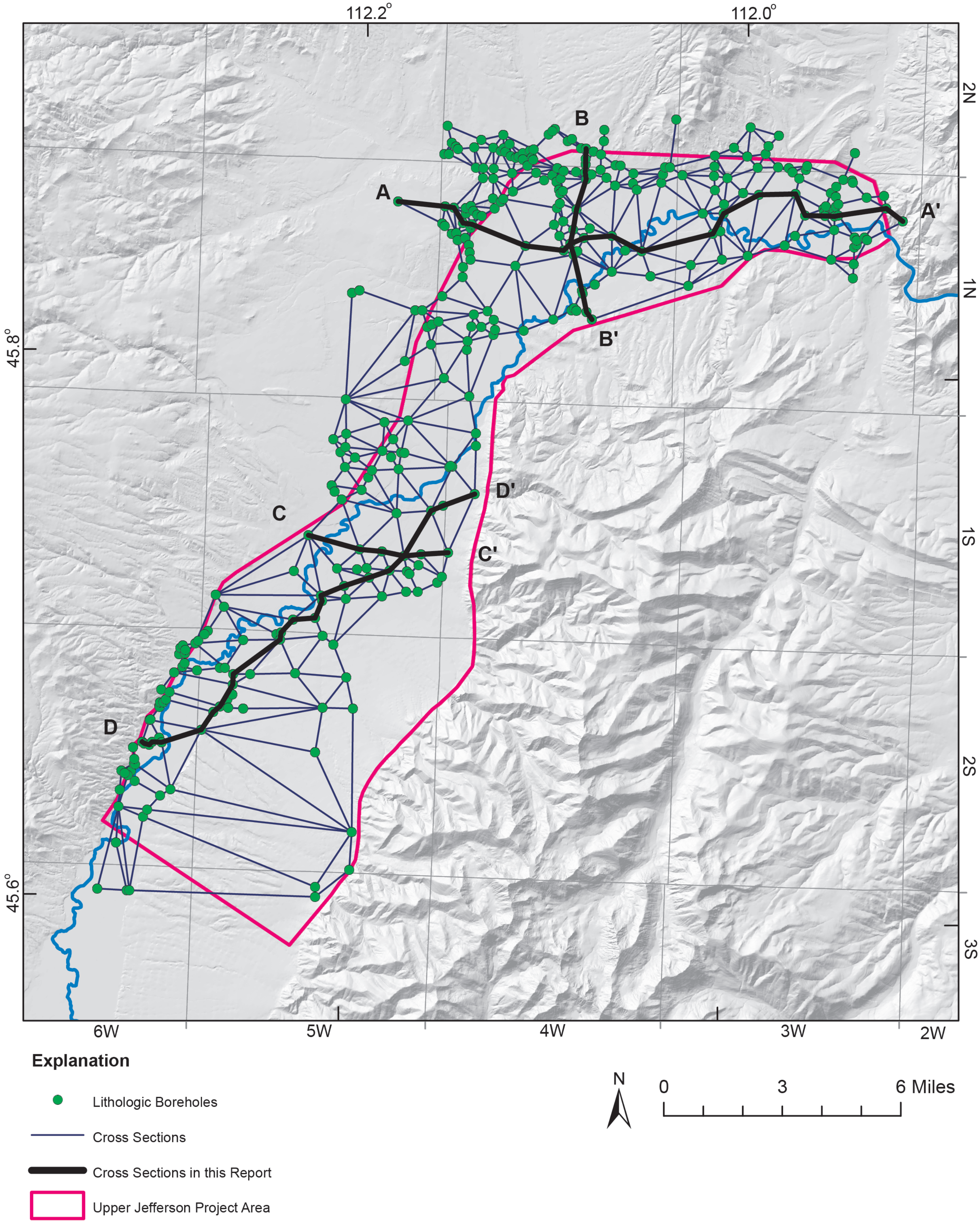


Figure 12. The hydrogeologic model developed for the Upper Jefferson study area included data from 349 boreholes, and involved the construction of 687 cross sections. Labeled cross sections are shown in figure 13.

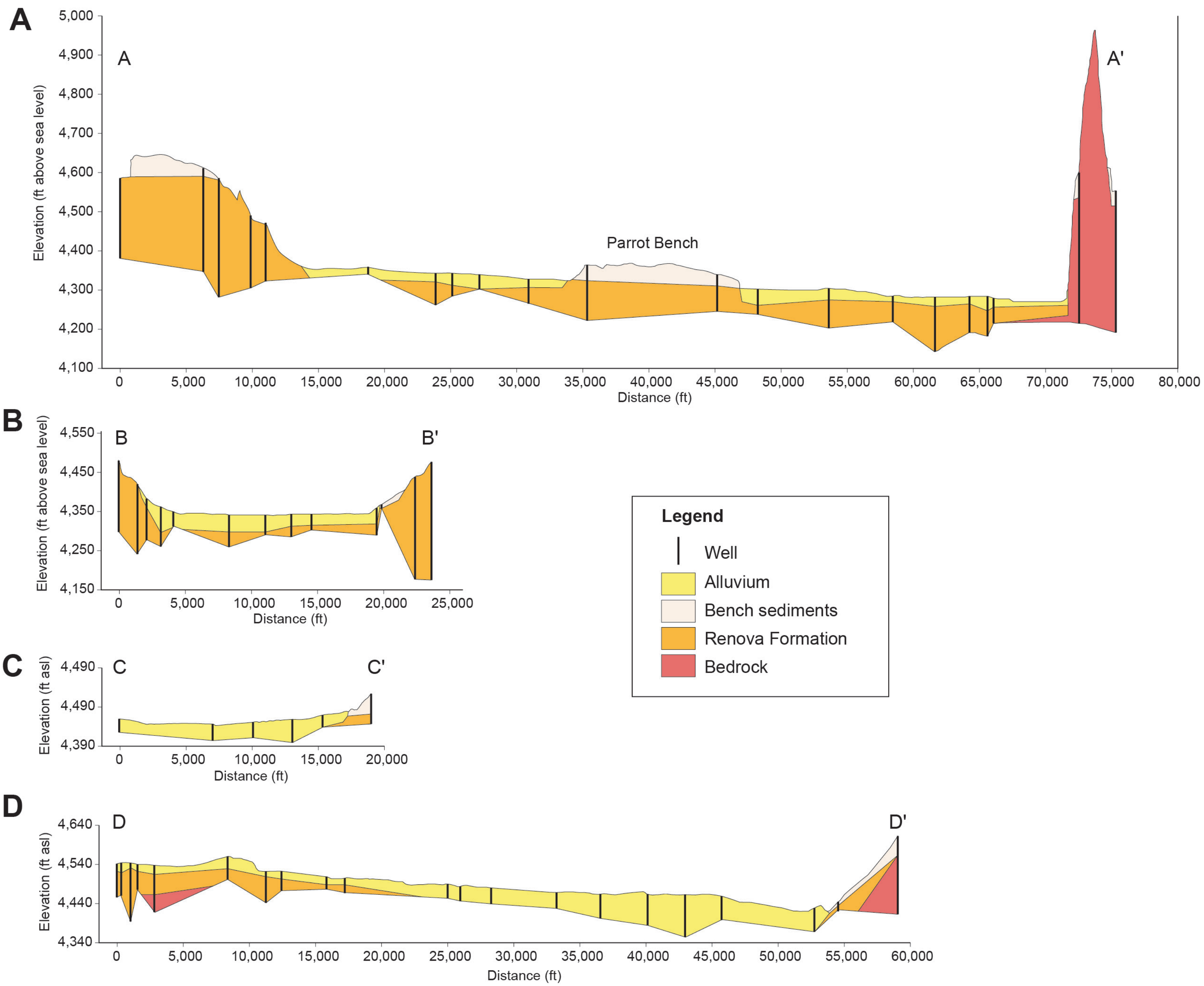


Figure 13. The hydrogeologic model shows that bench sediments are present near the mountain fronts, and are underlain by bedrock or Renova Formation sediments. The Renova Formation also underlies the alluvium. In most of the valley the alluvium is about 40 ft thick (cross sections A–A' and B–B'); however, in the Waterloo area (cross sections C–C' and D–D') it is over 150 ft. Cross section lines are shown in figure 12.

Table 3. Aquifer test results.

Test Name	Pumping Well GWIC ID	Observation Well GWIC IDs	Hydrogeologic Unit	Transmissivity (T; ft²/d)	Hydraulic Conductivity* (K; ft/d)	Storativity (S; unitless)
HCC Floodplain	277403	277404; 277405; 277406	Renova Formation	74 to 77	4	1.5×10^{-7} to 1.6×10^{-5}
HCC Bench	280980	280979	Renova Formation	255	26	0.20
Hunt Floodplain	279259	279258; 279260	Alluvium	41,000 to 44,500	2,050 to 2,225	0.14
Lazy TP Floodplain	279262	279261; 279263	Renova Formation	310 to 440	16 to 22	8.0×10^{-4} to 2.0×10^{-3}
Lazy TP Bench	280978	280977	Renova Formation	5,800	580	5.2×10^{-5}

*Hydraulic conductivity was estimated by dividing the transmissivity by the pumping well screen length.

fit to observations at two of the sites. Confined and unconfined models fit observations at the third and fourth sites, respectively. Transmissivity values from these tests ranged from 74 to 5,800 ft²/d, and the geometric mean hydraulic conductivity was 28 ft/d. Specific storage values ranged from 1.5×10^{-7} to 2×10^{-3}, and the unconfined test showed a specific yield value of 0.2. The calculated aquifer properties are comparable to literature values for silty sand to fine gravel (Heath, 1983).

Bench Sediments

The benches that lie between the mountain fronts and the modern floodplain consist of thick accumulations of Tertiary and Quaternary sediments (table 2; figs. 7, 13). The bench sediments are composed of fine- to coarse-grained sand and fine gravel, with minor amounts of silt and clay. This unit is underlain by the Renova Formation. Aquifer tests conducted in similar materials in the adjacent Boulder Valley (Bobst and others, 2016) indicate that hydraulic conductivity (K) ranges from about 22 to 750 ft/d, which is comparable to literature values for medium sand to fine gravel (Heath, 1983). Based on these K-values it is anticipated that wells completed in the saturated bench sediments would have yields of about 10–50 gpm. Aquifer tests were not conducted in these sediments for this study because they were not saturated at the drilling sites.

Alluvium

Quaternary alluvium is present in the modern floodplain adjacent to, and underlying, the Jefferson River and associated sloughs (figs. 7, 13). The alluvium is the most productive hydrogeologic unit in the study area. Most wells completed in the alluvium are capable of producing more than 50 gpm, and reported yields are as high as 1,000 gpm. Although permeable, the alluvium is less than 50 ft thick in most of the area. In the portion of the Jefferson Valley east of Whitehall, the alluvium is thickest below the Jefferson Slough, rather than below the modern river channel. Wells in the valley bottom east of Whitehall are often completed in sand lenses within the Renova Formation HGU, due to relatively thin alluvium. In the Waterloo area the alluvium is relatively thick, with wells completed at depths up to about 160 ft. An aquifer test conducted in the alluvium near Waterloo (fig. 10; well 37) in a clean gravel layer yielded a transmissivity of about

43,000 ft^2/d, a hydraulic conductivity of about 1,400 ft/d, and a specific yield of about 0.14 (Hunt Test; Bobst and Gebril, 2020; table 3). In many locations, the alluvium is directly connected to surface waters.

Regional Groundwater Flow

Since we view the HGUs as parts of a single system, a composite potentiometric surface map was developed for the study area that contoured groundwater levels from all HGUs. Surface-water bodies also informed development of the potentiometric surface, because surface water and groundwater are well connected in the study area. The map is based on water-level measurements from April 13th and 15th, 2015, prior to the irrigation season (fig. 14). Groundwater flow paths generally mimic the direction of surface-water flows (fig. 14). Groundwater flows into the study area in the south through the alluvium. Groundwater also enters through the alluvium along tributaries of the Jefferson River, and from mountain front recharge along the lateral edges of the study area. Groundwater flows north and east through the study area, towards the Jefferson Canyon (fig. 14). Bedrock is at or near the surface in the Jefferson Canyon, suggesting that much of the groundwater flows into the Jefferson River and other surface waters above the bedrock constriction.

Groundwater-Level Variations

Groundwater levels change over time in response to changes in recharge or discharge. Some of these changes are due to seasonal variations (e.g., infiltration of snowmelt, irrigation, summer versus winter well pumping patterns) while others reflect long-term changes (e.g., changes in groundwater pumping, changes in land use, lining irrigation canals, drought–wet cycles). Understanding the causes behind observed groundwater-level patterns provides for a better understanding of the system, and allows for improved prediction of the effects from proposed changes. In the study area, seasonally changing stresses include well pumping, irrigation canal leakage, irrigation recharge, plant evapotranspiration, snowmelt infiltration, and river stage. An overview of hydrograph patterns is provided below, with a summary categorization in appendix A, and a presentation of hydrographs in appendix D.

Seasonal Groundwater-Level Variations

Groundwater-level patterns depend on the location of the well with respect to hydrologic features (appendix A). Similar responses occur in wells that are directly influenced by the Jefferson River (fig. 15A); influenced by irrigation (fig. 15B); in floodplain areas, but are not directly influenced by the Jefferson River or irrigation (fig. 15C); and upgradient from irrigation (fig. 15D).

Wells completed near the river respond to the rise and fall of river stage. Maximum groundwater elevations generally occurred in early June, and minimum groundwater elevations occurred in late August. Site-specific short-term high water levels occurred during the winter due to ice jams on the river (fig. 15A).

Wells influenced by irrigation respond to recharge from irrigation water applied to fields in excess of available soil field capacity and canal leakage. Minimum groundwater elevations generally occurred just before irrigation begins in April, and maximum groundwater elevations occurred during the irrigation season (June–October, fig. 15B). Changes in groundwater levels in deep wells occurred somewhat later than in shallow wells. Some wells also respond to local pumping, resulting in low water levels in mid-summer due to lawn watering and nearby irrigation wells, but with high water levels in the spring and fall.

Wells in the floodplain, but not directly influenced by the application of irrigation water or the river, respond to increased pumping in the summer, primarily for lawn watering or irrigation pumping. This includes wells that are completed in areas that are not irrigated, and wells completed in irrigated areas where there is some separation between the monitored aquifer and the surficial aquifer. Maximum groundwater elevations generally occurred in March or April, and minimum groundwater elevations generally occurred in August (fig. 15C).

Wells completed in areas upgradient from irrigation respond to pumping and direct and indirect sources of precipitation recharge, including mountain front recharge. Since the time required for mountain front recharge to reach the wells can vary widely, peak groundwater elevations occurred from June to October. In some wells minimum groundwater elevations occurred in May, just before the onset of spring recharge. Other wells had minimum groundwater eleva-

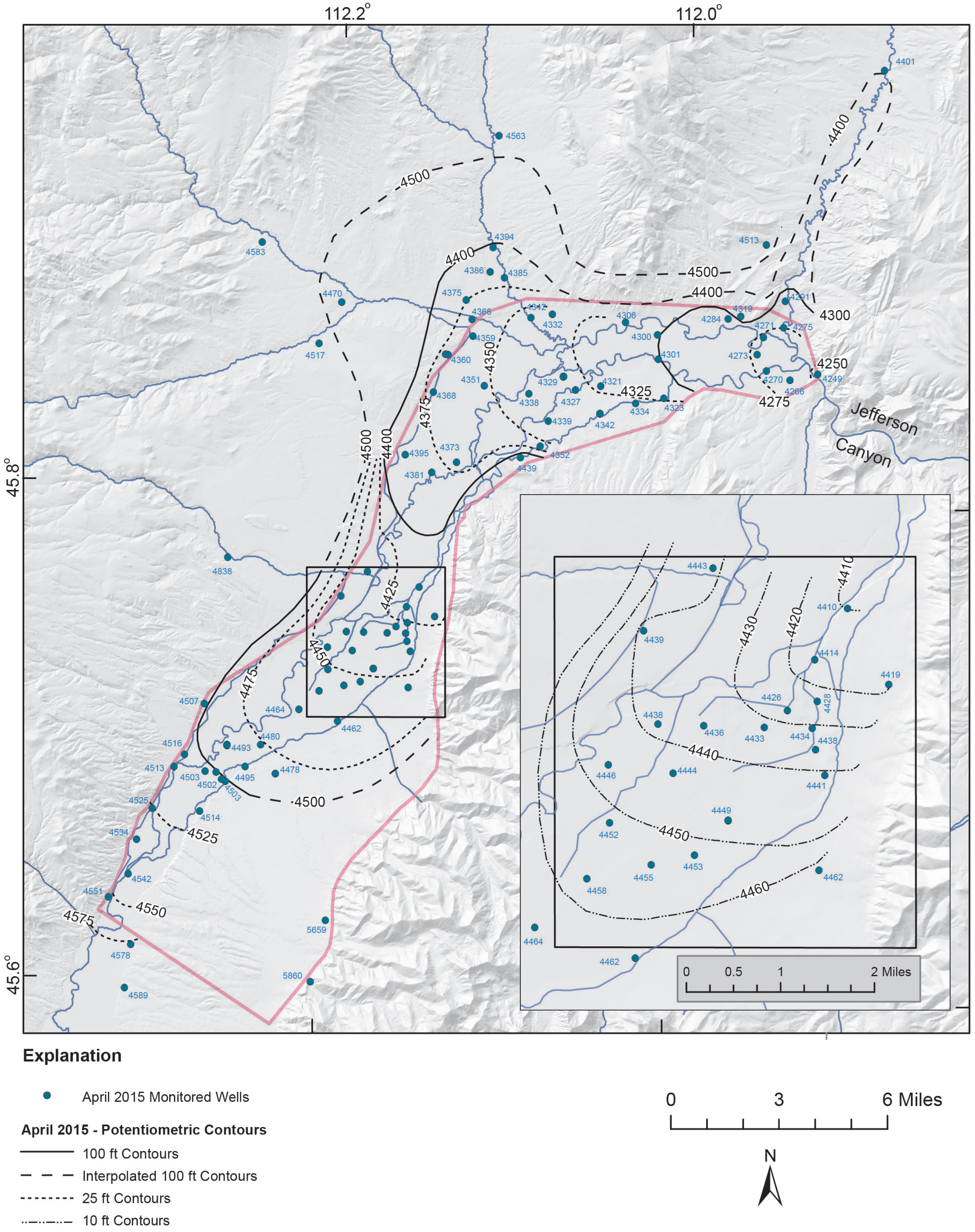


Figure 14. The April 2015 potentiometric surface is generally a subdued representation of the land surface, with groundwater flow through the unconsolidated sediments (fig. 7), toward the Jefferson Canyon (fig. 2).

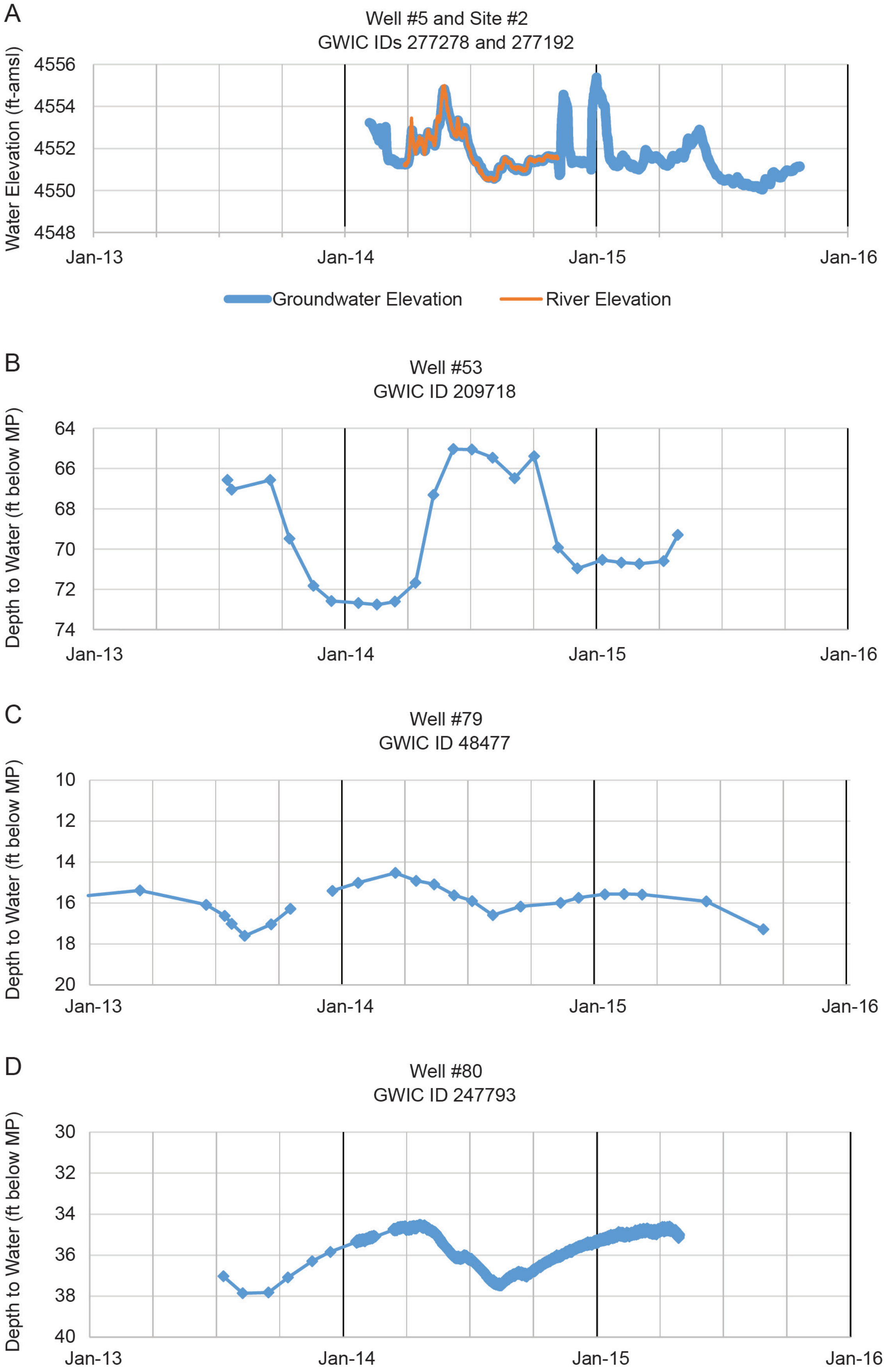


Figure 15. Groundwater-level variations depend on the well’s location. Wells may respond to changes in river stage (A), changing irrigation activities (B), may be in the floodplain, but not be directly affected by irrigation activities (C), or may be upgradient from irrigation activities and away from the river (D). Note variable scales on y-axes.

tions in July and August, in response to pumping for lawn irrigation (fig. 15D).

Long-Term Groundwater-Level Variations

Long-term changes in groundwater levels were evaluated in the 53 wells that had historical monitoring data (appendices A and D). Three of the hydrographs had apparent declines over the period of record (wells 6, 47, and 56; fig. 16), although this is based on only one measurement from 2011 at wells 6 and 56. Data from well 47 include 24 measurements from 2004 to 2005. These sites are separated from each other, with intervening wells showing no water-level decline, indicating the declines are not likely related to climate, or a reginal decline in water levels due to increased groundwater pumping. The decline in well 6 is attributed to local pumping causing a decline due to the low productivity of the bedrock aquifer. The decline in well 47 likely results from reduced flood irrigation near the well. The decline in well 56 may result from reported high flows in Fish Creek in the spring of 2011 (prior to this study; R. Smith, oral commun., 2014), and the water levels returning to its long-term normal elevation, or may result from local pumping causing a decline.

Canal Leakage

Canal leakage rates were investigated on the Parrot and Creeklyn Canals (figs. 4, 11; appendices B, C, and E), which divert up to 250 and 70 cfs, respectively. The estimated leakage rates were used in developing groundwater budgets and flow models (Gebril and Bobst, 2020, 2021).

Monitoring sites were established on the canals and on “blowouts” (where excess water is diverted from the canal). Eight sites were established on the Parrot Canal (sites 4, 6, 9, 10, 17, 22, 24, and 45; fig. 11), and two sites were established on its associated blowouts (sites 21 and 25; fig. 11). One unmonitored blowout, and the unmonitored diversion for the All Nations Ditch, occur on the Parrot Canal between the diversion (site 4) and Waterloo Road (site 6), so leakage rates were not estimated for that reach. Three sites were established on the Creeklyn Canal (sites 3, 7, and 13; fig. 11).

Observed flows were used to estimate net loss rates from the Parrot Canal. Canal leakage rates increase at higher flows due to the increased stage (Wooding, 1968). To evaluate the effects of flow rate and stage on canal leakage, the daily mean net loss rate in flow between monitoring stations was plotted vs. the daily mean flow for that day at the upstream station (fig. 17). We assume the smallest net loss at a given flow rate (i.e., the lower right side of the point cloud in fig. 17) corresponds to times when no diversions occurred between the stations. A line fitted to these points defines the relationship of canal leakage to flow for that canal reach. For each reach, we calculated an overall average leakage rate based on the observed average flow at the upstream station during the irrigation season. Average leakage rates for the Parrot Canal ranged from 1.0 to 1.6 cfs/mi, and the average was 1.3 cfs/mi. These results are similar to those from the synoptic measurements and ponding tests conducted by Ammon (2005) and Van Mullem (2006) when no diversions were occurring.

Two methods were applied to measurements from the Creeklyn Canal. There are no irrigation diversions along the 6.4-mi reach between the two upstream stations (sites 3 and 7; fig. 11), so the net difference in flow provides an estimate of leakage. The daily mean net loss rate was plotted vs. daily mean flow at the upstream station. A best-fit line defines the leakage-to-flow relationship for the upstream reach (fig. 18). The average leakage rate for this reach during the 2014 irrigation season was 1.4 cfs/mi. The calculated leakage in the downstream reach of the Creeklyn Canal (between sites 7 and 13; fig. 11), following the procedure applied to the Parrot Canal, averaged 6.6 cfs/mi. This value is about five times greater than for the upstream reach and is inconsistent with synoptic measurements and ponding tests conducted by previous investigators with irrigation diversions shut off (Ammon, 2005; Van Mullen, 2006). Therefore, we attribute this 6.6 cfs/mi rate to continuous irrigation diversions along this reach in 2014, rather than being representative of canal leakage alone.

Water Chemistry

Sampled sites were primarily selected to aid in understanding groundwater/surface-water interactions; however, since the alluvial water chemistry was similar to surface water, these data did not provide a reliable indicator of groundwater baseflow to streams. As described in the Methods section, we present water chemistry results from this and prior studies (appendices A and F). The wells that were

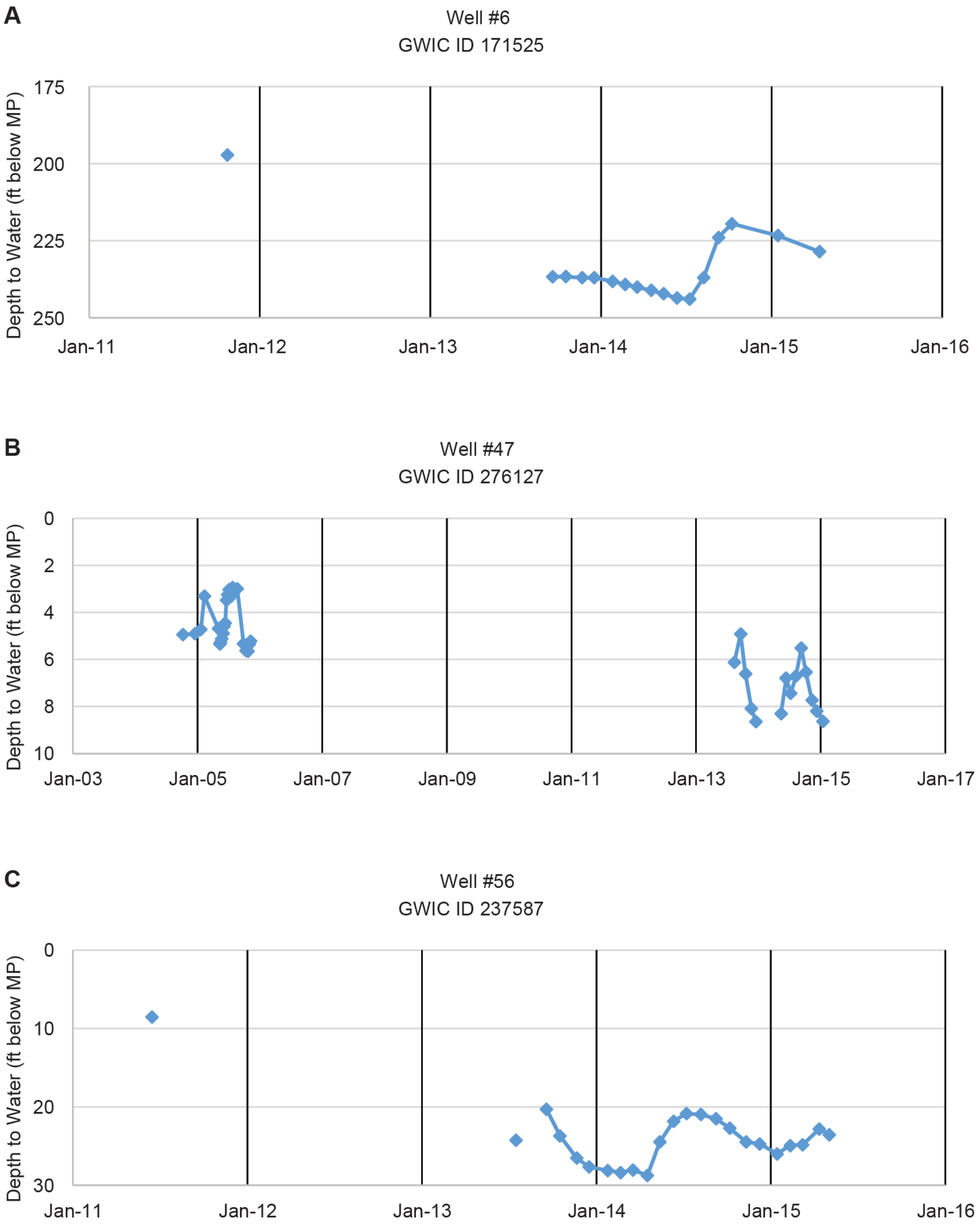


Figure 16. Long-term groundwater monitoring data showed apparent declines in 3 of the 53 wells evaluated.

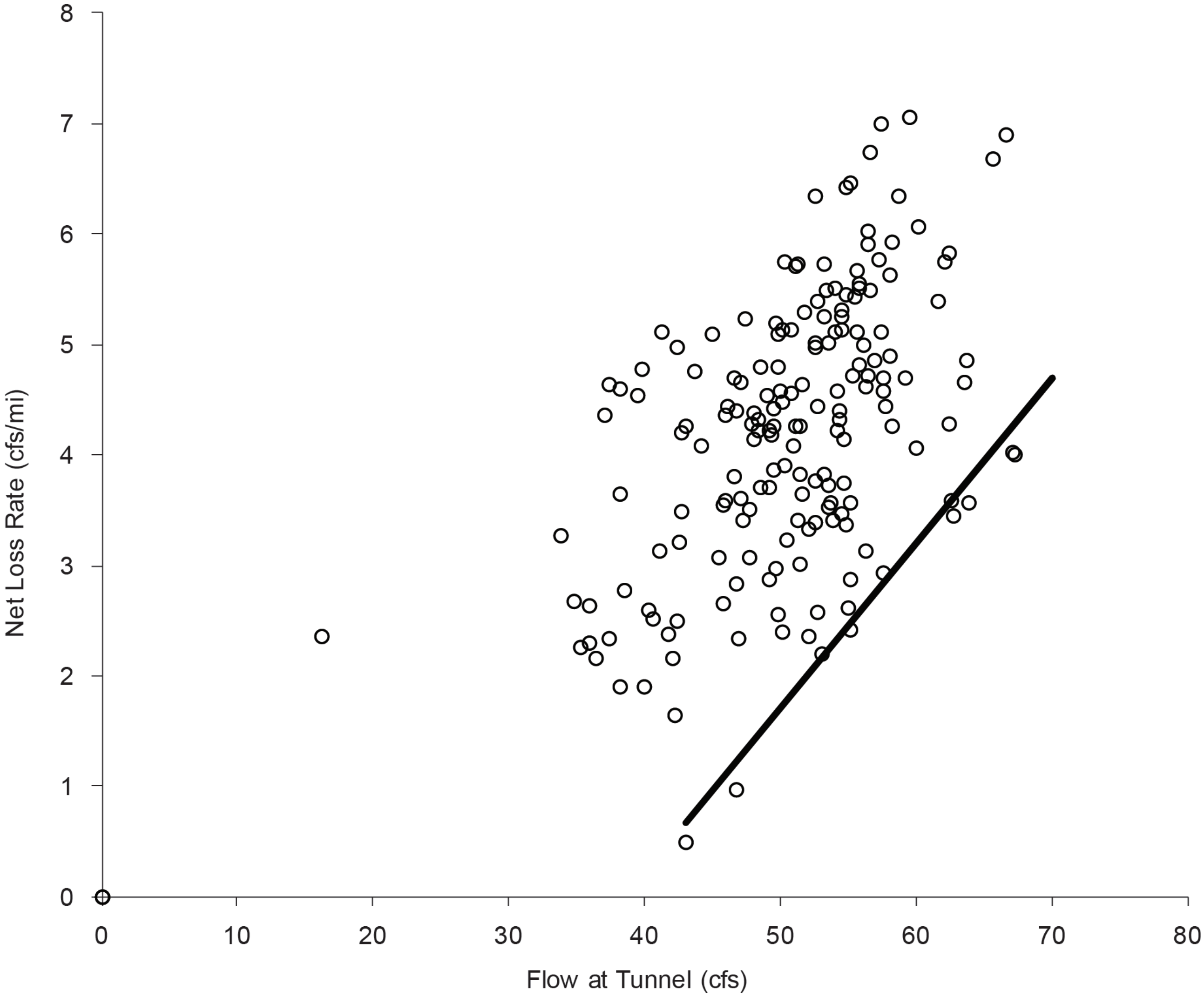


Figure 17. The rate of leakage from the Parrot Canal increased at higher flows. The black line is the best fit line for the subgroup of estimates that represent the lowest measured net loss at a given flow rate. The lowest measured loss values were used to estimate canal leakage because all diversions from the canal were not measured.

sampled over time did not show substantial variation in major ion chemistry; therefore for this discussion we used the sample results from the August 2014 synoptic sampling event. For wells with data from previous studies, if there were multiple samples, we used the most recent results. Results are compared to the Montana DEQ's primary, health-based standards for drinking water (maximum concentration limits, or MCLs), and their secondary standards (SMCLs), which are based on aesthetic qualities such as taste and smell (https://deq.mt.gov/Portals/112/Land/StateSuperFund/Documents/DEQ-7_June2019_Final.pdf?ver=2019-07-16-085110-630). The drinking water standards provide context for evaluating the water's suitability for human consumption (an important use of groundwater in the area), and provide a common set of metrics for all samples.

Groundwater

The groundwater in the Upper Jefferson Valley is typically of good quality. The water from 11 wells completed in the alluvium had water with total dissolved solids (TDS) concentrations that ranged from 121 to 672 mg/L, with a median value of 316 mg/L. The highest alluvial TDS value (672 mg/L) was from well 68, installed adjacent to Piedmont Pond. No samples were available from wells completed in the bench sediments. Ten of 12 wells completed in the Renova Formation had TDS values between 117 and 362 mg/L, with a median of 297 mg/L. The other two Renova Formation wells had TDS values of 2,567 and 4,216 mg/L. These relatively high TDS values are attributed to road salt at well 95, and hydrothermal influences at well 11 (near Silver Star). Three wells completed in bedrock had TDS values of 121, 187, and 278 mg/L.

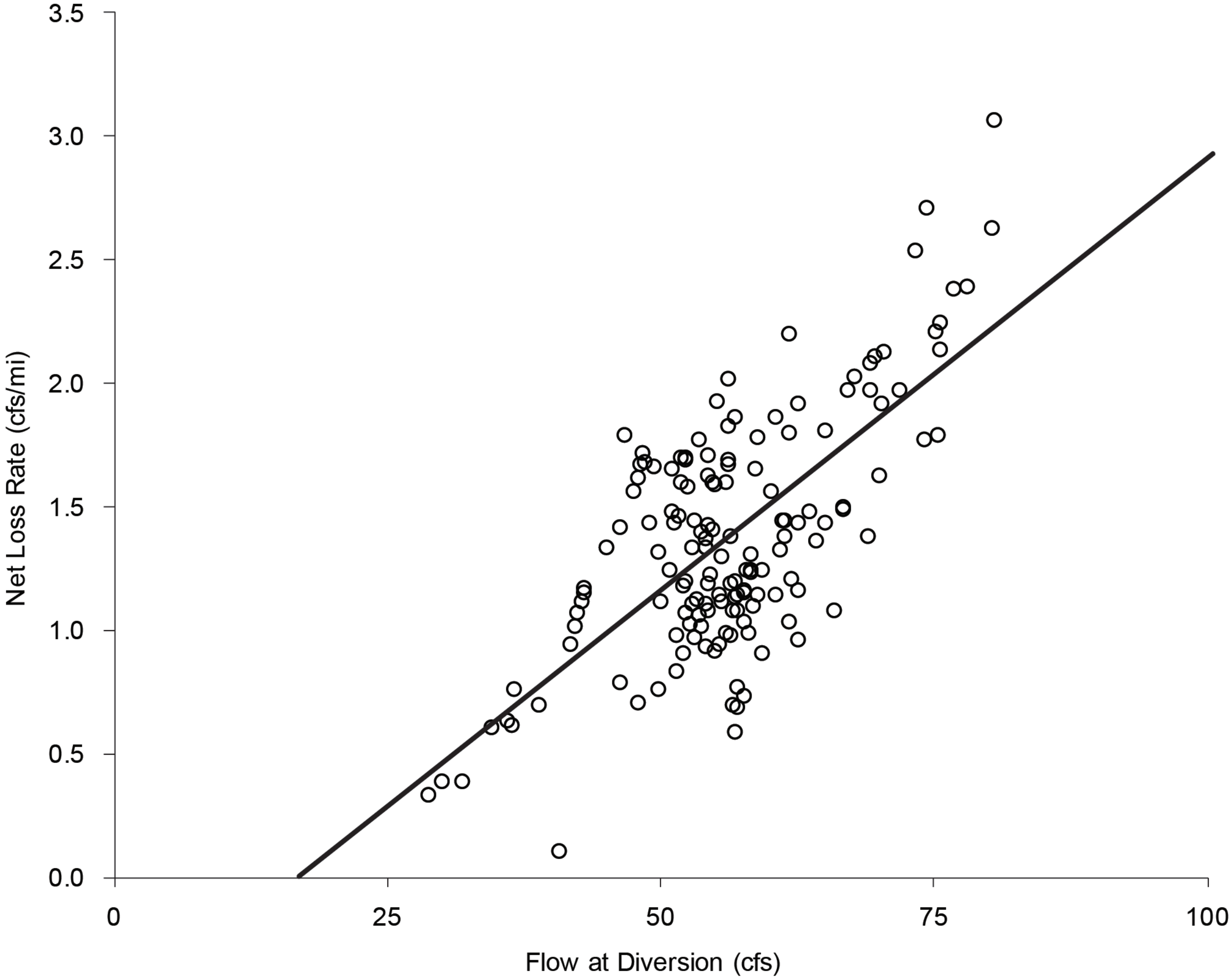


Figure 18. Canal leakage was estimated for the upstream reach of the Creeklyn Canal, between the upstream diversion from the Jefferson River at site 3 and the downstream station at site 7 (fig. 10), which is a 6.4-mi reach with no irrigation diversions. The line shows the best-fit relationship for this reach, and the average leakage rate for this reach was 1.4 cfs/mi.

Two wells had exceedances of the drinking water standards (appendix F). One sample from a well in the Renova Formation on the Parrot Bench exceeded the primary drinking water standard for arsenic (well 88; 18 µg/L; the arsenic MCL is 10 µg/L). Well 68, completed in the alluvium near Piedmont Pond, had iron (0.302 mg/L) and manganese (0.993 mg/L) concentrations above the secondary drinking water standards (0.3 and 0.050 mg/L, respectively), and arsenic was slightly less than the standard, at 9.4 µg/L. The samples collected from wells 88 and 68 also had relatively high silica, lithium, fluoride, and boron concentrations, indicative of hydrothermal influences (appendix F).

Calcium-bicarbonate type water was the dominant groundwater type in all sampled HGUs (fig. 19). This is consistent with the weathering of igneous rocks (granite and volcanics), gneiss, and limestone (Drever, 1997), which are the dominant rock types upstream of the study area. Major ion chemistry varied in some wells based on other sources of water or salts (fig. 19). Well 51, completed in Madison Group carbonate bedrock, was a calcium–magnesium bicarbonate water type, likely reflecting a dolomite ($CaMg(CO_3)_2$) influence. Wells 60, 62, and 104 had sodium as the dominate cation, and wells 60 and 62 had a bicarbonate-sulfate anion type (fig. 19). These wells are completed in the alluvium and the Renova Formation, and wells 60 and 62 are located near known hot springs at Renova (60) and Pipestone (62). Hydrothermal water is typically high in sodium (Metesh, 2000). Therefore, the groundwater in wells 60, 62, and 104 likely reflects hydrothermal influences in these areas. The sulfate influence may be due to hydrothermal waters, or anion exchange with clays. Wells 61, 63, and 68 had a calcium–sodium bicarbonate type water, suggesting a less pronounced hydrothermal influence. As noted above, the TDS in well 68 was also high relative to other wells in the alluvium. Plotting the water from

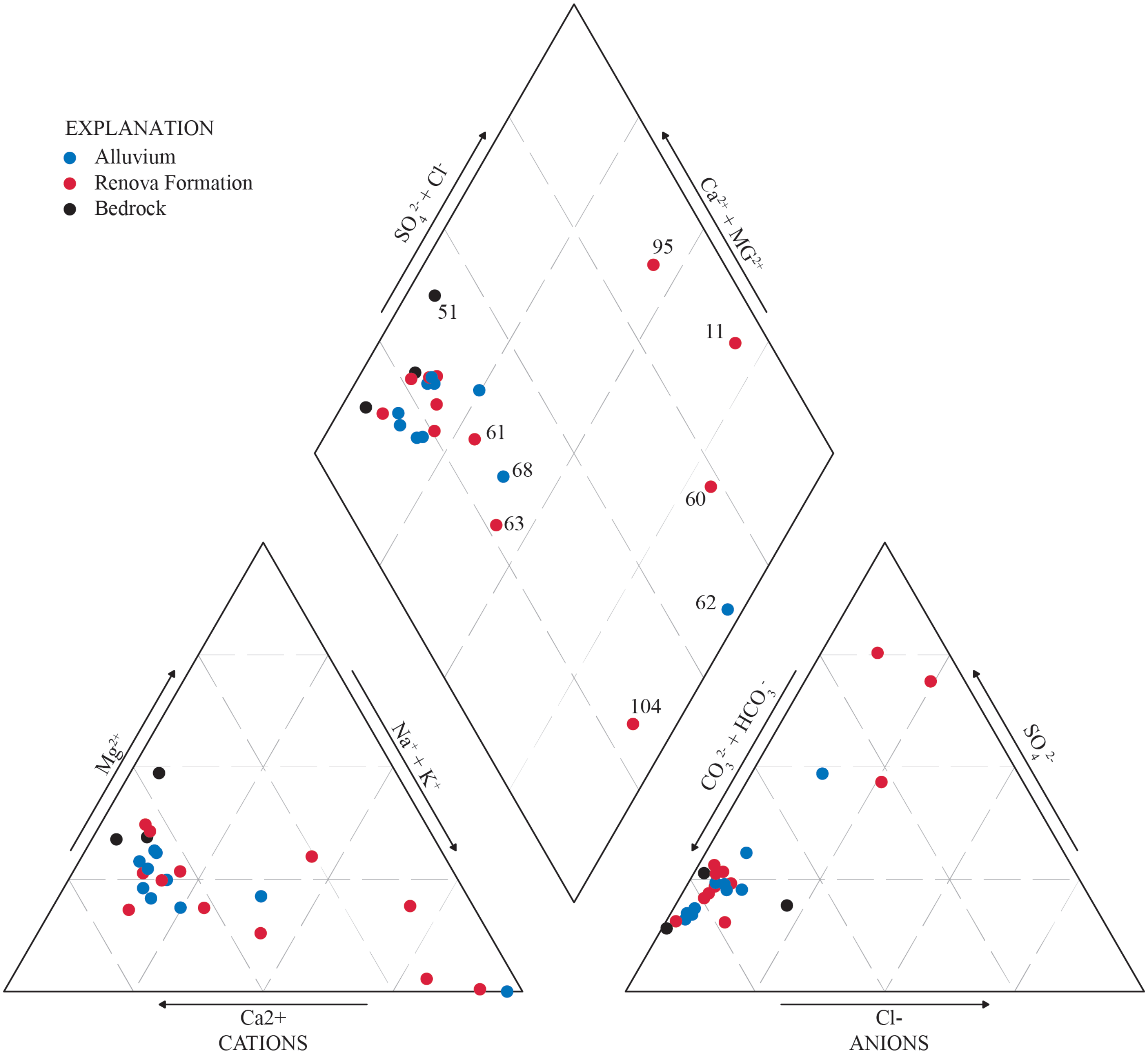


Figure 19. Groundwater from all sampled HGUs is predominantly Ca-HCO_3 type. Other wells appear to be affected by local sources of water and salt. See text for a discussion of these sources; labels are well numbers.

wells 60, 61, 62, 63, 68, and 104 on a Piper diagram (fig. 19) suggests two end member mixing between the dominant calcium-bicarbonate water types and a sodium-bicarbonate water type (hydrothermal), with anion exchange with clays in some areas causing sulfate to increase. Groundwater from wells 11 and 95 have sulfate as the dominant anion (sodium sulfate and mixed cation sulfate type waters). These wells also have the highest reported TDS values (4,216 and 2,567 mg/L, respectively). The chemistry of well 95 was evaluated during the Boulder Groundwater Investigation (Bobst and others, 2016), and it was concluded that it was likely influenced by road salt, with ion exchange with clays. Well 11 is located near highway 41, and may be similarly influenced by road salt; however, there is also known hydrothermal activity near well 11.

Surface Water

Surface waters in the Upper Jefferson Valley are typically of good quality; however, there is some variability. Excluding the sample from Piedmont Pond (site 29, see below), the TDS of sampled surface waters ranged from 218 to 344 mg/L, and the median was 263 mg/L (appendix G). Most surface waters were of a calcium-bicarbonate type, but the sample from Pipestone Creek (site 33) was calcium–sodium bicarbonate (fig. 20).

The water sample from Piedmont Pond (site 29) differed from the other surface-water samples (fig. 20). It had the highest TDS value at 631 mg/L, about 270 mg/L higher than the next highest surface-water sample. This pond is fed by groundwater, and there is no outlet, while the other samples were from flowing waters. The Piedmont Pond sample had relatively high concentrations of potassium, sulfate, and chloride (20.4, 185.2 and 53.8 mg/L, respectively). At 19 ug/L, the arsenic in concentration in this sample exceeded the primary drinking water standard of 10 µg/L, and was the highest arsenic concentration reported. The pond water sample had elevated silica, lithium, fluoride, and boron concentrations, similar to the groundwater in the area (well 68), and likely indicative of a hydrothermal influence (appendix G). Efflorescent crusts are common in the area near the pond, suggesting that the high relative abundance of sodium and sulfate ions may be partly due to the removal of calcium, magnesium, and bicarbonate by carbonate precipitation [e.g., precipitation of calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$)].

All samples from the Jefferson River, canals fed by the Jefferson River, Parson’s Slough, Willow Springs, and the Boulder River had similar geochemical signatures (fig. 20). Pipestone Creek and Whitetail Creek had higher sodium and lower magnesium concentrations relative to the other flowing waters. Water in the Slaughterhouse Slough was similar to that in the Jefferson River; however, in the Jefferson Slough inputs from Pipestone Creek (site 33) and Whitetail Creek (site 35) caused a shift towards a more sodium-rich composition (fig. 20).

Stable Water Isotopes

Most of the groundwater samples fall along the local meteoric water line (LMWL; fig. 21). This LMWL was developed for Butte, Montana, approximately 20 mi to the west of the study area (fig. 1; Gammons and others, 2006). The sample from well 68, near Piedmont Pond, falls below the LMWL (fig. 21), which is consistent with evaporation or a hydrothermal influence (Clark and Fritz, 1997).

Most of the surface-water samples also fell near the LMWL (fig. 21); however, the samples from Whitetail Creek (site 35) and Piedmont Pond (site 29) fall below this line. The isotopic signal from Whitetail Creek suggests an influence from evaporated irrigation water, or potentially hydrothermal sources in the drainage. Similarly, the pond values are attributed to hydrothermal effects on the groundwater that discharges to the pond, and evaporation from the pond.

The six sites in the Waterloo area that were sampled multiple times during this study showed some seasonal variation in isotopic signature (fig. 22). Three of the sites showed little seasonal change (well 51, site 16, and site 20). The other three sites (well 49, site 18, and site 19) had samples that fell further below the LMWL in November, suggesting an influence from relatively evaporated water.

Groundwater/Surface-Water Interactions

Water flows from surface waters to the groundwater and from the groundwater to surface waters in different areas of the study area. The direction of this flow depends on the relative elevation of the groundwater and surface water. That is, when stream stage is higher than the groundwater elevation (as is common on an alluvial fan), the stream water will infiltrate and recharge the aquifer. When groundwater is at a higher

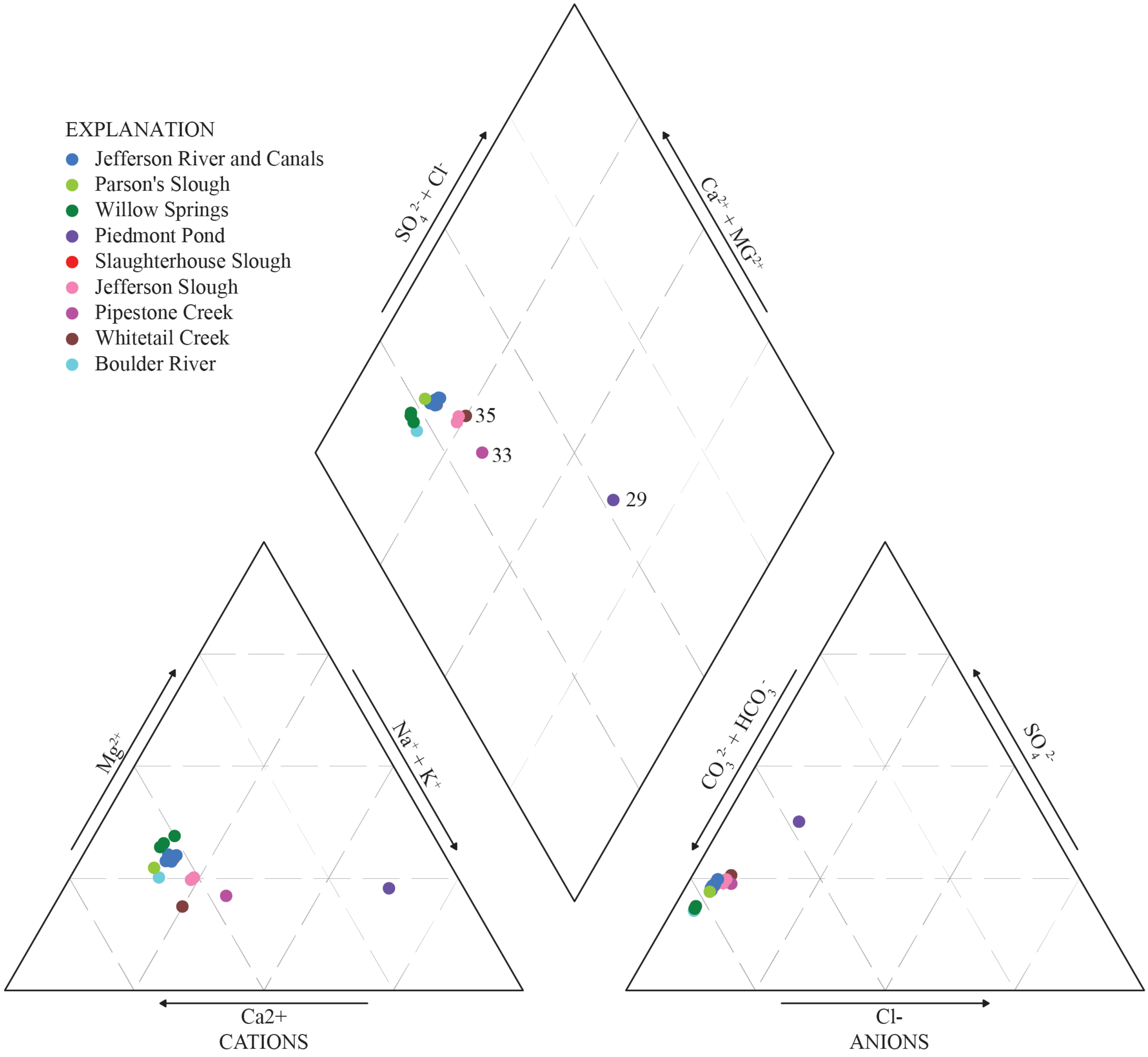


Figure 20. Surface waters are primarily of Ca-HCO_3 type. Pipestone and Whitetail Creeks (sites 33 and 35) have slightly higher relative Na concentrations than other streams, likely due to known hydrothermal activity in those drainages. Water from Piedmont Pond (site 29) differs from the others; see text for discussion. Labels are site numbers.

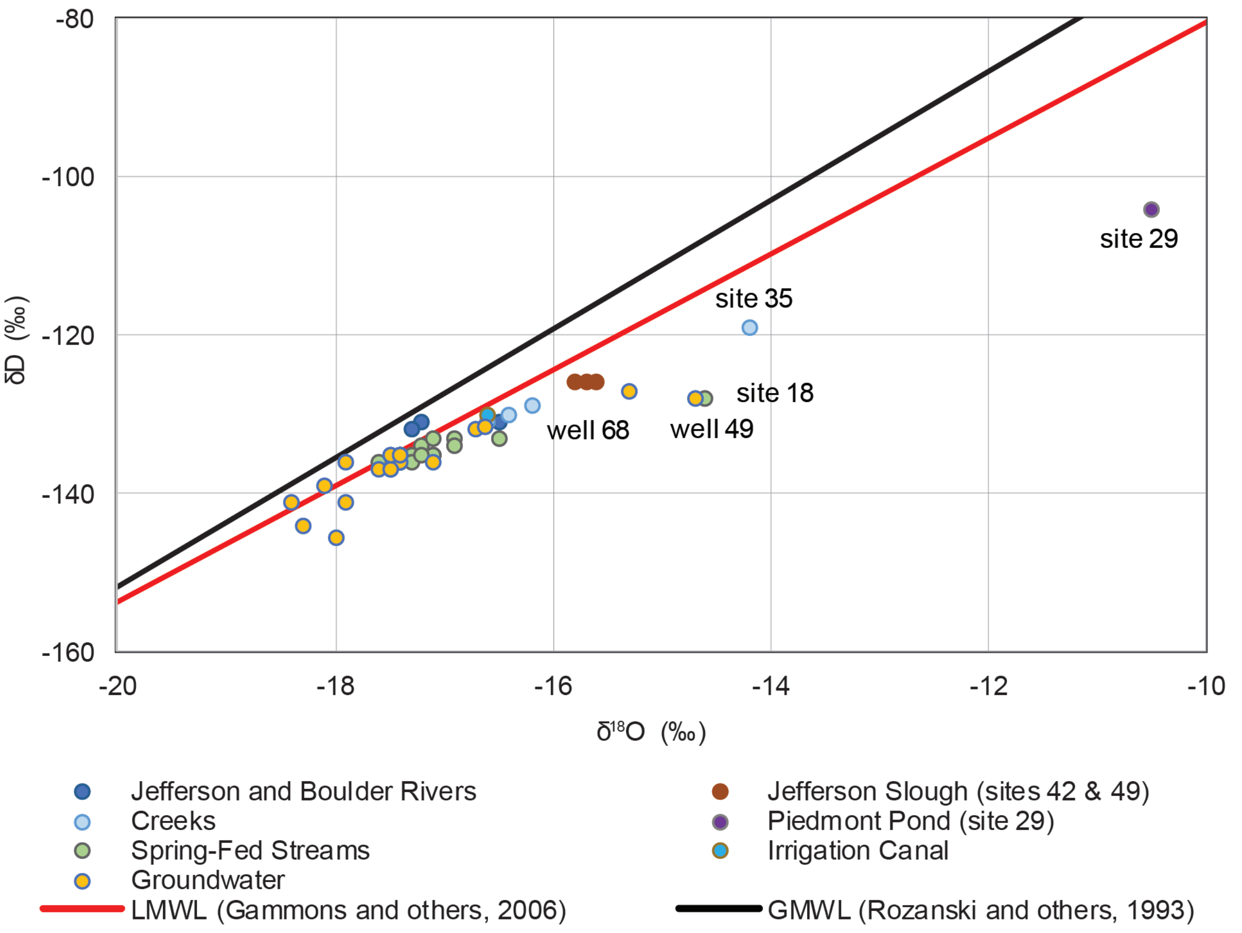


Figure 21. Stable isotopes for most surface-water and groundwater samples plot near the local meteoric water line (LMWL). The sample for Whitetail Creek (site 35) fell below the LMWL, suggesting an influence from evaporated irrigation return flows or hydrothermal inputs. The samples from Piedmont Pond (site 29) and the adjacent well (well 68) fell below the LMWL, consistent with the hydrothermal influences and evaporation inferred from major ion chemistry.

elevation than the stream (as is common upgradient from a bedrock notch), groundwater will flow into the stream. An understanding of the geographic distribution of gaining and losing stream reaches was needed to develop and evaluate the numerical models. This information was also important for developing the groundwater budgets.

The gaining and losing nature of surface waters in the Upper Jefferson area changes over both space and time (table 4, appendix C). Streams typically lose water to the aquifer during periods of high flow and elevated stage. Streams typically gain water from the aquifer during low-flow conditions, when stage is low. Given this, the geographic distribution of gaining and losing reaches varies over time; however, the overall distribution is consistent over time (fig. 23).

The Jefferson River gains from sites 1 to 5, is slightly losing from sites 5 to 8, and gains flow from sites 8 to 23. This downstream gaining reach is near Waterloo, where Parson's Slough and Willow Springs also gain water from the aquifer before flowing into the Jefferson River. The width of the alluvium also narrows just north of this area (fig. 7). There is a slight loss from site 23 to site 28. Near site 28 water is diverted from the Jefferson River to the Slaughterhouse Slough. The first reach of Slaughterhouse Slough (up to Kountz Road; site 30) is slightly gaining, and the next reach, including the diversion of some of the Slaughterhouse Slough water into Jefferson Slough, is gaining. This northern gaining reach of Slaughterhouse Slough occurs where Pipestone Creek and Whitetail Creek are also gaining, and this likely reflects groundwater inflow through the alluvium associated with these tributaries. The Jefferson River reach below Parrot Castle (from site 28 to site 31) is also slightly gaining. The Jefferson River from site 31 to 50 is neutral to slightly losing, and then in the lowest reach (from site 50 to site 53; just above the Jefferson Canyon) it is gaining. Along the neutral to slightly losing reach from site 31 to 50 the Jefferson River is generally at a higher elevation than the Jefferson Slough,

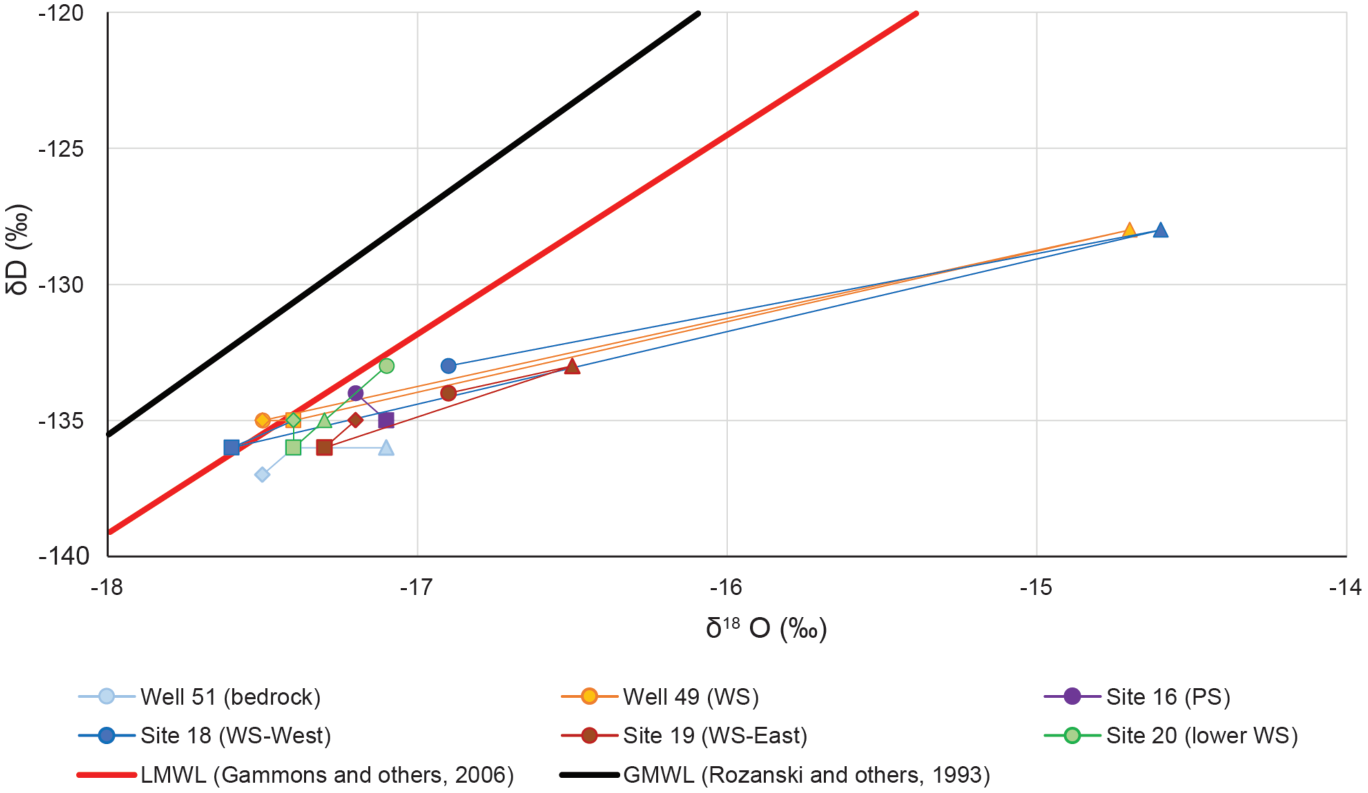


Figure 22. Six sites in the Waterloo area were sampled multiple times. The symbol shapes indicate the time of sampling (circle, August 2014; triangle, November 2014; square, January 2015; diamond, March 2015), and the colors represent the site. Three of the sampling locations (well 51, site 20, and site 16) showed little variation over time. The other three sites showed isotopic values that plotted further below the LMWL during the November 2014 sampling event.

so in these reaches the river likely loses flow to the groundwater system that subsequently discharges to the Jefferson Slough. The generally gaining conditions in the lower reach of the Jefferson Slough support this interpretation (fig. 23). Just above the Jefferson Canyon, most of the alluvial groundwater discharges to the Jefferson River due to the geometry of bedrock constriction.

The geochemical signatures of water samples were also used to aid in understanding groundwater/surface-water interactions. The alluvial groundwater near the Jefferson River was similar to the composition of the river (figs. 19–21, appendixes F, G). The fact that these waters have similar major ion chemistry is in itself an indication of the high degree of exchange between surface waters and the alluvial aquifer. The samples that were substantially different from the rest appear to be affected by hydrothermal sources (wells 62, 81, 100, and 59; site 33), evaporation (well 68 and site 29), or road salt (well 95).

Numerical Models

Waterloo Model

The Waterloo model was developed and calibrated using data collected during this study (2013–2015), and a preliminary groundwater budget. Gebril and Bobst (2021) discuss the modeling process, including model verification, sensitivity analysis, and predictive uncertainty analysis.

The groundwater budget generated with the calibrated model shows the importance of interactions between surface waters and the alluvial aquifer in the Waterloo area. The bidirectional exchange of water between surface water and the aquifer can be considered from the perspective of net stream gain (as presented in Gebril and Bobst, 2021, and consistent with the preliminary water budget), where the net stream gain is the gross gain minus the gross loss. From this perspective, flow into the model domain was composed of groundwater inflow through the alluvial aquifer (60%), irrigation recharge (16%), canal leakage (13%), and lateral groundwater inflow (11%). Similarly, outflow from the model domain consisted of net discharge to surface waters (58%) and groundwater outflow

Table 4. Summary of interpreted groundwater/surface-water interactions.

Reach	Method				Overall
	SW Flow Difference	SW Temperature Difference	GW/SW Elevations	GW/SW Temperatures	
Jefferson River—USGS Gage near Twin Bridges to Silver Star	Gain	Gain	Gain	Gain	Gaining
Jefferson River—Silver Star to Funston's	Loss	Loss/Neutral	---	---	Slightly Losing
Jefferson River—Funston's to USGS Gage at Parson's Bridge	Gain	Gain	---	---	Gaining
Jefferson River—USGS Gage at Parson's Bridge to Corbett's	Gain	Gain	Gain	Gain	Gaining
Jefferson River—Corbett's to Parrot Castle	---	Loss/Neutral	---	---	Slightly Losing
Jefferson River—Parrot Castle to Kountz Bridge	Gain	Slight Gain	Gain	Slight Gain	Slightly Gaining
Jefferson River—Kountz Bridge to Mayflower Bridge	Gain	Neutral	Neutral	Slight Loss	Neutral
Jefferson River—Mayflower Bridge to Cardwell	Loss	---	Loss	Slight Loss	Slightly Losing
Jefferson River—Cardwell to LaHood	Gain	Gain	---	---	Gaining
Slaughterhouse Slough at Parrot Castle—Slaughterhouse Slough at Kuntz Rd	Gain	Neutral	---	---	Slightly Gaining
Slaughterhouse Slough at Kountz—Jefferson Slough at Willow Brook	---	Gain	---	---	Gaining
Jefferson Slough—Willow Brook to Briggs	Loss	Loss/Neutral	---	---	Slightly Losing
Jefferson Slough—Briggs to Yellowstone Trail	---	Gain	---	---	Gaining
Jefferson Slough—Yellowstone Trail to Tebay Ranch	---	Loss/Neutral	---	---	Slightly Losing
Jefferson Slough—Tebay Ranch to Tebay Road	Variable	Variable	---	---	Neutral
Jefferson Slough—Tebay Road to Mulligan's	Loss	Variable	---	---	Slightly Losing
Jefferson Slough—Mulligan's to 359	Gain	Gain	---	---	Gaining
Jefferson Slough—359 to Mouth	---	Slight Loss	---	---	Slightly Losing
SS-PC + Fish Creek vs. SS @ Kountz Road	Gain	Neutral	---	---	Slightly Gaining
Pipestone Creek—Capp Lane to Mouth	Gain	Gain	---	---	Gaining
Whitetail Creek—Sailsbury's to Cemetary	Loss	Loss	---	---	Losing
Whitetail Creek—Cemetary to Mouth	Gain	Gain	---	---	Gaining

--- indicates that data were not available to use the method.

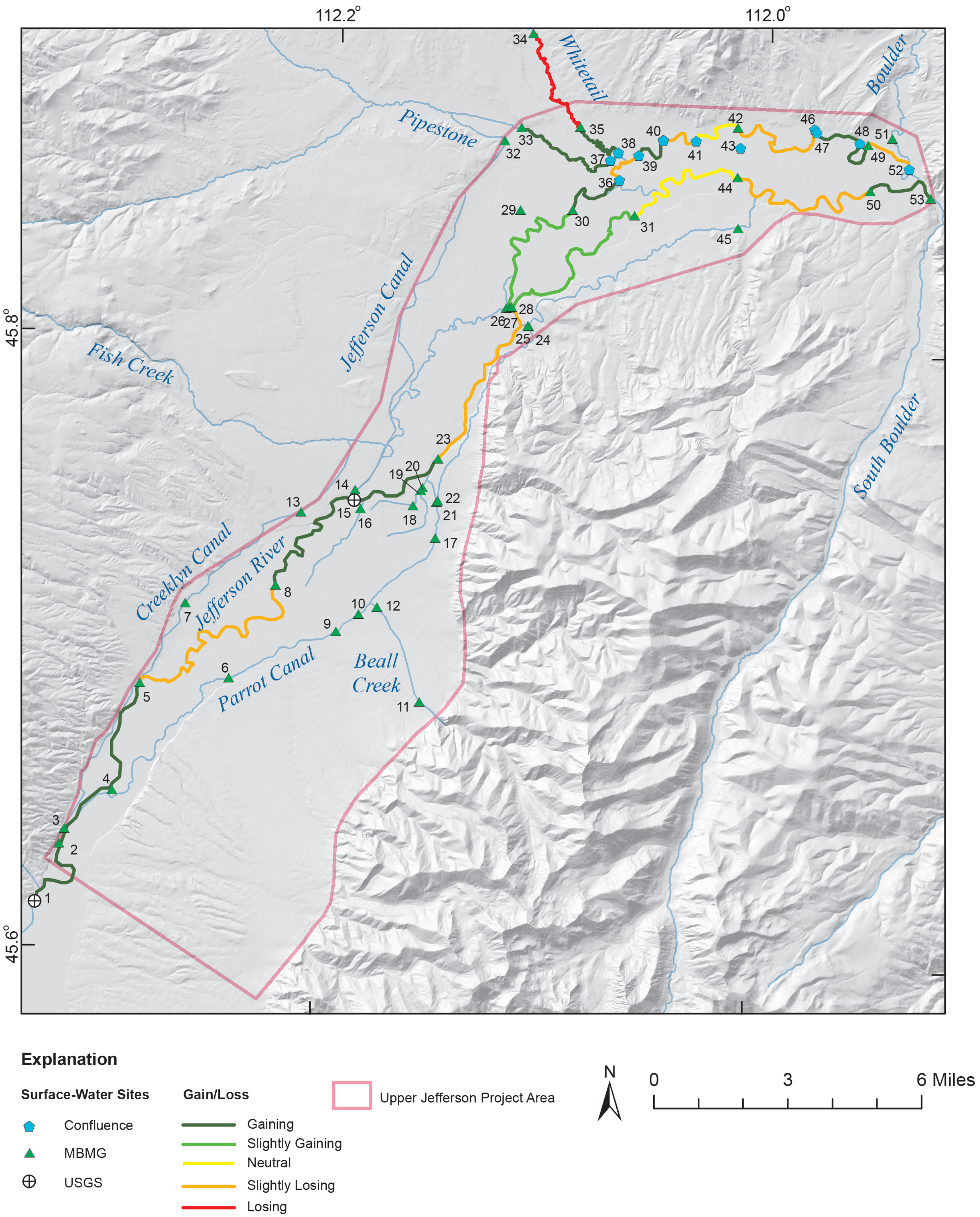


Figure 23. Monitoring results were analyzed in several different ways to aid in understanding groundwater/surface-water interactions. This figure shows the composite interpretation for each reach (also see table 4 and appendix C).

through the alluvium (42%), with evapotranspiration and well pumping being minor components of the total outflows (0.1 and 0.2% respectively).

The detailed modeling results also allow for evaluation of the exchange of water between the stream and the aquifer from the perspective of gross stream gains and losses. This view treats gross stream gains and losses as separate water budget components, rather than combining them into a net term. Viewing the budget from this perspective provides an understanding of the total amount of water moving through the system (rather than excluding the portion of the gains and losses that offset), and more clearly shows the relative importance of different sources and sinks; however, the gross stream gains and losses cannot be compared to independent field-based estimates (e.g., the preliminary water budget), since field measurements cannot reasonably be obtained at a fine enough spatial scale. Quantification of the groundwater budget from this perspective is derived from the calibrated model results, and is an important product of the modeling effort. These results show that the total amount of water moving through the alluvial aquifer on an annual basis is about 220,000 acre-ft. The modeled budget indicated that about 74% of all inflow to the alluvial aquifer came from the Jefferson River. The addition of this gross stream loss causes other inflows to decrease in their percent contribution, but maintaining their relative order, with the components being groundwater inflow through the alluvial aquifer (16%), irrigation recharge (4%), canal leakage (3%), and lateral groundwater inflow (3%). Similarly, the use of gross stream gain rather than net stream gain causes the percentage of the water going to different sinks to change, but the sinks are still dominated by gross stream gains (88%) and groundwater outflow (12%), with ET and wells being minor components of the budget (0.04 and 0.06%, respectively).

The Waterloo model simulates the effects of potential changes in irrigation practices on surface-water availability. Changes in groundwater discharge to Parson's Slough and Willow Springs during late summer (month of August) are particularly important because contributions from these streams support flows and pool connectivity in the Jefferson River, and the relatively cool groundwater discharge aids in lowering river temperature.

Modeling included 18 hypothetical water management scenarios that may affect surface-water availability during the late summer (table 5, fig. 24). Five of these scenarios are extreme: (1) lining all the

Table 5. Waterloo model scenarios.

Scenario	Description*
0	Base Run—Transient
C1	No seepage—Parrot & Creeklyn
C2	No seepage—Parrot Reach 1
C3	No seepage—Parrot Reach 2
C4	No seepage—Parrot Reach 3
C5	No seepage—Parrot Reach 4
C6	No seepage—Parrot Reach 5
C7	No seepage—Creeklyn Reach 1
C8	No seepage—Creeklyn Reach 2
C9	No seepage—Creeklyn Reach 3
F1	Flood to Pivot—All Areas
F2	Flood to Pivot—Area 1
F3	Flood to Pivot—Area 2
F4	Flood to Pivot—Area 3
F5	Flood to Pivot—Area 4
F6	Flood to Pivot—Area 5
CF	No canal seepage & areas 1–5 converted to pivot
SS1	Split Season Irrigation in Areas 1–5
SS2	Split Season Irrigation for all fields

*See figure 24 for the locations of the features.

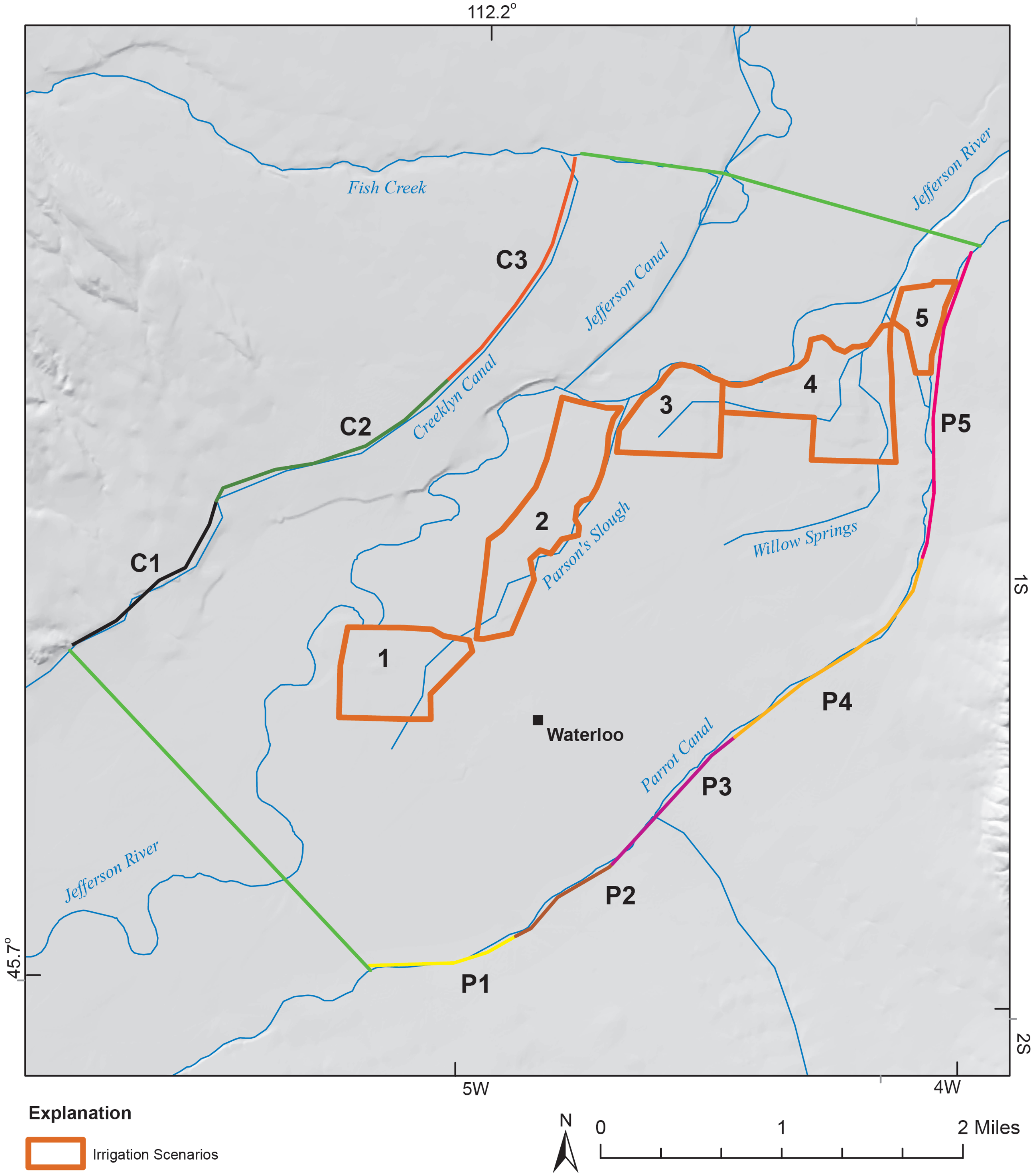


Figure 24. The locations of canal segments and irrigated fields used in the Waterloo model predictive scenarios. Figure shows Parrot canal segments, P1 to P5, and Creeklyn Canal segments, C1 to C3. The irrigated areas 1 to 5 were variously converted from flood to pivot irrigation in the simulations.

canals (scenario C1), (2) converting all flood irrigation to pivot (scenario F1), (3) lining all the canals and converting all flood irrigation to pivot irrigation (scenario CF), (4) applying split season irrigation to some flood-irrigated fields (scenario SS1), and (5) applying split season irrigation to all irrigated fields (scenario SS2). The remaining scenarios test the impact of partial changes in irrigation practices; that is, lining individual canal segments or converting a single flood-irrigated area to a pivot system (table 5; Gebril and Bobst, 2021).

In order to evaluate long-term effects of irrigation management practices, all predictive simulations were run for 20 years and compared to a baseline simulation where there was no change in irrigation practices. Results are reported for 2024, which is the last complete calendar year simulated. Changes in water management were applied beginning in model year 2016.

Scenario C1 involved lining the Parrot and Creeklyn Canals, which reduces recharge to the underlying aquifer. Results show that it takes over 1 year for a new equilibrium to be established; however, most of the change occurs during the first year. Relative to the baseline, scenario C1 resulted in a combined reduction in groundwater flow to Parson Slough and Willow Springs of 6 cfs in August (table 6, fig. 25), which is about a 10% decrease from the baseline of 57 cfs in combined August flow. Scenario C1 resulted in an 18 cfs reduction in Jefferson River discharge, which includes the reduction in discharge to Parson's Slough and Willow Springs, and reductions in direct groundwater discharges to the Jefferson River. This reduction in the flow of the Jefferson River represents a 2.4% decline from the baseline flow of 720 cfs (table 6, fig. 26).

Scenario F1 consisted of converting five flood-irrigated areas to center pivot, thus reducing irrigation recharge to the underlying aquifer. Similar to C1, it takes over 1 year for a new equilibrium to be established, but most of the change occurred in the first year. Relative to baseline, combined surface-water flow from Parson's Slough and Willow Springs to the Jefferson River was reduced by about 7 cfs in August, a 12% reduction (table 6, fig. 25). Flow in the Jefferson River at Corbett station decreased by about 13 cfs in August, a 1.8% reduction (table 6, fig. 26).

Scenario CF combines C1and F1. In comparison to the base run, the combined late summer flow in Parson's Slough and Willow Springs was reduced by about 13 cfs, a 22% reduction (table 6, fig. 25). Late summer flow in the Jefferson River at Corbett station decreased by 31 cfs, a 4.3% reduction (table 6, fig. 26).

Table 6. Waterloo modeled stream depletion after 10 years.

	Parson's Slough				Willow Springs				Jefferson River (Corbett Station)			
Scenario	Change in Mean Annual Flow (cfs)	Change in July Flow (cfs)	Change in August Flow (cfs)	Percent Change in August Flow	Change in Mean Annual Flow (cfs)	Change in July Flow (cfs)	Change in August Flow (cfs)	Percent Change in August Flow	Change in Mean Annual Flow (cfs)	Change in July Flow (cfs)	Change in August Flow (cfs)	Percent Change in August Flow
C1	-0.8	-1.0	-1.6	-9.0%	-2.0	-2.4	-4.1	-11.3%	-8.2	-11.9	-17.0	-2.4%
C2	-0.1	-0.1	-0.1	-0.6%	0.0	0.0	-0.1	-0.1%	-1.1	-1.1	-1.7	-0.2%
C3	-0.3	-0.4	-0.6	-3.4%	-0.2	-0.2	-0.4	-1.1%	-2.1	-2.5	-4.1	-0.6%
C4	-0.2	-0.2	-0.4	-2.5%	-0.2	-0.2	-0.5	-1.3%	-1.7	-1.5	-2.7	-0.4%
C5	-0.2	-0.2	-0.3	-2.0%	-0.6	-0.7	-1.3	-3.5%	-2.0	-2.0	-3.3	-0.5%
C6	-0.3	-0.3	-0.4	-2.5%	-1.5	-2.0	-3.3	-8.9%	-3.7	-3.9	-6.3	-0.9%
C7	-0.2	-0.2	-0.3	-2.0%	-0.6	-0.7	-1.3	-3.5%	-2.8	-3.5	-4.9	-0.7%
C8	-0.2	-0.2	-0.3	-2.0%	-0.6	-0.7	-1.3	-3.5%	-2.9	-4.0	-5.4	-0.7%
C9	-0.2	-0.2	-0.3	-2.0%	-0.6	-0.7	-1.3	-3.5%	-3.0	-3.5	-4.8	-0.7%
F1	-0.3	-0.4	-0.3	-1.3%	-2.7	-4.8	-6.4	-17.4%	-6.4	-10.2	-12.8	-1.8%
F2	-0.2	-0.3	-0.4	-2.3%	-0.6	-0.7	-1.3	-3.6%	-2.7	-2.8	-4.3	-0.6%
F3	-0.2	-0.3	-0.4	-2.1%	-0.6	-0.7	-1.3	-3.5%	-2.3	-2.3	-3.6	-0.5%
F4	-0.2	-0.3	-0.4	-2.1%	-0.7	-0.8	-1.4	-3.8%	-1.9	-2.2	-3.3	-0.5%
F5	0.0	-0.1	-0.1	-0.4%	-2.5	-4.5	-6.2	-16.7%	-3.9	-6.8	-9.4	-1.3%
F6	-0.2	-0.2	-0.3	-2.0%	-0.7	-0.8	-1.4	-3.9%	-2.3	-2.3	-3.7	-0.5%
CF	-1.0	-1.4	-1.9	-10.4%	-4.6	-7.1	-10.4	-28.2%	-14.7	-22.0	-29.7	-4.1%
SS1	-0.1	-0.1	-0.2	-1.2%	-2.4	-4.1	-6.3	-17.1%	-4.7	-7.4	-12.1	-1.7%
SS2	0.5	0.8	-0.1	-0.5%	-2.0	-3.2	-6.1	-16.6%	-1.6	-0.6	-10.3	-1.4%

Note. See table 5 and figure 24 for additional scenario details.
Increases in flow shown with yellow highlight.

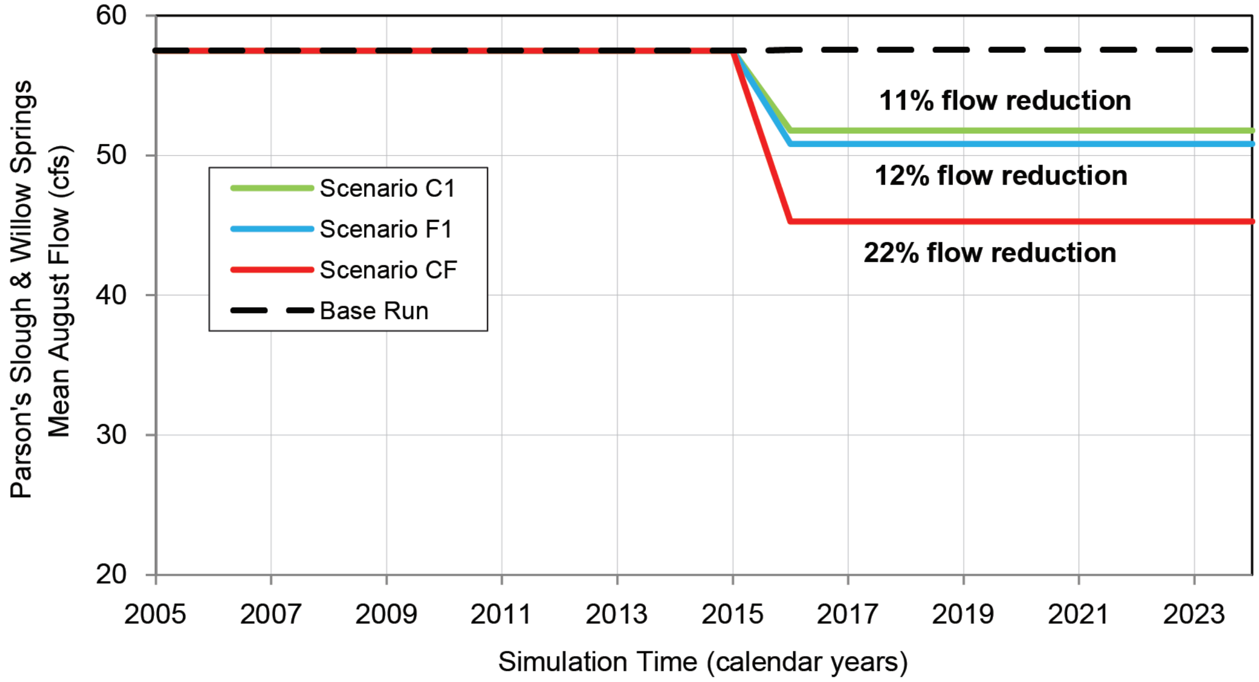


Figure 25. Eliminating leakage from the Parrot and Creeklyn Canals (scenario C1), reduced groundwater flow to Parson's Slough and Willow Springs in August by 6.0 cfs; an 11% reduction in flow. Conversion of all five flood-irrigated fields to pivot irrigation (scenario F1) reduced groundwater discharge to the streams by 7.0 cfs; a 12% reduction. Lining canals and converting all five fields to pivot irrigation reduced groundwater discharge to the streams by 12.8 cfs; a 22% reduction.

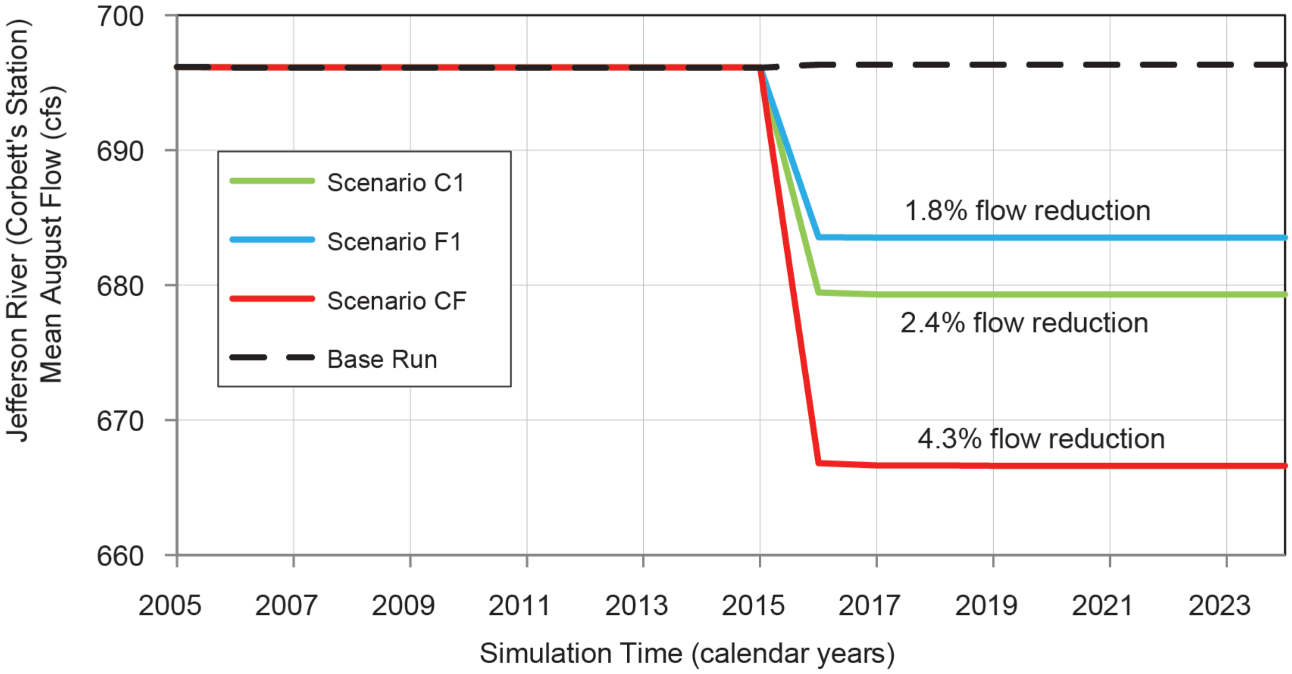


Figure 26. Eliminating leakage from the Parrot and Creeklyn Canals (scenario C1) caused a 17.5 cfs reduction in total groundwater flow to the Jefferson River in August (including groundwater flow to Parson's Slough and Willow Springs); resulting in a 2.4% reduction in mean August flow. Conversion of all five fields to pivot irrigation (scenario F1) caused a 13.2 cfs reduction in total groundwater discharge to the Jefferson River; a 1.8% reduction in mean August flow. When the canals were lined, and all five fields were converted to pivot (scenario CF), total groundwater flow to the Jefferson River was reduced by 30.6 cfs; a 4.3% reduction.

The split season irrigation scenarios (SS1 and SS2) simulate attempting to mitigate the effects of changing irrigation efficiency (converting from flood to pivot irrigation) by providing flood irrigation recharge from mid-April until the end of June, and switching to pivot irrigation rates from July to mid-October. The canals are unlined for these scenarios. Scenario SS1 modeled using this approach at the same fields converted from flood to pivot irrigation in scenario F1 (fig. 24, table 5). Results showed that compared to F1, SS1 increased July flow in Parson's Slough by 0.3 cfs, generating a 0.1 cfs reduction from baseline compared to 0.4 cfs; in Willow Springs there was a 0.7 cfs increase in July flows relative to F1, with a 4.1 cfs reduction from baseline compared to 4.8 cfs. On the Jefferson River there was a 2.7 cfs increase in July flows relative to F1, with a 7.4 cfs reduction compared to 10.2 cfs. SS1 showed less of a change compared to F1 in August, with the difference between SS1 and F1 for Parson's Slough, Willow Springs, and the Jefferson River being 0.0, 0.1, and 0.6 cfs, respectively. The similarity between groundwater discharge in August in SS1and F1 is attributed to the rapid dissipation of the groundwater mound created in the spring due to the proximity of the managed fields to surface waters (fig. 24) and to the high-transmissivity aquifer. Scenario SS2 simulated split season irrigation at all irrigated fields in the model domain, which increased the average distance between split season irrigated fields and surface waters (Gebril and Bobst, 2021). This provided greater, but still incomplete, mitigation (table 6), with August flow reductions to Parson's Slough, Willow Springs, and the Jefferson River of 0.2, 0.4, and 2.5 cfs less than under F1. Scenario SS2 increased mean annual and July groundwater discharge to Parson's Slough compared to baseline, because some pivot-irrigated fields were converted to split season irrigation.

In general, Willow Springs is more sensitive to changes in water management than Parson's Slough. For example, in scenarios C1, F1, and CF, August flow reduction in Willow Springs was 4.1 cfs, 6.4 cfs, and 10.4 cfs, respectively, whereas flow reduction in Parson's Slough was 1.6 cfs, 0.3 cfs, and 1.9 cfs (table 6). Parson's Slough lies between Willow Springs and the Jefferson River, and these surface-water features act as boundaries that limit effects to Parson's Slough from actions beyond them.

Scenarios C2 to C6 represented lining individual segments of the Parrot Canal, and scenarios C7 to C9 represented lining segments of the Creeklyn Canal (fig. 24). Lining upstream (southern) segments of the Parrot Canal had relatively little effect on the outflow of Willow Springs; lining downstream segments increased the effects to Willow Springs (table 6). Lining various segments of the Creeklyn Canal caused slight reductions in groundwater discharge to Parson's Slough and Willow Springs (0.3 and 1.3 cfs reductions in August flows, respectively), and reduced flows in the Jefferson River by 4.9 to 5.4 cfs. This is consistent with the Jefferson River providing a hydrologic boundary (fig. 24), so that reductions in groundwater recharge on one side of the river cause little change in groundwater discharge to surface waters on the other side.

Scenarios F2 to F6 simulated changes in irrigation recharge resulting from various fields converting from flood irrigation to pivot. Groundwater discharge to the Jefferson River, Willow Springs, and Parson's Slough were more affected by conversion of adjacent fields, and the magnitude of the effect was proportional to the size of the converted fields (fig. 24, table 6).

Analysis of the Waterloo model (Gebril and Bobst, 2021) showed uncertainty in model results of about 10% for simulations of groundwater discharge to Parson's Slough and Willow Springs, and about 3% for groundwater discharge to the Jefferson River. In practical terms, model results that show a 1 cfs effect on Willow Springs should be regarded as a prediction between 0.9 cfs and 1.1 cfs.

Whitehall Model

Similar to the Waterloo model, the Whitehall model was developed and calibrated using data collected during this study (2013–2015), and a preliminary groundwater budget. A sensitivity analysis was conducted on the model, and a predictive uncertainty analysis was used to evaluate the likely error in model predictions (Gebril and Bobst, 2020).

Similar to the Waterloo model, modeled groundwater budgets were developed for the Whitehall area from the perspective of net stream gain, for comparison with field-derived estimates, and from the perspective of gross stream gains and losses to more clearly show the relative importance of different sources and sinks (Gebril and Bobst, 2020). The budget generated with the calibrated model quantifies the interactions between surface waters and the alluvial aquifer. This

Table 7. Whitehall model scenarios.

Scenario	Description*
0	Base Run—Transient
1	23 homes on 10-acre lots in non-irrigated area; pumping from layer 1
2	23 homes on 10-acre lots in irrigated area; pumping from layer 1
3	23 homes on 10-acre lots in non-irrigated area; pumping from layer 1
4	23 homes on 10-acre lots in non-irrigated area; pumping from layer 2
5	5 homes on 20-acre lots in non-irrigated area; pumping from layer 2
6	10 homes on 10-acre lots in non-irrigated area; pumping from layer 2
7	20 homes on 5-acre lots in non-irrigated area; pumping from layer 2

*See figure 27 for the locations of the scenarios.

budget shows that the total amount of water moving through the aquifer is about 74,000 acre-ft/yr. Seventy-four percent of the simulated inflow to the groundwater system was from the Jefferson River, while areal recharge (both irrigated and non-irrigated areas) contributed 16%, canal leakage added 8%, and alluvial and lateral groundwater inflow combined to provide 2% of the inflow. Groundwater discharge to surface waters (primarily the Jefferson River and Jefferson Slough) was 97% of total outflows. The other 3% of outflows included wells, down-valley groundwater outflow, pond evaporation, and riparian ET.

The Whitehall model simulates potential effects to surface-water flows from groundwater use and conversion of irrigated lands related to hypothetical subdivisions. The scenarios examine effects of “exempt wells.” Of particular concern was the potential for reduced late summer flows in the Jefferson River and Jefferson Slough.

Seven hypothetical scenarios were compared to a baseline run where the level of development was the same as during this study. These scenarios were developed to characterize the effects of additional subdivisions on surface-water availability during the late summer (table 7, fig. 27). The scenarios test development at lot sizes typical for the Upper Jefferson Valley, of 5, 10, and 20 acres at various locations within the model area. These included development in irrigated and non-irrigated areas, and with wells completed in the alluvium and the underlying Renova Formation. The metric used to compare these scenarios was the reduction in groundwater discharge to surface-water features (rivers and drains) in August, 10 yr after development (table 8). “Stream depletion” refers to groundwater pumping that results in reduced stream flow.

Scenarios 1 and 2 compared the effects of residential development in irrigated vs. non-irrigated areas on the bench north of Jefferson Slough. Both scenarios simulate wells completed in the alluvium at 23 homes completed on 10-acre lots. Scenario 1 simulated development in a non-irrigated area; wells added to the baseline model pumped at rates equal to the consumptive water use estimated for homes in this physiographic setting (Gebril and Bobst, 2020). Scenario 2 simulated development in irrigated areas; wells added to the baseline model pumped at rates equal to the additional consumptive water use and irrigation recharge

Table 8. Whitehall modeled stream depletion after 10 years.

	August Stream Depletion				
Scenario	ft^3/d	acre-ft/mo	cfs	gpm	gpm/home
1	825	0.59	0.010	4.3	0.2
2	11,850	8.43	0.137	61.6	2.7
3	1,497	1.07	0.017	7.8	0.3
4	1,207	0.86	0.014	6.3	0.3
5	96	0.07	0.001	0.5	0.1
6	196	0.14	0.002	1.0	0.1
7	399	0.28	0.005	2.1	0.1

Note. The annual average pumping rate is 0.3 gpm/home.

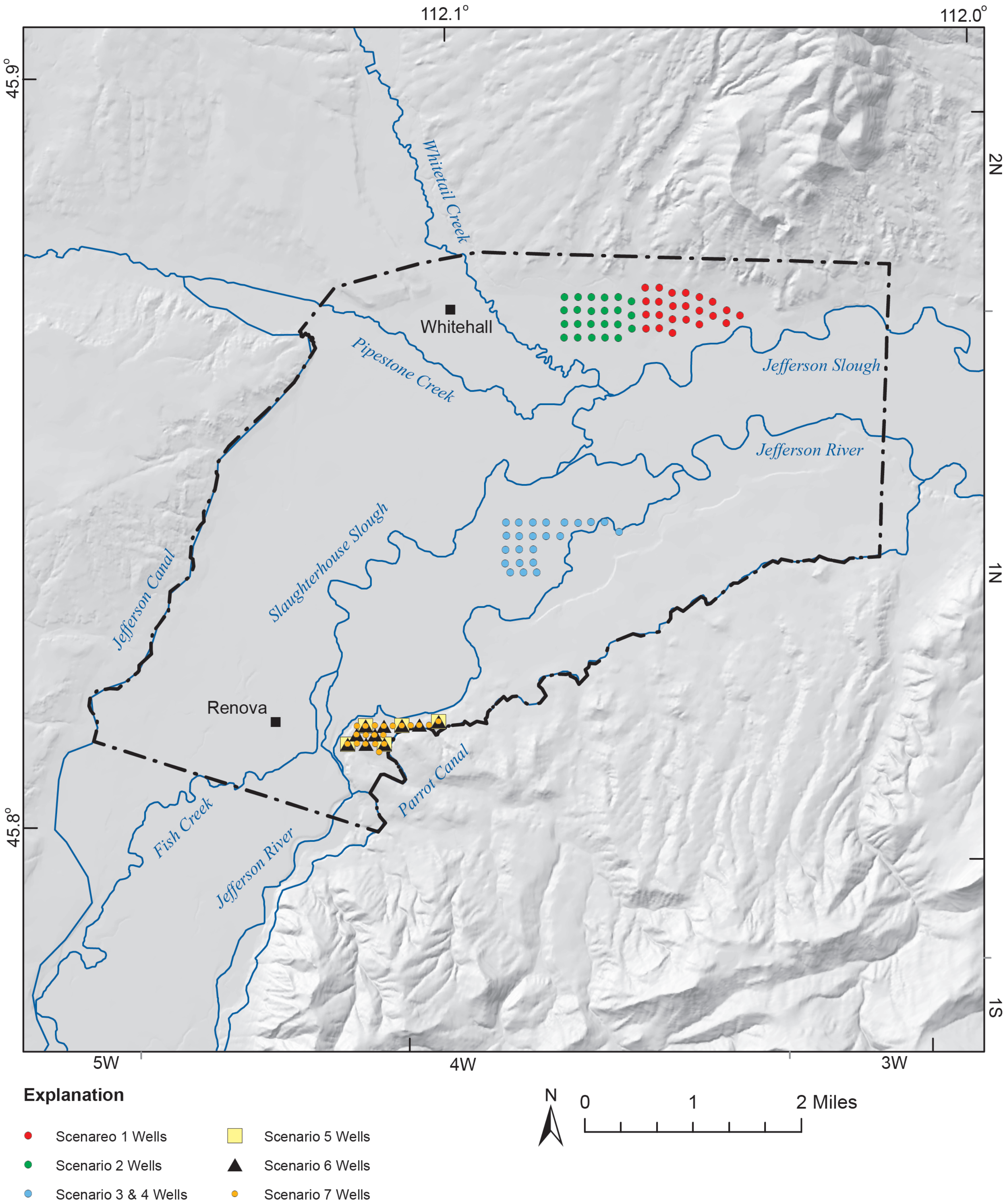


Figure 27. Modeled scenarios simulated additional subdivisions to assess effects of increased groundwater use and changes in land use on surface-water flows in the late summer.

was eliminated from the developed area. Scenario 2 caused about 14 times the simulated stream depletion in scenario 1. These simulations showed stream depletion rates of 0.59 and 8.43 acre-ft in August (table 8). These stream depletions represent about 0.02% or less of the average August flow of 633 cfs on the Jefferson River at site 31 in 2014.

Scenarios 3 and 4 compared the effects of pumping water from the alluvium vs. pumping from the underlying Renova Formation. Both scenarios simulated 23 homes on 10-acre lots in a non-irrigated area. The model indicates that pumping from the alluvium resulted in August stream depletion of 1.07 acre-ft compared to 0.86 acre-ft while pumping from the Renova Formation (table 8). These stream depletions represent about 0.002% of the 2014 average August flow in the Jefferson River at site 31.

Scenarios 1 and 3 provide a comparison of groundwater development at different distances from surface water (fig. 27). In these scenarios, development occurred in non-irrigated areas with pumping from the alluvium, but in scenario 3 the development was closer to surface-water features. Scenario 3 stream depletion in August was 1.07 acre-ft, almost twice that of scenario 1, at 0.59 acre-ft. While the total volume of stream depletion will equal the volume of consumptive use over the long term, there is less lag time between pumping and related depletion in scenario 3 because the wells are closer to the stream (Theis, 1941; Kendy and Bredehoeft, 2006).

Scenarios 5, 6, and 7 compared the effects of different well densities on stream depletion. All wells were completed in the Renova Formation, in the same 100-acre area south of the Jefferson River (fig. 27). Homes were on 20-acre, 10-acre, or 5-acre lots, with 5, 10, or 20 simulated wells, respectively (table 7). The model results show a linear relationship between the total pumping and stream depletion (table 8).

Analysis of uncertainty in the Whitehall model performed by Gebril and Bobst (2020) showed that the error associated with simulations of stream depletion is about 50%. In practical terms, model results that show stream depletion of 1 acre-ft should be regarded as a prediction ranging from 0.5 to 1.5 acre-ft.

DISCUSSION

Measurements of groundwater elevations over time, groundwater and stream elevations, stream flows, and modeling provide evidence of the interactions between surface waters and the alluvial aquifer in the Upper Jefferson area. These data demonstrate that groundwater and surface waters in this area are a single resource. “Conjunctive management” refers to policies and practices that recognize the interconnection between the aquifers and the watershed. As discussed below, findings in this report indicate that changes to irrigation practices affect recharge to groundwater and subsequent discharge of groundwater to surface water; efforts to increase irrigation efficiency may have unintended consequences on the groundwater and surface-water systems (Lonsdale and others, 2020).

Changing Irrigation Practices—Waterloo Area

Monitoring and modeling in the Waterloo area show that changing irrigation practices will likely reduce groundwater flow to surface waters. A simulation that included an extreme change to current conditions, lining all irrigation canals and converting all flood-irrigated fields to pivot irrigation, showed reductions in groundwater discharge to Willow Springs, Parson’s Slough, and the Jefferson River of about 27 to 33 cfs. In the context of target flows developed for the drought management plan for the Jefferson River (50 cfs above Parson’s Slough), this represents a large change. While this result is specific for the Waterloo area, the underlying concept applies throughout the Upper Jefferson Valley, and generally for many irrigated valleys in western Montana. Canal leakage, and irrigation water that infiltrates past the root zone, provide substantial groundwater recharge. Therefore, changes in irrigation practices have the potential to reduce groundwater levels and groundwater discharge to surface waters (Lonsdale and others, 2020).

Increased Development—Whitehall Area

As expected, modeling of the Whitehall area shows that pumping water for residential developments from the unconsolidated to poorly consolidated aquifers (alluvium, bench sediments, and Renova Formation) causes surface-water flow reductions. Over the long term, the volumetric reduction in groundwater discharge to streams will equal the volume of groundwater that is consumptively used. The model showed the largest effects on stream flow in a simulation that replaced an irrigated field with 23 residential wells, because the groundwater extraction was combined with a reduction in irrigation recharge. These conditions reduced August groundwater discharge to streams by about 8 acre-ft. A similar development scenario in a non-irrigated area, such that there was no simulated change to irrigation recharge, caused a reduction of about 0.6 acre-ft. Under these circumstances, changes in land use that reduce groundwater recharge, such as converting irrigated fields to other uses, can impart larger reductions in groundwater discharge to streams than the effects of additional wells.

The model scenarios presented here caused a maximum stream depletion of 8 acre-ft/mo, which is a small percentage of the overall stream flows. Because stream depletion increases linearly with increased groundwater pumping (e.g., Theis, 1941; Jenkins, 1968; Bredehoeft, 2002; Kendy and Bredehoeft, 2006; Konikow and Leake, 2014), we can extrapolate from these results. Due to the errors inherent in stream flow measurements, it is difficult to reliably measure changes of less than about 5%, so this can be used as a “measurable” change criteria. If groundwater use developed to supply one residence per 10-acre lot, and this development replaced existing irrigated fields, as in scenario 2, about 6,200 additional homes would result in a 5% reduction in mean August stream flow. If this development occurred on unirrigated land, as in scenario 1, the consumptive use from about 89,000 homes could be supplied from the alluvial aquifer to cause the same effect (however, the entire study area is about 167,000 acres, so at a 10-acre lot size only 16,700 homes would be possible). Although the effects of residential pumping are much less than the effects from changes in land use, reducing consumptive use in residential developments could be achieved by reducing outdoor water use. This would further increase the number of homes that could be supplied while causing a reduction in stream flow of less than 5%.

RECOMMENDATIONS

The Upper Jefferson Drought Management Plan has been a key component to maintain minimum flows in the Jefferson River during drought conditions. Implementation of this plan since 2000 has provided documented increases in low flows and increases in fish populations (Spoon, FWP, oral commun., 2015).

The drought management plan can be supplemented with long-term projects to maintain or increase water storage in shallow aquifers. For shallow-aquifer storage mechanisms to be effective at increasing late summer stream flows, groundwater recharge should be emphasized while stream flows are high, and irrigation efficiency should be emphasized when stream flows are low. That is, the system should be charged up in the spring, and then diversions from the river minimized during low flows.

Strategies that seek to increase irrigation efficiency, for example, lining canals to reduce diversions, should be weighed against the reduction to groundwater recharge and the timing of subsequent declines in groundwater discharge to surface water. Modeling shows that flood-irrigated fields and unlined canals provide substantial groundwater recharge. Converting irrigated lands to almost any other use, or lining canals, will decrease groundwater recharge, and decrease seasonal groundwater storage. Loss of groundwater recharge will reduce groundwater discharge to surface waters, but the location and timing of those effects will depend on the site-specific hydrogeologic system. Reduction in groundwater discharge to surface waters will be most evident in smaller groundwater-fed streams, such as Willow Spring or Parson’s Slough.

Modeling demonstrates the utility of split season irrigation to increase dry season stream flows relative to a simple conversion from flood to pivot irrigation. The application of excess water while water is abundant, and using more efficient irrigation methods when water is scarce, can help maintain late season flows. Our modeling also shows that if the transmissivity of the aquifer is high, and/or the fields are close to surface waters, the groundwater mound may dissipate too rapidly to supplement flows throughout the summer. Conversely, if the fields are too far from the river, and/or the transmissivity of the aquifer is too low, increased groundwater discharge to surface waters may occur after the low flow period. The models developed for this project could be adapted to evaluate site-specific settings. While these modeling results are instructive, there are few cases where split season irrigation has been implemented, and results are anecdotal (Dodge, JRWC, written commun. 2019; Schwend, DNRC, written commun., 2019). Site-specific studies of the effects of split season irrigation on groundwater recharge, storage, and discharge would be useful.

The modeled effects to dry season stream flows from increased residential development were slight; however, any new consumptive use of water will reduce the availability of water downstream. The effect of increased groundwater use related to housing developments could be mitigated by reducing domestic consumptive water use. Detailed analysis of water use in the Townview subdivision, near Helena, showed that about 98% of the consumptive water use was for irrigating yards (Waren and others, 2012; Bobst and others, 2014). Reducing the amount of irrigated lawn could be a key component of a groundwater conservation program.

Some wells monitored during this study showed a decline in groundwater elevations relative to data collected in previous studies. The wells with declines were geographically distributed, so it is unlikely that the effects are due to a regional decline in groundwater levels; however, it would be useful to conduct additional monitoring at these sites so that the cause of the declines could be better understood.

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APPENDIX A

GROUNDWATER MONITORING NETWORK

Appendix A: Groundwater Monitoring Network

Well #	GWIC ID	HGU	Trans	Sampled	First GWE Reading	Last GWE Reading	# of GWE Measurements	Aquifer Code	Setting	Max GWE	Min GWE
1	107608	Bench	No	No	8/10/11	4/13/15	18	120SNGR	Irrigation Influence	Sept	April
2	232116	Bedrock	Yes	Yes$^+$	10/23/08	9/16/15	10,072	330MDSN	Up-Gradient From Irrigation	July	May
3	107345	Bench	No	No	8/9/11	4/13/15	19	120SNGR	Irrigation Influence	Oct	Feb
4	260584	Bedrock	No	No	8/10/11	4/13/15	18	500GNSC	Up-Gradient From Irrigation	Jan	Sept
5	277278	Alluvium	Yes	No	2/10/14	10/28/15	14,744	110ALVM	Near River	June	Aug
6	171525	Bedrock	No	No	10/24/11	4/13/15	17	211TBBT	Up-Gradient From Irrigation	July	Oct
7	135213	Alluvium	No	No	8/18/11	4/13/15	19	111SNGR	Irrigation Influence	Sept	March
8	107380	Alluvium	No	No	10/19/11	4/13/15	19	111SNGR	Floodplain w/o Irrigation Influence	March	Aug
9	154158	Renova	No	Yes	10/24/11	10/24/11	1	120SNGR	---	---	---
10	262622	Alluvium	No	No	8/21/11	4/13/15	19	111SNGR	Irrigation Influence	June	April
11	8989	Renova	No	Yes$^+$	---	---	-	120SDMS	---	---	---
12	157742	Alluvium	No	No	10/23/11	4/13/15	19	111SNGR	Irrigation Influence	June	April
13	276116	Alluvium	No	No	4/6/05	4/13/15	38	110ALVM	Irrigation Influence	June	April
14	276115	Alluvium	No	No	4/6/05	4/13/15	38	110ALVM	Irrigation Influence	June	April
15	277280	Renova	Yes	No	2/10/14	10/28/15	15,298	120SDMS	Near River	June	Aug
16	262423	Alluvium	No	Yes$^+$	8/10/11	4/13/15	19	112SNGR	Irrigation Influence	June	March
17	276117	Alluvium	No	No	4/6/05	4/13/15	38	110ALVM	Irrigation Influence	June	April
18	276114	Alluvium	No	No	4/6/05	5/4/15	43	110ALVM	Irrigation Influence	July	March
19	280980	Renova	No	Yes	12/9/14	5/4/15	7	120SDMS	Irrigation Influence	NR	April
20	280979	Renova	No	No	12/9/14	5/4/15	7	120SDMS	Irrigation Influence	NR	April
21	107346	Bench	No	No	8/21/11	4/13/15	19	120SNGR	Irrigation Influence	July	April
22	277403	Renova	Yes	Yes	2/27/14	5/4/15	9,991	120SNGR	Near River	May	Aug
23	277404	Renova	No	No	2/27/14	5/4/15	14	120SNGR	Near River	May	Aug
24	277405	Renova	No	No	2/27/14	5/4/15	14	120SNGR	Near River	May	Aug
25	277406	Alluvium	Yes	No	2/27/14	5/4/15	10,018	110ALVM	Near River	May	Aug
26	107330	Alluvium	No	No	10/18/11	5/4/15	24	111SNGR	Irrigation Influence	June	March
27	276113	Alluvium	Yes	No	4/6/05	5/4/15	2,918	110ALVM	Irrigation Influence	Aug	NR
28	257377	Renova	No	No	6/21/11	5/4/15	23	120SNGR	Up-Gradient From Irrigation	Dec	Aug
29	261912	Alluvium	No	No	6/21/11	5/4/15	24	111SNGR	Irrigation Influence	June	April
30	259547	Alluvium	No	No	9/30/10	5/4/15	24	112SNGR	Irrigation Influence	Aug	April
31	195941	Alluvium	No	No	6/16/11	5/4/15	24	111SNGR	Irrigation Influence	Sept	April
32	276041	Alluvium	No	No	10/25/13	5/4/15	19	110ALVM	Irrigation Influence	Sept	April
33	107080	Alluvium	No	Yes$^+$	6/20/91	9/16/15	128	112SNGR	Floodplain w/o Irrigation Influence	May	Sept
34	107055	Renova	No	No	10/8/04	4/13/15	42	120SDMS	Irrigation Influence	Oct	May
35	276038	Alluvium	No	No	4/7/05	4/13/15	26	110ALVM	Irrigation Influence	Oct	April
36	279258	Alluvium	Yes	No	9/9/14	9/16/15	1,849	110ALVM	Irrigation Influence	Sept	April
37	279259	Alluvium	No	Yes	9/9/14	9/16/15	11	110ALVM	Irrigation Influence	Sept	April
38	279260	Alluvium	No	No	9/9/14	5/4/15	10	110ALVM	Irrigation Influence	Sept	April
39	276287	Alluvium	Yes	No	4/6/05	5/4/15	10,551	110ALVM	Irrigation Influence	June	April

Appendix A: Groundwater Monitoring Network

Well #	GWIC ID	HGU	Trans	Sampled	First GWE Reading	Last GWE Reading	# of GWE Measurements	Aquifer Code	Setting	Max GWE	Min GWE
40	277329	Alluvium	No	No	4/6/05	5/4/15	36	110ALVM	Irrigation Influence	July	April
41	276111	Alluvium	No	No	12/17/04	5/4/15	43	110ALVM	Irrigation Influence	Aug	April
42	276109	Alluvium	No	No	12/17/04	5/4/15	45	110ALVM	Irrigation Influence	Sept	April
43	276108	Alluvium	No	No	10/8/04	5/4/15	47	110ALVM	Irrigation Influence	July	April
44	276107	Alluvium	No	No	10/8/04	5/4/15	47	110ALVM	Irrigation Influence	July	March
45	276106	Alluvium	No	No	10/8/04	5/4/15	47	110ALVM	Irrigation Influence	Aug	April
46	276103	Alluvium	No	No	10/8/04	5/4/15	47	110ALVM	Irrigation Influence	Sept	April
47	276127	Alluvium	No	No	10/8/04	4/13/15	44	110ALVM	Irrigation Influence	Sept	April
48	276105	Alluvium	No	No	10/8/04	5/4/15	49	110ALVM	Irrigation Influence	NR	NR
49	277868	Alluvium	No	Yes	5/14/14	5/4/15	17	110SNGR	Irrigation Influence	Oct	April
50	276112	Alluvium	No	No	12/17/04	5/4/15	43	110ALVM	Irrigation Influence	Sept	April
51	277080	Bedrock	No	Yes	10/8/04	5/4/15	37	330MDSN	Irrigation Influence	Sept	April
52	276285	Alluvium	Yes	No	12/17/04	5/4/15	11,174	110ALVM	Irrigation Influence	June	April
53	230730	Alluvium	Yes	No	6/21/11	5/4/15	10,532	111SNGR	Irrigation Influence	June	April
54	107023	Bedrock	Yes	Yes	7/27/11	4/13/15	10,637	211BDBT	Up-Gradient From Irrigation	June	April
55	209718	Bench	No	No	7/19/13	5/4/15	23	120SNGR	Irrigation Influence	June	April
56	237587	Bench	No	No	6/16/11	5/4/15	24	112SNGR	Up-Gradient From Irrigation	July	April
57	156080	Alluvium	No	No	7/16/13	5/4/15	24	110ALVM	Irrigation Influence	Aug	April
58	237722	Alluvium	Yes	No	7/19/13	5/4/15	11,182	110ALVM	Irrigation Influence	June	April
59	48626	Alluvium	No	Yes$^+$	7/19/13	5/4/15	22	111SNGR	Irrigation Influence	June	April
60	250485	Renova	No	Yes$^+$	10/8/08	5/4/15	56	120SDMS	Up-Gradient From Irrigation	Dec	Aug
61	219670	Renova	No	Yes$^+$	10/8/08	5/4/15	55	120SDMS	Irrigation Influence	Sept	April
62	265807	Alluvium	No	Yes$^+$	9/19/13	4/15/15	15	110SNGR	Irrigation Influence	Oct	April
63	48667	Renova	No	Yes$^+$	6/23/93	9/2/15	94	120SDMS	Irrigation Influence	July	March
64	236176	Renova	Yes	No	7/19/13	4/15/15	10,712	120SDMS	Up-Gradient From Irrigation	April	Aug
65	171688	Bench	No	No	7/19/13	5/4/15	23	120SDMS	Irrigation Influence	Sept	April
66	274315	Renova	No	No	7/19/13	5/4/15	23	120SDMS	Up-Gradient From Irrigation	Sept	May
67	274314	Renova	No	No	7/19/13	5/4/15	23	120SDMS	Up-Gradient From Irrigation	Sept	April
68	277282	Alluvium	Yes	Yes	2/12/14	10/28/15	14,606	111SNGR	Irrigation Influence w/pumping	Sept	Aug
69	48569	Alluvium	No	No	7/29/10	5/4/15	24	111ALVM	Irrigation Influence w/pumping	June	Aug
70	48577	Renova	No	Yes$^+$	5/18/09	9/16/15	42	120SNGR	Irrigation Influence	Oct	April
71	158744	Renova	No	No	7/18/13	5/4/15	22	120SDMS	Up-Gradient From Irrigation	Dec	Aug
72	48521	Alluvium	No	No	7/18/13	4/15/15	19	110ALVM	Irrigation Influence w/pumping	Oct	July
73	48522	Alluvium	No	No	7/18/13	5/4/15	22	110ALVM	Irrigation Influence	Sept	April
74	179168	Alluvium	Yes	No	7/18/13	8/7/14	2,007	110ALVM	Up-Gradient From Irrigation	July	Feb
75	49088	Renova	No	No	12/18/13	4/15/15	12	120SDMS	Up-Gradient From Irrigation	Dec	Sept
76	49087	Renova	Yes	No	12/18/13	4/15/15	5,646	120SDMS	Near River	Jan	Aug
77	49103	Renova	No	No	12/18/13	4/15/15	10	120SDMS	Up-Gradient From Irrigation	Jan	June
78	49097	Renova	No	No	12/18/13	5/4/15	18	120SDMS	Floodplain w/o Irrigation Influence	Nov	July

Appendix A: Groundwater Monitoring Network

Well #	GWIC ID	HGU	Trans	Sampled	First GWE Reading	Last GWE Reading	# of GWE Measurements	Aquifer Code	Setting	Max GWE	Min GWE
79	276284	Alluvium	No	No	12/18/13	5/4/15	18	110ALVM	Floodplain w/o Irrigation Influence	Dec	July
80	281350	Renova	No	No	7/17/13	5/4/15	23	120SDMS	Up-Gradient From Irrigation	March	Aug
81	48477	Alluvium	No	Yes[+]	9/30/92	9/2/15	100	110ALVM	Floodplain w/o Irrigation Influence	March	Aug
82	247793	Renova	Yes	No	7/17/13	5/4/15	10,512	120SDMS	Floodplain w/o Irrigation Influence	May	Aug
83	279261	Renova	Yes	No	9/16/14	5/4/15	4,601	120SDMS	Near River	May	Sept
84	279262	Renova	No	Yes	9/16/14	5/4/15	9	120SDMS	Near River	May	Sept
85	279263	Renova	No	No	9/16/14	5/4/15	12	120SDMS	Near River	May	Sept
86	277285	Alluvium	Yes	No	2/13/14	10/28/15	14,605	110ALVM	Near River	June	Aug
87	280977	Renova	Yes	No	10/23/14	5/4/15	1,847	120SDMS	Irrigation Influence	Sept	April
88	280978	Renova	No	Yes	2/13/15	9/16/15	4	120SDMS	Irrigation Influence	Sept	April
89	276427	Renova	No	No	7/24/13	5/4/15	22	120SDMS	Irrigation Influence	June	March
90	274320	Alluvium	Yes	No	7/17/13	5/4/15	11,188	110ALVM	Irrigation Influence w/pumping	Sept	Aug
91	224219	Renova	No	No	5/20/09	3/11/15	22	120SDMS	Irrigation Influence	Oct	April
92	48378	Renova	No	No	7/18/13	5/4/15	23	120SDMS	Irrigation Influence	June	Jan
93	277286	Alluvium	Yes	Yes	2/11/14	10/28/15	14,605	111SNGR	Near River	June	Aug
94	250384	Renova	No	No	5/19/09	4/15/15	23	120SNGR	Irrigation Influence	Oct	April
95	215992	Renova	No	Yes[+]	4/20/06	9/2/15	67	120SNGR	Up-Gradient From Irrigation	June	Aug
96	175429	Bedrock	No	No	7/18/13	4/15/15	13	400LHOD	Up-Gradient From Irrigation	NR	NR
97	265186	Alluvium	Yes	Yes[+]	3/16/12	9/14/15	12,252	110ALVM	Near River	June	Sept
98	49049	Renova	No	No	8/1/91	3/19/14	88	120SDMS	Up-Gradient From Irrigation	June	Jan
99	192299	Bedrock	No	No	3/8/12	4/15/15	32	400LHOD	Irrigation Influence	June	March
100	265188	Alluvium	Yes	Yes[+]	3/16/12	10/28/15	33,165	110ALVM	Near River	June	Sept
101	48364	Alluvium	No	No	7/18/13	4/15/15	16	110ALVM	Near River	June	Aug
102	265122	Renova	No	No	7/17/13	4/15/15	17	120SDMS	Near River	June	April
103	277287	Alluvium	Yes	No	2/11/14	10/28/15	13,975	110ALVM	Near River	June	Sept
104	127960	Renova	No	Yes[+]	4/3/08	6/12/16	58	120SNGR	Near River	May	Aug
105	276465	Alluvium	No	No	12/18/13	4/15/15	9	110ALVM	Near River	June	April
106	274470	Bench	No	No	8/13/13	9/20/13	2	110ALVF	Up-Gradient From Irrigation	NR	NR

*Aquifer Test Site

GWE, Groundwater Elevation.

Highlighted cells indicate wells with monitoring data that predates this study.

NR, Not Recorded.

[+] Sampled during a previous study.

GWIC Aquifer Codes are defined at: https://mbmggwic.mtech.edu/sqlserver/v11/help/reports/listAquifer.asp

Wells identified as "Up-Gradient From Irrigation" are beyond the influence of irrigation recharge.

APPENDIX B

SURFACE-WATER MONITORING SITES

Appendix B. Surface-Water Monitoring Sites

Site Number	GWIC or USGS ID	Name	Organization	Data Type			
				Temp	Stage	Discharge	Quality
1	06026500	Jefferson River near Twin Bridges	USGS	X	X	X	X
2	277192	Jefferson River at Hells Canyon	MBMG	X	X		
3	274576	Creeklyn Canal at Diversion	MBMG	X	X	X	
4	274578	Parrot Canal at Diversion	MBMG	X	X	X	
5	277191	Jefferson River at Silver Star	MBMG	X	X	X	
6	278155	Parrot Canal at Waterloo Road	MBMG	X	X	X	
7	274577	Creeklyn Canal at Nelson's	MBMG	X	X	X	
8	278427	Jefferson River at Funston's	MBMG	X	X	X	X
9	278796	Parrot Canal at Bench Road	MBMG	X	X	X	
10	278798	Parrot Canal at Gornick Road	MBMG	X	X	X	
11	277323	Beall Creek above Diversion	MBMG	X	X		
12	278357	Beall Creek above Parrot Canal	MBMG	X	X	X	
13	277190	Creeklyn Canal at Cutoff Road	MBMG	X	X	X	
14	274575	Jefferson Canal at Diversion	MBMG	X	X	X	X
15	06027600	Jefferson River at Parson's Bridge	USGS	X	X	X	X
16	277129	Parson's Slough at Loomont	MBMG	X	X	X	X
17	274579	Parrot Canal at Hunt's	MBMG	X	X	X	X
18	277126	Willow Springs West Fork	MBMG	X	X	X	X
19	279379	Willow Springs East Fork	MBMG	X	X	X	X
20	274881	Lower Willow Springs	MBMG	X	X	X	X
21	278154	Kernow Blowout (Parrot)	MBMG	X	X	X	
22	274882	Parrot Canal at Willow Springs	MBMG	X	X	X	
23	278156	Jefferson River at Corbett's	MBMG	X	X	X	X
24	277320	Parrot Canal before Tunnel	MBMG	X	X	X	
25	277321	Tunnel Blowout (Parrot)	MBMG	X	X	X	
26	278400	Fish Creek (inflow to Slaughterhouse)	MBMG	X	X	X	X
27	277189	Slaughterhouse Slough Diversion	MBMG	X	X	X	
28	278863	Jefferson River at Parrot Castle	MBMG	X	X		X
29	277194	Piedmont Pond	MBMG	X	X		X
30	278354	Slaughterhouse Slough at Kountz Rd	MBMG	X	X	X	X
31	277193	Jefferson River at Kountz Rd	MBMG	X	X	X	
32	274883	Jefferson Canal at Markowski Rd	MBMG	X	X	X	
33	274885	Pipestone Creek at Capp Ln	MBMG	X	X	X	X
34	277322	Whitetail Creek at Sailsbury's	MBMG	X	X	X	
35	274574	Whitetail Creek at Cemetary	MBMG	X	X	X	X
36	287489	Jefferson Slough at Willow Grove	Confluence	X	X	X	
37	287491	Pipestone Creek at Mouth	Confluence	X	X	X	
38	287492	Whitetail Creek at Mouth	Confluence	X	X	X	
39	287493	Jefferson Slough at Briggs	Confluence	X	X	X	
40	287494	Jefferson Slough at Yellowstone Trail	Confluence	X			
41	287495	Jefferson Slough at Tebay Ranch	Confluence	X	X	X	
42	274564	Jefferson Slough at Tebay Lane	MBMG	X	X	X	X
43	287503	Tebay Ditch	Confluence	X			
44	274566	Jefferson River at Mayflower	MBMG	X	X	X	X
45	274580	Parrot Canal at Mayflower	MBMG	X	X	X	
46	287504	Jefferson Slough at I90/MT69	Confluence	X			
47	287506	Jefferson Slough at Mulligan's	Confluence	X	X	X	
48	287505	Boulder Ditch	Confluence	X			
49	274565	Jefferson Slough at 359	MBMG	X	X	X	X
50	278401	Jefferson River at Cardwell	MBMG	X	X	X	
51	263602	Boulder River	MBMG	X	X	X	X
52	287507	Jefferson Slough near Mouth*	Confluence	X			
53	274573	Jefferson River at LaHood	MBMG	X	X	X	X

*Note: Called "Boulder River mouth" by Confluence.

Data for MBMG sites are available from http://mbmggwic.mtech.edu/

Data for USGS sites are available from https://waterdata.usgs.gov/mt/

APPENDIX C

A REACH BY REACH ASSESSMENT OF GROUNDWATER/SURFACE-WATER INTERACTIONS

Appendix C. A reach by reach assessment of groundwater/surface-water interactions.

C1. Introduction

The geographic distribution of gaining and losing reaches is important qualitative information for evaluating the results of numerical modeling. Stream and groundwater monitoring data were analyzed in four ways to aid in understanding groundwater/surface-water interactions in the study area. These were (1) comparing stream flows from the upstream to downstream ends of a reach; (2) comparing water temperatures from the upstream to downstream ends of a reach; (3) comparing time-series groundwater and surface-water elevations measured at close proximity to each other; and (4) comparing time-series groundwater and surface-water temperatures measured at close proximity to each other. These methods were used in combination to understand groundwater/surface-water interactions on a reach basis. There was not sufficient data to evaluate each of these indicators on every reach. The results are summarized in table 4 and fig. 22 in the main body of this report. To summarize the results of all available indicators on a reach basis each reach was classified as gaining, slightly gaining, neutral, slightly losing, or losing. For gaining and losing reaches all of the available methods indicated a net gain or loss all of the time. For slightly gaining and slightly losing reaches most methods indicated net gains or losses most of the time. Reaches were assigned as neutral when they did not show clear gaining or losing behavior (see table 4 in the main body of the report).

We attempted a fifth method to evaluate groundwater: surface-water interactions, examining geochemical signatures to identify gaining reaches and to quantify the magnitude of those gains. However, the groundwater chemistry in the alluvial aquifer is similar to that in surface water, and a reliable groundwater tracer could not be identified in surface waters. This finding suggests that there is substantial exchange occurring between surface waters and the alluvial aquifer.

C2. Overview of Data Analysis

Net Change in Stream Flow

Comparing time-series stream flows from the upstream to downstream ends of a reach (net flow difference) can provide some information on net gains or losses. While major diversions and tributaries were monitored, there were some unmonitored diversions and tributaries, so these results are qualitative. Even if all diversions and tributaries were measured, the cumulative measurement error often makes it difficult to quantify small gains or losses. Synoptic flow measurements are shown in tables C1-1 to C1-4, and differences in flows based on hourly discharges calculated from stage readings and rating curves are shown in figures C2-1 to C2-9.

Change in Stream Temperature

The temperature above and below a reach can be used to qualitatively identify gaining reaches. This approach is not quantitative because heat exchange with the atmosphere and solar heating also occur. Groundwater discharge to a stream causes the surface-water temperature to cool during the summer and warm during the winter. When this effect was large enough to overcome heat exchange with the atmosphere and solar heating, we classified it as gaining. Figures C3-1 to C3-7 illustrate changes in stream temperature between sites based on hourly readings.

Groundwater/Surface-Water Elevations

The elevations of the stream and groundwater at a particular site can be used to identify the direction of the hydrologic gradient at that site. While this is a measurement of the hydraulic gradient at that site, it cannot be assumed that it is valid at the reach scale. The differences between surface-water and groundwater elevations at six sites where wells were installed immediately adjacent to surface waters are shown in figures C4-1 to C4-3.

Groundwater/Surface-Water Temperatures

The temperature of the surface water and groundwater at a particular site can be used to identify gaining or losing conditions. In a losing stream, the diel temperature signal in the surface water will be transmitted to the groundwater by both advection and conduction. In a gaining stream, the advection of groundwater into the stream will prevent the stream's dial signal from reaching the groundwater, and the amplitude of the dial signal in the surface water may be reduced. Similar to groundwater/surface-water elevations, extrapolating this up to the reach scale may be inaccurate. Comparisons among groundwater, surface-water, and air temperatures are shown in figures C4-1 to C4-3.

C3. Results

A. Jefferson River

USGS Gage near Twin Bridges to Silver Star

Monitoring within this reach was conducted by the USGS at a gage near Twin Bridges (site 1), by MBMG at FWP's Hells Canyon access site (site 2 and well 5), and by MBMG at FWP's Silver Star access site (site 5 and well 15). Stream discharge, stream stage, and stream temperature were measured at the USGS site. Stream elevation, stream temperature, groundwater elevation, and groundwater temperature were measured at the FWP Hells Canyon site. Stream discharge, stream elevation, stream temperature, groundwater elevation, and groundwater temperature were measured at Silver Star. The Hells Canyon station was 2.1 river miles downstream of the USGS gage, and the Silver Star station was 4.5 river miles downstream of the Hells Canyon station.

The net change in stream discharge between the USGS gage and the Silver Star gage is effected by diversions for the Creeklyn and Parrot Canals. From May through September 2014 the average diversion to the Creeklyn Canal was 56 cfs, and the average diversion to the Parrot Canal was 173 cfs. After accounting for these diversions there was a net decrease in flow between these stations during springtime high stream flows and a net increase in flow during low stream flows (fig. C2-1A). From April 15 to July 15, 2014, the average net reduction in flow between these stations was 332 cfs. From July 15 to November 1, 2014 the average net increase in flow was 60 cfs. The transition from decreasing to increasing flow occurred at about 1,200 cfs.

In 2014 stream temperatures were monitored from July to September at the USGS station near Twin Bridges, and from April to November for the MBMG stations at Hells Canyon and Silver Star. Over the 2.1-mi reach from the USGS station to Hells Canyon there is little apparent change in stream temperature (fig. C3-1A). Over the 4.5-mi reach from Hells Canyon to Silver Star, surface-water temperatures cooled during August, and warmed during October and November. During April–July and September there was little apparent change in stream temperature (fig. C3-1B). This is consistent with it being a neutral or losing stream during the early summer, and gaining during the late summer and into the fall. Little change is observed in September since surface-water temperatures, air temperatures, and groundwater temperatures are similar (figs. C4-1C and C4-1F).

At Hells Canyon and Silver Star stream elevation and groundwater elevations were monitored from April to November 2014 (figs. C4-1A, C4-1B, C4-1D, and C4-1E). At the Hells Canyon site groundwater elevations were generally lower than surface-water elevations from the start of monitoring (April 2) until June 30th. Surface-water elevations were generally lower than groundwater elevations from June 30th through August 15th. From August 15th to the end of monitoring (November 10th) groundwater elevations were slightly lower than surface-water elevations. At the Silver Star site, groundwater elevations continuously exceeded surface-water elevations. These data indicate that the Jefferson River changes over time, from gaining and losing, at the Hells Canyon site. The river is consistently gaining at the Silver Star site.

Near stream groundwater temperatures were monitored at Hells Canyon and Silver Star (figs. C4-1C and C4-1F). At both sites there is no measurable daily temperature signal, and groundwater temperatures stay well above freezing in the winter. This indicates that at these points, there is insufficient flow from the stream to the groundwater to transmit the stream's heat signature to the wells. Notably, the groundwater temperature at Silver Star shows only 2ºC of seasonal variation, and it is considerably warmer than other wells (average of 14.8ºC compared to 8.5ºC at Hells Canyon). This is attributed to local hydrothermal features.

Silver Star to Funston's

This reach extends 6.1 mi from Silver Star to Funston's (site 8). Stream discharge, stream stage, and stream temperature were measured at Funston's from July to November, 2014.

Stream flow at Funston's was typically less than at Silver Star. 2014 average flow was 46 cfs less at Funston's (table C1-1 and figs. C2-1C and C2-1D).

In 2014, surface-water temperatures warmed between Silver Star and Funston's from July through early September. Surface-water temperatures cooled during October and November (fig. C3-1D). During late September there was little apparent change in stream temperature because surface-water temperatures and air temperatures were similar (figs. C3-1D and C4-1F). These data are consistent with a losing or neutral stream during the monitoring period (July to November).

Funston's to USGS Gage at Parson's Bridge

The USGS gage at Parson's Bridge (site 15) is 4.1 mi downstream of the gage at Funston's, downstream of Parson's Bridge and the diversion to the Jefferson/Fish Creek Canal, and upstream from Parson's Slough. The Parson's Bridge gage recorded stream discharge, stage, and temperature from July to September, 2014.

Flow at the USGS gage at Parson's Bridge is affected by the diversion for the Jefferson canal. After the effects of the Jefferson canal are subtracted, the net change in flow along this reach varies between no change and increasing flow (tables C1-1 and C1-2; figs. C2-1E and C2-1F). The flow at Parson's Bridge was similar to the flow at Funston's in July 2014. During early

August, while stream stages were their lowest, the flow at Parson's Bridge was greater than the flow at Funston's. Stream stage increased in mid-August, which corresponded to a transition to similar flows at the two stations. In September, as stage fell, flows transitioned back to higher flows at Parson's Bridge. Stage increased at the end of September, and flows again became similar at both sites. These transitions occurred at a flow of about 600 cfs.

Surface-water temperatures cooled between Funston's and Parson's Bridge during July and August, 2014. During September there was little apparent change in stream temperature (fig. C3-1E). This is consistent with the stream gaining during low flows, and near neutral during higher flows.

USGS Gage at Parson's Bridge to Corbett's

MBMG's Corbett gage (site 23) was located 2.7 mi downstream of the USGS gage at Parson's Bridge. Stream discharge, stream stage, and stream temperature were recorded at this station. A domestic well approximately 120 ft from the Jefferson River (GWIC ID 230730; well 53) was monitored with a transducer at the Corbett site, providing a record of groundwater temperature and elevation.

Parson's Slough (site 16) and Willow Springs (site 20) flow into the Jefferson River between these stations. The Kernow blowout for the Parrot canal (site 21), which discharges to Willow Springs below site 20, also occurs in this reach. Previous work found that groundwater discharges to the Jefferson River along this reach (MDEQ, 2014a; WET, 2006, 2010a,b). Stream flow at the Corbett station was greater than at Parson's Bridge throughout 2014 (table C1-1 and figs. C2-2A, C2-2B). Taking into account the observed flows from Parson's Slough, Willow Springs, and the Kernow blowout, the 2014 monthly average flow increases were: July, 194 cfs; August, 50 cfs; and September, 16 cfs.

In 2014, surface-water temperatures cooled between Parson's Bridge and Corbett's during July and August (fig. C3-1F). September brought a slight cooling during warmer periods and slight warming during cooler periods. This is consistent with the stream consistently gaining groundwater.

Groundwater elevations at the Corbett station continuously exceeded stream elevations (figs. C4-2A, C4-2B). When the Parrot Canal turned on in mid-April 2014, groundwater elevations rose by 7 ft in 14 days. When the Parrot Canal was off, from 7/3/14 to 7/8/14, groundwater levels dropped by 4 ft. When the Parrot Canal was turned back on, groundwater levels rose by 3 ft. The maximum difference between groundwater and river elevations occurred in August, and was about 14 ft. This difference decreased over time and was about 11 ft when the canal was shut off on 10/20/14. Groundwater levels declined after the irrigation season, falling back to their pre-irrigation levels before the canal was turned on again in the spring of 2015.

Groundwater temperatures do not show dial variations, and only show slight seasonal variations, at the Corbett station. The minimum groundwater temperature in 2014, 12.1ºC, occurred in late June. This is consistent with gaining stream conditions, demonstrating that the surface-water temperature signal is not being transmitted to groundwater.

Corbett's to Parrot Castle

The Parrot Castle gage (site 28) was located 4.7 mi downstream of the Corbett gage, below the Slaughterhouse Slough diversion. Stream stage and temperature were monitored at this station. Discharge was not measured at this location due to safety concerns.

Surface-water temperatures warmed during 2014 between Corbett's and Parrot Castle in July, August, and September (fig. C3-2A). In October, there was slight warming during warmer periods and slight cooling during cooler periods. November surface-water temperatures declined between these stations, consistent with a stream that is either losing or neutral over this reach.

Parrot Castle to Kountz Bridge

The Kountz Bridge gage (site 31) was located 4.6 mi downstream of the Parrot Castle gage. A monitoring well (well 86) was also installed adjacent to the river at this site. This station was monitored for stream elevations, discharge, and temperature, and for groundwater elevations and temperatures.

While stream flow was not measured at Parrot Castle, we developed a net change in flow comparison using data from the Corbett station, 9.3 mi upstream. This shows that flows declined between these stations during July and August but increased slightly during September. Note that the Slaughterhouse Slough diversion is within this reach. The average monthly net difference in flows for 2014 were: July, 188 cfs lower; August 58 cfs lower; and September, 6 cfs higher (table C1-1 and figs. C2-2C, C2-2D). When the measured diversion into Slaughterhouse Slough is taken into account these values become: July, 121 cfs lower; August, 5 cfs higher; September, 47 cfs higher.

Surface-water temperatures cooled slightly between Parrot Castle and Kountz Bridge during July, 2014, but there was no systematic warming or cooling during August and September (fig. C3-2C). This suggests that the river is gaining along this reach since it did not warm due to heat exchange and solar insolation during the warmest/sunniest time of the year; however, the gains were also not large enough to cause cooling.

Groundwater elevations at the Kountz Bridge station were consistently higher than stream elevations (figs. C4-2D, C4-2E). The difference in elevations was smallest during high stream flows, and greatest during baseflow conditions on the stream. Groundwater elevations also responded to ice jams on the river during the winter (fig. C4-2D).

Groundwater temperatures at the Kountz Bridge site showed a seasonal signal; however, they did not approach zero degrees C in the winter (fig. C4-2F). The minimum recorded groundwater temperature was 4.4ºC on 3/9/14. This is consistent with a stream that is gaining since a buffered seasonal temperature signal is being transmitted to groundwater.

Kountz Bridge to Mayflower Bridge

The Mayflower Bridge gage (site 44) was located 3.3 mi downstream of the Kountz Bridge station. A monitoring well was also installed at this site (GWIC ID 277286; well 93). Stream elevations, discharge, and temperature, and groundwater elevations and temperatures were monitored at this station.

Stream flows at the Mayflower station in 2014 were generally greater than at the Kountz Bridge station (table C1-1 and figs. C2-2E, C2-2F). Some portion of this increase is due to the return of Slaughterhouse Slough to the Jefferson River 0.5 mi above the Mayflower gage. There is a net loss along this reach during high flows, and net gains occurred during the remainder of the monitoring period.

Surface-water temperatures showed little change between Kountz Bridge and Mayflower Bridge during high flows (April to June) in 2014. Surface waters warmed between these sites in July (fig. C3-2D), consistent with a stream that is losing to neutral.

Groundwater elevations at the Mayflower station remained lower than surface-water elevations throughout the monitoring period (figs. C4-3A, C4-3B). Groundwater elevations responded to ice jams in the river during the winter. These observations indicate losing conditions at this station.

Groundwater temperatures in the Mayflower well showed a seasonal signal, and the minimum recorded groundwater temperature was 2.3ºC on 3/16/14. Groundwater temperatures did not show dial variations (fig. C4-3C). These observations are consistent with losing conditions at this station.

Mayflower Bridge to Cardwell

The Cardwell gage (site 50) was installed 4.2 mi downstream of Mayflower Bridge. Tail water from the Parrot Canal enters the Jefferson River within this reach. A monitoring well was also installed at the Cardwell site (GWIC ID 277287; well 103). Monitoring included stream elevations, discharge, and temperature, and groundwater elevations and temperatures. The stream gage was installed in early April 2014, but was destroyed during high flows in early May. Subsequently, periodic manual flow and stage measurements were collected through early November 2014.

Comparison of synoptic flow measurements at Mayflower Bridge and Cardwell shows a decrease in flow between these stations (table C1-1; figs. C2-3A, C2-3B).

There was no apparent change in stream water temperature between these sites in April and early May 2014; however, any influence of groundwater inflow would be difficult to detect during high springtime flows (fig. C3-2E).

Groundwater elevations at the Cardwell site were consistently lower than surface-water elevations (figs. C4-3D, C4-3E). Groundwater elevations also responded to ice jams. These findings indicate losing conditions at this site.

Groundwater temperatures show a strong seasonal fluctuation, but they do not show dial variations and do not approach zero in the winter. This indicates slightly losing conditions at this site.

Cardwell to LaHood

The LaHood gage (site 53) was located 1.9 river miles downstream of the Cardwell station. Stream elevations, discharge and temperature were recorded at this station. Discharge measurements were made during low flows in 2013; however, due to safety concerns, they were not collected in 2014.

The Jefferson Slough enters the Jefferson River within this reach. The Jefferson Slough obtains its water from partial diversion of Slaughterhouse Slough, and inflow from Pipestone Creek, Whitetail Creek, and the Boulder River (see below). Synoptic flow measurements from September to October 2013 showed that flow at the LaHood station varied from being less than the combined inflows to being higher than the inflows. The September to October average difference (post-irrigation) showed an average net flow increase of 44 cfs (tables C1-1, C1-2, and C1-3).

Surface-water temperatures between Cardwell Bridge and LaHood showed warming during April and May, suggesting groundwater inflow (fig. C3-2F). The longer record comparing surface-water temperatures at Mayflower to LaHood shows cooling during July, also suggesting groundwater inflow (fig. C3-3A).

B. Jefferson Slough

The Jefferson Slough begins as a diversion from the Slaughterhouse Slough. Major tributaries to the Slough include Pipestone Creek, Whitetail Creek, and the Boulder River. Pipestone Creek flows into Whitetail Creek just above its confluence with the Jefferson Slough.

Slaughterhouse Slough at Kountz Road to Jefferson Slough at Willow Grove

The Willow Grove station (site 36) was 1.7 mi downstream of the Slaughterhouse Slough station (site 30), and 0.6 mi below the diversion from Slaughterhouse Slough to the Jefferson Slough. Discharge and temperature were monitored at the Slaughterhouse Slough station by MBMG and at the Willow Grove station by Confluence. Surface-water temperature comparisons show little systematic change during April, May, June, and September, likely due to high flows and the similarity between air and water temperatures. Cooling occurred between these stations in July and August, and warming occurred in October and November (fig. C3-3B), consistent with groundwater inflow along this reach.

Willow Brook to Briggs

The Briggs Station (site 39) was 1.2 mi downstream of the Willow Grove station. Whitetail Creek flows into the Jefferson Slough within this reach, including flow from Pipestone Creek, which joins Whitetail Creek 0.2 mi above the confluence with the Jefferson Slough. Stream temperature and discharge were monitored by Confluence at the Briggs station, and in Pipestone and Whitetail Creeks (sites 37 and 38) above their confluence.

The discharge measured at Briggs during 2014 was often lower than the combined inflows to this reach; however, flows were similar at times (table C1-3 and figs. C2-3C, C2-3D). These differences indicate losing conditions.

Stream temperature can be modeled as a conservative tracer to aid in understanding groundwater/surface-water interactions. Modeled and observed temperatures are compared in the same way as upstream and downstream temperatures. The observed flows and temperatures at the mouth of Pipestone Creek, at the mouth of Whitetail Creek, and of the Jefferson Slough at Willow Brook were used to model the stream temperature at Briggs Lane. Comparison of the modeled to observed temperatures at Briggs Lane in 2014 show that the stream warms in July and August and cools during October and November relative to expected temperatures under conservative conditions (fig. C3-3E). This indicates the stream is under losing to neutral conditions along this reach.

Briggs to Tebay Ranch

The Tebay Ranch station (site 41) was 2.1 mi downstream of the Briggs station. The Yellowstone Trail station (site 40) was located within this reach, 1.1 mi downstream of the Briggs station. Confluence monitored temperature at the Yellowstone station, and temperature and discharge at Tebay Ranch.

Flows typically increased between the Briggs and Tebay Ranch stations. At times the gains were near zero, likely due to irrigation diversions (table C1-3 and figs. C2-3E, C2-3F).

Comparison of temperatures between the Briggs and Yellowstone stations during 2014 showed slightly cooler temperatures at the Yellowstone station during July and August. Little change was seen during the rest of the year (fig. C3-3F). These observations indicate a gain along this sub-reach.

Comparison of temperatures between the Yellowstone and Tebay Ranch stations during 2014 showed that temperatures warmed during the summer and showed little change during the rest of the year (fig. C3-4A). This suggests a neutral to losing character along this sub-reach.

Comparison of temperatures from the Briggs and Tebay Ranch stations during 2014 showed that there was much less warming during the summer compared to conditions along the reach between the Yellowstone and Tebay Ranch stations. This indicates that the upper reach, from Briggs to Yellowstone, is gaining, and the reach from Yellowstone to Tebay Ranch is losing or neutral (fig. C3-4B).

Tebay Ranch to Tebay Lane

The Tebay Lane station (site 42) was 1.4 mi downstream of the Tebay Ranch station. MBMG monitored stream temperature and discharge at the Tebay Lane station.

The change in net flow between these stations was temporally variable, with frequent changes from a net gain and a net loss; however, the greatest losses occurred at higher flows (table C1-3 and figs. C2-4A, C2-4B).

Comparison of temperatures from the Tebay Ranch and Tebay Lane stations during 2014 showed that there was slight warming between these stations from June to September and show little change for the rest of the year (fig. C3-4C).

Tebay Lane to Mulligan

The Mulligan station (site 47) was 2.7 mi downstream of the Tebay Lane station. This reach also included the I90/MT69 station (site 46), which was 0.2 mi upstream of the Mulligan station. During 2014, Confluence monitored temperature and discharge at the Mulligan station and temperature at the I90/MT69 station.

Discharge at the Mulligan station in 2014 was generally similar to or less than the discharge at Tebay Lane. Flows at these stations were similar to each other in the spring, and there was generally a net decrease in flow during the irrigation season (table C1-3 and figs. C2-4C and C2-4D).

Mean daily stream temperatures in 2014 at Tebay Lane and I90/MT69 were similar in July and August, suggesting that atmospheric warming was offset by groundwater inflows. Additionally, the amplitude of the dial temperature signal is lower at the I90/MT69 station than at Tebay Lane (fig. C3-4D).

Temperatures at the Mulligan station were similar to those at Tebay Lane during June and July, 2014, and were warmer than those at Tebay Lane during April and May (fig. C3-4E). These observations suggest an overall gaining reach.

Mulligan to 359

The 359 station (site 49) was 3.1 mi downstream of the Mulligan station. MBMG monitored stream discharge and temperature at this station.

Synoptic flow measurements in 2014 generally showed an increase in flow between these sites, but flow decreased during a few events (table C1-3 and figs. C2-4E, C2-4F). This is likely due to intermittent events, such as irrigation or mining withdrawals, on a generally gaining reach.

The dial temperature amplitude was lower at the 359 station, with measurable cooling during the summer and warming during the winter (fig. C3-4F). These observations are consistent with a gaining reach. Comparison of the Tebay Ranch station to the 359 station (fig. C3-5A), further supports interpretation of gaining conditions in this portion of the Jefferson Slough.

359 to Mouth

The most downstream station on the Jefferson Slough (site 52; called Boulder River mouth by Confluence) is 1.3 mi downstream of the 359 station, 0.8 mi downstream of the confluence with the Boulder River, and 0.9 mi upstream from the mouth. Confluence monitored temperature at this station during July and August 2014.

Similar to the Briggs station, the combination of temperature at the Jefferson Slough at 359 and the Boulder River was modeled as a conservative tracer and compared to observed values. This analysis shows that July and August observed stream temperatures were warmer than modeled, indicating losing or neutral conditions along this reach (fig. C3-5B).

C. Other surface waters

Slaughterhouse Slough Parrot Castle to Kountz Road

The Slaughterhouse Slough was monitored for flow and stream temperature where it is diverted from the Jefferson River at Parrot Castle (site 27), and where it crosses Kountz Road (site 30). Fish Creek, which flows into Slaughterhouse Slough 0.1 mi below site 27, was also monitored (site 26).

Data from 2014 show that the combined flow of Slaughterhouse Slough at Parrot Castle and Fish Creek at Parrot Castle was slightly less than the flow at Kountz Road during much of the year. While this suggests gaining conditions, June flows decreased between these stations, likely due to irrigation diversions (figs. C2-8C, C2-8D).

Similar to the Briggs station, the water temperature from Slaughterhouse Slough at Parrot Castle and Fish Creek at Parrot Castle was modeled as a conservative tracer and compared to observed. Observed stream temperatures were similar to modeled (fig. C3-7A). Groundwater inflow along this reach is sufficient to balance heat exchange with the atmosphere and solar insulation.

Pipestone Creek Capp Lane to Mouth

MBMG monitored discharge and stream temperature in Pipestone Creek at Capp Lane (site 33). Confluence monitored discharge and stream temperature at the mouth of Pipestone Creek (site 37), which is 3.0 mi downstream of Capp Lane.

Discharge measurements from 2014 show that flow increased between these stations and the largest increase occurred after mid-August (table C1-3 and figs. C2-9A, C2-9B). For example, in June 2014 average flow increased by 4.4 cfs along this reach, while in September average flow increased by 10.0 cfs.

Stream temperatures showed a lower amplitude of the dial signal at the mouth station; there was cooling between these stations in June, July, and August, and warming between them in November (fig. C3-7C). It appears that this reach of Pipestone Creek is gaining.

Whitetail Creek Salsbury to Cemetery

MBMG monitored discharge and stream temperature in Whitetail Creek at Salsbury (site 34) and at the Whitehall Cemetery (site 35). The Cemetery station is 4.0 mi downstream of the Salsbury station.

Discharge measurements at these stations in 2014 showed similar flows from early April to mid-May, followed by lower flows at the Cemetery for the rest of the year (table C1-3 and figs. C2-9C, C2-9D). In September, the difference in flow averaged 3.4 cfs. Some portion of this net loss is likely due to irrigation diversions.

Stream temperatures during 2014 showed warming conditions in July and August, with little change during the rest of the year (fig. C3-7D), which indicates that this reach is losing or neutral.

Whitetail Creek Cemetery to Mouth

Confluence monitored discharge and stream temperature on Whitetail Creek near its mouth (site 38). This station is 1.9 mi downstream of the Cemetery station.

Discharge measurements at these stations show that there is always an increase in flows between these stations (table C1-3 and figs. C2-9E, C2-9F), indicating a gain along this reach.

Stream temperatures in Whitetail Creek exhibit little change between these stations. This indicates that groundwater inflows are sufficient to offset by heat exchange with the atmosphere and solar insolation

Appendix C1 - Synoptic Stream Flows (cfs)

Table C1-1 - Jefferson River

		Dates	2013				
ID #	Site Name	8/21	8/29	9/6-9/9	9/26-9/27	10/11	10/24
06026500	Jefferson River near Twin Bridges (USGS)	*228*	*609*	*719*	*1260*	*1270*	*1090*
277191	Jefferson River at Silver Star	---	---	---	---	---	---
278427	Jefferson River at Funston's	---	---	---	---	---	---
06027600	Jefferson River at Parsons Bridge near Silver Star (USGS)	*51*	*158*	*359*	*896*		
278156	Jefferson River at Corbett's	---	---	---	---	---	---
277193	Jefferson River at Kountz Bridge	---	---	---	---	---	---
274566	Jefferson River at Mayflower Bridge	127	---	376	1070	971	1060
278401	Jefferson River at Cardwell Bridge	---	---	---	---	---	---
274573	Jefferson River at LaHood	*146*	246	463	1282	*1335*	*1174*

		Dates	2014							
ID #	Site Name	4/25	5/2	5/12	5/21-5/23	6/6	6/18-6/20	6/30-7/2	7/17-7/18	7/29-7/30
06026500	Jefferson River near Twin Bridges (USGS)	*3220*	*2580*	*3690*	*5290*	*6170*	*5710*	*4480*	*1530*	*620*
277191	Jefferson River at Silver Star	2784	*2104*	3252	4612	*5185*	4833	2889	1152	425
278427	Jefferson River at Funston's	---	---	---	---	---	---	---	*1267*	416
06027600	Jefferson River at Parsons Bridge near Silver Star (USGS)	---	---	---	---	---	---	*3200*	*1220*	*373*
278156	Jefferson River at Corbett's	---	---	---	---	---	---	---	1179	432
277193	Jefferson River at Kountz Bridge	*2504*	1717	*2856*	3846	4552	4240	3384	1173	398
274566	Jefferson River at Mayflower Bridge	*2789*	*2005*	*3185*	4473	4994	4378	3447	1321	374
278401	Jefferson River at Cardwell Bridge	---	---	---	4715	5276	4575	3611	1332	370

		Dates	2014							
ID #	Site Name	8/12-8/14	8/26	9/2	9/18	9/23	9/30	10/14	10/21	11/4
06026500	Jefferson River near Twin Bridges (USGS)	*507*	*1370*	*1050*	*671*	*672*	*1210*	*1140*	*1110*	*1310*
277191	Jefferson River at Silver Star	352	*1273*	*943*	*562*	*540*	*1083*	*1064*	*1096*	*1311*
278427	Jefferson River at Funston's	327	*1194*	*882*	499	*502*	*1027*	*1032*	*1099*	*1228*
06027600	Jefferson River at Parsons Bridge near Silver Star (USGS)	*253*	*1110*	*847*	*515*	*526*	*1070*	---	---	---
278156	Jefferson River at Corbett's	347	1316	*1002*	544	*547*	1120	1074	*1148*	*1309*
277193	Jefferson River at Kountz Bridge	296	*1174*	895	*565*	509	---	---	1034	---
274566	Jefferson River at Mayflower Bridge	297	---	913	---	565	---	---	1074	1165
278401	Jefferson River at Cardwell Bridge	385	---	1065	---	---	---	---	*1153*	---

Black Values from stream gaging. Red values from rating curves. Values from rating curves are daily averages for the first day of the period.

Appendix C1 - Synoptic Stream Flows (cfs)
Table C1-2 - Major Diversions from and Tributaries to the Jefferson River - Excluding Jefferson Slough

Dates 2013

ID #	Site Name	7/14	7/16	7/21	7/24	8/20-8/22	9/6-9/9	9/19	9/26-9/27	10/10-10/11	10/24-10/25
274576	Creeklyn Canal at Diversion	62	59	59	51	37	*57*	*41*	*off*	*off*	*off*
274578	Parrot Canal at Diversion	167	180	176	145	87	123	*143*	89	87	6
277129	Parson's Slough	---	---	---	---	---	---	---	6	---	---
274881	Willow Springs	---	---	---	---	---	---	20	*31*	*27*	15
278154	Kernow Blowout (Parrot)	---	---	---	---	---	---	---	---	---	---
277321	Tunnel Blowout (Parrot)	---	---	---	---	---	---	---	---	---	---
277189	Slaughterhouse Slough at Parrot Castle (Diversion)	---	---	---	---	---	---	---	---	---	---
263602	Boulder River	*25*	*33*	*36*	*33*	*12*	*22*	*30*	46	107	94

Dates 2014

ID #	Site Name	3/28	4/24-4/25	5/1-5/2	5/9	5/12	5/21-5/23	5/30	6/4-6/6	6/18-6/20
274576	Creeklyn Canal at Diversion	*off*	*off*	*47*	59	*56*	67	*64*	59	59
274578	Parrot Canal at Diversion	2	145	*109*	139	*146*	211	247	177	224
277129	Parson's Slough	1	3	*3*	3	4	3	9	15	13
274881	Willow Springs	11	12	*11*	*12*	15	14	---	19	14
278154	Kernow Blowout (Parrot)	---	62	---	---	47	52	47	39	67
277321	Tunnel Blowout (Parrot)	---	2	*1*	*2*	*1*	0	0	1	4
277189	Slaughterhouse Slough at Parrot Castle (Diversion)	---	*223*	156	---	*229*	---	---	---	---
263602	Boulder River	---	*335*	388	*422*	*348*	800	*1051*	614	*379*

Dates 2014

ID #	Site Name	6/30-7/2	7/11	7/16-7/18	7/29-7/31	8/7-8/8	8/12-8/14	8/26	9/1-9/4	9/18
274576	Creeklyn Canal at Diversion	*52*	53	*63*	*55*	57	*58*	*52*	47	*41*
274578	Parrot Canal at Diversion	*229*	145	*170*	*199*	201	*225*	*170*	178	*171*
277129	Parson's Slough	8	*6*	1	11	*13*	11	16	*10*	10
274881	Willow Springs	17	*16*	17	15	*17*	17	22	*20*	16
278154	Kernow Blowout (Parrot)	11	*14*	16	11	*6*	7	*27*	*46*	1
277321	Tunnel Blowout (Parrot)	2	*0*	0	0	*0*	0	0	*0*	*0*
277189	Slaughterhouse Slough at Parrot Castle (Diversion)	---	---	104	29	*33*	28	*120*	87	*36*
263602	Boulder River	243	*89*	84	47	*47*	43	*132*	79	*63*

ID #	Site Name	9/23-9/24	9/30	10/6-10/8	10/14	10/20-10/21	10/28	11/4
274576	Creeklyn Canal at Diversion	*56*	*54*	off	*off*	off	*off*	off
274578	Parrot Canal at Diversion	*166*	*178*	95	*117*	*11*	*5*	*15*
277129	Parson's Slough	*9*	13	*8*	11	*5*	4	---
274881	Willow Springs	*15*	19	*13*	16	*10*	14	*17*
278154	Kernow Blowout (Parrot)	*0*	32	*1*	6	*13*	*off*	*off*
277321	Tunnel Blowout (Parrot)	*0*	*0*	*0*	*0*	*3*	*off*	*off*
277189	Slaughterhouse Slough at Parrot Castle (Diversion)	40	*95*	*83*	*79*	87	*115*	*105*
263602	Boulder River	*52*	*100*	*110*	*106*	104	*116*	*120*

Black Values from stream gaging. *Red* values from rating curves. Values from rating curves are daily averages for the first day of the period.

Appendix C1 - Synoptic Stream Flows (cfs)
Table C1-3 - Jefferson Slough

Dates 2013

ID #	Site Name	7/14	7/16	7/21	7/24	8/20-8/22	9/6-9/9	9/19	9/26-9/27	10/10-10/11	10/24-10/25
274885	Pipestone Creek at Capp Ln	---	---	---	---	---	10.5	*13.8*	*21.0*	*13.8*	13.4
274574	Whitetail Creek at Cemetary	---	---	---	---	*0.0*	*4.4*	*9.9*	16.1	10.9	11.1
274564	Jefferson Slough at Tebay Lane	---	---	---	---	6.9	*55.0*	*79.0*	92.2	49.7	41.2
274565	Jefferson Slough at 359	---	---	---	---	2.5	*41.1*	*51.2*	89.2	57.2	44.4

Dates 2014

ID #	Site Name	3/28	4/24-4/25	5/1-5/2	5/9	5/12	5/21-5/23	5/30	6/4-6/6	6/18-6/20
278354	Slaughterhouse Slough at Kountz Road	---	*242*	179	*254*	*247*	333	*590*	397	379
287489	Jefferson Slough at Willow Brook (Confluence)	*2.4*	*2.8*	*6.1*	*14.3*	*16.2*	*16.2*	*23.5*	*22.5*	*28.3*
274885	Pipestone Creek at Capp Ln	---	32.2	*23.1*	*24.5*	*17.3*	20.4	*12.0*	15.3	26.9
287491	Pipestone Creek at Mouth (Confluence)	*18.7*	*38.1*	*27.5*	*23.8*	*16.3*	*20.5*	*12.7*	*12.7*	*25.8*
277322	Whitetail Creek at Sailsbury's	---	19.4	*10.3*	*21.4*	*18.1*	17.4	*35.9*	13.4	12.9
274574	Whitetail Creek at Cemetary	---	15.7	*12.3*	*21.0*	*17.1*	14.4	*26.4*	18.9	8.8
287492	Whitetail Creek at Mouth (Confluence)	*8.4*	*13.3*	*6.7*	*13.3*	*12.3*	*16.5*	*27.4*	*15.4*	*14.3*
287493	Jefferson Slough at Briggs (Confluence)	*9.2*	*39.4*	*26.3*	*39.4*	*35.0*	*48.3*	*68.4*	*52.7*	*59.4*
274564	Jefferson Slough at Tebay Ranch (Confluence)	*22.0*	*56.8*	*48.2*	*74.5*	*64.0*	*61.0*	*80.9*	*56.9*	*74.0*
274564	Jefferson Slough at Tebay Lane	---	*54.0*	47.1	*53.0*	*51.0*	57.4	*76.0*	54.8	75.1
287506	Jefferson Slough at Mulligan (Confluence)	*40.8*	*52.4*	*47.6*	*50.4*	*49.6*	*53.4*	*61.9*	*54.3*	*58.8*
274565	Jefferson Slough at 359	---	*58.4*	41.8	*55.1*	*35.3*	51.9	*105.3*	48.5	74.0

Dates 2014

ID #	Site Name	6/30-7/2	7/11	7/16-7/18	7/29-7/31	8/7-8/8	8/12-8/14	8/26	9/1-9/4	9/18
278354	Slaughterhouse Slough at Kountz Road	296	*124*	119	41.7	*73.5*	*52.3*	*171*	*144*	*68.7*
287489	Jefferson Slough at Willow Brook (Confluence)	*19.5*	*9.4*	*7.6*	*11.3*	*18.5*	*19.5*	*9.1*	*3.6*	---
274885	Pipestone Creek at Capp Ln	13.8	*12.1*	10.4	3.5	*12.9*	*11.5*	*23.2*	*16.2*	*12.0*
287491	Pipestone Creek at Mouth (Confluence)	*17.2*	*15.7*	*12.7*	*9.3*	*13.5*	*12.1*	*32.1*	*23.8*	*18.7*
277322	Whitetail Creek at Sailsbury's	17.8	*8.6*	13.2	5.6	*8.6*	4.3	*38.0*	20.3	*13.9*
274574	Whitetail Creek at Cemetary	15.4	*4.6*	14.2	3.1	*6.1*	3.7	*27.1*	19.5	*12.4*
287492	Whitetail Creek at Mouth (Confluence)	*17.6*	*8.4*	*16.5*	*2.3*	2.0	*3.6*	*32.8*	*26.1*	*12.3*
287493	Jefferson Slough at Briggs (Confluence)	*50.5*	*19.8*	*22.0*	*17.7*	22.9	*22.0*	*70.6*	*50.5*	*32.9*
274564	Jefferson Slough at Tebay Ranch (Confluence)	*71.5*	*30.3*	*23.2*	*19.6*	12.1	*20.9*	*68.9*	*49.1*	*37.5*
274564	Jefferson Slough at Tebay Lane	50.2	*18.0*	*50.0*	5.6	*24.0*	14.1	*68.0*	51.3	*34.0*
287506	Jefferson Slough at Mulligan (Confluence)	---	*16.7*	*19.1*	---	*12.7*	*7.1*	---	---	---
274565	Jefferson Slough at 359	49.4	*17.5*	20.9	7.4	*13.2*	12.5	*67.6*	48.8	*30.9*

ID #	Site Name	9/23-9/24	9/30	10/6-10/8	10/14	10/20-10/21	10/28	11/4
278354	Slaughterhouse Slough at Kountz Road	296	*122*	119	41.7	*101*	*132*	*123*
287489	Jefferson Slough at Willow Brook (Confluence)	*4.1*	---	*4.6*	*1.6*	*2.3*	*2.3*	---
274885	Pipestone Creek at Capp Ln	*13.6*	*18.6*	*21.6*	*15.1*	*11.6*	*16.6*	*17.4*
287491	Pipestone Creek at Mouth (Confluence)	*19.6*	*26.5*	*25.8*	*18.7*	*16.3*	*21.2*	*22.2*
277322	Whitetail Creek at Sailsbury's	*12.3*	*19.2*	*14.8*	*15.6*	*15.2*	*15.6*	*14.5*
274574	Whitetail Creek at Cemetary	*10.9*	*16.7*	*12.6*	*12.5*	*11.9*	*12.3*	*12.4*
287492	Whitetail Creek at Mouth (Confluence)	*11.3*	*18.8*	*13.3*	*13.3*	*13.3*	*13.3*	*13.3*
287493	Jefferson Slough at Briggs (Confluence)	*24.1*	*46.1*	*32.9*	*37.2*	*28.5*	*35.0*	*35.0*
274564	Jefferson Slough at Tebay Ranch (Confluence)	*27.3*	*49.1*	*43.1*	*49.1*	*32.2*	*43.1*	*43.1*
274564	Jefferson Slough at Tebay Lane	27.0	*51.0*	*40.0*	*50.0*	36.9	*47.0*	44.6
287506	Jefferson Slough at Mulligan (Confluence)	---	---	---	---	---	---	---
274565	Jefferson Slough at 359	29.5	*44.7*	*41.2*	*43.8*	*38.3*	*43.0*	46.4

Black Values from stream gaging. *Red* values from rating curves. Values from rating curves are daily averages for the first day of the period.

Appendix C1 - Synoptic Stream Flows (cfs)
Table C1-4 - Parrot Canal

		Dates		2013						
ID #	Site Name	7/14	7/16	7/21	7/24	8/22	9/6-9/9	9/26-9/27	10/10-10/11	10/24
274578	Parrot Canal at Diversion	167	180	177	145	87	123	89	87	6
274579	Parrot Canal at Hunt's	---	---	---	---	3	*54*	67	62	0
274882	Parrot Canal at Willow Springs	---	---	---	---	---	67	36	49	0
274580	Parrot Canal at Mayflower	---	---	---	---	3	*25*	37	39	0

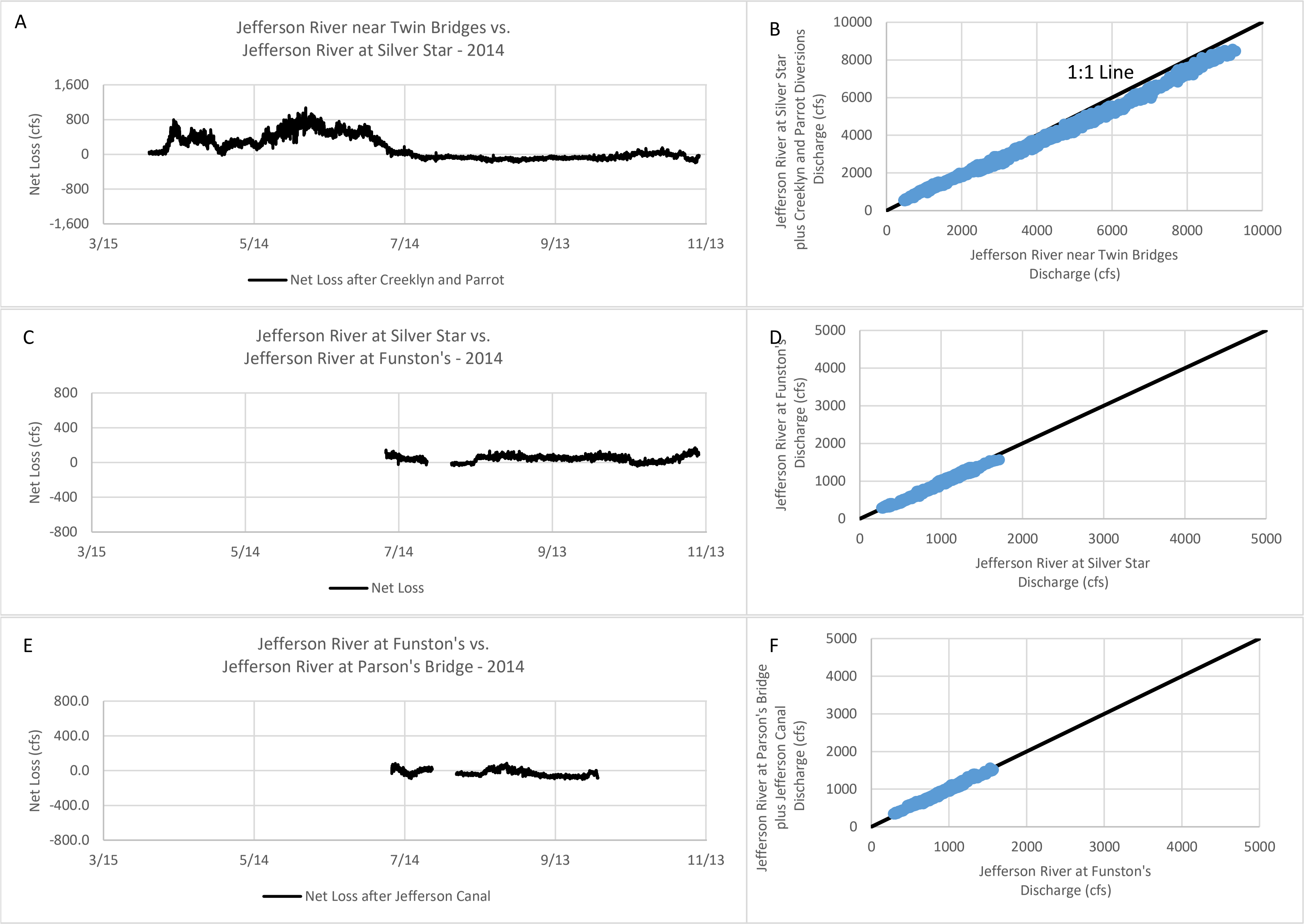
		Dates		2014						
ID #	Site Name	4/24-4/25	5/9	5/12	5/22-5/23	5/30	6/4-6/6	6/18-6/20	7/1-7/2	7/11
274578	Parrot Canal at Diversion	145	139	*128*	211	247	177	224	*203*	145
278155	Parrot Canal at Waterloo Road	119	*109*	116	179	178	*153*	174	129	*160*
278796	Parrot Canal at Bench Road	---	---	---	---	---	---	---	---	---
278798	Parrot Canal at Gornick Road	---	---	---	---	---	---	---	---	---
278357	Beall Creek above Parrot Canal	---	---	---	---	---	4	3	4	*2*
274579	Parrot Canal at Hunt's	116	*85*	104	126	130	*110*	156	*124*	*109*
278154	Kernow Blowout (Parrot)	62	---	47	52	47	39	67	11	14
274882	Parrot Canal at Willow Springs	54	*54*	58	72	72	70	70	82	*74*
277320	Parrot Canal before Tunnel	43	*51*	*51*	49	52	56	57	50	*57*
277321	Tunnel Blowout (Parrot)	2	*2*	*1*	0	*0*	1	4	2	*0*
274580	Parrot Canal at Mayflower	28	18	*21*	19	27	12	28	*25*	20

		Dates		2014					
ID #	Site Name	7/16-7/18	7/29-7/30	8/12-8/13	8/26	9/18	9/30	10/6	10/14
274578	Parrot Canal at Diversion	*149*	*176*	*199*	*149*	*150*	*157*	95	95
278155	Parrot Canal at Waterloo Road	159	149	*137*	111	*111*	*122*	*84*	92
278796	Parrot Canal at Bench Road	125	118	113	101	89	106	*83*	78
278798	Parrot Canal at Gornick Road	127	111	107	101	67	103	*33*	78
278357	Beall Creek above Parrot Canal	2	1	1	1	1	*2*	*1*	*2*
274579	Parrot Canal at Hunt's	*124*	*99*	88	*94*	60	*92*	*57*	*77*
278154	Kernow Blowout (Parrot)	16	11	7	27	1	32	1	6
274882	Parrot Canal at Willow Springs	72	70	78	52	51	49	*58*	67
277320	Parrot Canal before Tunnel	46	59	56	44	*46*	*48*	*53*	*63*
277321	Tunnel Blowout (Parrot)	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
274580	Parrot Canal at Mayflower	*11*	*15*	*19*	*38*	*16*	*26*	*22*	*39*

Black Values from stream gaging. *Red* values fromrating curves. Values
from rating curves are daily averages for the first day of the period.

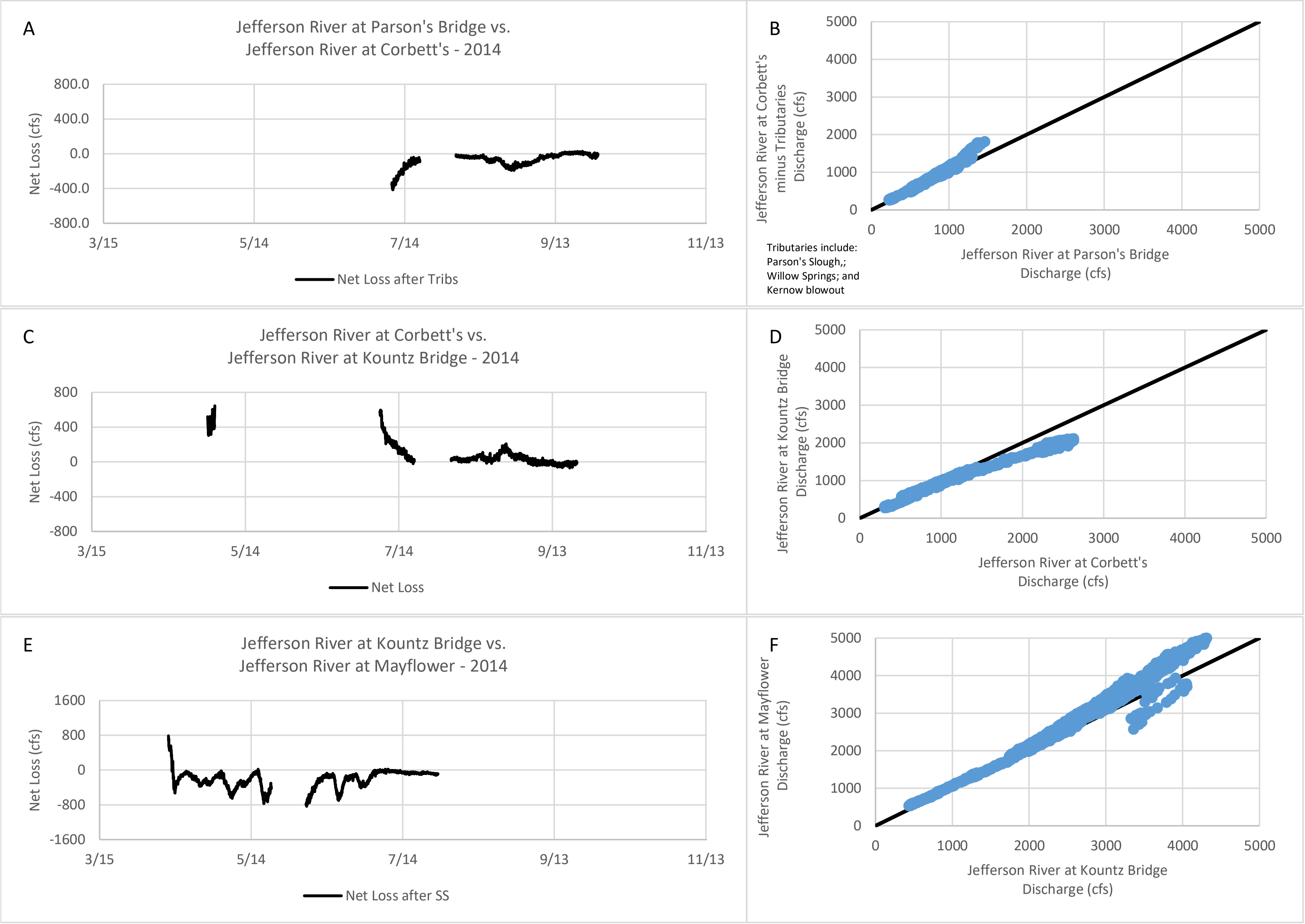
Appendix C2. Net Changes in Stream Flow

Figure C2-1



Appendix C2. Net Changes in Stream Flow

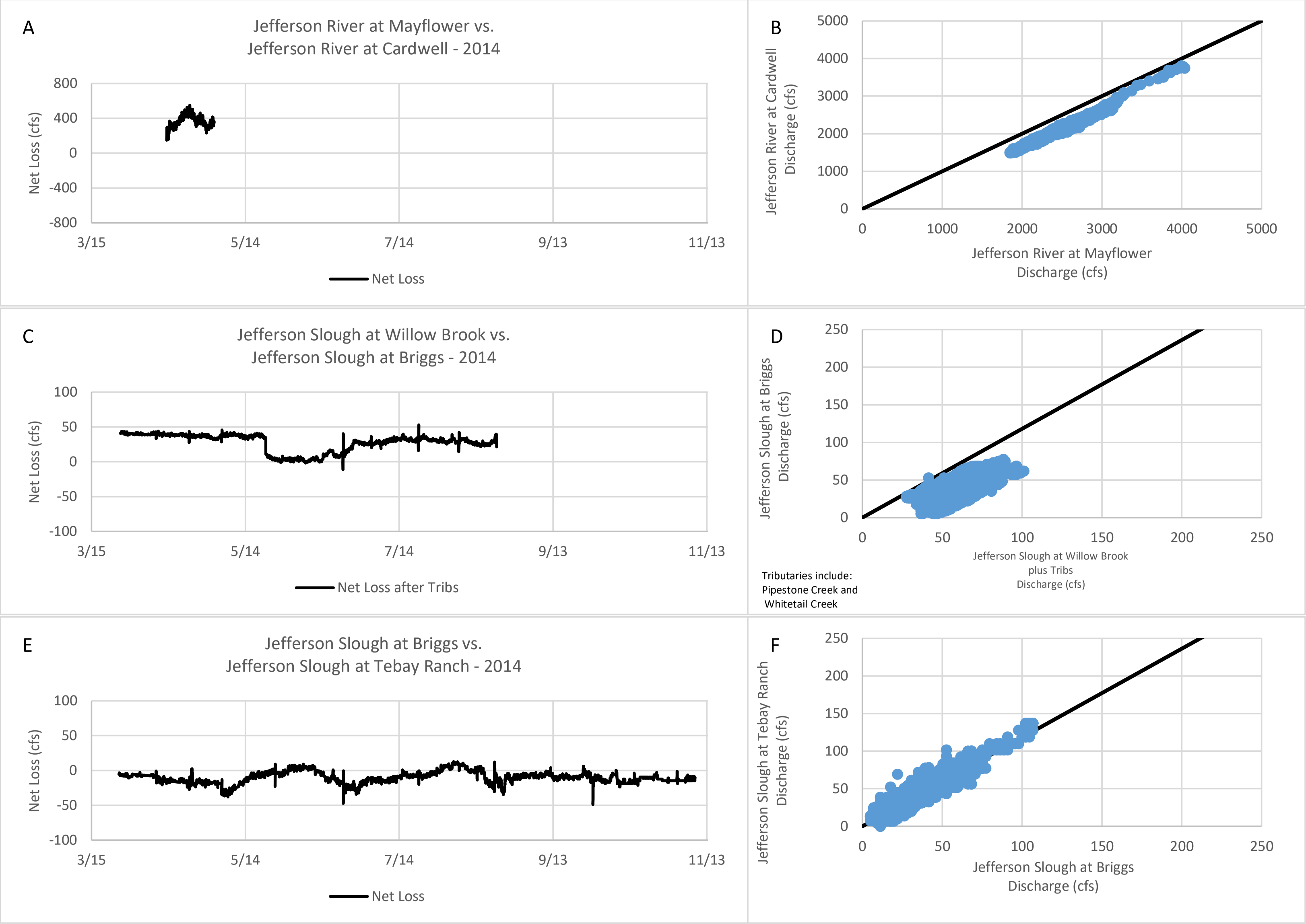
Figure C2-2



Tributaries include:
Parson's Slough,;
Willow Springs; and
Kernow blowout

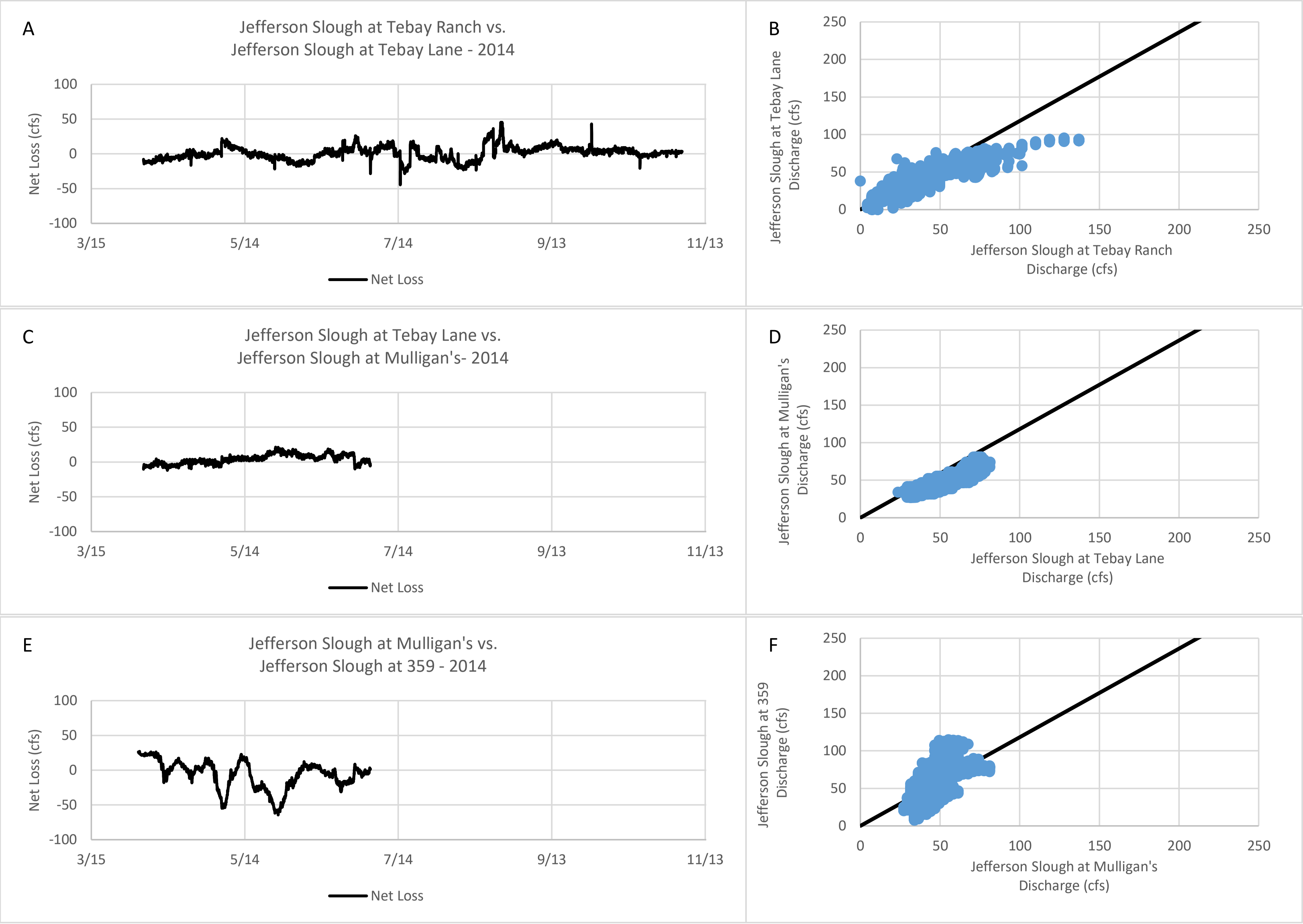
Appendix C2. Net Changes in Stream Flow

Figure C2-3



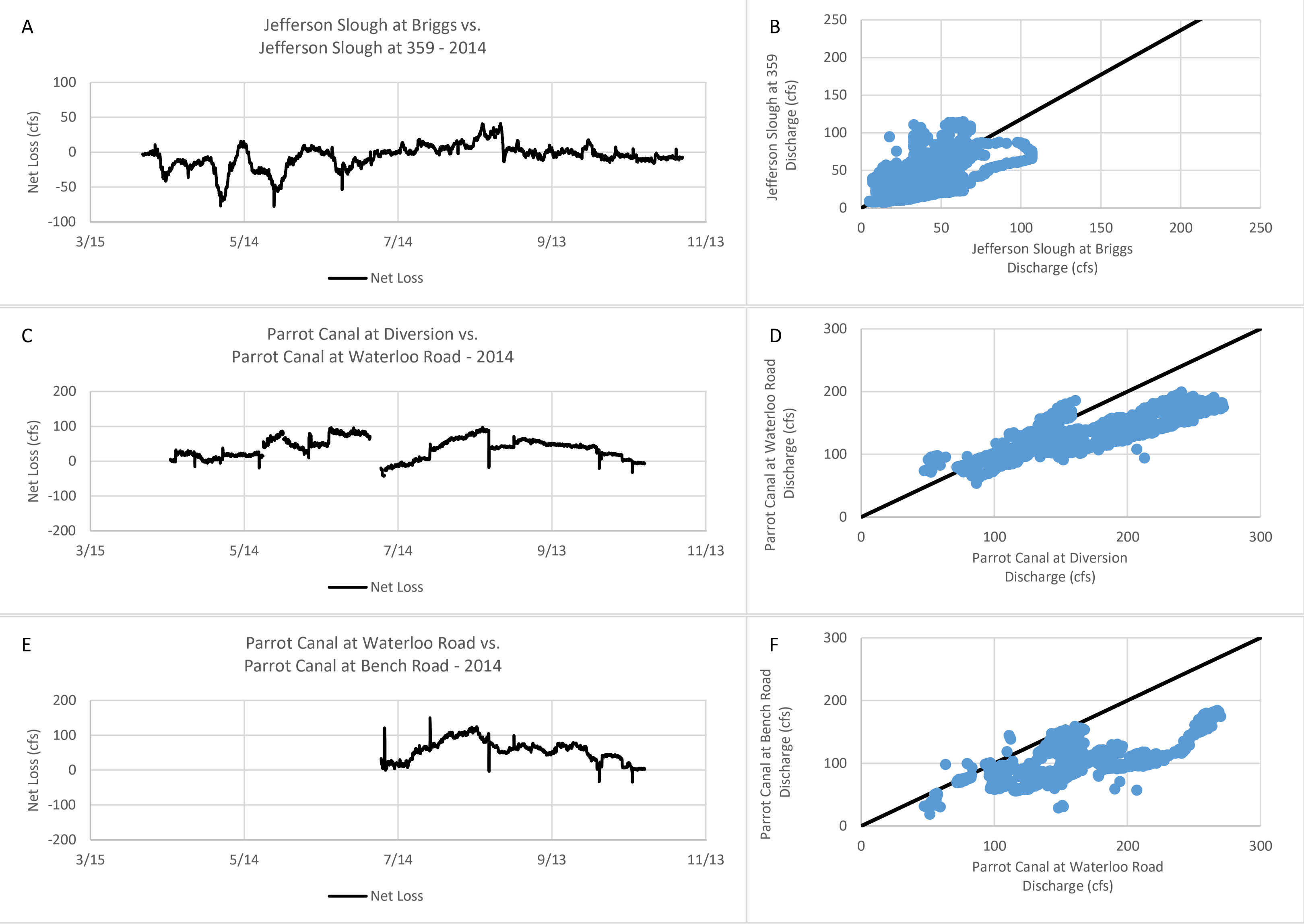
Appendix C2. Net Changes in Stream Flow

Figure C2-4



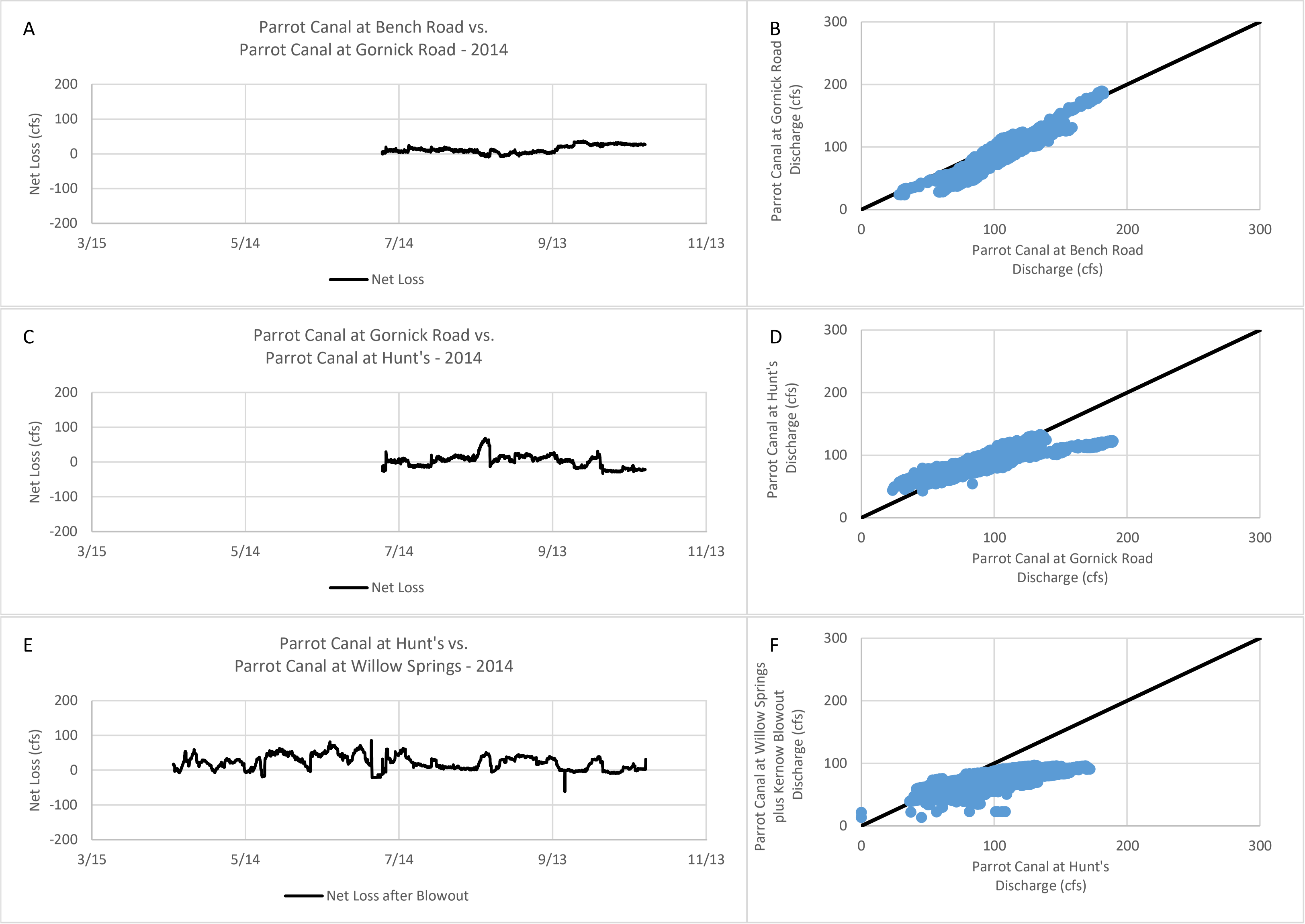
Appendix C2. Net Changes in Stream Flow

Figure C2-5



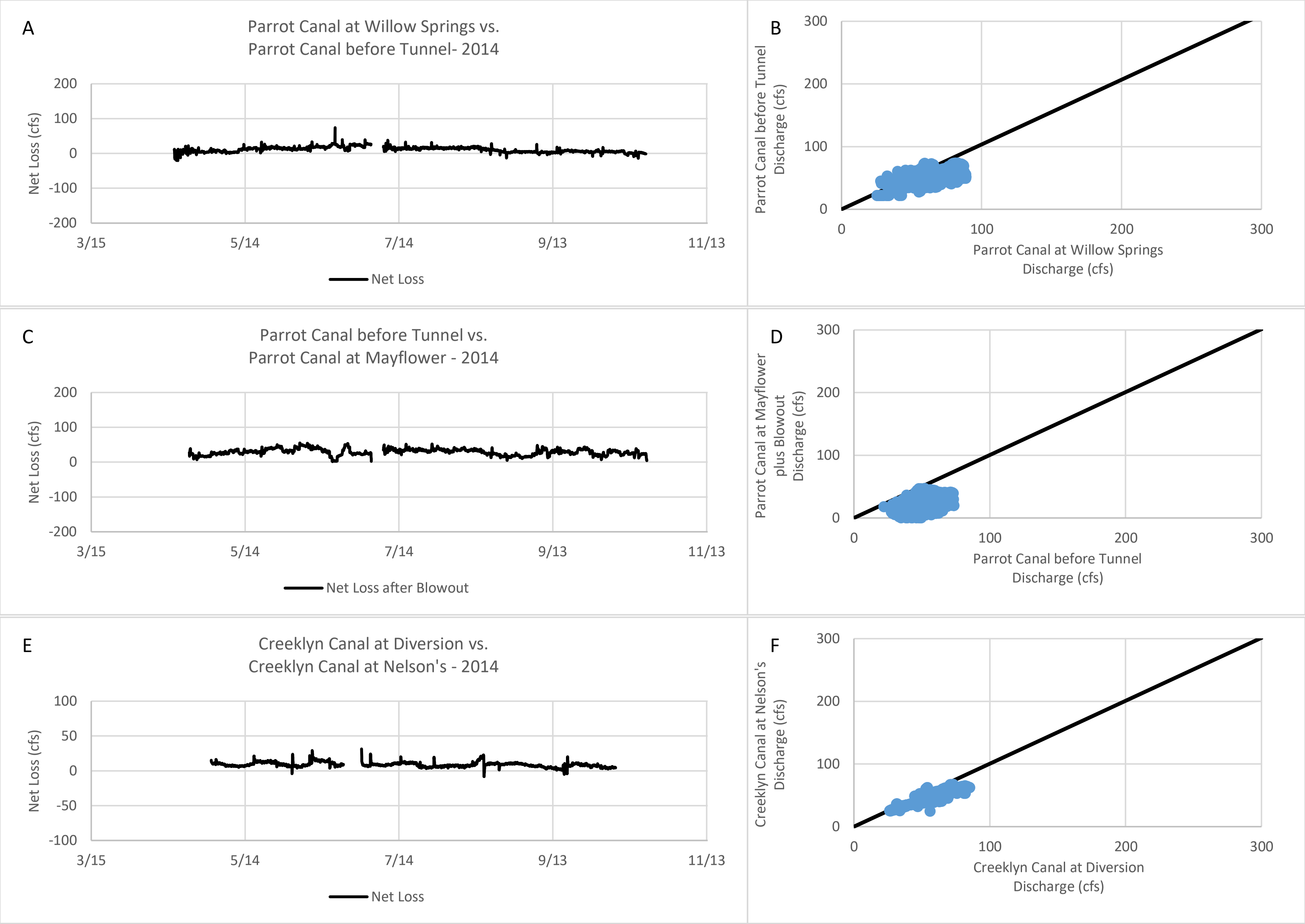
Appendix C2. Net Changes in Stream Flow

Figure C2-6



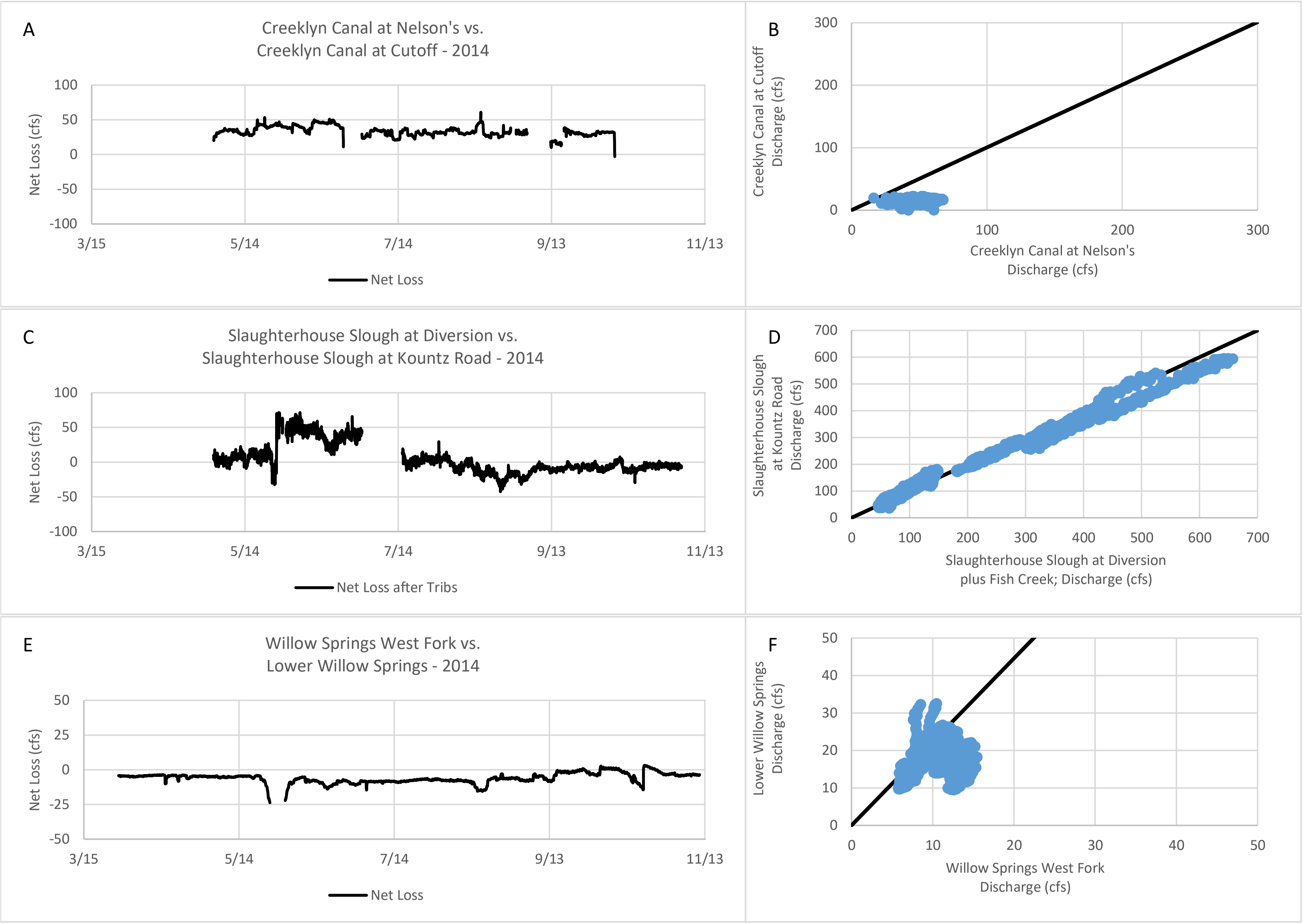
Appendix C2. Net Changes in Stream Flow

Figure C2-7



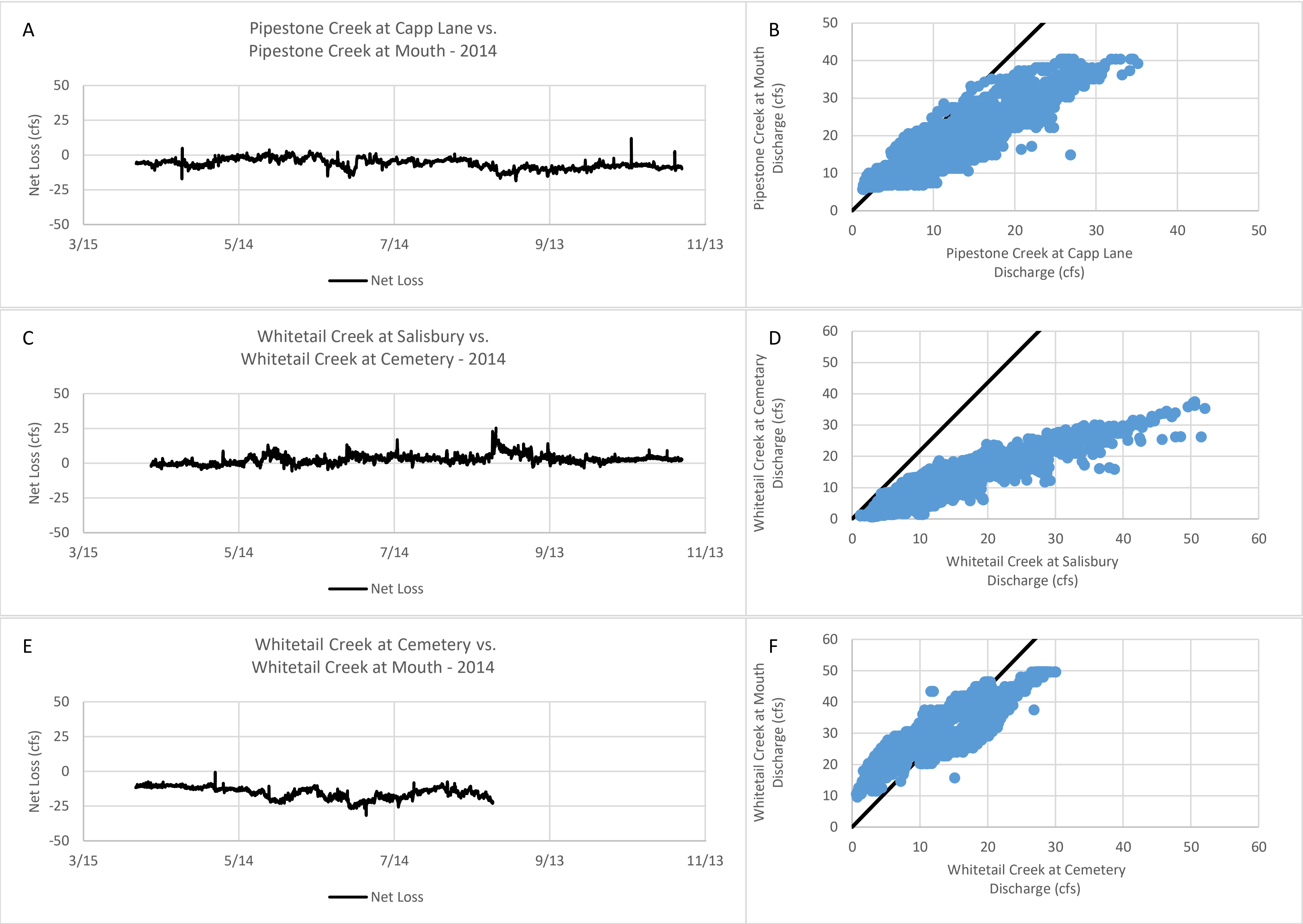
Appendix C2. Net Changes in Stream Flow

Figure C2-8



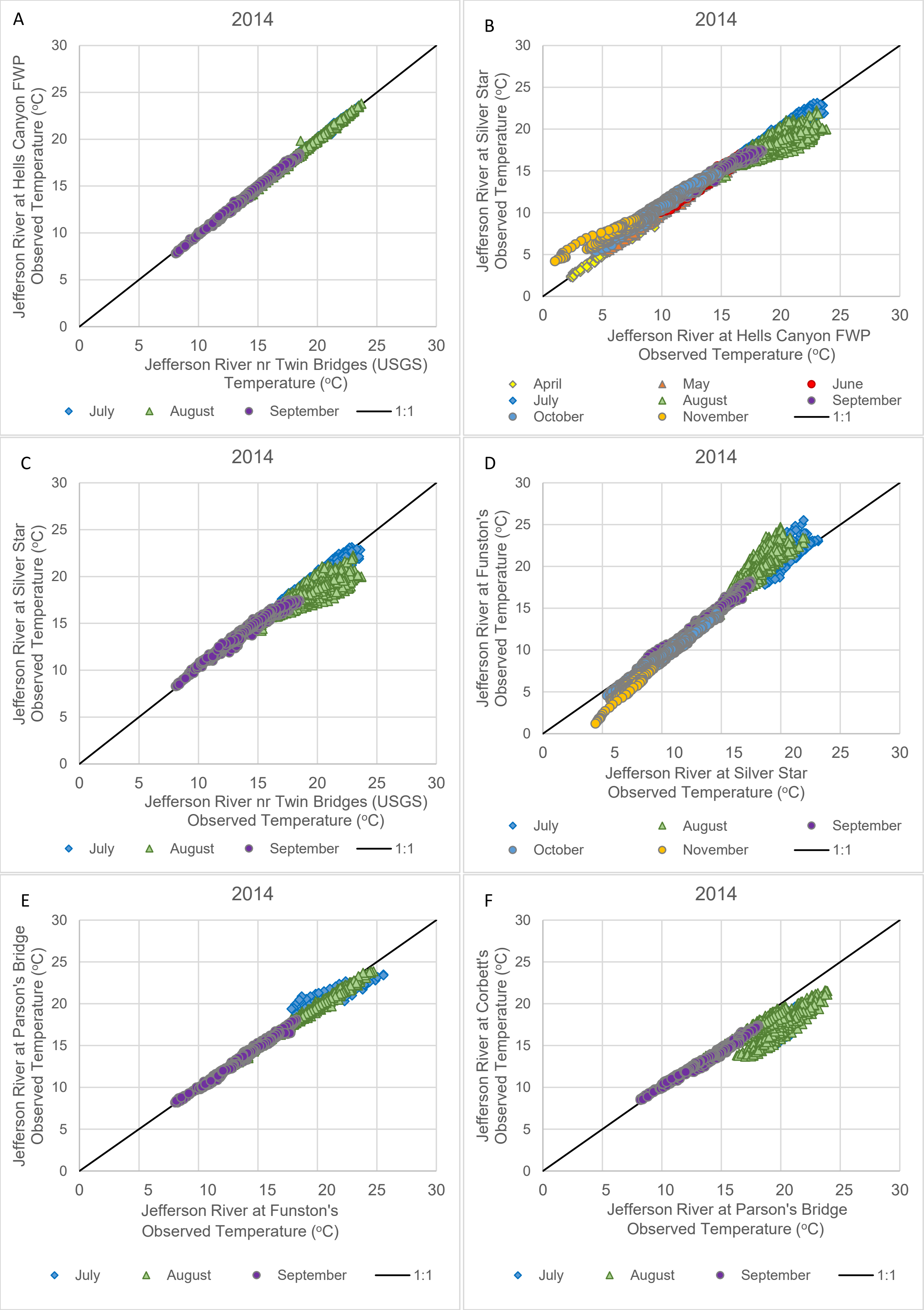
Appendix C2. Net Changes in Stream Flow

Figure C2-9



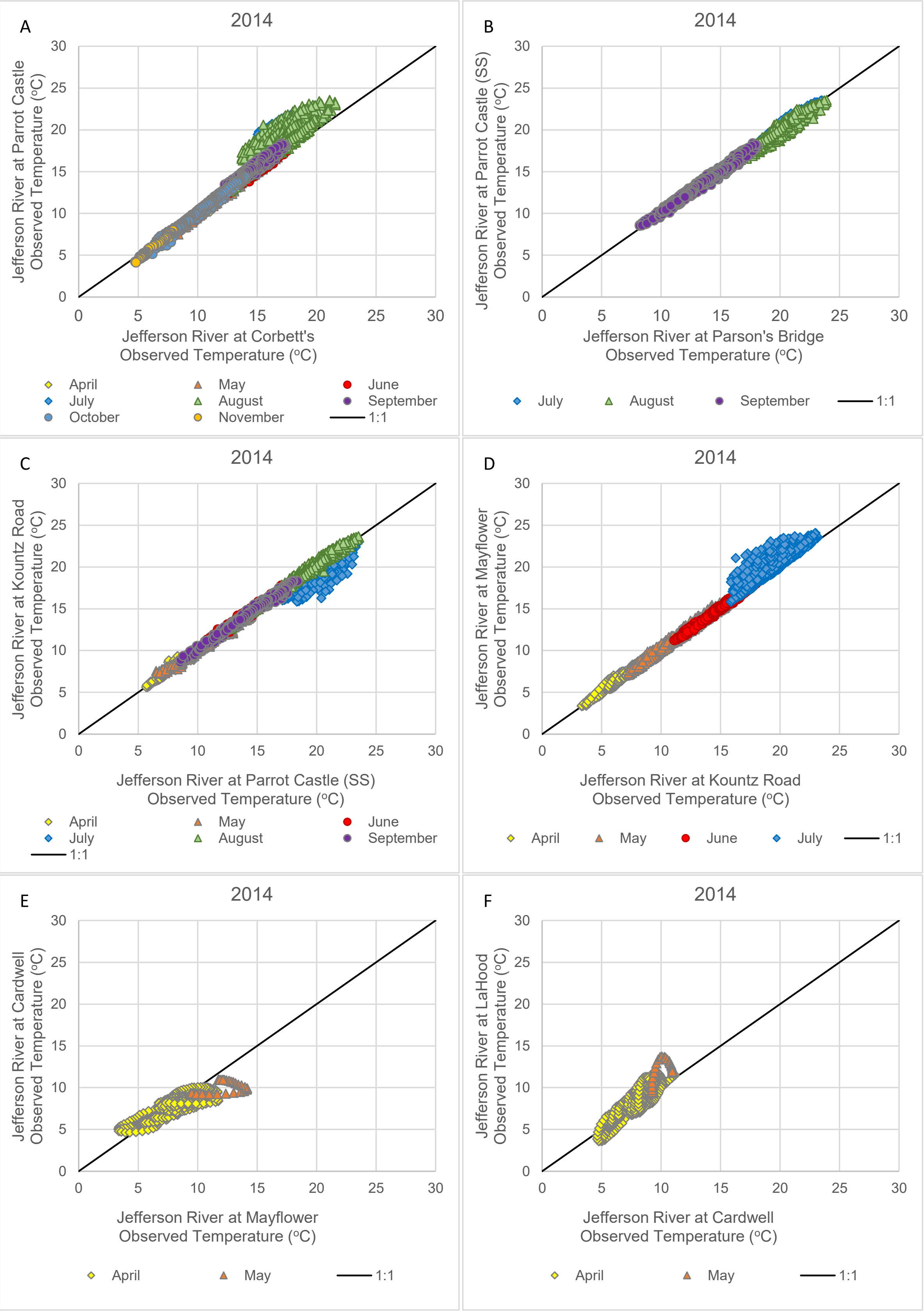
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-1



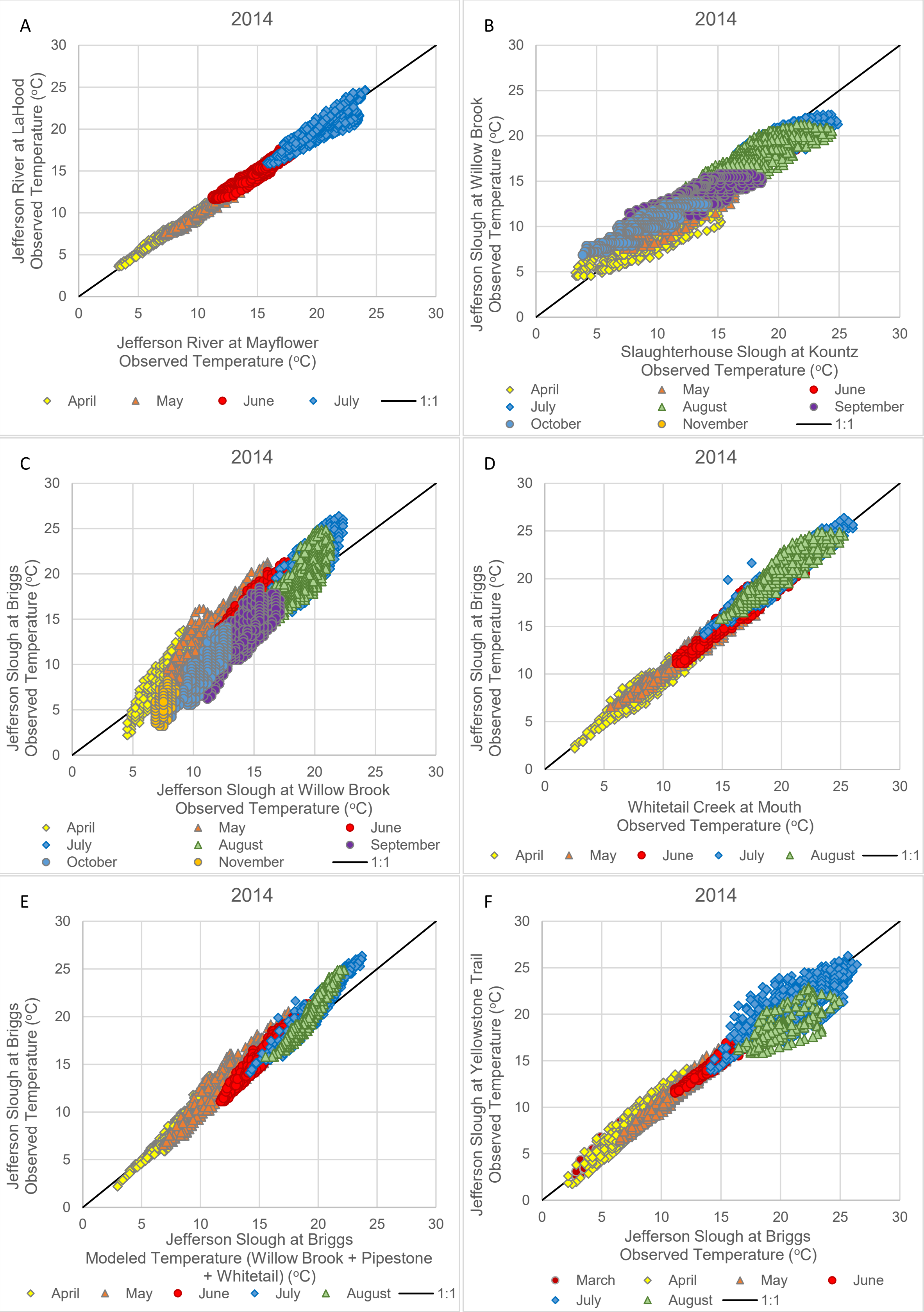
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-2



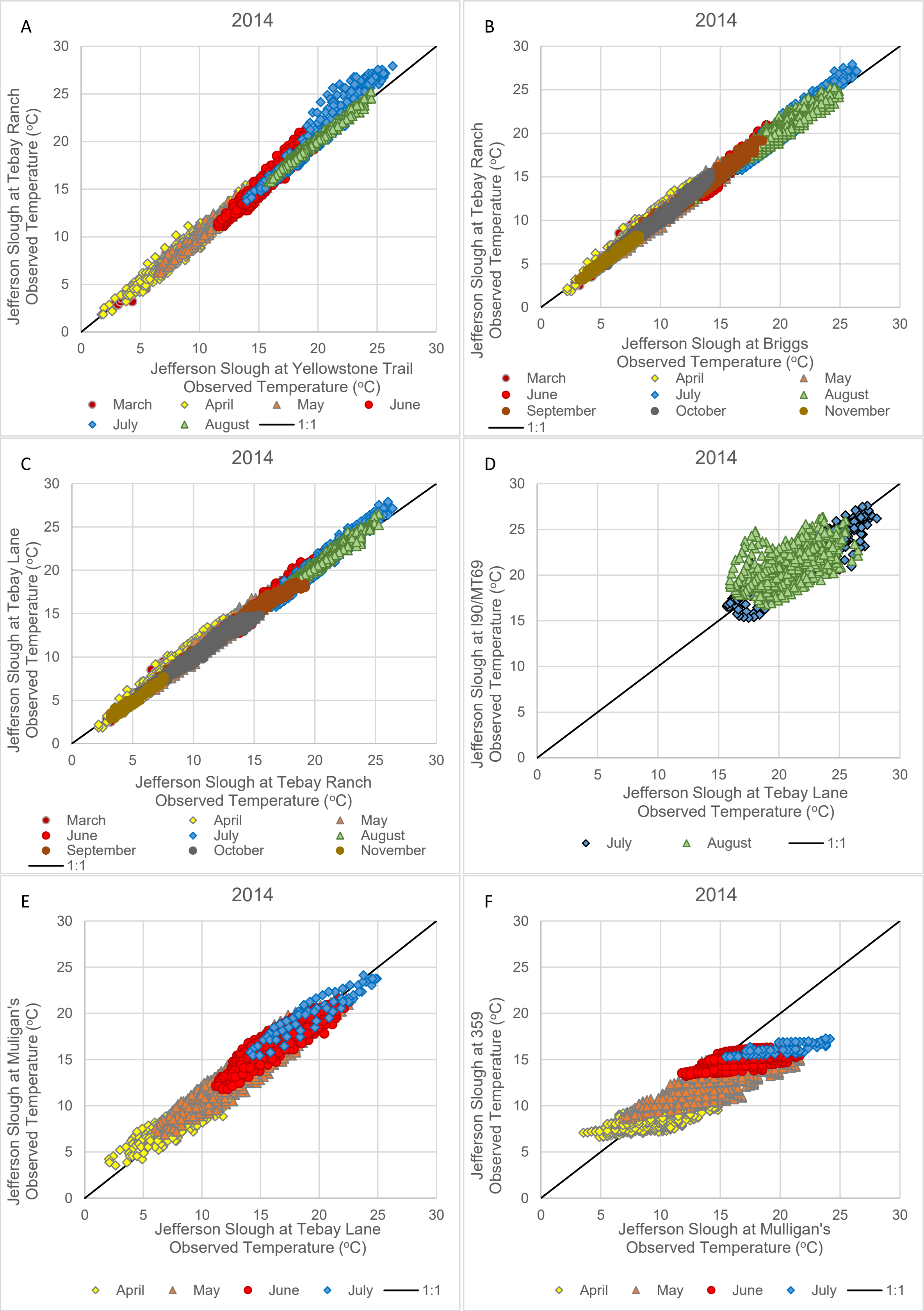
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-3



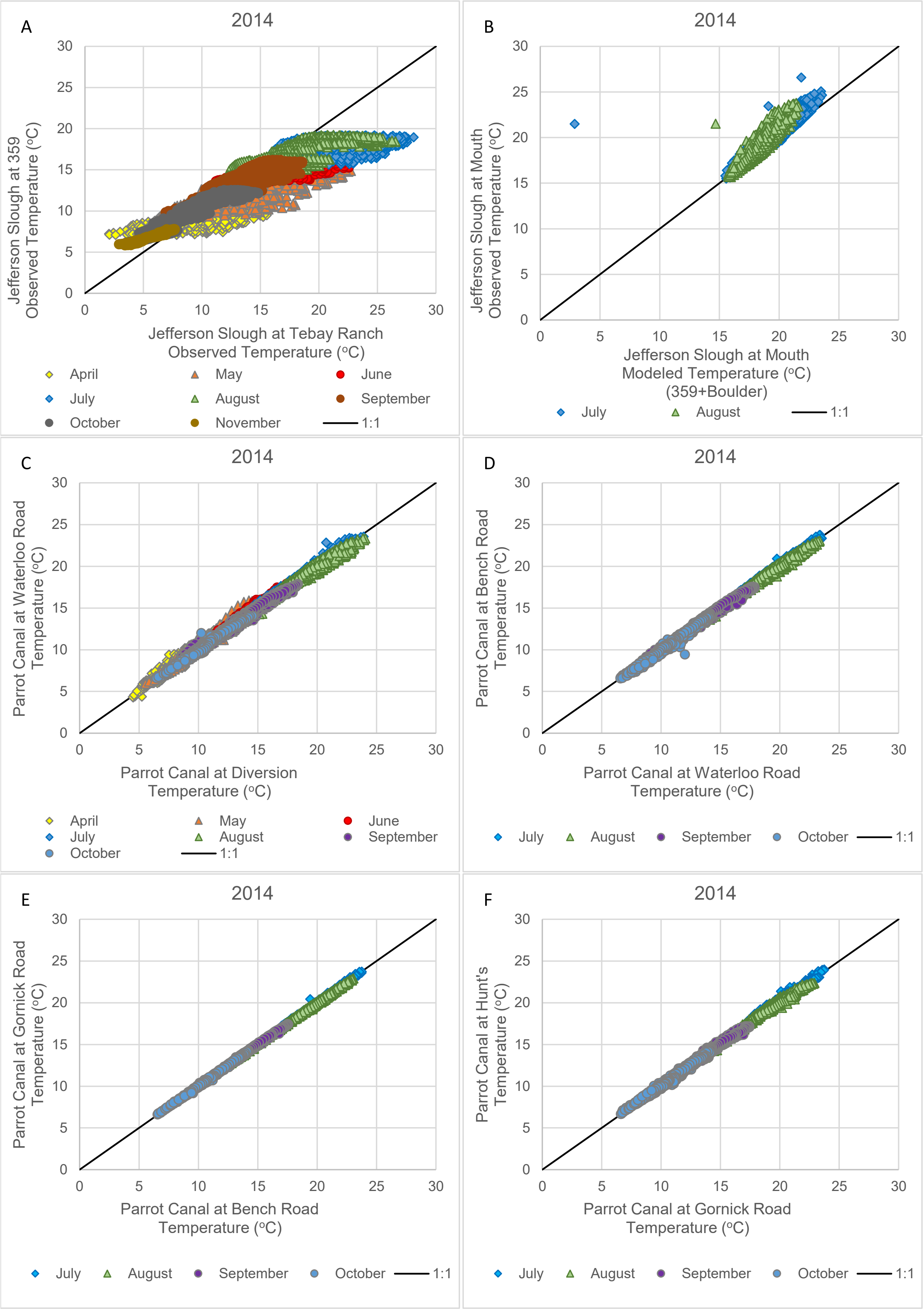
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-4



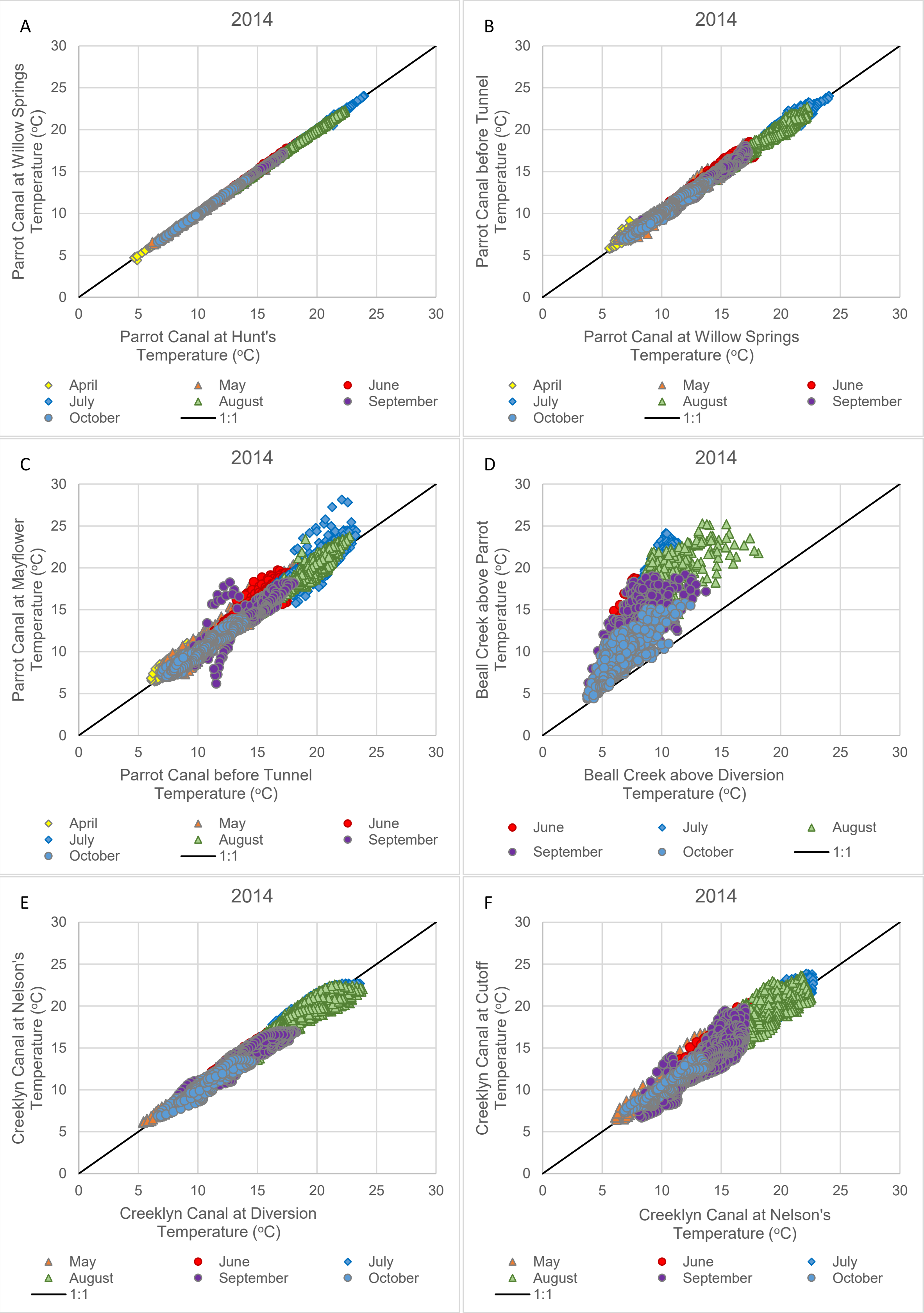
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-5



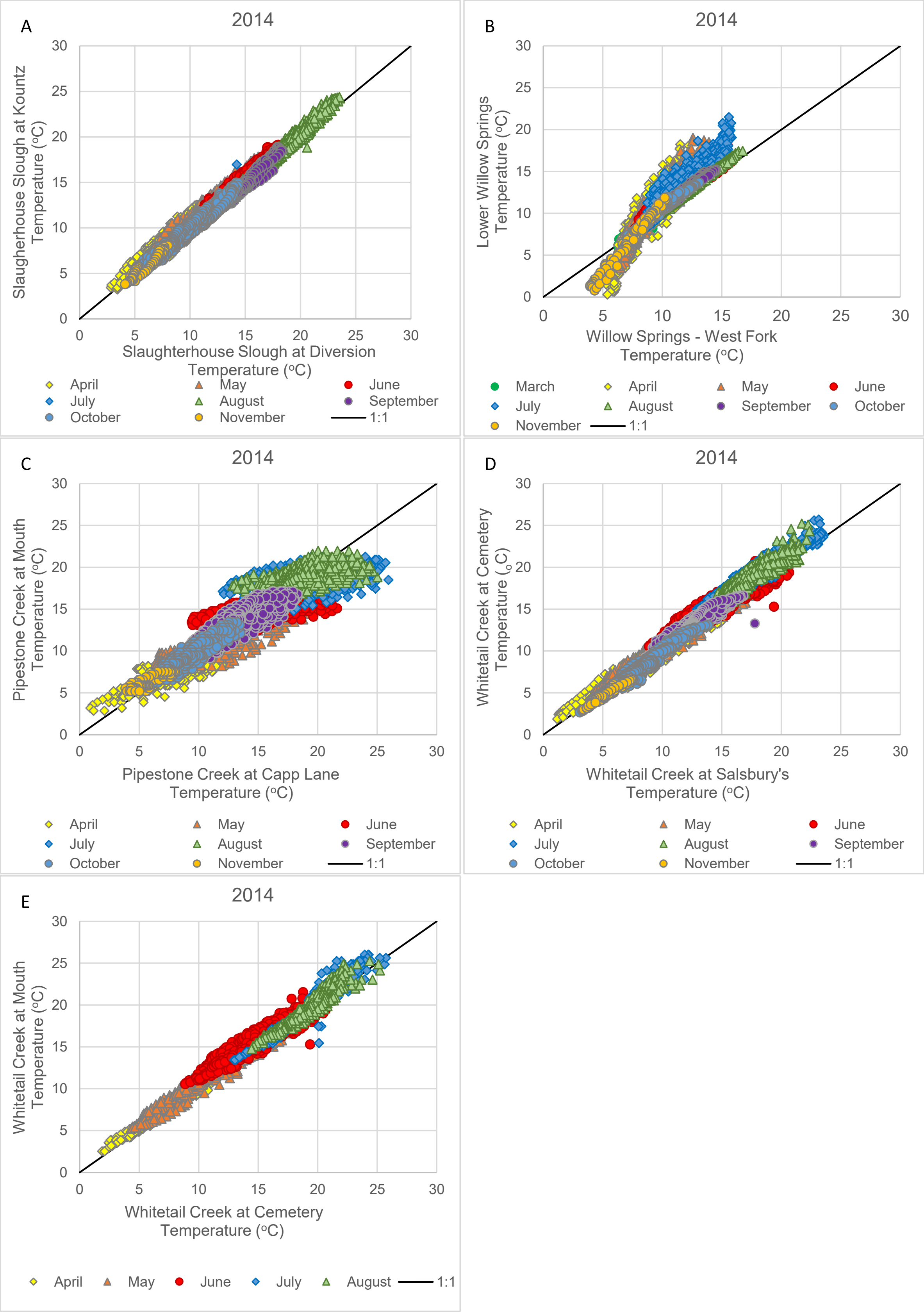
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-6



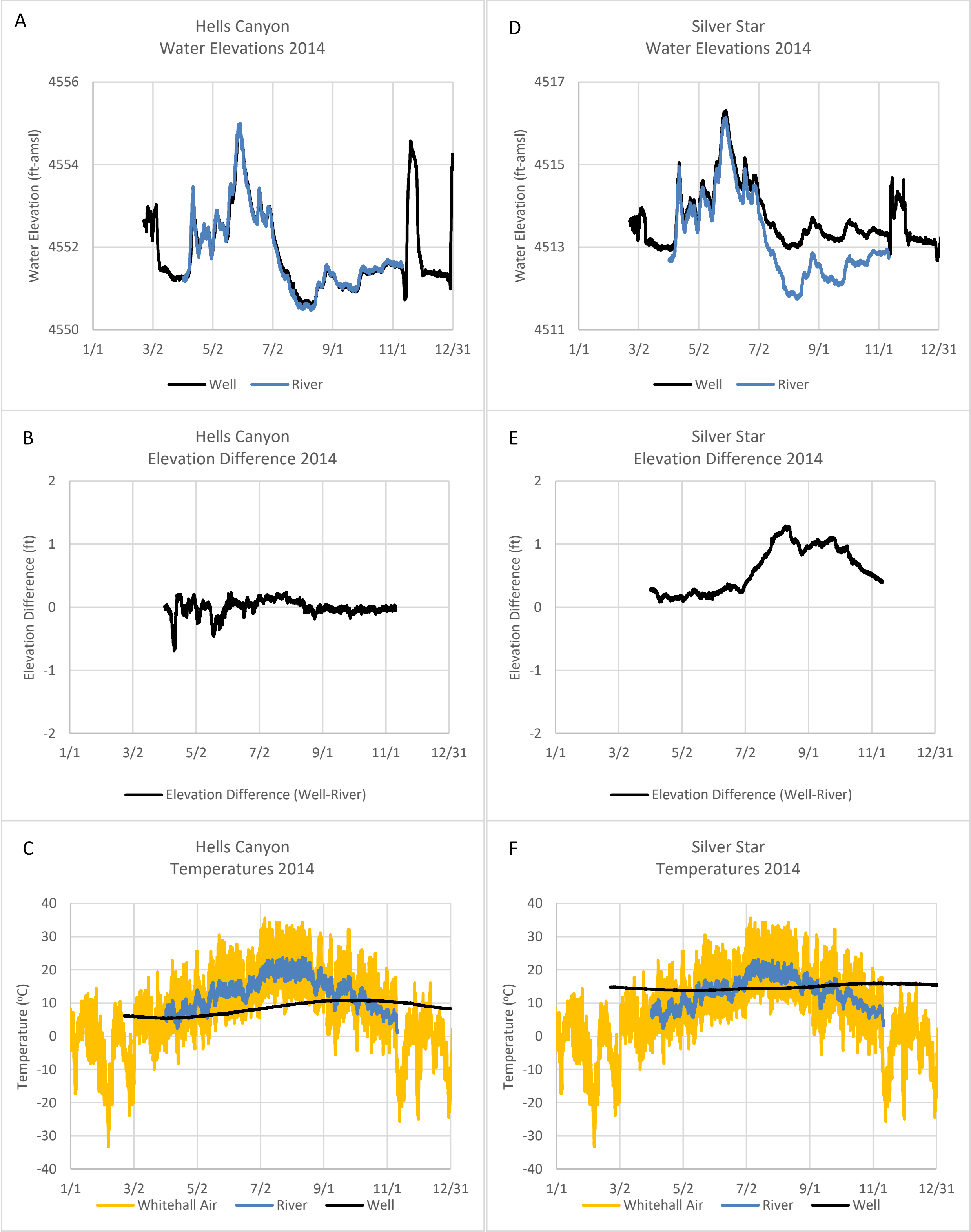
Appendix C3. Surface-Water Temperature Comparisons

Figure C3-7



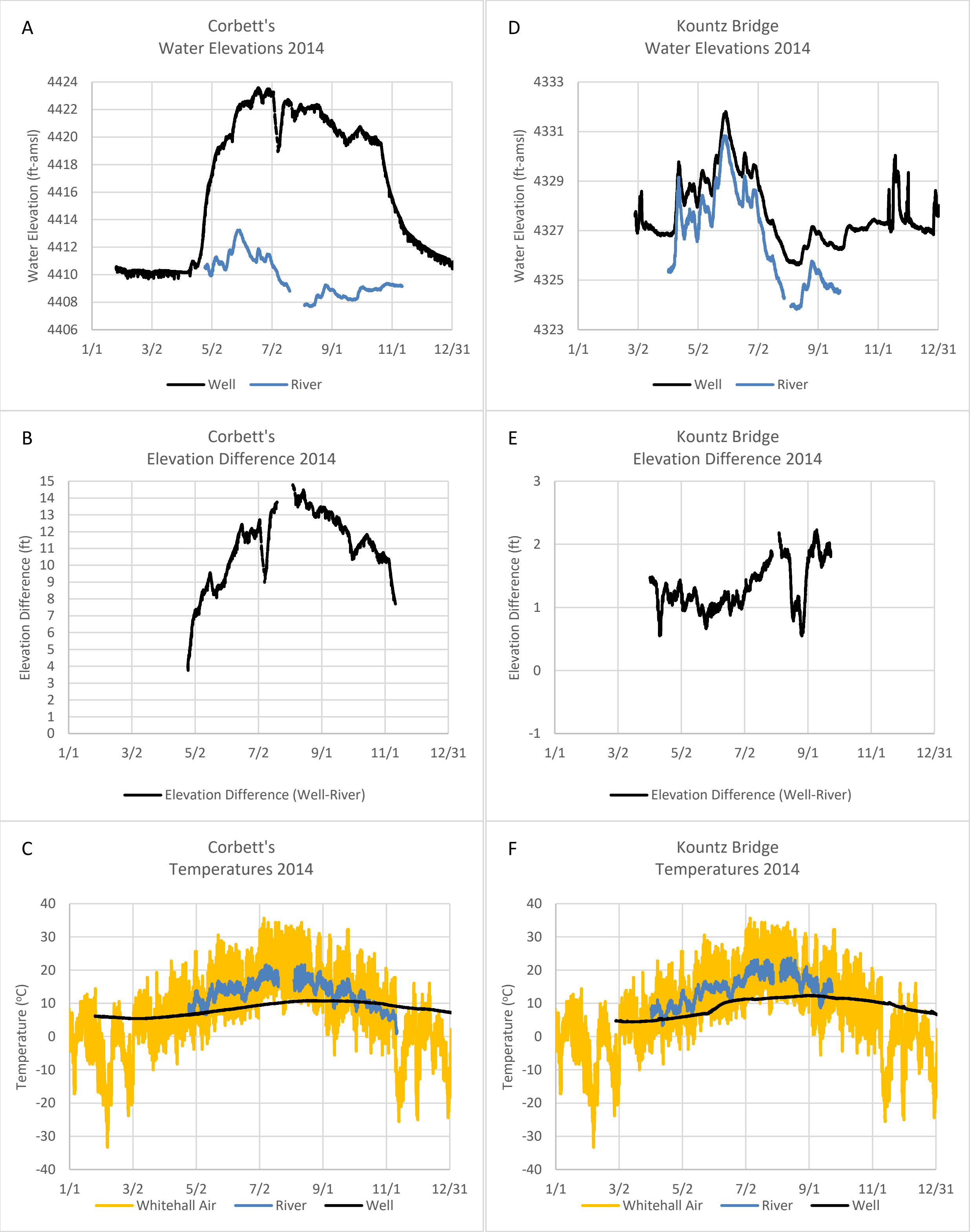
Appendix C4. Comparison of Groundwater and Surface-Water Elevations and Temperatures

Figure C4-1



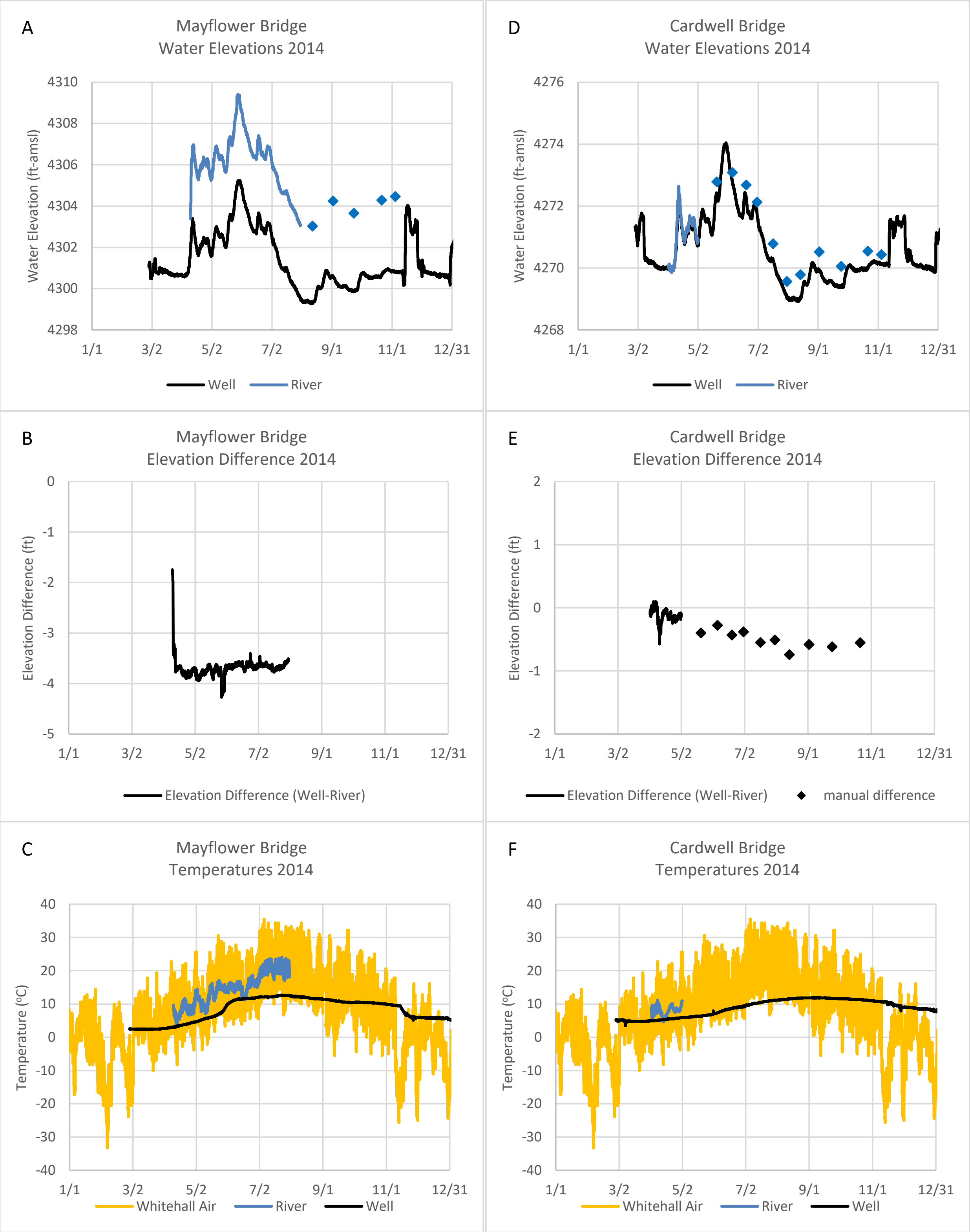
Appendix C4. Comparison of Groundwater and Surface-Water Elevations and Temperatures

Figure C4-2



Appendix C4. Comparison of Groundwater and Surface-Water Elevations and Temperatures

Figure C4-3

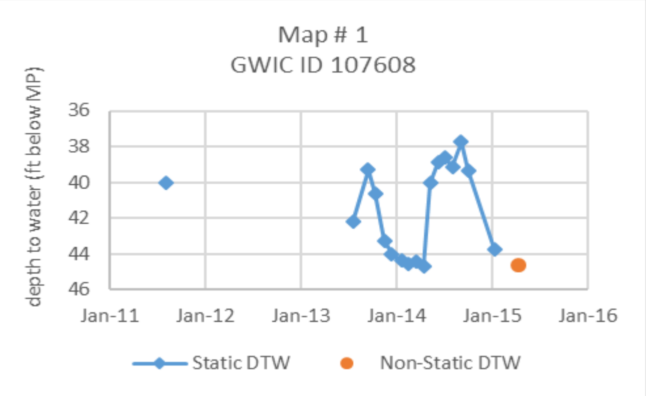


APPENDIX D

GROUNDWATER HYDROGRAPHS

Appendix D: Groundwater Hydrographs.

Note that x and y scales vary site to site.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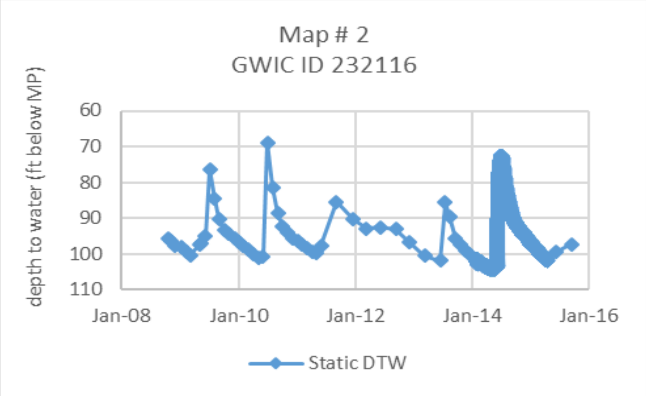
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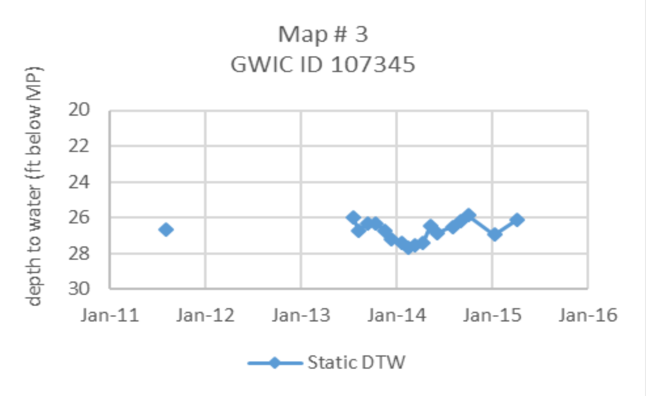
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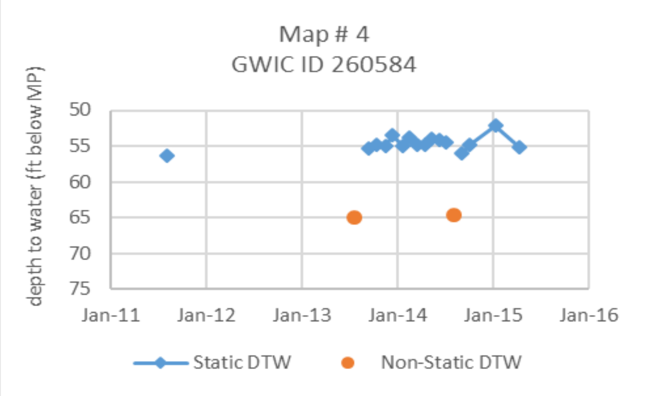
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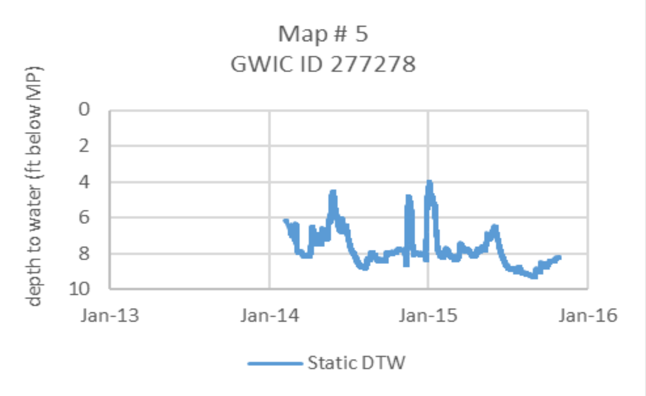
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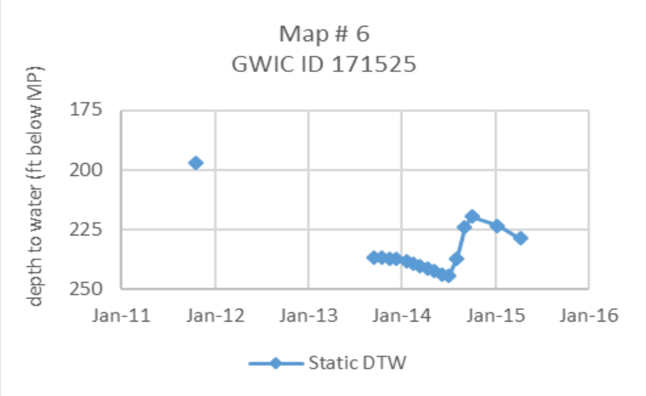
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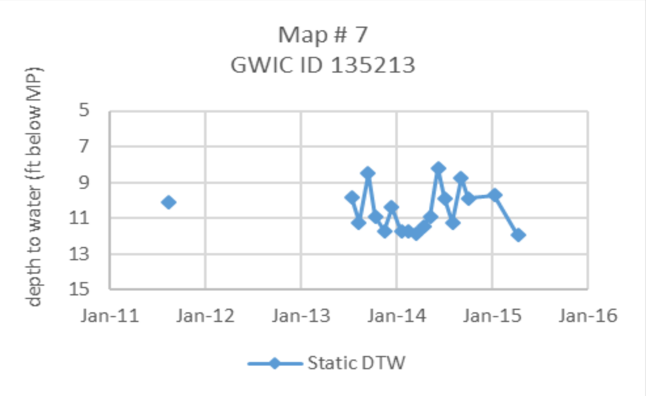
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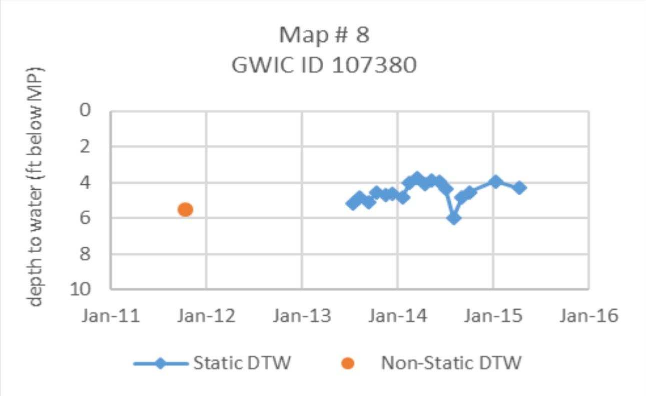
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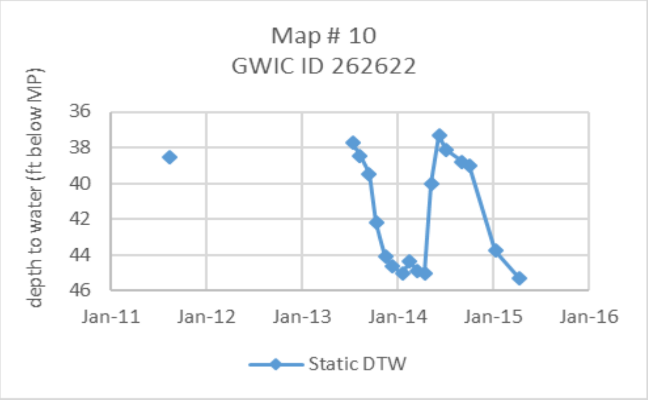
Appendix D: Groundwater Hydrographs.

Note that x and y scales vary site to site.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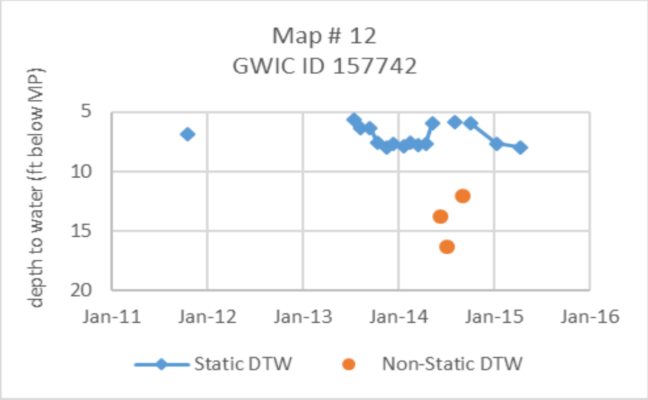
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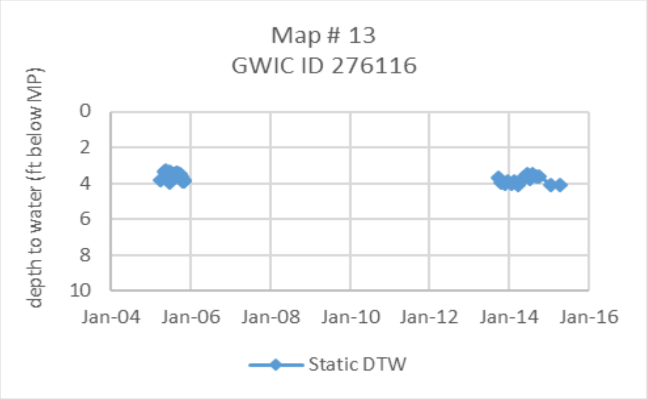
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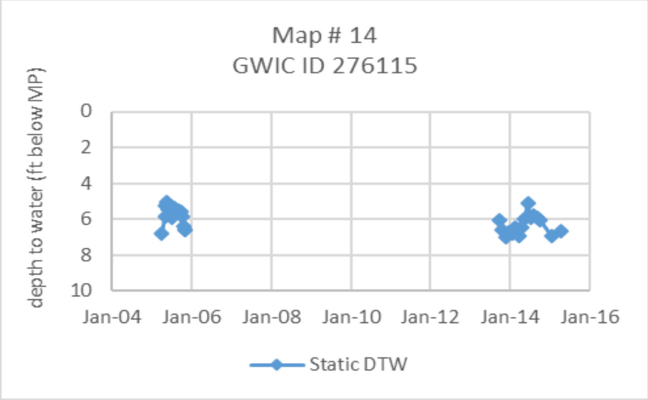
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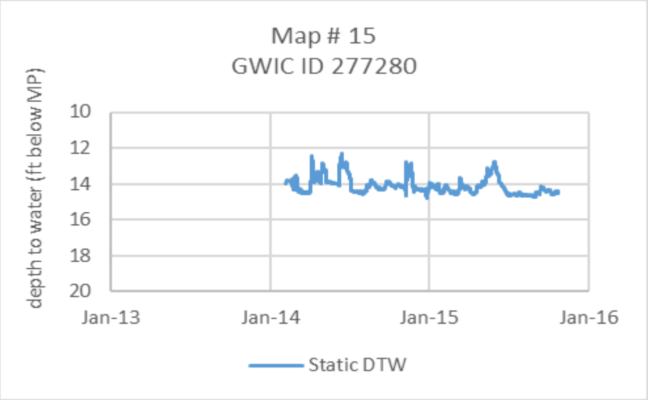
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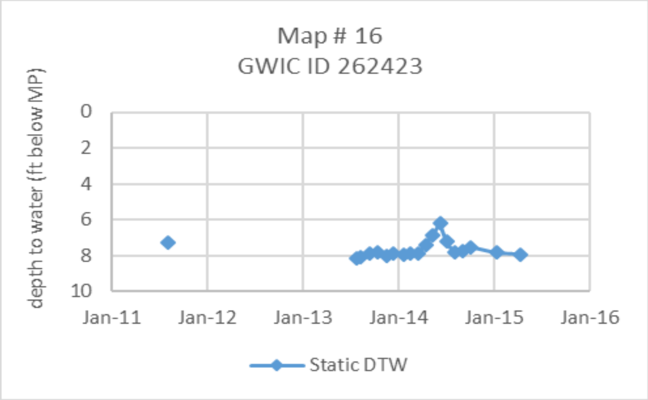
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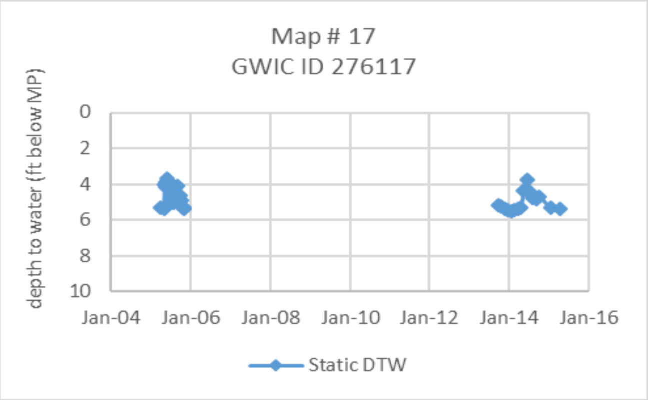
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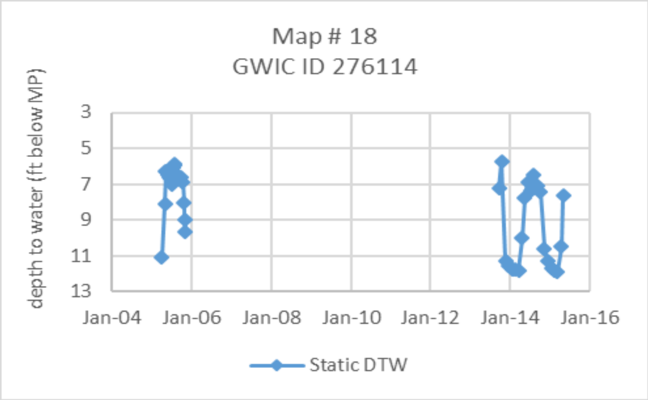
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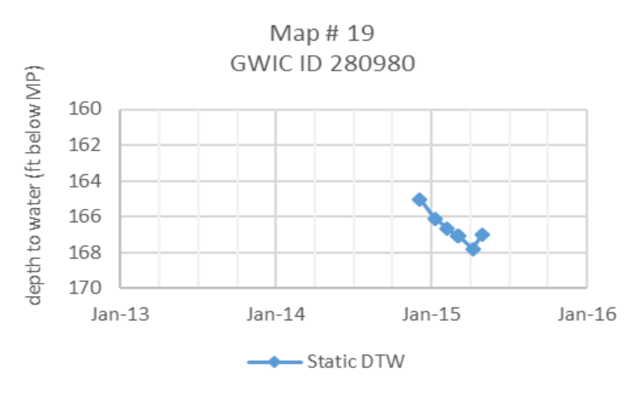
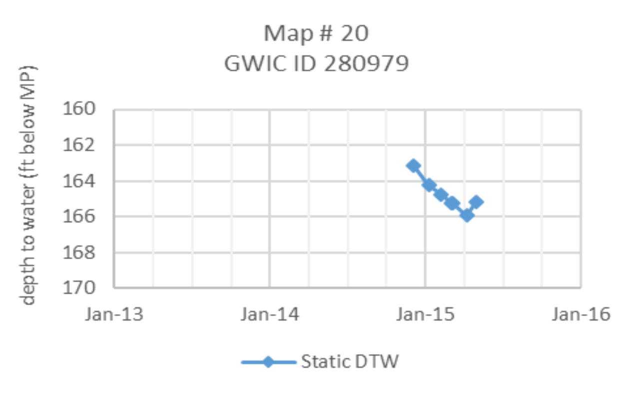
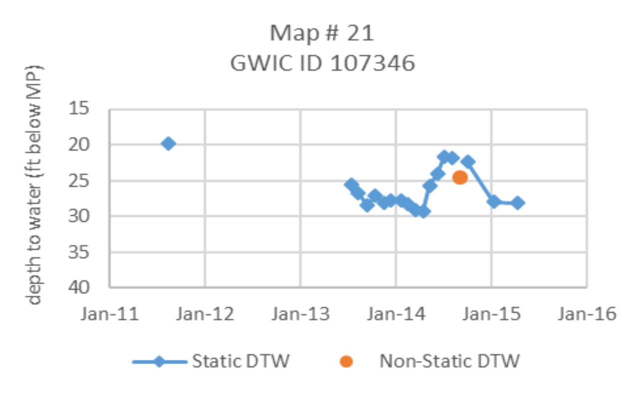
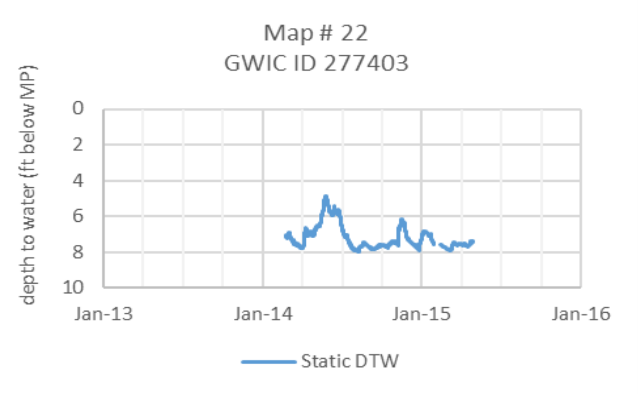
Appendix D: Groundwater Hydrographs.

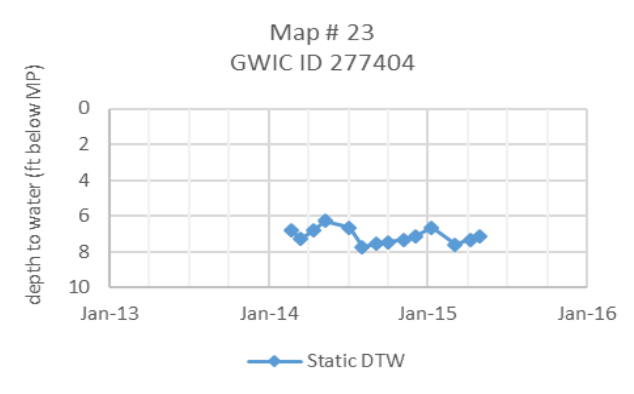
Note that x and y scales vary site to site.

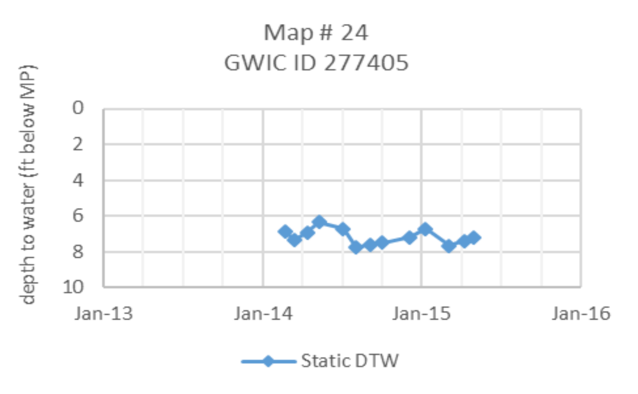


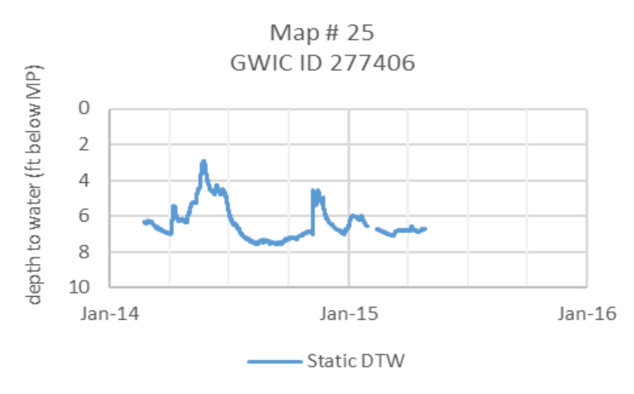


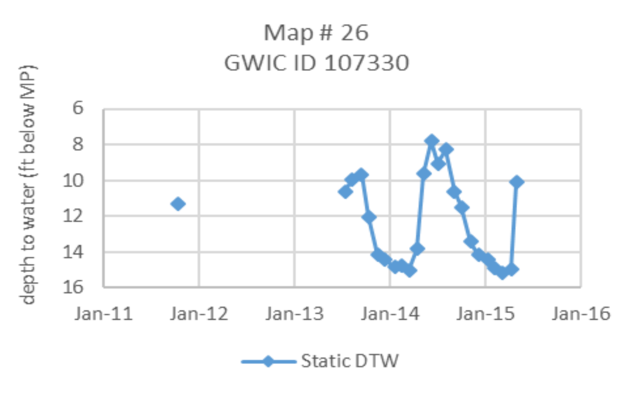






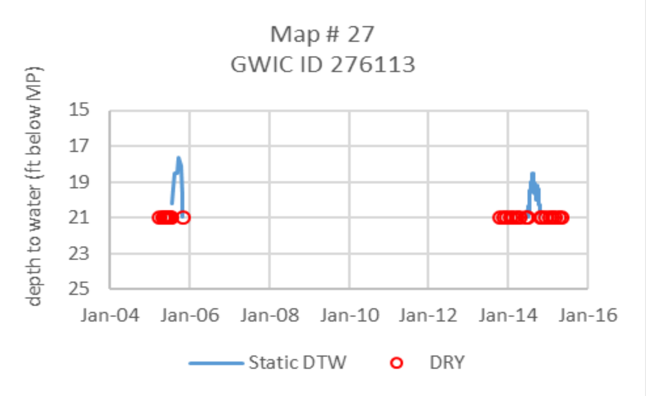


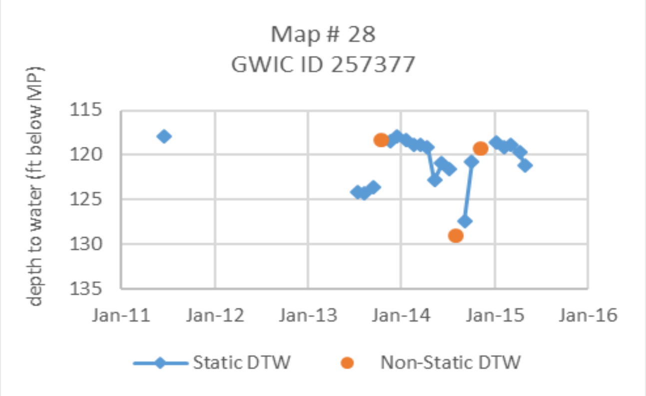


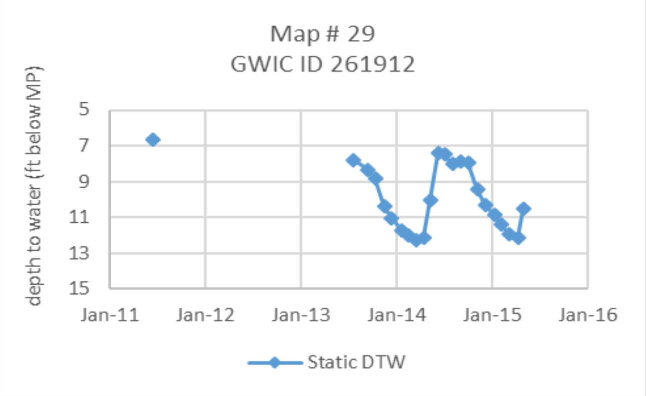


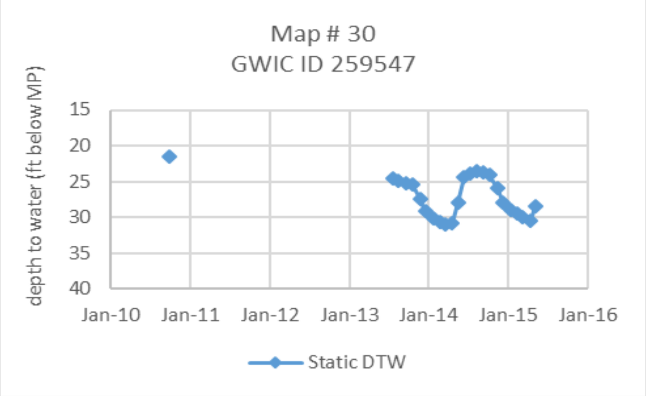
Appendix D: Groundwater Hydrographs.

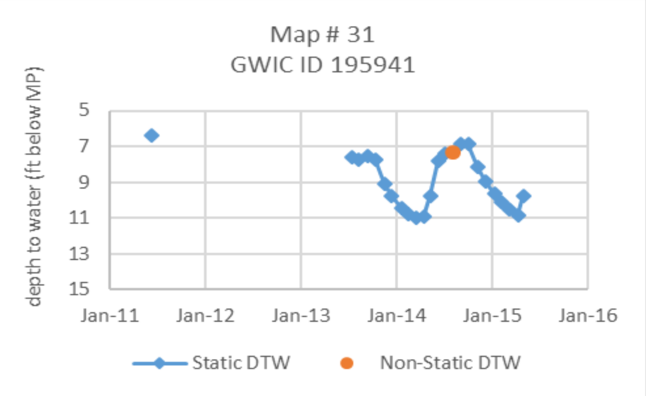
Note that x and y scales vary site to site.

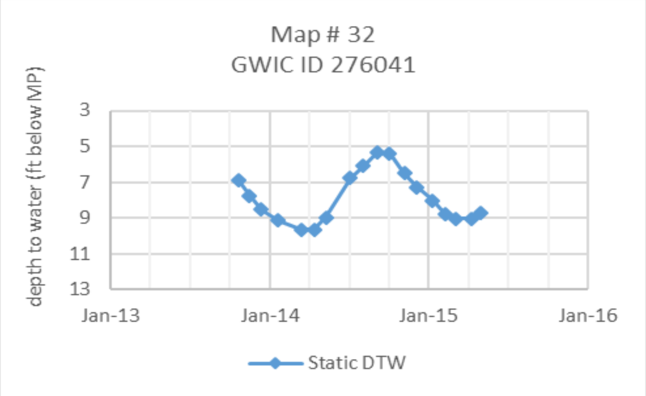


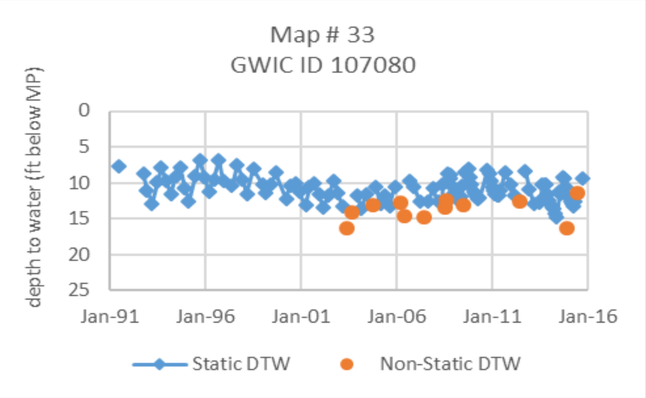


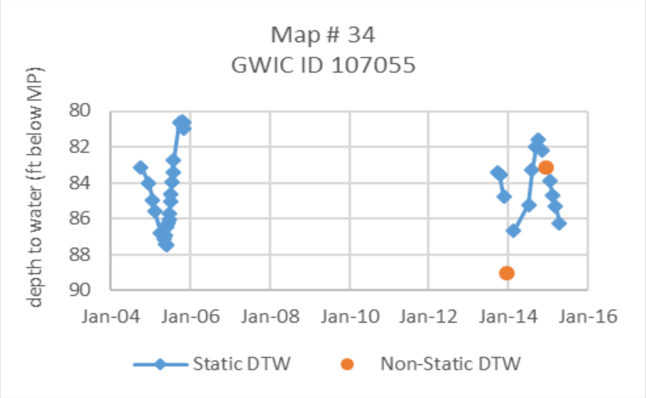






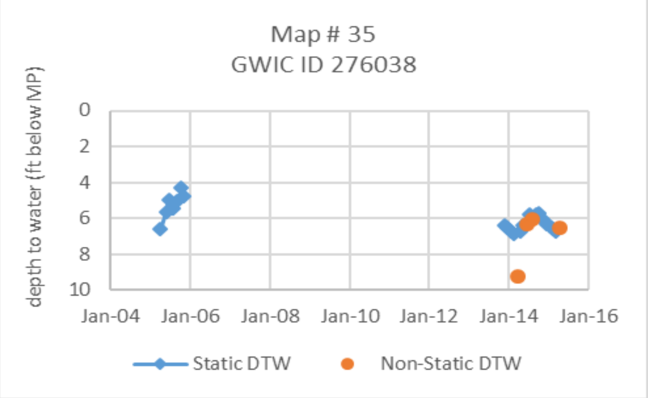






Appendix D: Groundwater Hydrographs.

Note that x and y scales vary site to site.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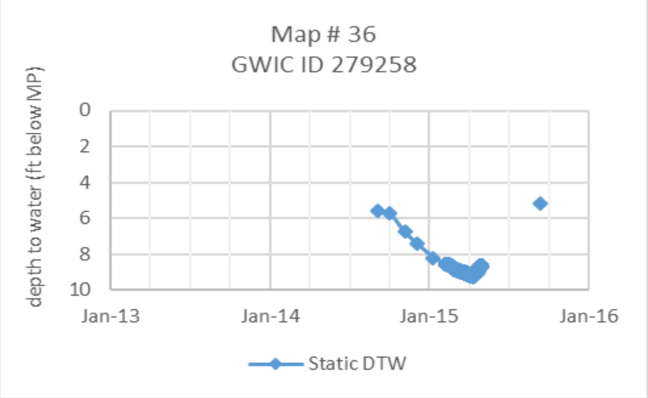
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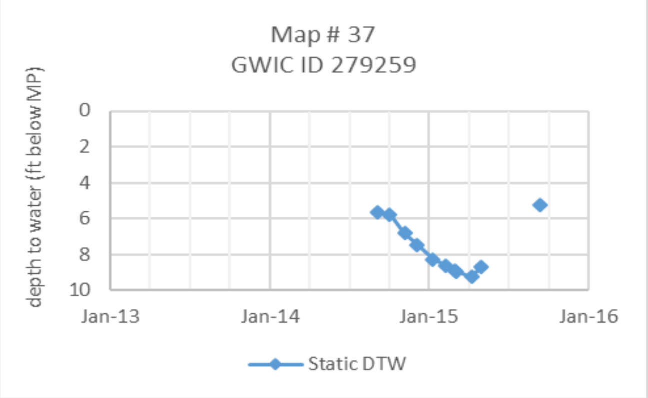
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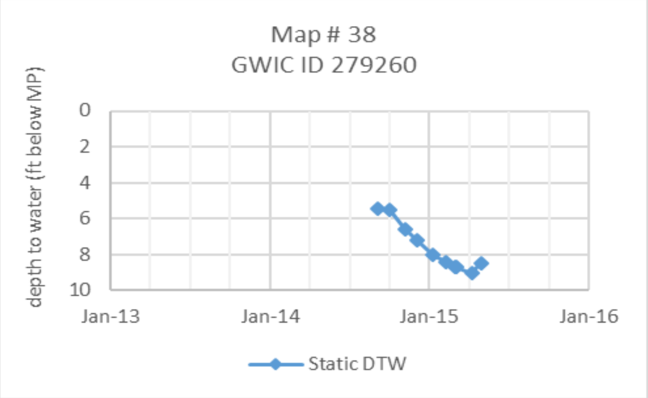
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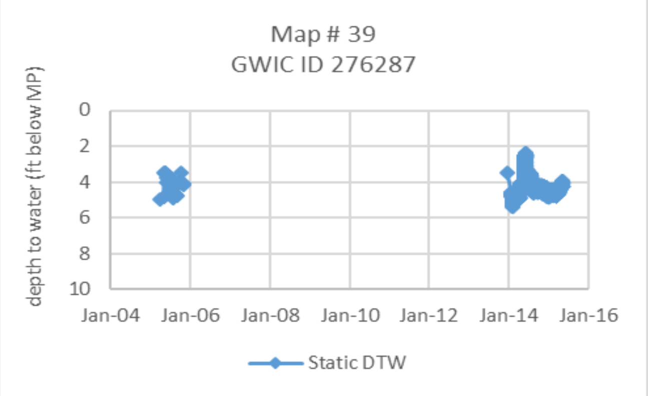
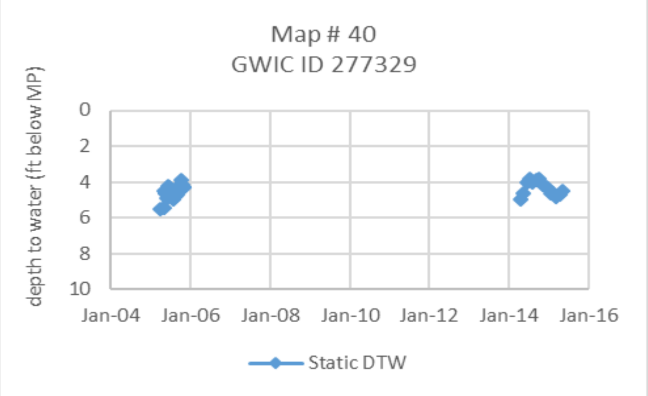

Map # 39
GWIC ID 276287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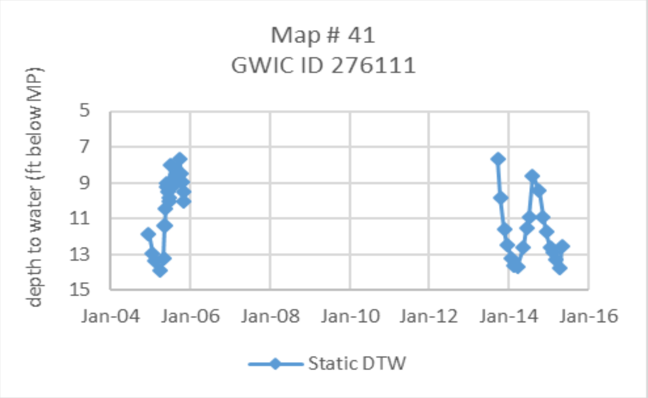
GWIC ID 277329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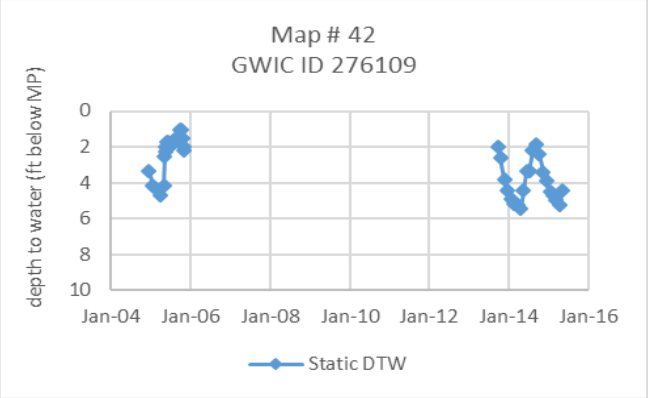
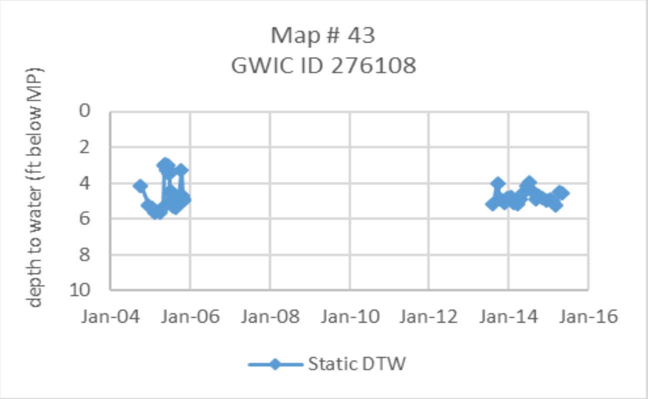
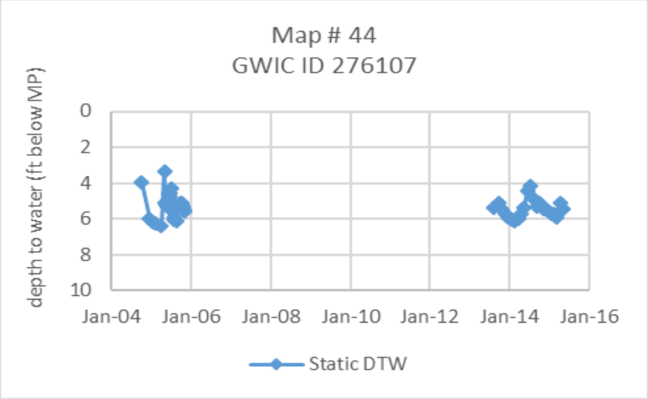
GWIC ID 276111

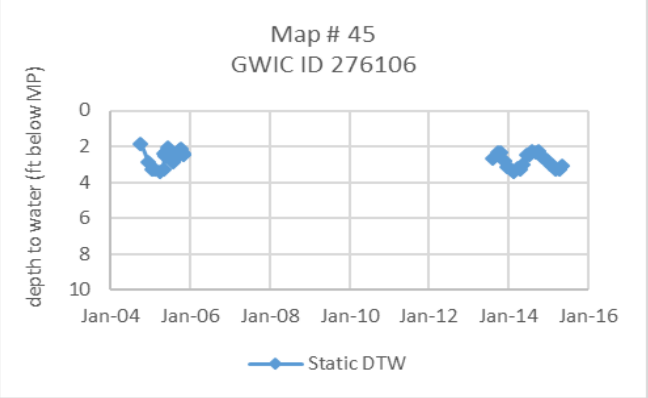

Map # 42
GWIC ID 276109

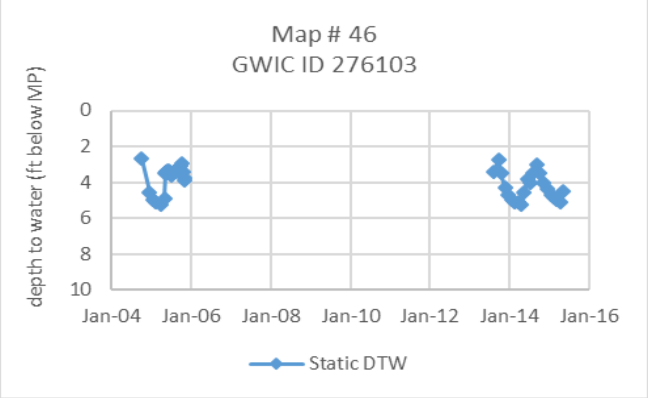
Appendix D: Groundwater Hydrographs.

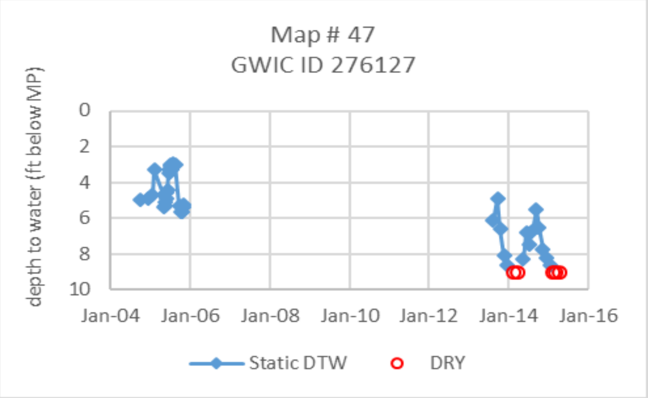
Note that x and y scales vary site to site.

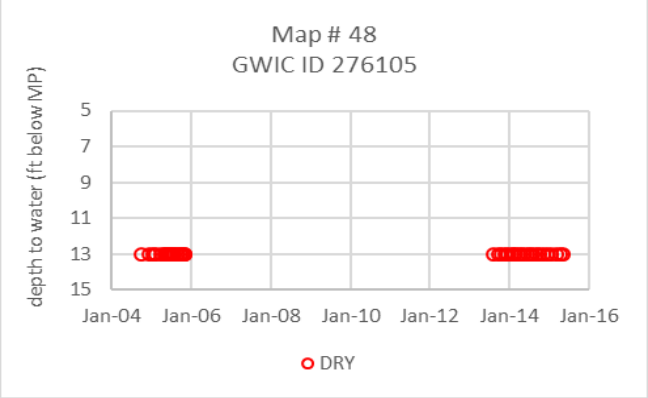


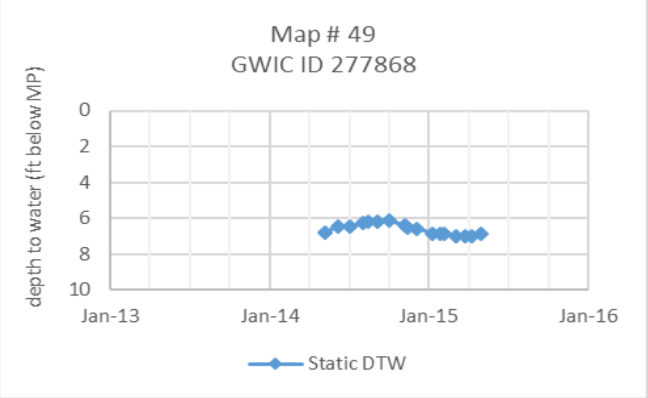


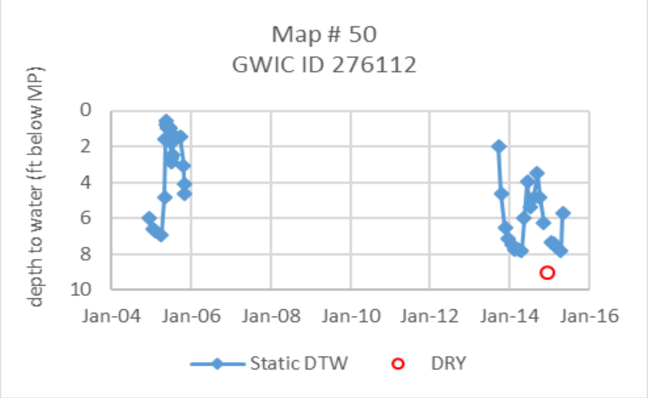






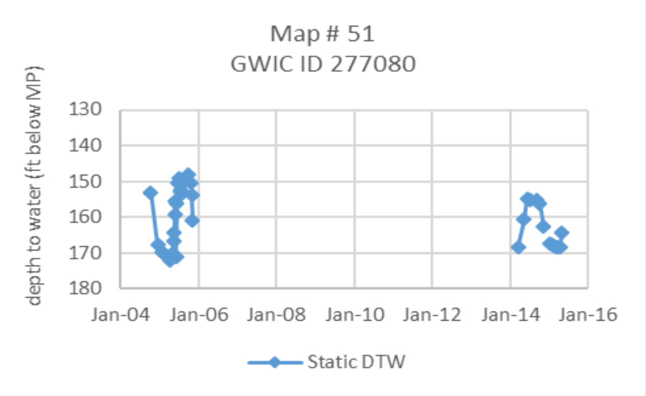


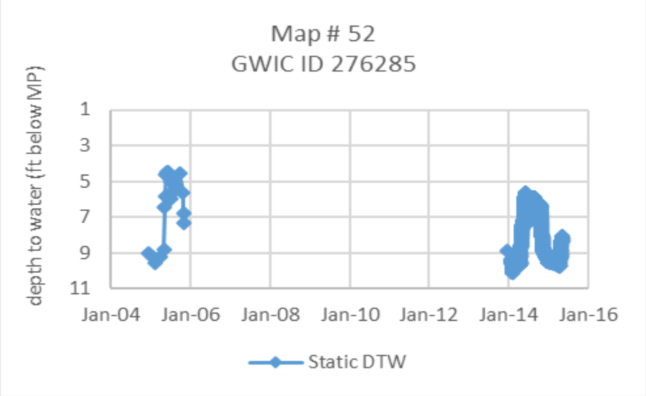


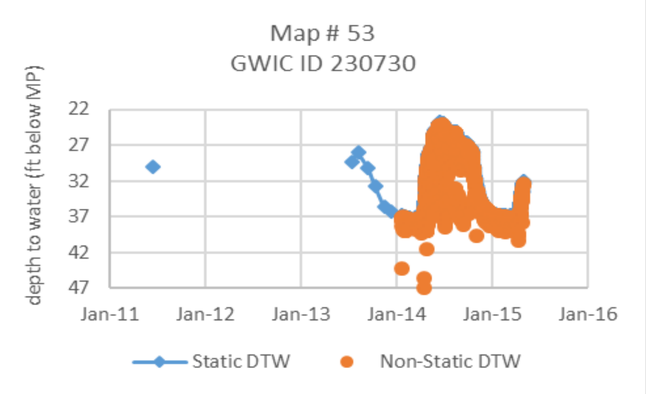


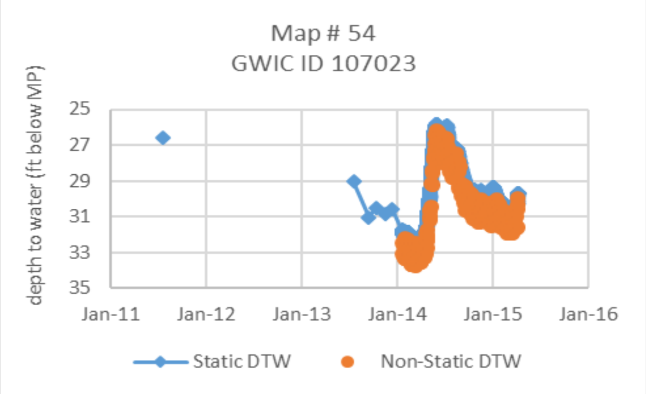
Appendix D: Groundwater Hydrographs.

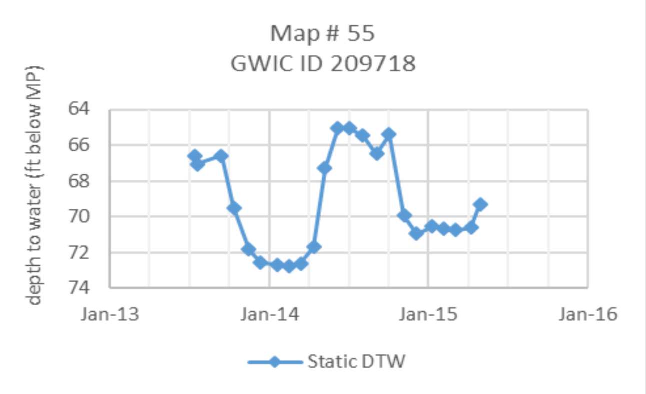
Note that x and y scales vary site to site.

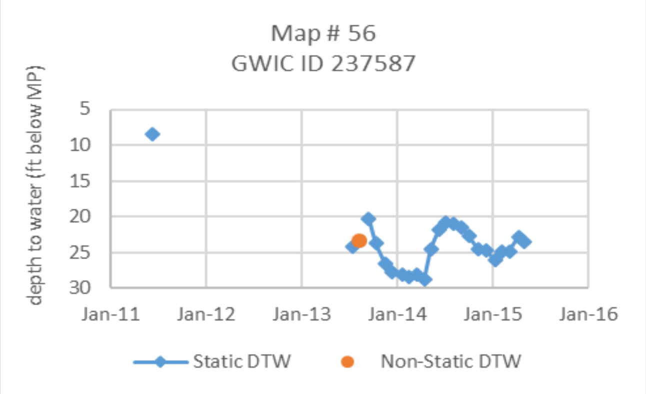


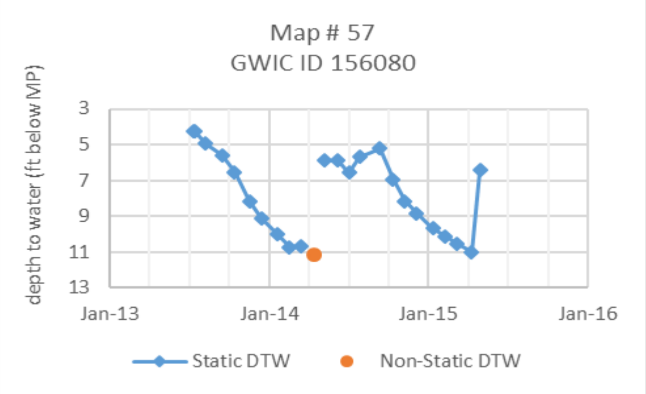


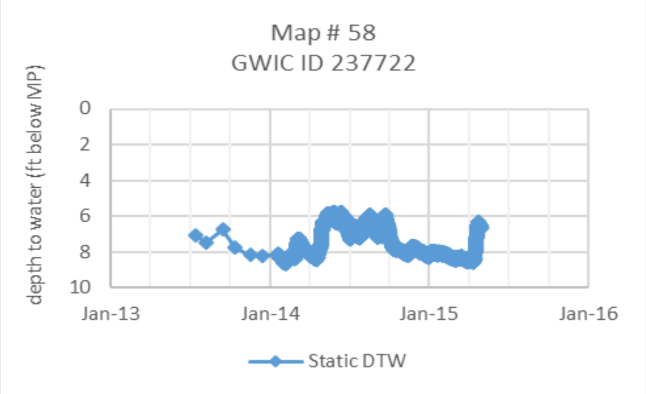






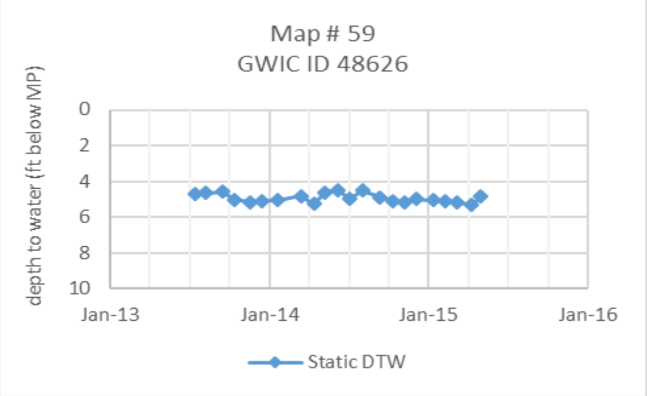


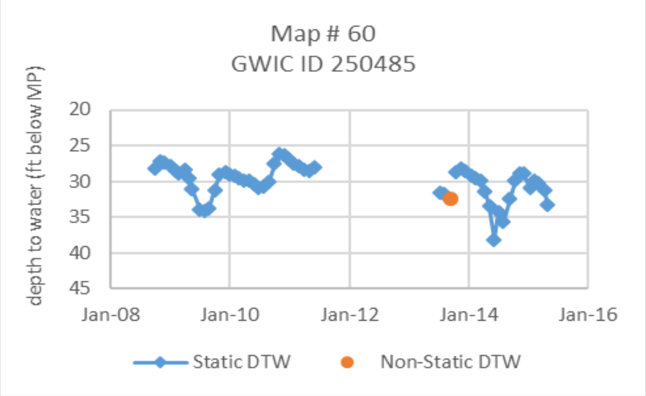


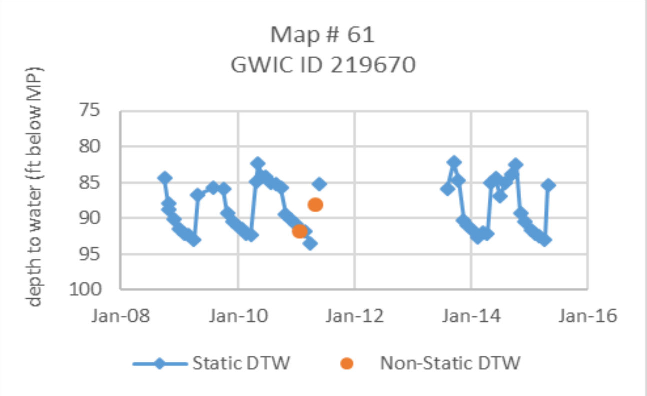


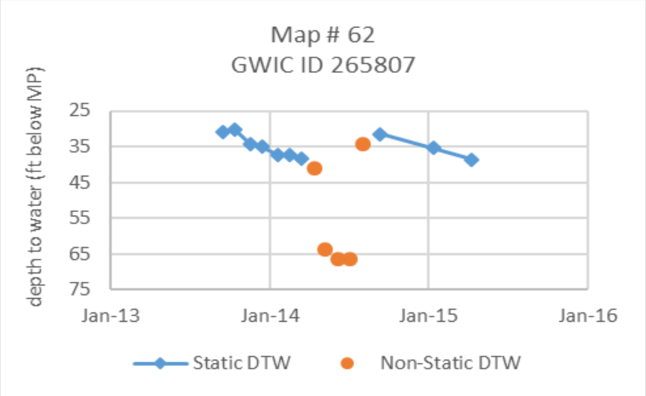
Appendix D: Groundwater Hydrographs.

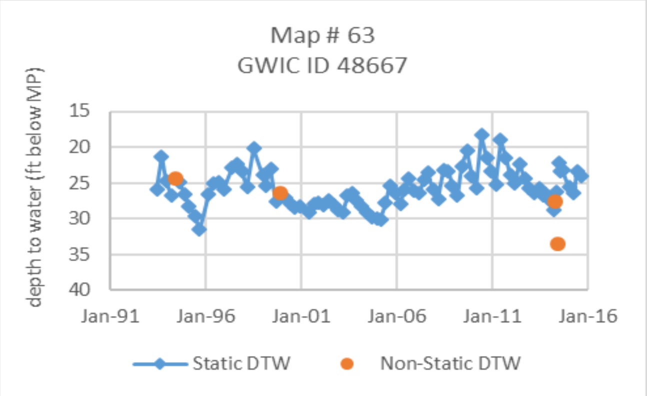
Note that x and y scales vary site to site.

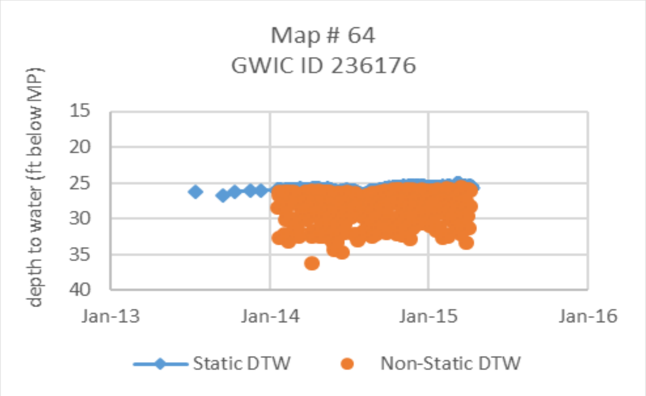


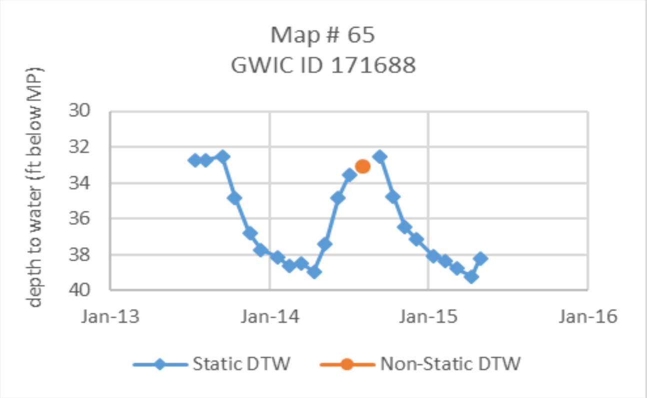


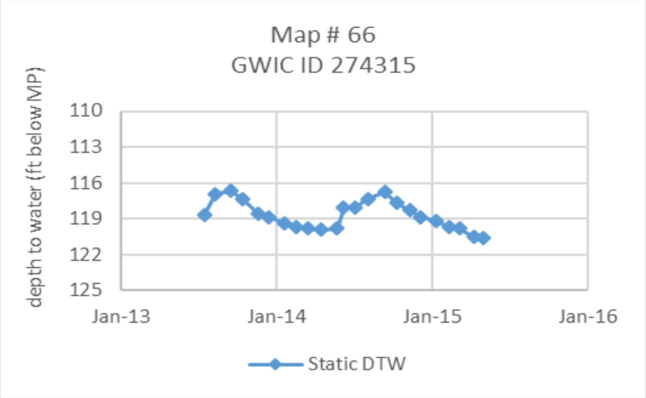






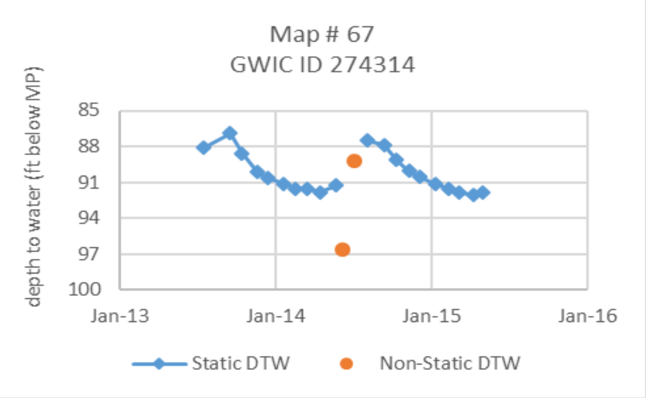


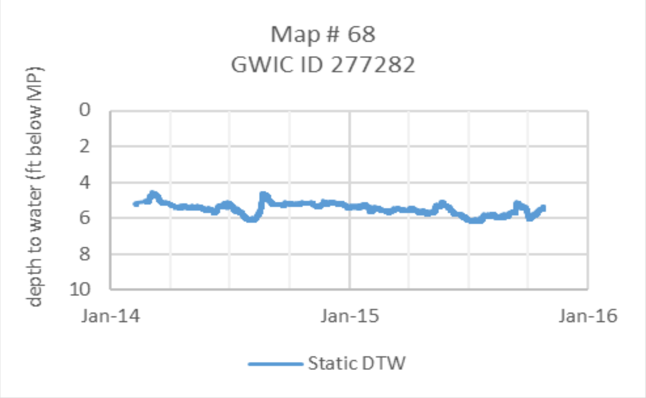


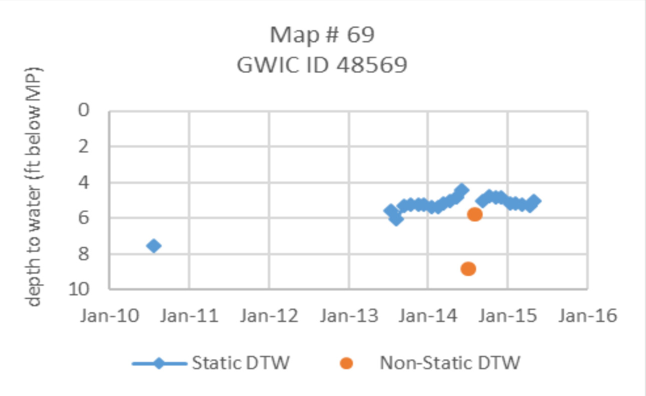


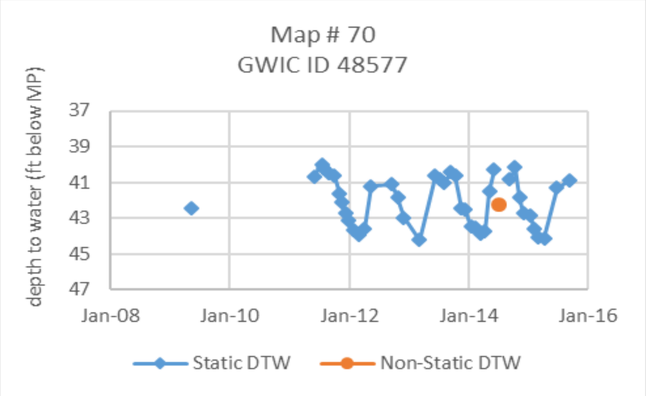
Appendix D: Groundwater Hydrographs.

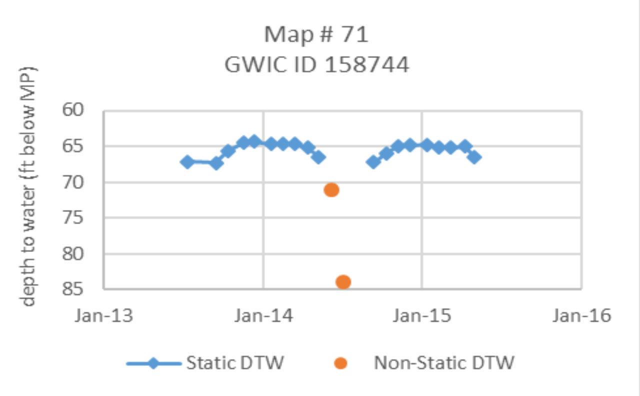
Note that x and y scales vary site to site.

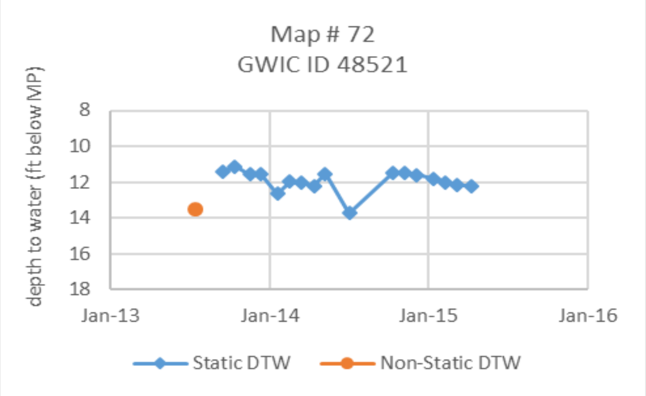


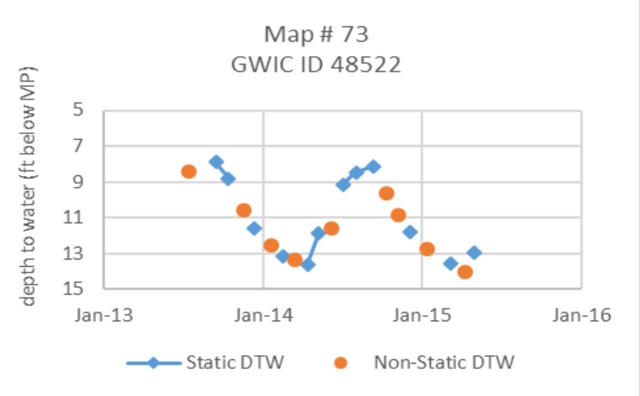


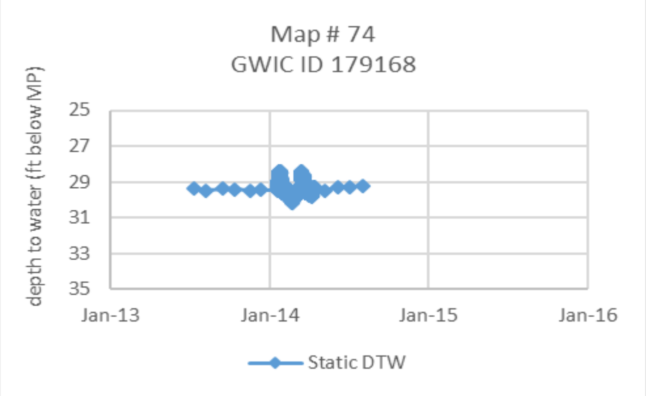






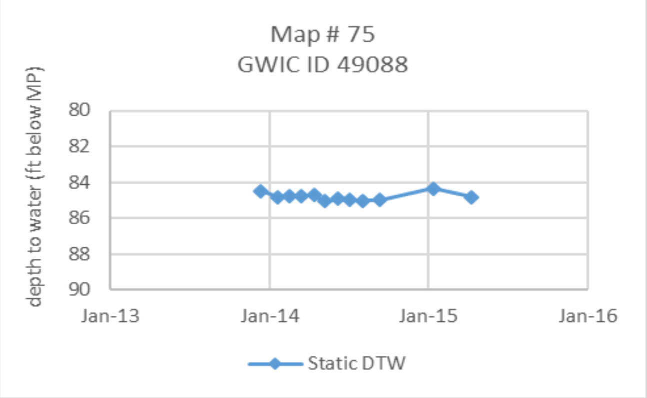


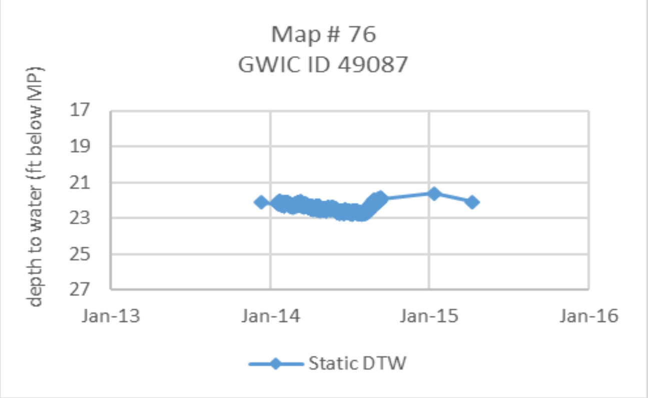




Appendix D: Groundwater Hydrographs.

Note that x and y scales vary site to site.


Map # 75
GWIC ID 49088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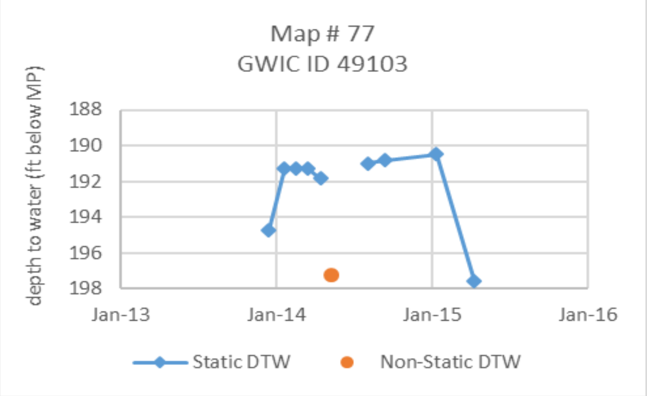
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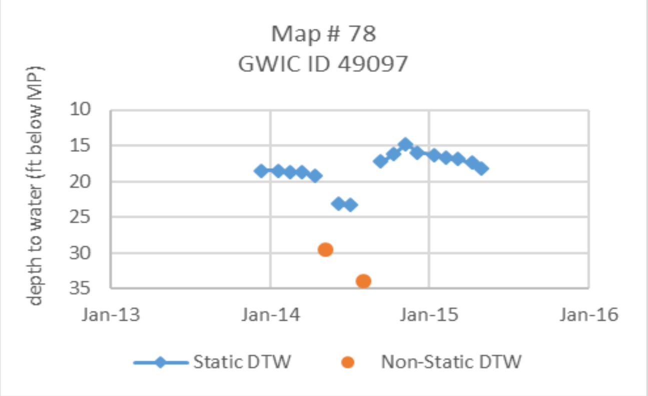
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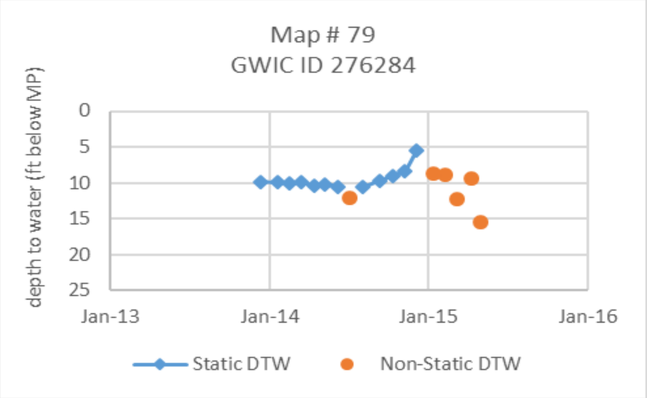
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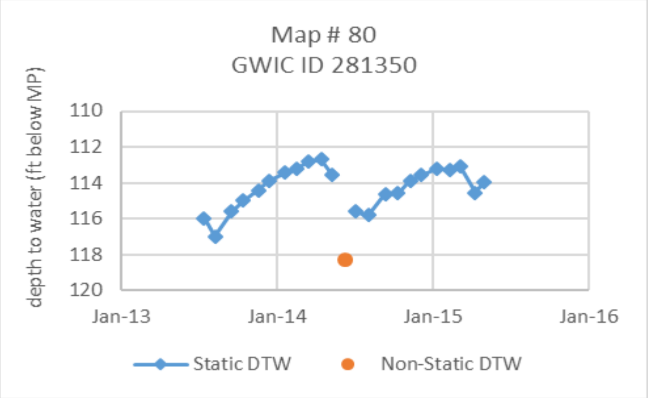
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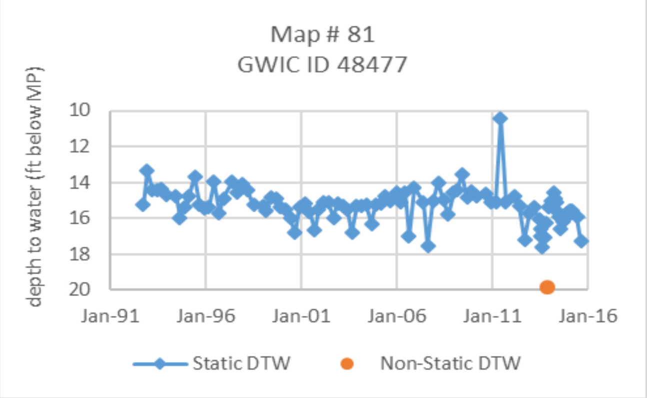
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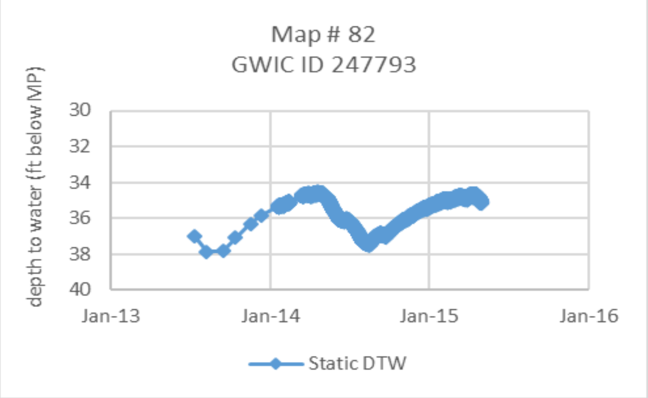
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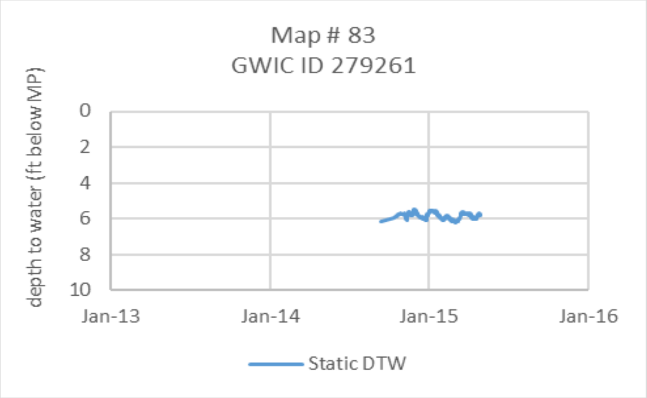
Appendix D: Groundwater Hydrographs.

Note that x and y scales vary site to site.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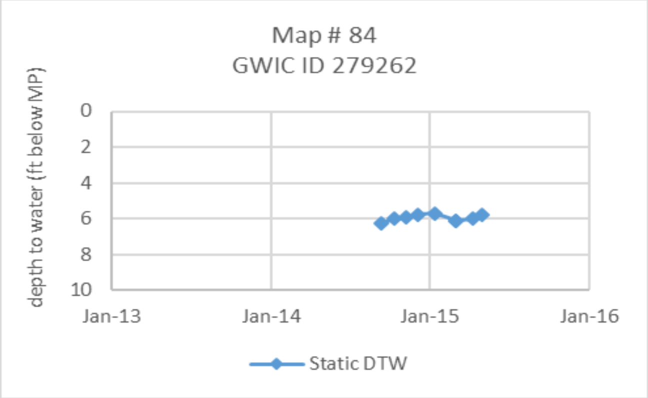
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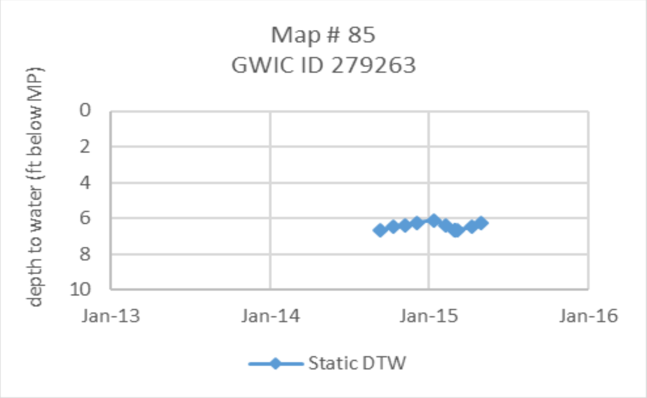
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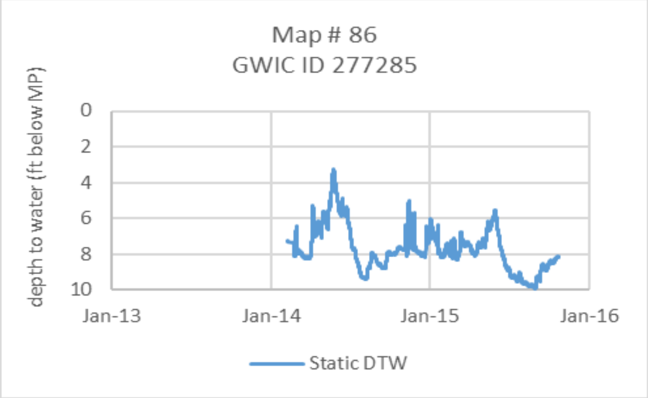
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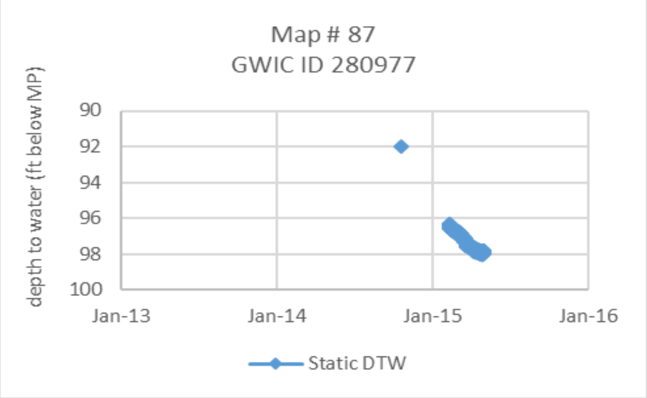
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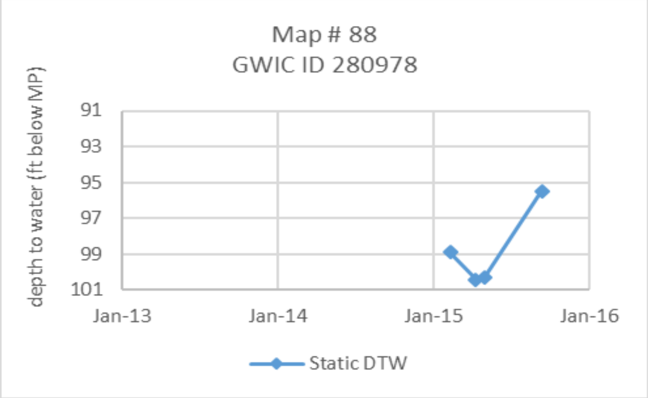
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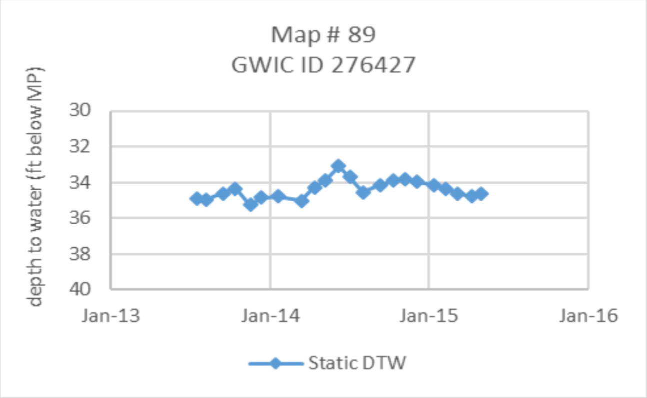
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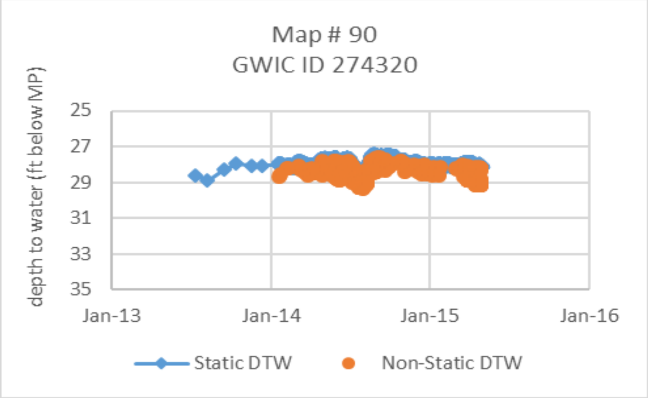
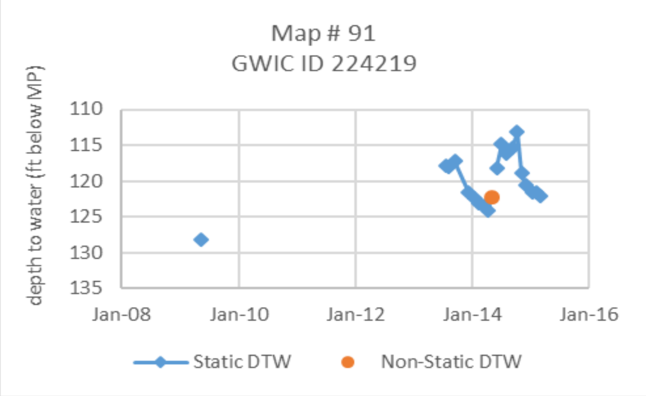
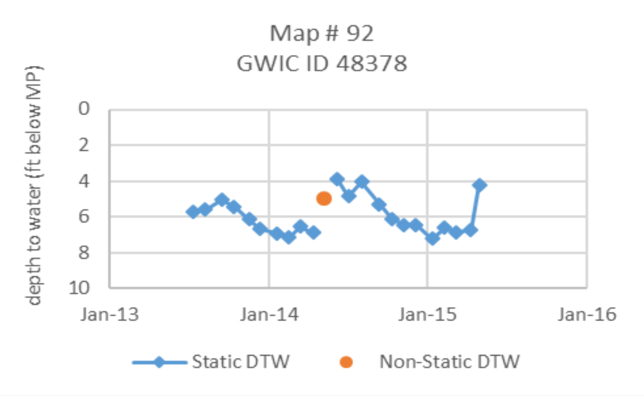
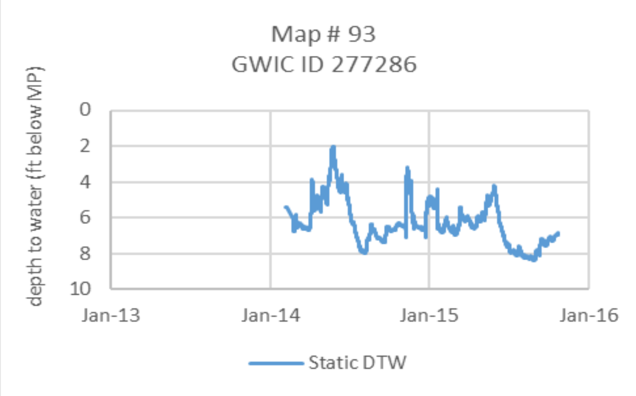

Map # 90
GWIC ID 274320

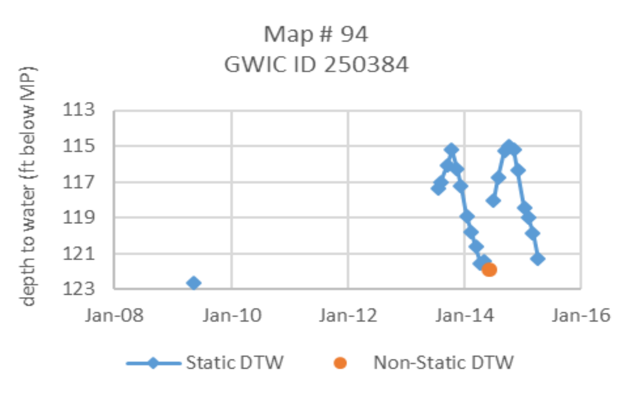
Appendix D: Groundwater Hydrographs.

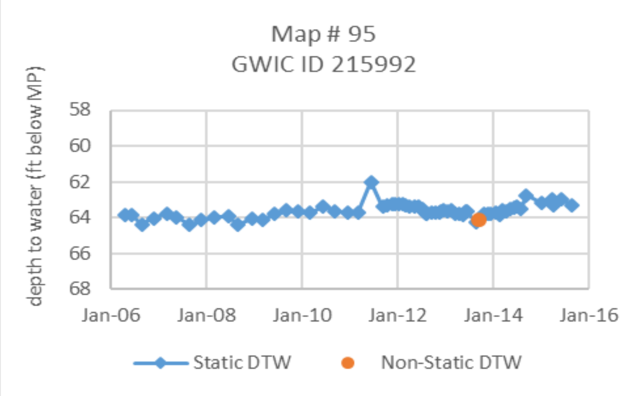
Note that x and y scales vary site to site.

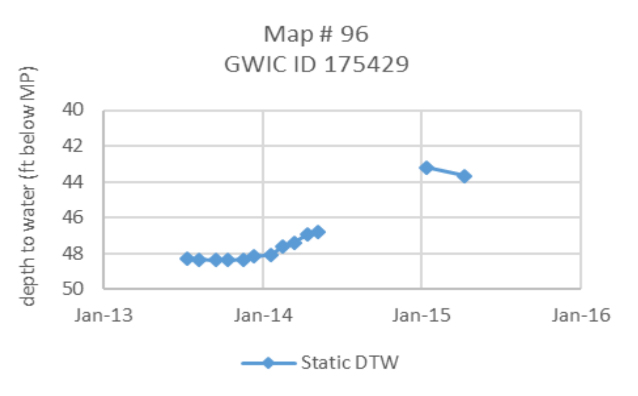


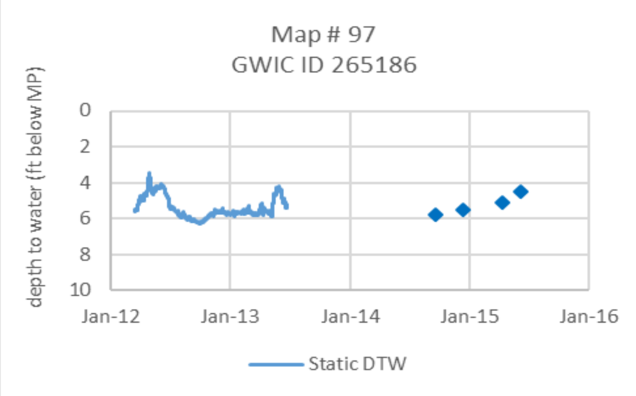


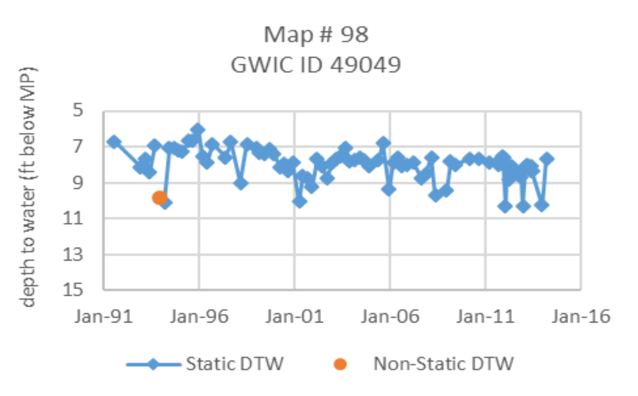






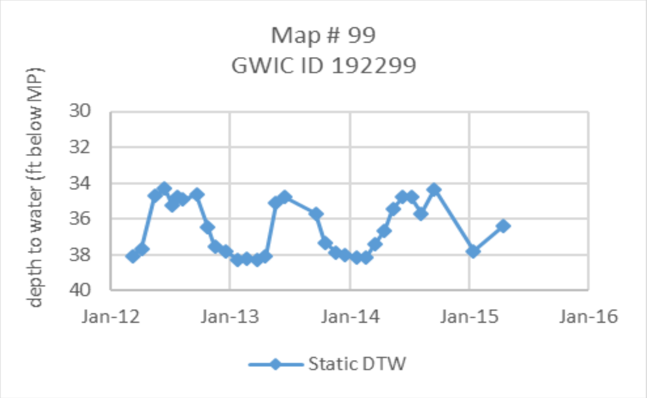


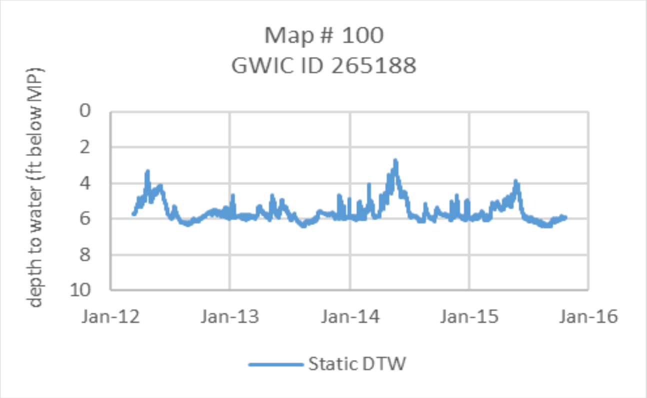


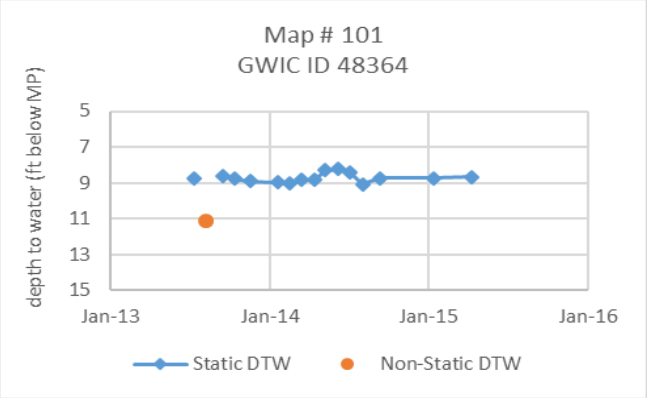


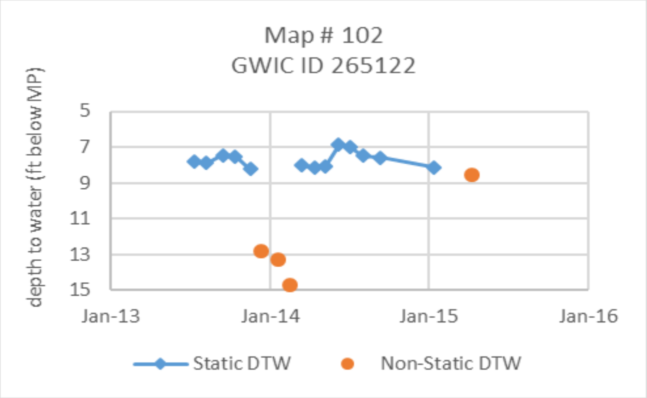
Appendix D: Groundwater Hydrographs.

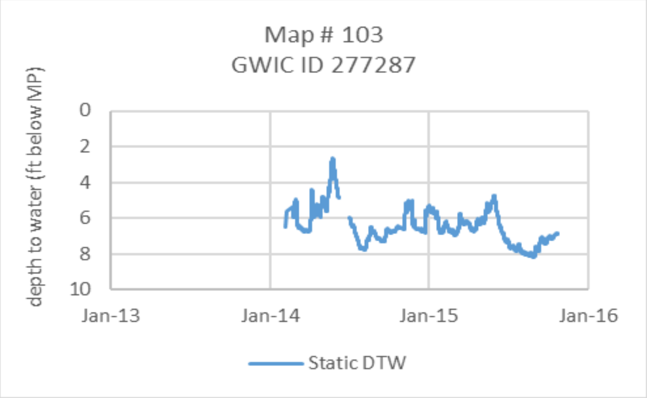
Note that x and y scales vary site to site.

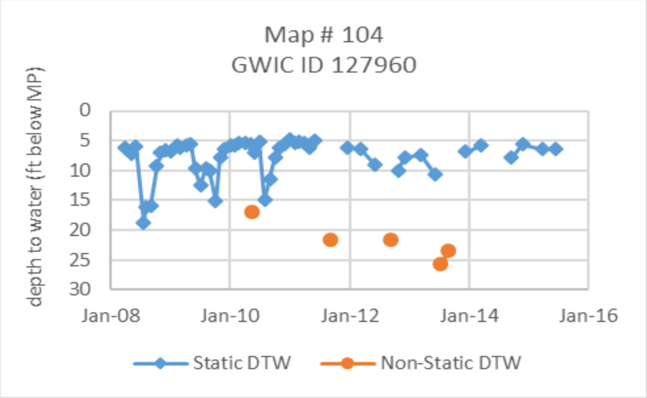


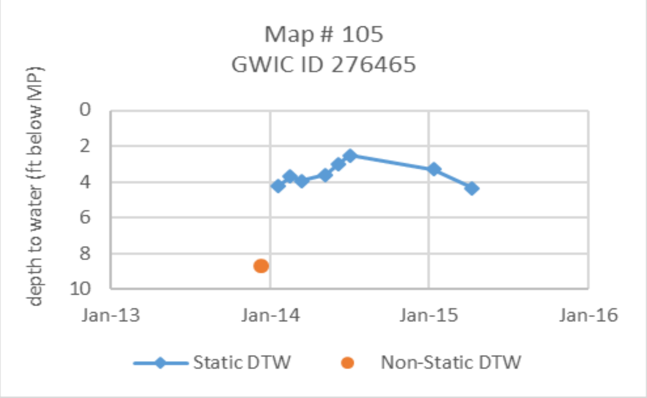


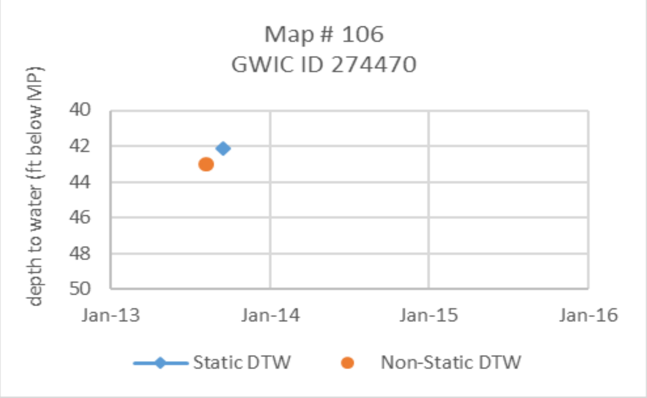










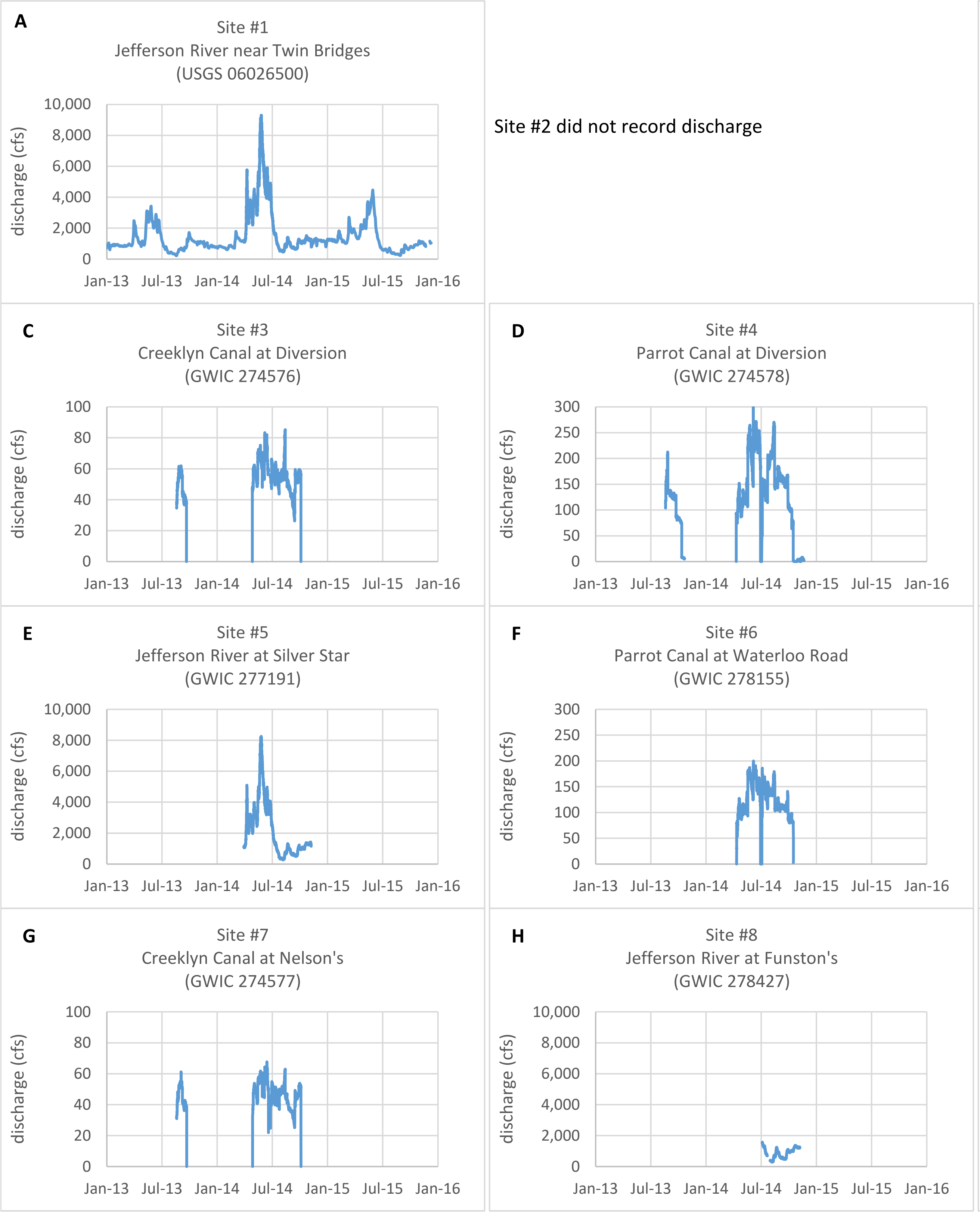


APPENDIX E

SURFACE-WATER HYDROGRAPHS AND THERMOGRAPHS

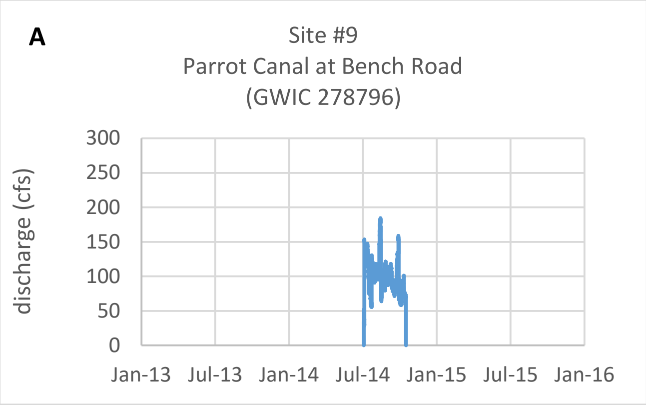
Appendix E: Surface-Water Hydrographs

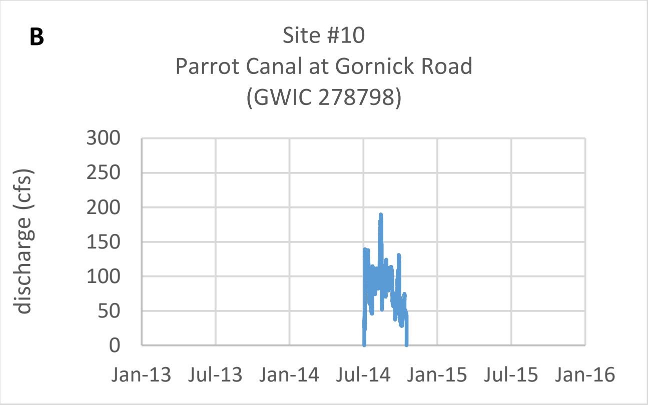
Figure E1-1



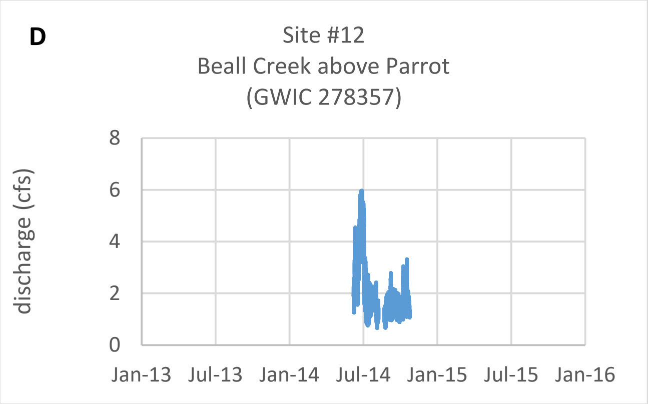
Appendix E: Surface-Water Hydrographs

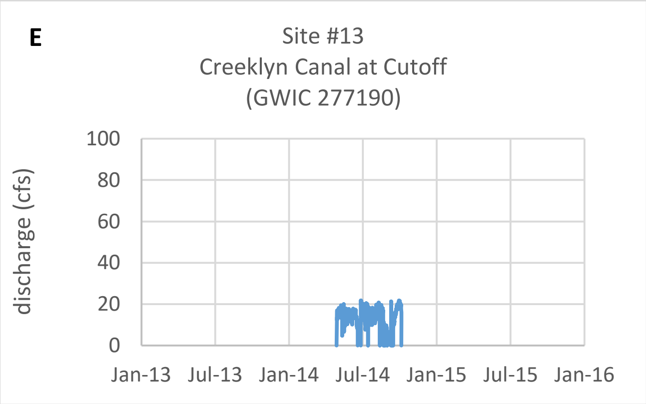
Figure E1-2

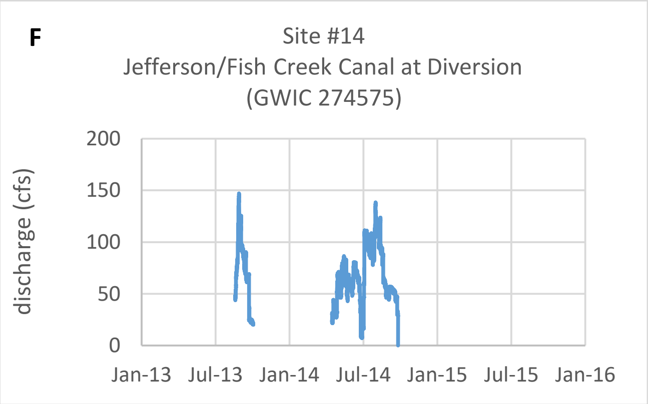


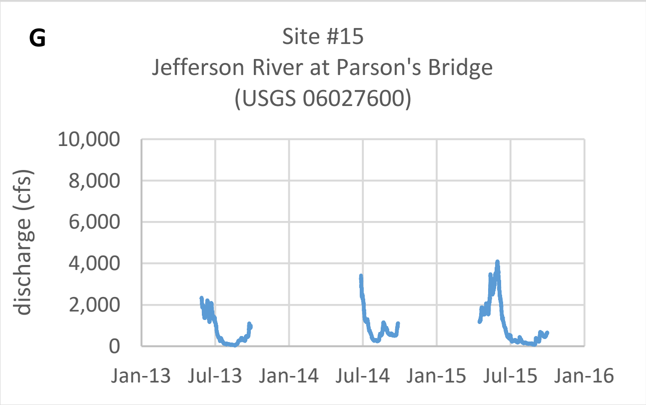


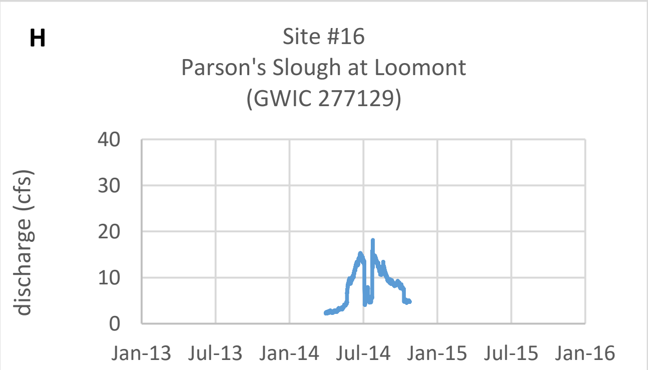
Site #11 did not record discharge







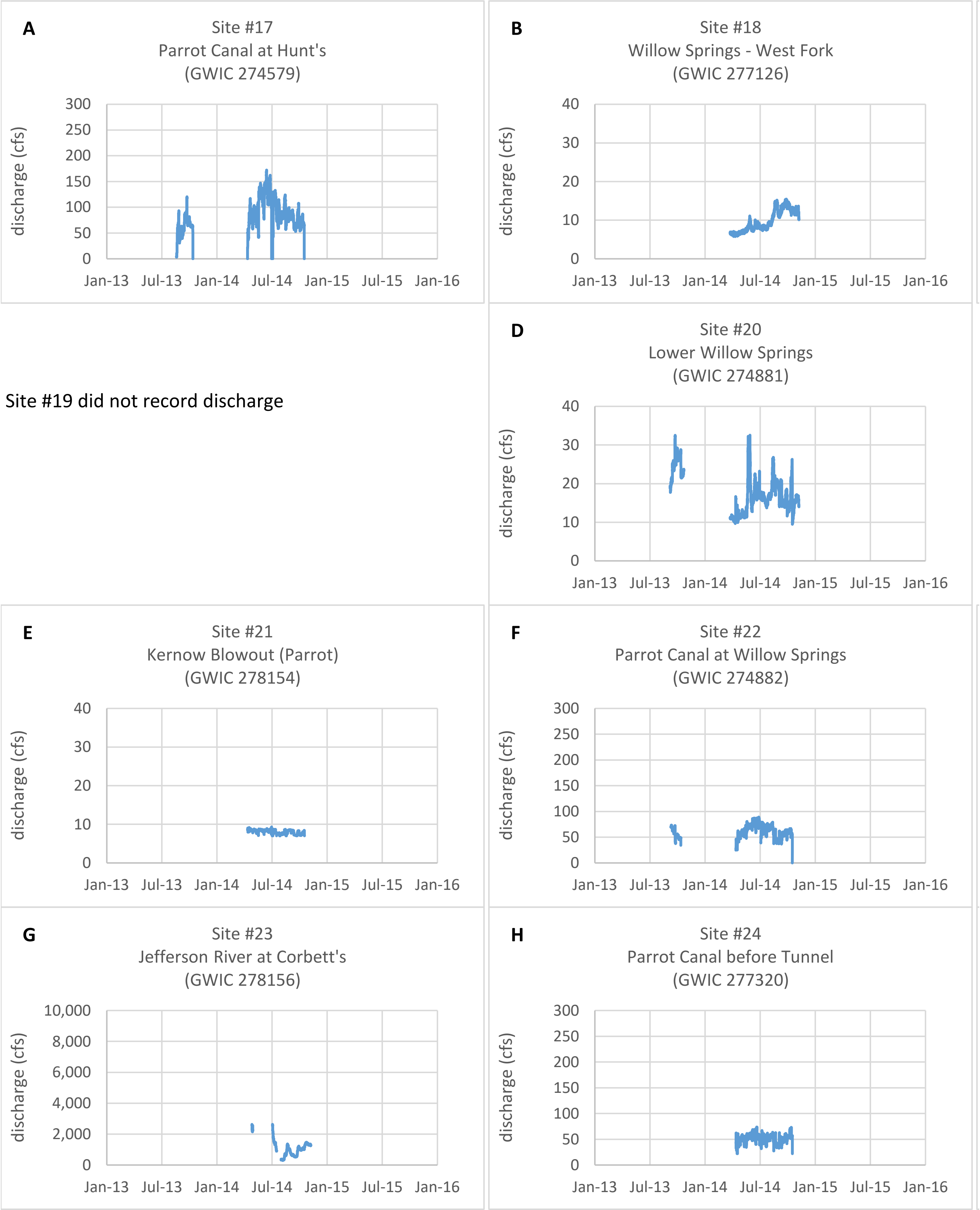




note that flow was often split into an ungaged channel.

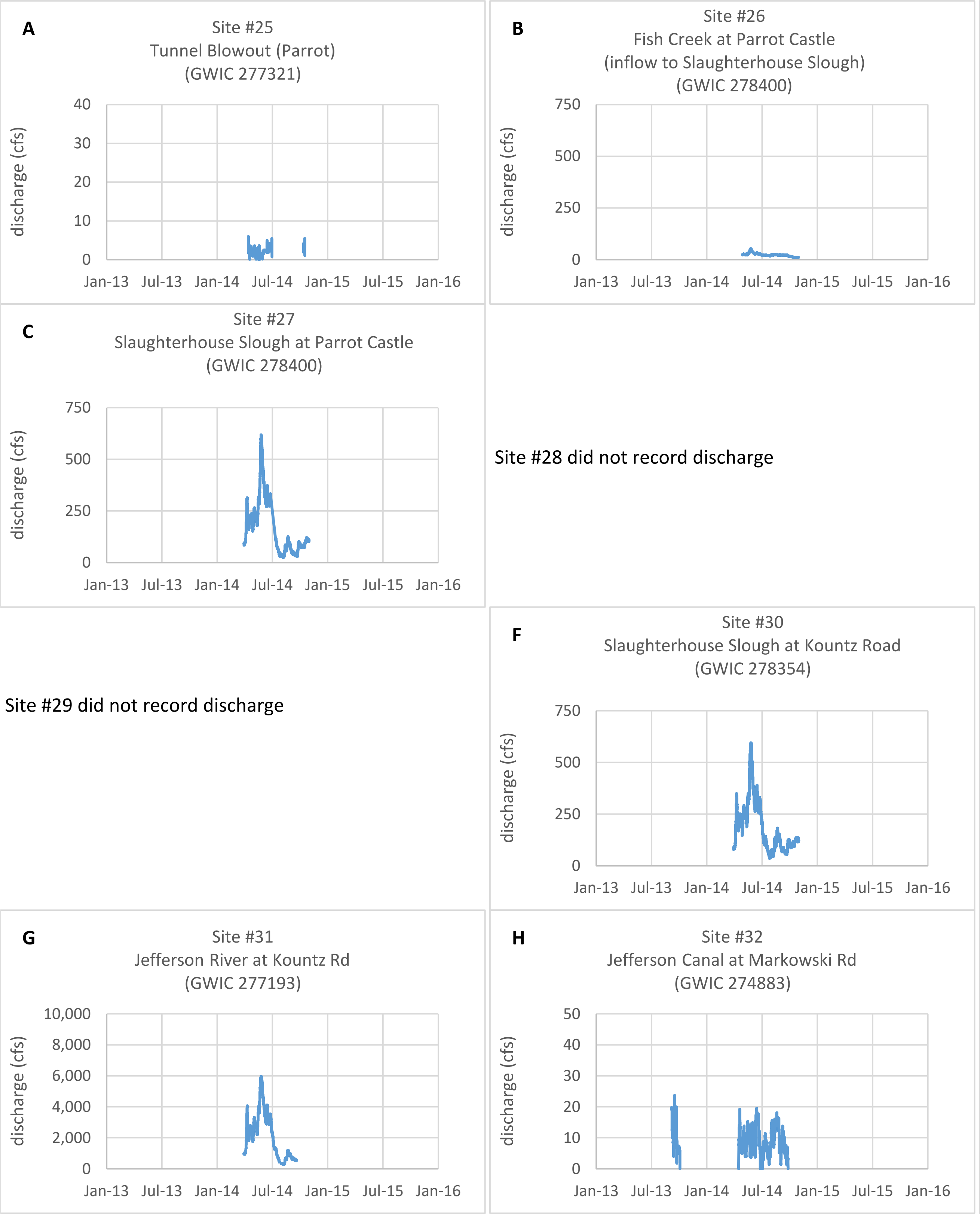
Appendix E: Surface-Water Hydrographs

Figure E1-3



Appendix E: Surface-Water Hydrographs

Figure E1-4

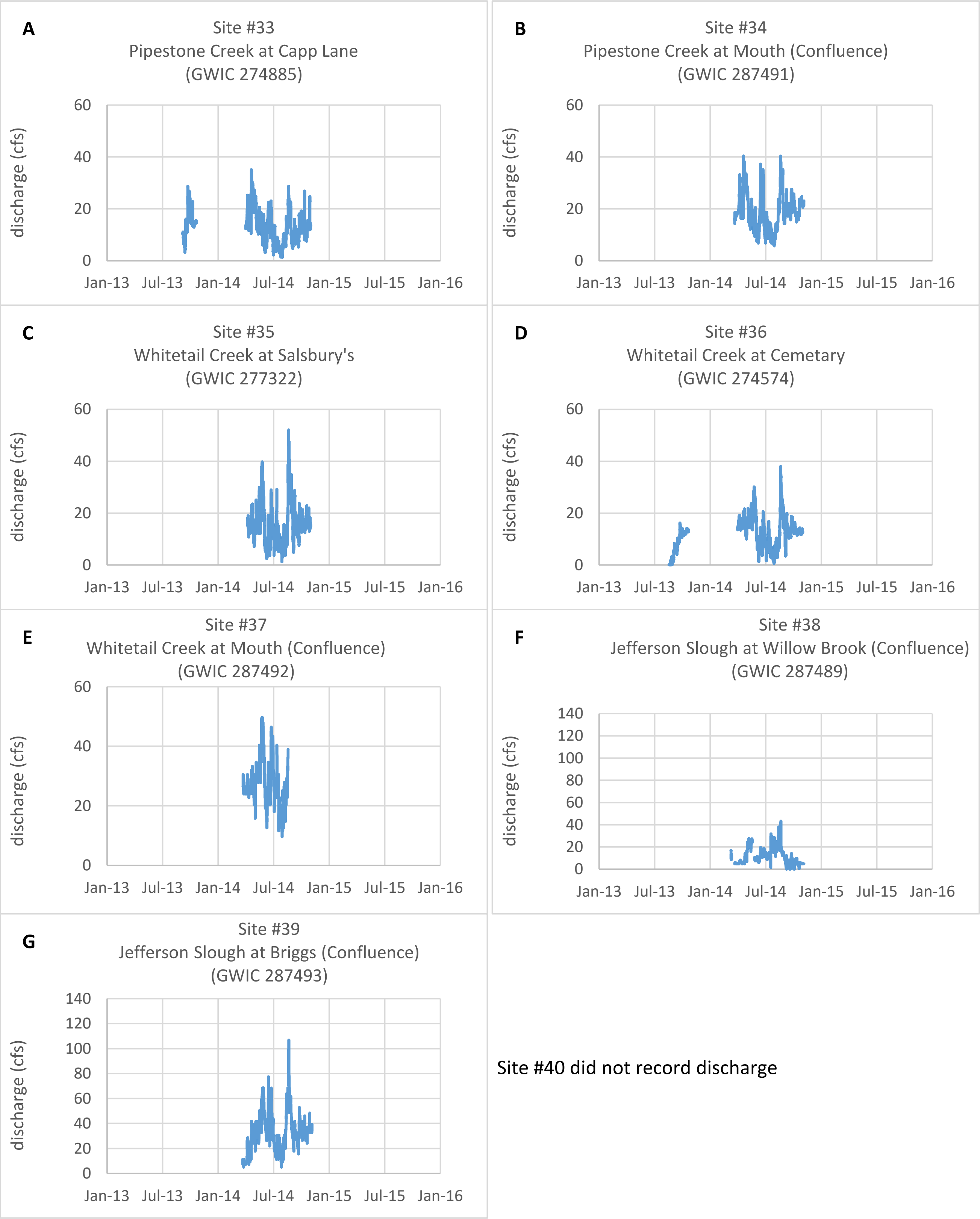


Site #28 did not record discharge

Site #29 did not record discharge

Appendix E: Surface-Water Hydrographs

Figure E1-5



A Site #33 Pipestone Creek at Capp Lane (GWIC 274885)

B Site #34 Pipestone Creek at Mouth (Confluence) (GWIC 287491)

C Site #35 Whitetail Creek at Salsbury's (GWIC 277322)

D Site #36 Whitetail Creek at Cemetary (GWIC 274574)

E Site #37 Whitetail Creek at Mouth (Confluence) (GWIC 287492)

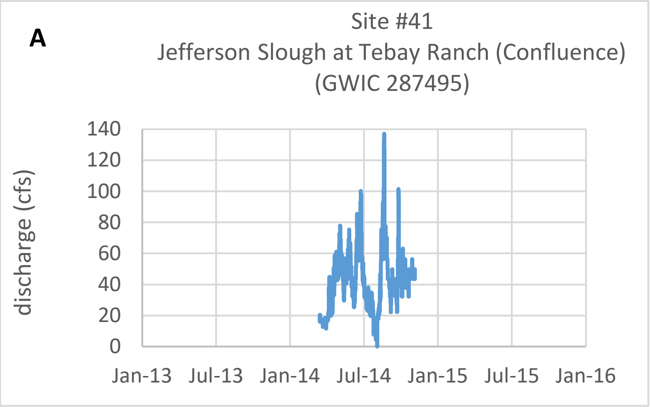
F Site #38 Jefferson Slough at Willow Brook (Confluence) (GWIC 287489)

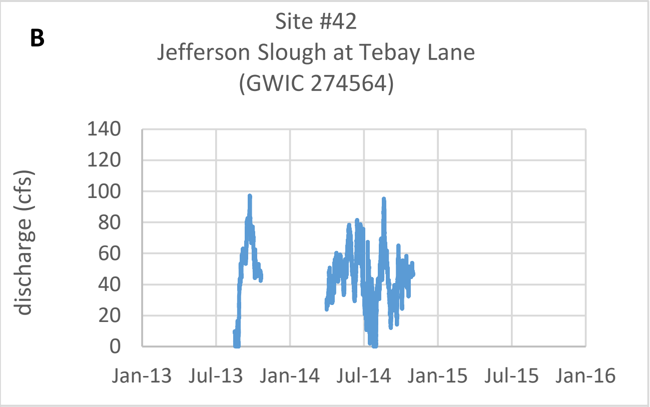
G Site #39 Jefferson Slough at Briggs (Confluence) (GWIC 287493)

Site #40 did not record discharge

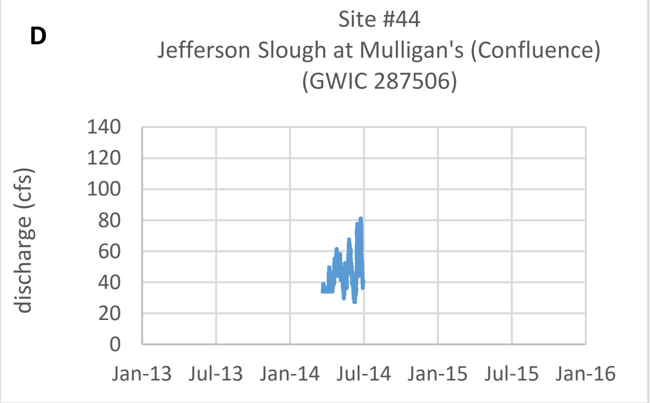
Appendix E: Surface-Water Hydrographs

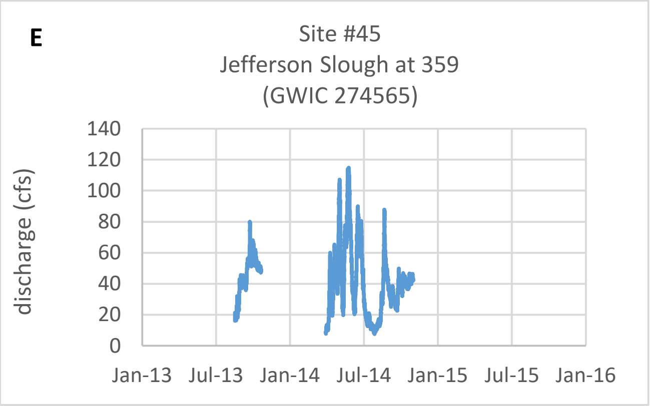
Figure E1-6

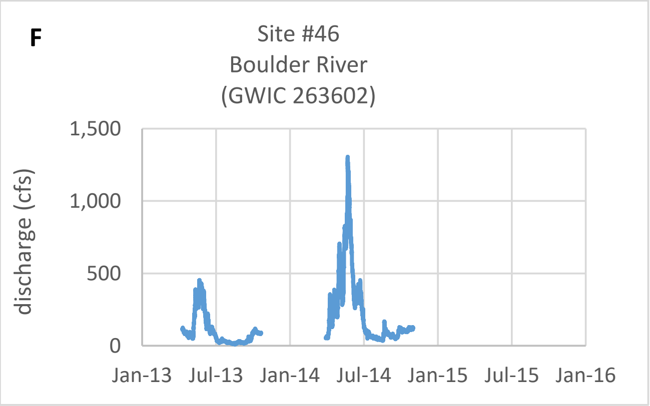




Site #43 did not record discharge





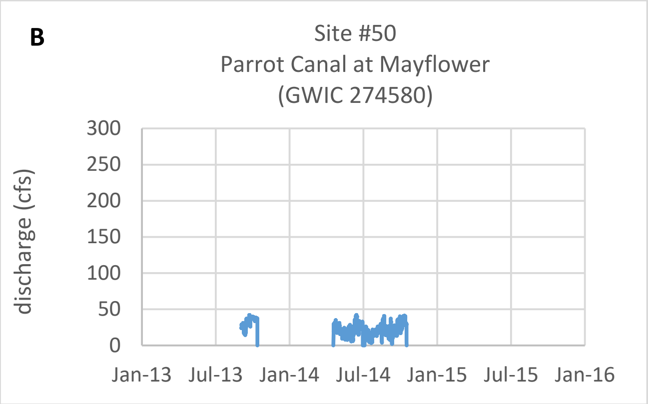


Site #47 did not record discharge

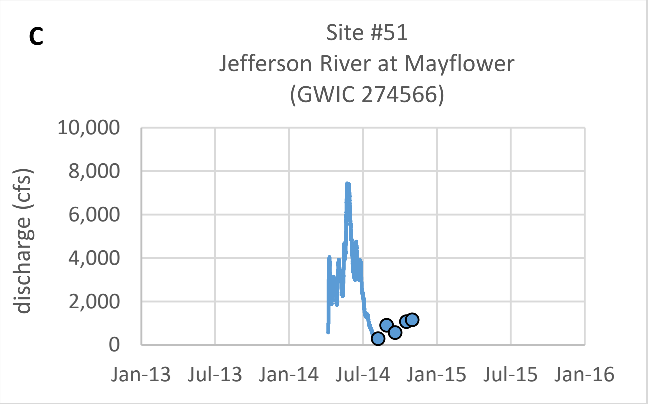
Site #48 did not record discharge

Appendix E: Surface-Water Hydrographs
Figure E1-7

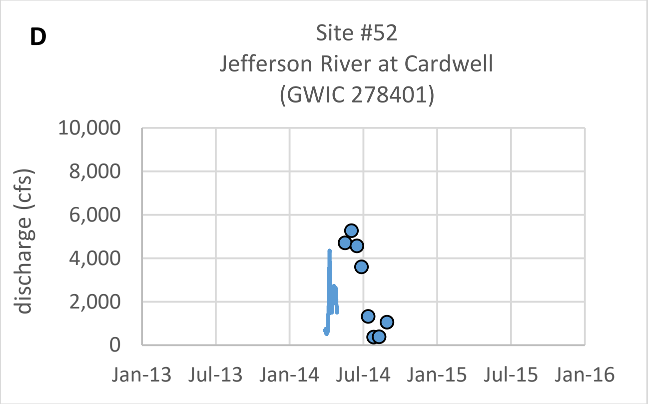
Site #49 did not record discharge



Site #50
Parrot Canal at Mayflower
(GWIC 274580)



Site #51
Jefferson River at Mayflower
(GWIC 274566)

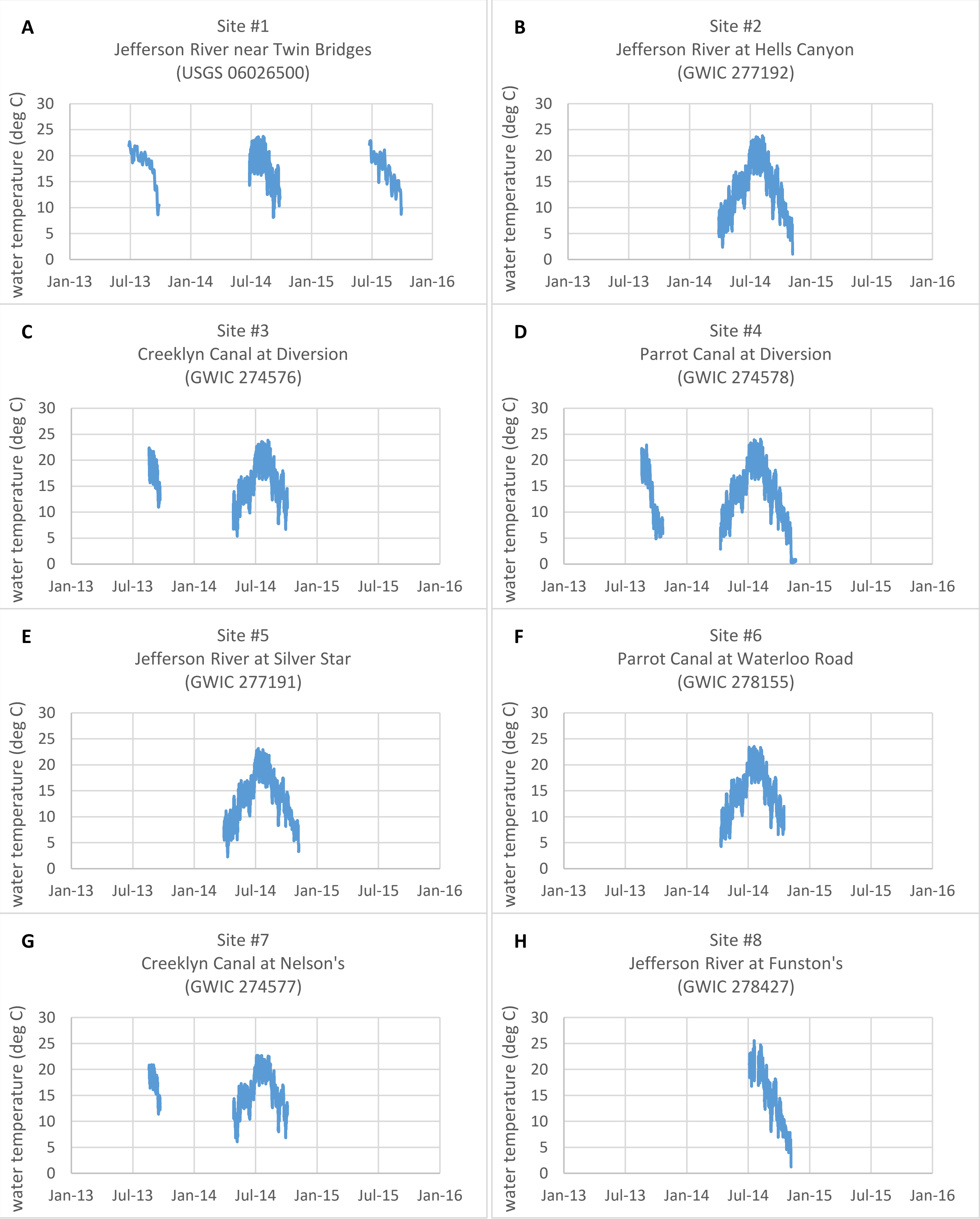


Site #52
Jefferson River at Cardwell
(GWIC 278401)

Site #53 did not record discharge

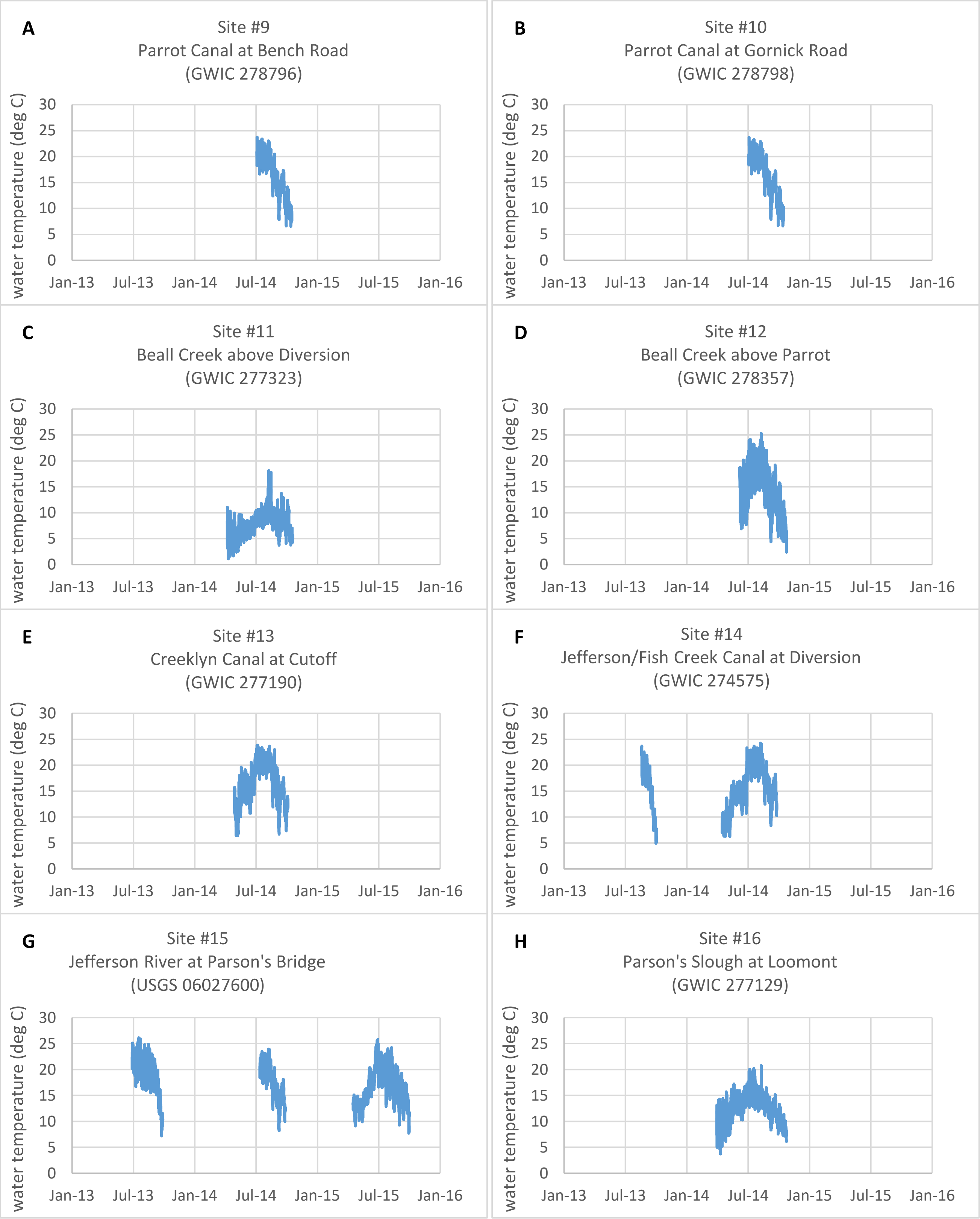
Appendix E: Surface-Water Thermographs

Figure E2-1



Appendix E: Surface-Water Thermographs

Figure E2-2



A Site #9 Parrot Canal at Bench Road (GWIC 278796)

B Site #10 Parrot Canal at Gornick Road (GWIC 278798)

C Site #11 Beall Creek above Diversion (GWIC 277323)

D Site #12 Beall Creek above Parrot (GWIC 278357)

E Site #13 Creeklyn Canal at Cutoff (GWIC 277190)

F Site #14 Jefferson/Fish Creek Canal at Diversion (GWIC 274575)

G Site #15 Jefferson River at Parson's Bridge (USGS 06027600)

H Site #16 Parson's Slough at Loomont (GWIC 277129)

Appendix E: Surface-Water Thermographs

Figure E2-3

A Site #17 Parrot Canal at Hunt's (GWIC 274579)

B Site #18 Willow Springs - West Fork (GWIC 277126)

Site #19 did not record temperature

D Site #20 Lower Willow Springs (GWIC 274881)

E Site #21 Kernow Blowout (Parrot) (GWIC 278154)

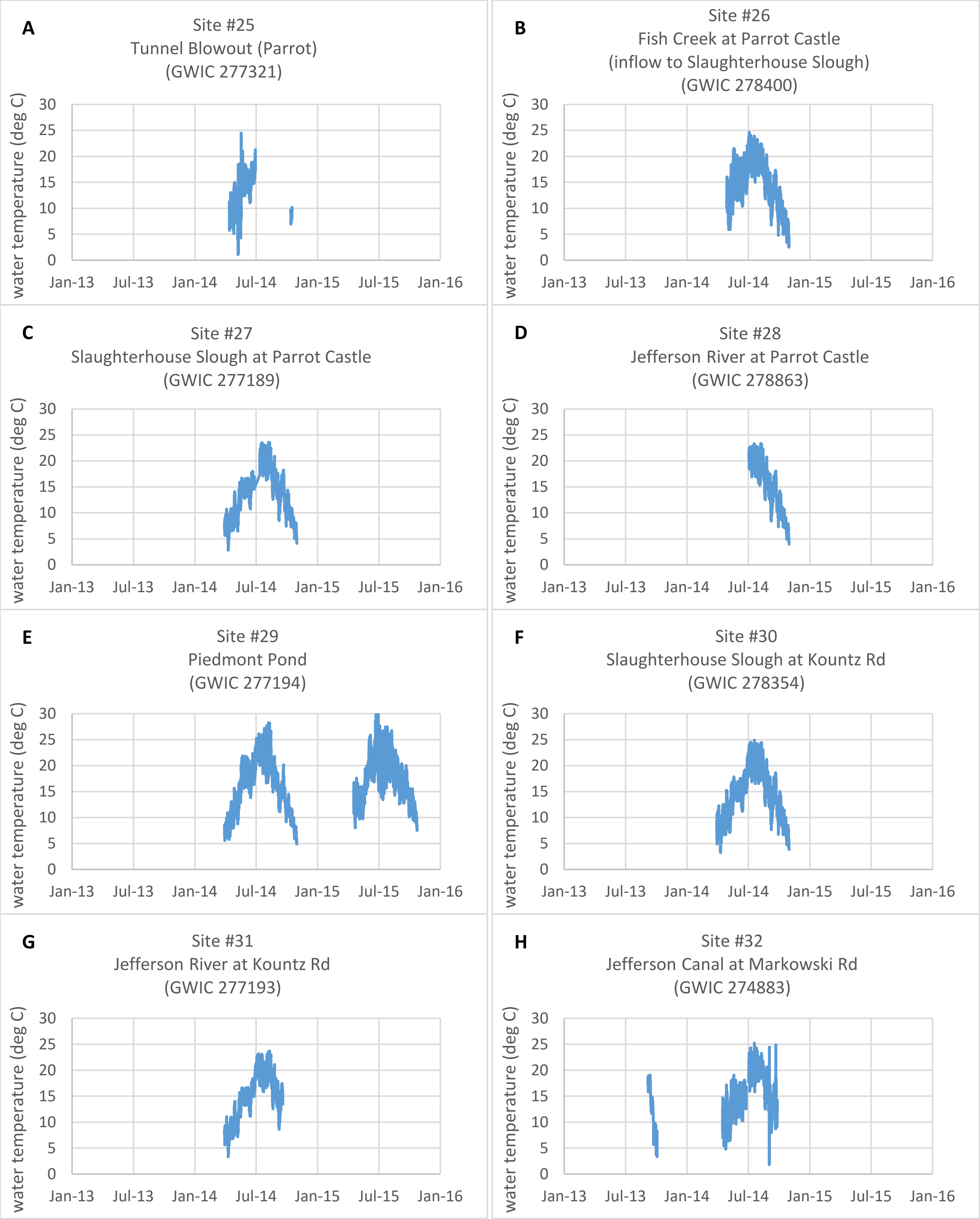
F Site #22 Parrot Canal at Willow Springs (GWIC 274882)

G Site #22 Jefferson River at Corbett's (GWIC 278156)

H Site #24 Parrot Canal before Tunnel (GWIC 277320)

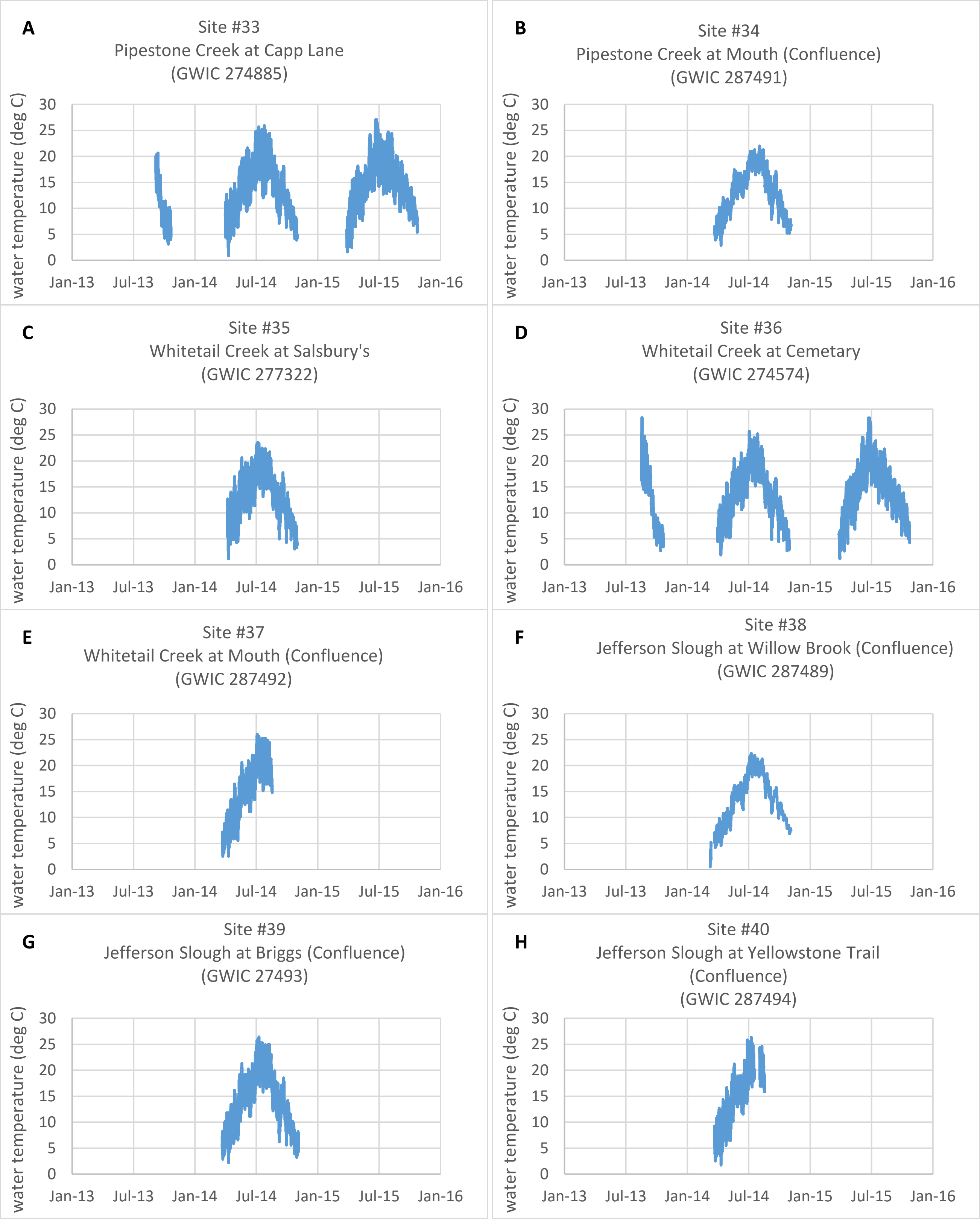
Appendix E: Surface-Water Thermographs

Figure E2-4



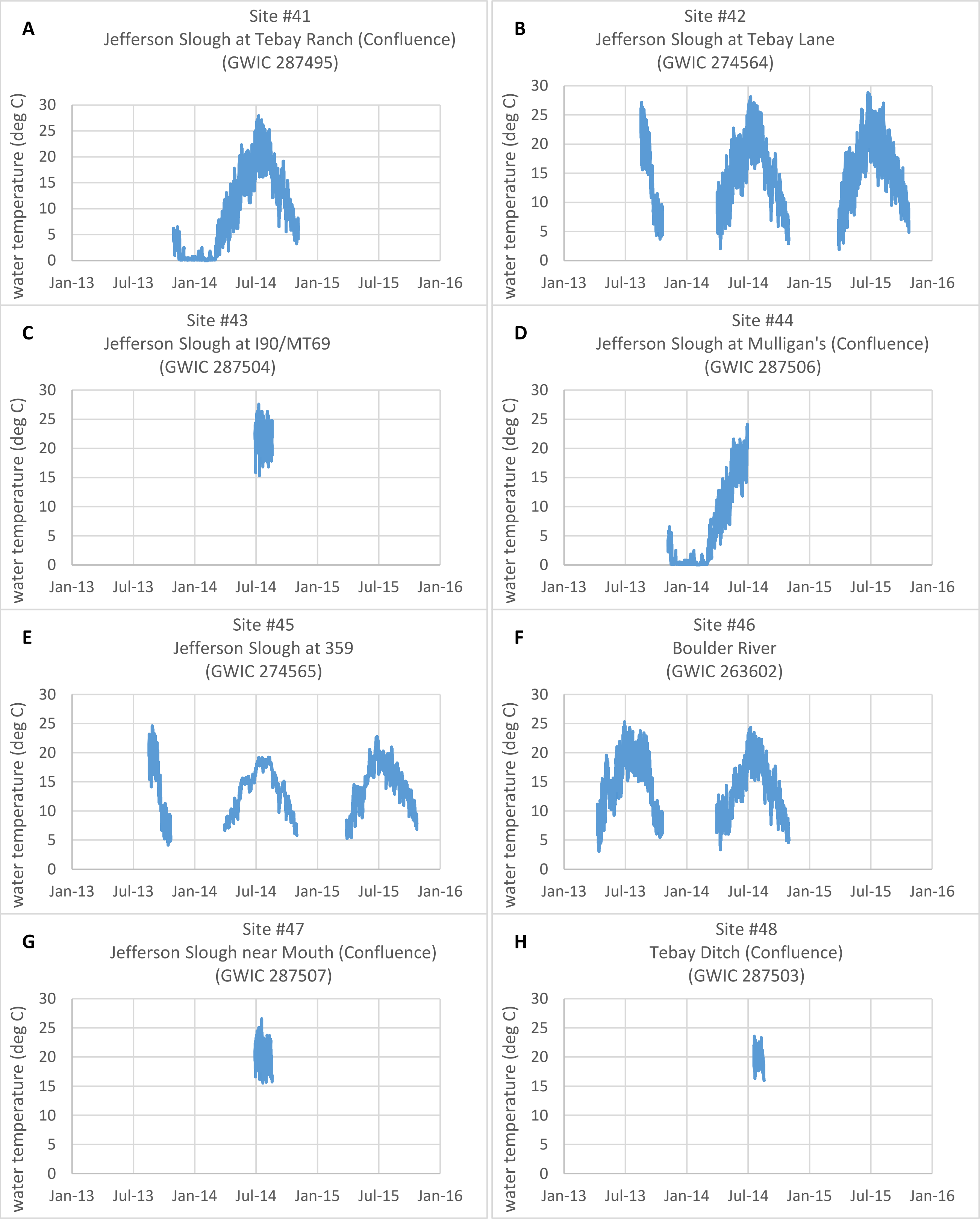
Appendix E: Surface-Water Thermographs

Figure E2-5



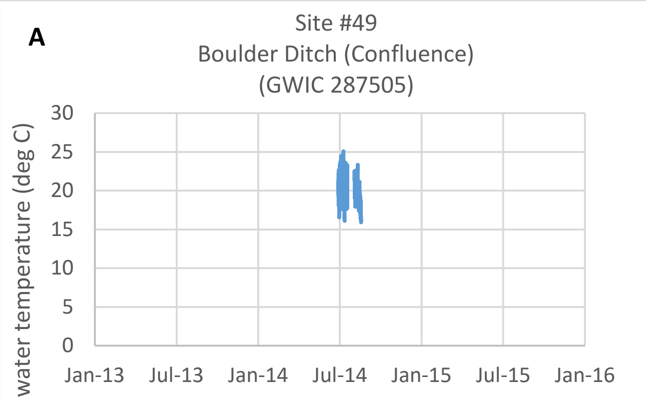
Appendix E: Surface-Water Thermographs

Figure E2-6

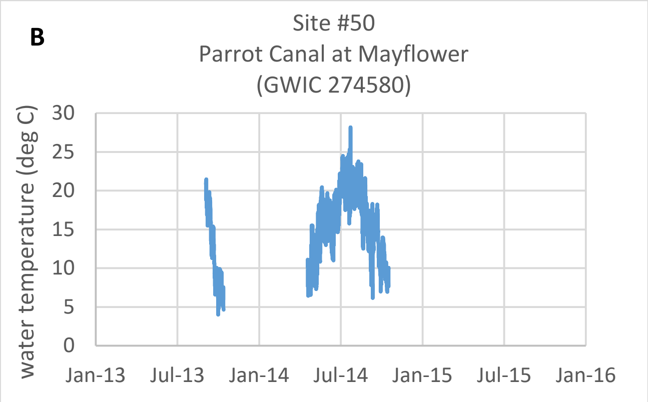


Appendix E: Surface-Water Thermographs

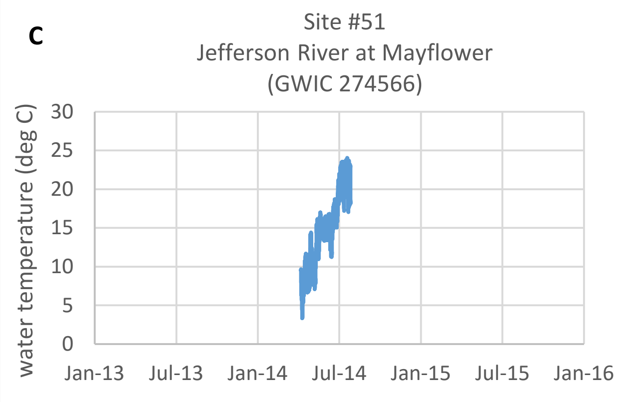
Figure E2-7


A

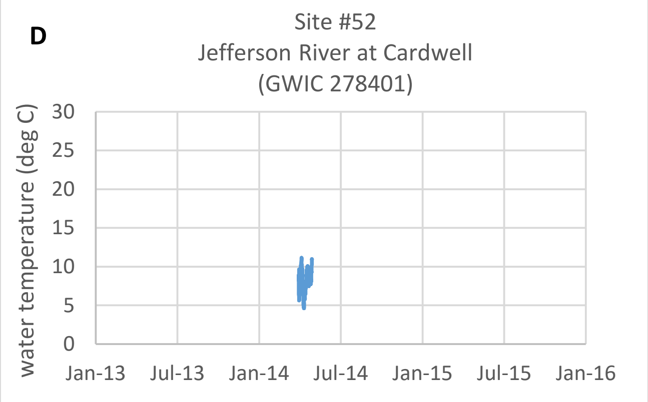
Site #49
Boulder Ditch (Confluence)
(GWIC 287505)


B

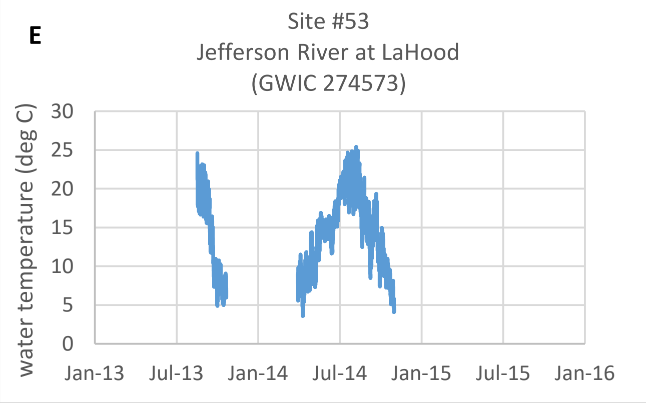
Site #50
Parrot Canal at Mayflower
(GWIC 274580)


C

Site #51
Jefferson River at Mayflower
(GWIC 274566)


D

Site #52
Jefferson River at Cardwell
(GWIC 278401)


E

Site #53
Jefferson River at LaHood
(GWIC 274573)

APPENDIX F

SELECTED GROUNDWATER-QUALITY RESULTS

Appendix F. Selected Groundwater-Quality Results

Well #	Gwic Id	Site Name	HGU	Sample Date/Time	Water Temp (°C)	Lab pH	Lab SC (µS/cm)	TDS (mg/L)	Ca (mg/L	Mg (mg/L)	Na (mg/L)	K (mg/L)	Hardness	SAR
		Drinking Water Standards (mcl)												
		(smcl)												
9	154158	HCC Ranch State Section	Renova	8/22/2014 12:08	10.8	8.23	199	117	22.5	9.4	3.2	1.4	95	0.1
19	280980	MBMG-HCCB-PW	Renova	3/6/2015 10:15	10.7	7.56	204	117	23.0	9.3	4.1	1.6	96	0.2
22	277403	HCCA * MBMG OW-1	Renova	2/13/2015 13:00	9.4	7.23	372	268	51.0	13.6	11.1	3.7	184	0.4
37	279259	MBMG-HA-PW	Alluvium	2/26/2015 8:30	9.1	7.11	437	264	57.1	17.0	11.4	2.5	212	0.3
49	277868	WILLOW SPRINGS STOCK WELL	Alluvium	8/19/2014 11:05	10.0	7.86	385	239	47.2	16.3	11.4	3.0	185	0.4
49	277868	WILLOW SPRINGS STOCK WELL	Alluvium	11/18/2014 13:24	9.1	7.72	392	246	48.7	17.6	13.4	3.1	194	0.4
49	277868	WILLOW SPRINGS STOCK WELL	Alluvium	1/30/2015 12:48	9.5	7.82	388	240	48.1	16.7	12.1	3.0	189	0.4
49	277868	WILLOW SPRINGS STOCK WELL	Alluvium	3/30/2015 13:10	10.0	7.85	375	234	46.4	16.1	11.4	3.8	182	0.4
51	277080	HUNT, DEAN * HUNT - 1	Bedrock	11/18/2014 10:13	9.6	7.81	468	278	47.1	30.6	6.1	1.3	244	0.2
51	277080	HUNT, DEAN * HUNT - 1	Bedrock	1/30/2015 13:58	10.1	7.85	461	280	47.3	30.9	6.0	1.3	245	0.2
51	277080	HUNT, DEAN * HUNT - 1	Bedrock	3/30/2015 14:05	10.2	7.90	465	275	46.8	30.2	5.7	1.6	241	0.2
54	107023	POWERS JIM	Bedrock	8/20/2014 10:10	9.0	6.99	184	122	21.1	8.0	3.5	1.8	86	0.2
68	277282	MBMG PEIDMONT POND WELL * FWP	Alluvium	8/20/2014 15:37	10.8	6.66	958	672	87.4	28.5	91.0	14.1	335	2.2
84	279262	MBMG-TPA-PW	Renova	3/17/2015 9:40	9.2	7.22	458	316	66.8	11.1	14.4	5.2	212	0.4
88	280978	MBMG-LTPB-PW	Renova	3/24/2015 8:15	14.3	7.26	444	318	49.9	15.4	17.8	8.2	188	0.6
93	277286	MBMG MAYFLOWER WELL * FWP	Alluvium	8/21/2014 11:13	13.1	7.32	332	216	40.2	10.9	13.6	3.6	145	0.5
93	277286	MBMG MAYFLOWER WELL * FWP (DUP)	Alluvium	8/21/2014 11:35	13.4	7.33	335	216	39.7	11.0	13.3	3.7	144	0.5

µS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
µg/L, micrograms per liter (ppb)
mcl, maximum contaminate level
smcl, secondary maximum contaminate level (aesthetic)
highlight indicates exceedance of a drinking water standard

Appendix F. Selected Groundwater-Quality Results

Well #	Gwic Id	Site Name	HCO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	Alkalinity	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	NO_3-N (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Br (µg/L)	Cu (µg/L)
		Drinking Water Standards (mcl)								10	4	10			1,300
		(smcl)		250	250		0.3	0.050							
9	154158	HCC Ranch State Section	107.2	15.5	1.4	89	0.018 J	<0.002 U	10.0	0.23	0.05 J	0.40	1.7 J	<10 U	<0.5 U
19	280980	MBMG-HCCB-PW	92.2	14.9	8.2	75	<0.015 U	<0.002 U	8.8	1.40	0.10	0.84	5.3	89	1.6 J
22	277403	HCCA * MBMG OW-1	181.9	52.2	6.4	149	<0.015 U	0.002 J	41.5	<0.010 U	0.42	1.97	18.4	<10 U	<0.5 U
37	279259	MBMG-HA-PW	236.0	39.6	5.4	194	<0.015 U	<0.002 U	13.9	1.25	0.21	0.46	17.4	<10 U	0.6 J
49	277868	WILLOW SPRINGS STOCK WELL	215.7	32.7	5.4	177	0.025 J	0.002 J	14.3	3.04	0.16	0.330 J	20.2	<10 U	<0.5 U
49	277868	WILLOW SPRINGS STOCK WELL	219.2	33.9	5.2	180	<0.015 U	<0.002 U	13.9	2.50	0.14	0.330 J	21.3	<10 U	<0.5 U
49	277868	WILLOW SPRINGS STOCK WELL	215.7	33.2	5.2	177	0.023 J	0.002 J	14.4	2.00	0.16	0.350 J	21.6	<10 U	<0.5 U
49	277868	WILLOW SPRINGS STOCK WELL	211.5	31.3	5.3	174	<0.015 U	<0.002 U	14.1	1.88	0.10	0.360 J	21.8	<10 U	<0.5 U
51	277080	HUNT, DEAN * HUNT - 1	189.2	46.7	39.3	155	<0.015 U	<0.002 U	10.5	3.75	0.11	0.99	9.4	197	0.7 J
51	277080	HUNT, DEAN * HUNT - 1	190.0	46.6	39.7	156	<0.015 U	<0.002 U	10.3	4.01	0.13	0.95	9.6	276	5.4
51	277080	HUNT, DEAN * HUNT - 1	188.6	44.1	37.7	155	<0.015 U	<0.002 U	10.5	3.75	0.09	0.99	9.7	259	3.7
54	107023	POWERS JIM	89.9	25.2	1.5	74	<0.015 U	<0.002 U	15.4	0.13	0.12	0.82	4.8	<10 U	5.3
68	277282	MBMG PEIDMONT POND WELL * FWP	466.7	122.0	44.8	383	0.302	0.993	51.9	<0.010 U	0.91	9.38	146.4	224	10.3
84	279262	MBMG-TPA-PW	216.2	64.9	9.9	177	<0.015 U	<0.002 U	38.4	0.21	0.25	2.20	20.9	77	<0.5 U
88	280978	MBMG-LTPB-PW	224.1	47.9	8.1	184	<0.015 U	<0.002 U	59.8	0.24	0.37	17.95	31.6	<10 U	0.80 J
93	277286	MBMG MAYFLOWER WELL * FWP	177.3	32.2	5.3	145	<0.015 U	0.043 J	23.2	0.030 J	0.27	2.53	31.1	<10 U	1.0 J
93	277286	MBMG MAYFLOWER WELL * FWP (DUP)	178.1	32.9	5.5	146	<0.015 U	0.039 J	23.4	0.06	0.27	2.48	31.0	<10 U	1.0 J

mS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
mg/L, micrograms per liter (ppb)
mcl, maximum contaminate level
smcl, secondary maximum contaminate level (aesthetic)
highlight indicates exceedance of a drinking water standard

Appendix F. Selected Groundwater-Quality Results

Well #	Gwic Id	Site Name	Li (µg/L)	Mo (µg/L)	Ni (µg/L)	Sr (µg/L)	Ti (µg/L)	U (µg/L)	V (µg/L)	Zn (µg/L)	Rb (µg/L)	W (µg/L)	δD $(^{o}/_{oo})$	$\delta^{18}O$ $(^{o}/_{oo})$
		Drinking Water Standards (mcl)						30						
		(smcl)								5,000				
9	154158	HCC Ranch State Section	<2.0 U	<0.1 U	<0.1 U	78	12.4	0.9	1.03	2.0	<0.10 U	<0.10 U	-18.1	-139
19	280980	MBMG-HCCB-PW	<2.0 U	1.6	0.2 J	80	16.0	0.6	1.63	2.9	0.47 J	0.57	-18.4	-141
22	277403	HCCA * MBMG OW-1	18.6	2.9	<0.1 U	297	33.9	3.4	2.12	4.0	3.50	0.59	-18.3	-144
37	279259	MBMG-HA-PW	<2.0 U	1.3	<0.1 U	215	40.0	2.7	1.36	6.7	0.65	<0.10 U	-17.4	-135
49	277868	WILLOW SPRINGS STOCK WELL	<2.0 U	0.8	<0.1 U	180	28.5	1.7	1.14	<0.5 U	0.68	<0.10 U	-14.7	-128
49	277868	WILLOW SPRINGS STOCK WELL	<2.0 U	0.5	<0.1 U	186	36.2	1.9	1.63	16.0	0.64	<0.10 U	-17.5	-135
49	277868	WILLOW SPRINGS STOCK WELL	<2.0 U	0.7	<0.1 U	180	33.5	1.8	1.59	6.1	0.66	<0.10 U	-17.4	-135
49	277868	WILLOW SPRINGS STOCK WELL	<2.0 U	0.7	<0.1 U	189	33.8	1.9	1.78	12.0	0.66	<0.10 U	-17.5	-135
51	277080	HUNT, DEAN * HUNT - 1	2.2 J	1.5	<0.1 U	215	35.9	1.8	1.62	56.8	0.93	0.31 J	-17.5	-137
51	277080	HUNT, DEAN * HUNT - 1	2.3 J	1.5	<0.1 U	211	35.9	1.9	1.67	70.5	0.91	0.32 J	-17.1	-136
51	277080	HUNT, DEAN * HUNT - 1	2.4 J	1.6	<0.1 U	227	35.4	2.0	1.76	131.3	0.96	0.35 J	-17.4	-136
54	107023	POWERS JIM	2.6 J	2.5	<0.1 U	69	12.6	0.7	0.21 J	9.4	<0.10 U	<0.10 U	-17.9	-136
68	277282	MBMG PEIDMONT POND WELL * FWP	28.3	8.9	2.7	526	50.1	6.9	2.25	<1.3 U	5.27	8.35	-15.3	-127
84	279262	MBMG-TPA-PW	7.8 J	2.4	<0.1 U	491	45.7	7.2	3.08	1.3 J	4.66	0.26 J	-17.9	-141
88	280978	MBMG-LTPB-PW	11.7	2.6	<0.1 U	462	31.0	27.5	17.3	0.7 J	7.10	0.52	-17.4	-136
93	277286	MBMG MAYFLOWER WELL * FWP	11.3	1.8	0.5 J	273	21.6	1.5	3.28	<0.5 U	1.91	<0.10 U	-17.5	-137
93	277286	MBMG MAYFLOWER WELL * FWP (DUP)	10.8	1.6	0.4 J	270	20.6	1.3	2.84	<0.5 U	1.92	<0.10 U	-17.6	-137

mS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
mg/L, micrograms per liter (ppb)
mcl, maximum contaminate level
smcl, secondary maximum contaminate level (aesthetic)
highlight indicates exceedance of a drinking water standard

APPENDIX G

SELECTED SURFACE-WATER QUALITY RESULTS

Appendix G. Selected Surface-Water Quality Results

Gwic Id	Site Name	Sample Date/Time	Water Temp (°C)	Lab pH	Lab SC (µS/cm)	TDS (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Hardness	SAR	HCO_3 (mg/L)
	Drinking Water Standards (mcl)												
	(smcl)												
278427	JEFFERSON RIVER AT FUNSTON'S	8/20/2014	18.3	8.36	382	255	45.1	15.9	15.6	4.3	178	0.5	188.0
274575	JEFFERSON CANAL AT DIVERSION	8/20/2014 12:08	19.0	8.45	389	256	45.6	15.4	15.1	4.3	177	0.5	189.2
278156	JEFFERSON RIVER AT CORBETT'S	8/20/2014 12:50	18.9	8.49	394	257	46.9	16.2	14.4	4.0	184	0.4	196.6
278863	JEFFERSON RIVER AT PARROT CASTLE	8/20/2014 14:30	19.1	8.55	385	252	45.4	15.5	14.7	4.2	177	0.5	185.4
274566	JEFFERSON RIVER AT MAYFLOWER BRIDGE	8/21/2014 12:05	17.2	8.30	409	260	48.1	16.2	15.8	4.2	187	0.5	199.1
274573	JEFFERSON RIVER AT LAHOOD	8/21/2014 12:50	18.7	8.32	410	262	48.1	15.7	16.1	4.1	185	0.5	199.0
278400	FISH CREEK AT PARROT CASTLE	8/20/2014 14:05	17.9	8.15	405	263	48.4	15.6	14.6	4.1	185	0.5	208.9
278354	SLAUGHTERHOUSE SLOUGH AT KOUNTZ ROAD	8/20/2014	NR	8.66	390	262	47.5	16.3	16.3	4.4	185	0.5	190.0
274574	WHITETAIL AT WHITEHALL CEMETERY	8/21/2014 14:45	18.4	7.98	345	223	41.5	8.5	19.0	3.8	138	0.7	156.0
274885	PIPESTONE AT CAPP LANE	8/21/2014 15:20	21.1	8.24	478	316	48.8	13.4	36.1	5.1	177	1.2	221.1
274564	JEFFERSON SLOUGH AT TEBAY LN	8/22/2014 9:25	15.6	8.16	445	289	49.0	14.7	23.8	4.7	183	0.8	213.9
274564	JEFFERSON SLOUGH AT TEBAY LN	8/22/2014 9:50	15.9	8.16	447	289	49.0	14.6	23.8	4.7	183	0.8	213.8
274565	JEFFERSON SLOUGH AT 359	8/22/14	15.4	8.07	459	298	50.9	14.8	24.1	4.8	188	0.8	220.5
263602	BOULDER RIVER AT CANDLESTICK BRIDGE	8/21/2014 13:25	18.0	8.33	340	218	43.1	11.4	13.7	2.1	154	0.5	177.5
277129	PARSONS SLOUGH NORTH OF LOOMONT	8/19/2014	16.7	8.18	518	344	69.0	20.0	19.1	3.5	255	0.5	277.4
277129	PARSONS SLOUGH NORTH OF LOOMONT	11/18/2014 9:00	2.6	7.35	566	361	73.6	21.7	22.3	3.0	273	0.6	283.4
277129	PARSONS SLOUGH NORTH OF LOOMONT	1/30/2015 9:55	4.5	7.51	523	345	72.4	20.5	19.8	3.2	265	0.5	267.6
277129	PARSONS SLOUGH NORTH OF LOOMONT	3/30/2015 10:15	8.6	7.48	547	350	70.0	20.7	19.0	9.2	260	0.5	271.0
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	8/19/2014 11:55	14.6	8.12	438	284	54.8	19.8	14.6	3.2	218	0.4	245.1
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	11/18/2014 11:03	5.4	7.82	391	247	47.2	18.1	13.4	3.0	192	0.4	219.7
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	1/30/2015 11:46	8.0	8.01	377	235	46.7	16.7	11.3	4.7	185	0.4	209.3
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	3/30/2015 11:55	11.3	8.18	354	225	44.8	16.4	10.6	3.0	180	0.4	200.4
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	3/30/2015 12:15	10.2	8.21	360	226	45.4	16.7	10.6	3.0	182	0.4	200.2
279379	EAST FORK WILLOW SPRINGS	8/19/2014 13:15	17.7	8.24	475	308	55.1	23.1	17.3	4.7	233	0.5	262.8
279379	EAST FORK WILLOW SPRINGS	11/18/2014 11:35	5.5	8.13	466	302	53.2	23.4	17.0	4.7	229	0.5	256.3
279379	EAST FORK WILLOW SPRINGS	1/30/2015 10:43	6.4	8.12	436	288	51.0	23.1	16.6	5.3	222	0.5	240.0
279379	EAST FORK WILLOW SPRINGS	3/30/2015 10:55	11.1	8.20	415	272	47.2	22.2	15.5	4.9	209	0.5	227.9
274881	LOWER WILLOW SPRINGS	8/19/2014 12:47	16.6	8.30	425	281	52.7	19.9	14.5	3.5	213	0.4	238.2
274881	LOWER WILLOW SPRINGS	11/18/2014 12:04	6.1	8.22	390	252	47.0	18.3	14.2	3.2	193	0.4	216.5
274881	LOWER WILLOW SPRINGS	11/18/2014 12:25	6.2	8.03	415	256	47.1	18.6	14.3	3.2	194	0.4	231.5
274881	LOWER WILLOW SPRINGS	1/30/2015 11:08	6.8	8.23	391	250	46.4	17.4	12.7	10.4	188	0.4	202.6
274881	LOWER WILLOW SPRINGS	3/30/2015 11:18	11.8	8.29	352	225	44.2	16.5	11.2	3.1	178	0.4	196.0
274579	PARROT DITCH AT HUNT'S	8/19/2014	19.6	8.45	370	242	42.9	15.2	14.9	4.3	170	0.5	179.6
277194	PIEDMONT POND	8/20/2014 16:02	21.4	8.41	894	631	28.4	27.2	130.7	20.4	183	4.2	297.8

µS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
µg/L, micrograms per liter (ppb)
U, undetected quantity below detection limit
J, Estimated quantity above detection limit but below reporting limit
highlight indicates exceedance of a drinking water standard

mcl, maximum contaminant level
smcl, secondary maximum contaminant level (aesthetic)
NR, Not Reported

Appendix G. Selected Surface-Water Quality Results

Gwic Id	Site Name	SO_4 (mg/L)	Cl (mg/L)	Alkalinity	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	NO_3-N (mg/L)	F (mg/L)	As (µg/L)	B (µg/L)	Br (µg/L)	Cu (µg/L)	Li (µg/L)
	Drinking Water Standards (mcl)							10	4	10			1,300	
	(smcl)	250	250		0.3	0.050								
278427	JEFFERSON RIVER AT FUNSTON'S	53.0	8.7	161	0.047 J	0.018 J	15.0	<0.01 U	0.29	3.0	31	<10 U	0.80 J	11.3
274575	JEFFERSON CANAL AT DIVERSION	53.2	8.7	163	0.047 J	0.023 J	15.6	<0.01 U	0.29	3.2	30	<10 U	0.69 J	11.8
278156	JEFFERSON RIVER AT CORBETT'S	49.8	8.2	172	0.034 J	0.016 J	15.1	0.13	0.26	2.7	28	<10 U	0.73 J	10.5
278863	JEFFERSON RIVER AT PARROT CASTLE	51.2	8.4	163	0.040 J	0.020 J	15.2	<0.01 U	0.28	3.1	30	<10 U	0.79 J	10.8
274566	JEFFERSON RIVER AT MAYFLOWER BRIDGE	51.1	8.4	168	0.025 J	0.017 J	15.9	<0.01 U	0.27	3.0	30	<10 U	<0.50 U	12.2
274573	JEFFERSON RIVER AT LAHOOD	51.1	8.6	170	0.020 J	0.016 J	16.5	<0.01 U	0.28	3.3	32	<10 U	0.63 J	12.1
278400	FISH CREEK AT PARROT CASTLE	49.5	8.8	173	0.032 J	0.014 J	17.2	<0.01 U	0.28	2.7	28	<10 U	0.58 J	10.8
278354	SLAUGHTERHOUSE SLOUGH AT KOUNTZ ROAD	51.6	9.0	169	0.025 J	0.016 J	16.2	<0.01 U	0.29	3.2	29	<10 U	0.62 J	12.1
274574	WHITETAIL AT WHITEHALL CEMETERY	45.9	10.0	128	0.098	0.031 J	17.2	0.07	0.27	3.7	44	<10 U	1.09 J	4.0 J
274885	PIPESTONE AT CAPP LANE	60.7	15.9	185	0.038 J	0.022 J	23.6	0.06	0.75	5.0	82	37 J	0.82 J	17.7
274564	JEFFERSON SLOUGH AT TEBAY LN	56.9	12.1	177	0.065 J	0.044 J	21.0	<0.01 U	0.41	3.8	51	<10 U	0.66 J	13.5
274564	JEFFERSON SLOUGH AT TEBAY LN	57.1	12.1	177	0.044 J	0.044 J	21.4	<0.01 U	0.41	3.8	50	<10 U	0.55 J	12.8
274565	JEFFERSON SLOUGH AT 359	61.0	12.7	180	0.026 J	0.092	21.3	0.07	0.40	3.7	51	<10 U	0.67 J	13.2
263602	BOULDER RIVER AT CANDLESTICK BRIDGE	32.0	5.8	151	<0.015 U	0.019 J	18.9	0.10	0.39	6.1	49	<10 U	2.02	17.3
277129	PARSONS SLOUGH NORTH OF LOOMONT	64.6	11.3	231	<0.015 U	0.022 J	18.0	0.11	0.20	1.8	33	<10 U	<0.50 U	13.2
277129	PARSONS SLOUGH NORTH OF LOOMONT	70.9	12.1	232	<0.015 U	0.028 J	17.7	0.29	0.28	1.6	35	<10 U	<0.50 U	14.5
277129	PARSONS SLOUGH NORTH OF LOOMONT	68.5	12.1	220	<0.015 U	0.047 J	16.8	0.27	0.24	1.5	35	81	0.70 J	12.5
277129	PARSONS SLOUGH NORTH OF LOOMONT	65.1	16.7	222	<0.015 U	0.064	16.2	0.20	0.16	1.6	33	66	1.25 J	12.9
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	45.7	7.6	203	<0.015 U	0.002 J	14.7	0.84	0.15	0.8	26	<10 U	0.68 J	3.8 J
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	37.4	5.6	180	<0.015 U	0.006 J	13.3	1.26	0.10	0.5	19	<10 U	<0.50 U	<2.0 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	33.0	7.2	171	<0.015 U	<0.002 U	12.2	1.30	0.13	0.5	17	<10 U	<0.50 U	<2.0 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	32.2	5.0	167	<0.015 U	<0.002 U	11.2	1.08	0.07	0.5	18	<10 U	<0.50 U	<2.0 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	31.3	4.8	169	<0.015 U	<0.002 U	11.4	1.12	0.07	0.5	18	<10 U	<0.50 U	2.1 J
279379	EAST FORK WILLOW SPRINGS	48.1	8.0	221	<0.015 U	0.006 J	18.3	0.52	0.22	0.8	32	<10 U	0.66 J	5.3 J
279379	EAST FORK WILLOW SPRINGS	50.4	8.3	212	<0.015 U	0.007 J	16.9	0.85	0.20	0.6	34	<10 U	<0.50 U	6.1 J
279379	EAST FORK WILLOW SPRINGS	46.8	8.6	199	<0.015 U	0.006 J	16.1	0.70	0.21	0.6	32	<10 U	0.52 J	6.4 J
279379	EAST FORK WILLOW SPRINGS	43.7	7.4	192	<0.015 U	0.003 J	14.2	0.65	0.16	0.6	29	<10 U	<0.50 U	5.1 J
274881	LOWER WILLOW SPRINGS	44.1	7.6	200	<0.015 U	0.003 J	15.7	0.80	0.17	0.8	25	<10 U	<0.50 U	3.6 J
274881	LOWER WILLOW SPRINGS	38.0	6.8	183	0.026 J	0.006 J	14.2	1.12	0.12	0.5	21	<10 U	<0.50 U	<2.0 U
274881	LOWER WILLOW SPRINGS	38.0	5.8	189	<0.015 U	0.004 J	13.9	1.12	0.13	0.6	21	<10 U	<0.50 U	<2.0 U
274881	LOWER WILLOW SPRINGS	35.0	11.2	171	<0.015 U	<0.002 U	12.8	0.98	0.14	0.5	19	<10 U	<0.50 U	<2.0 U
274881	LOWER WILLOW SPRINGS	32.8	5.1	167	<0.015 U	<0.002 U	11.5	0.90	0.08	0.5	21	<10 U	<0.50 U	<2.0 U
274579	PARROT DITCH AT HUNT'S	47.6	7.9	156	0.082	0.009 J	15.0	<0.01 U	0.28	3.0	29	<10 U	0.71 J	11.0
277194	PIEDMONT POND	185.2	53.8	254	<0.015 U	0.021 J	32.0	0.05 J	0.87	19.4	174	241	0.68 J	34.1

µS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
µg/L, micrograms per liter (ppb)
U, undetected quantity below detection limit
J, Estimated quantity above detection limit but below reporting limit
highlight indicates exceedance of a drinking water standard

mcl, maximum contaminant level
smcl, secondary maximum contaminant level (aesthetic)
NR, Not Reported

Appendix G. Selected Surface-Water Quality Results

Gwic Id	Site Name	Mo (µg/L)	Ni (µg/L)	Sr (µg/L)	Ti (µg/L)	U (µg/L)	V (µg/L)	Zn (µg/L)	Rb (µg/L)	W (µg/L)
	Drinking Water Standards (mcl)					30				
	(smcl)							5,000		
278427	JEFFERSON RIVER AT FUNSTON'S	2.5	0.32 J	313	26.4	2.2	1.2	<0.5 U	2.8	0.35 J
274575	JEFFERSON CANAL AT DIVERSION	2.4	0.31 J	317	29.5	2.3	1.1	<0.5 U	2.9	0.26 J
278156	JEFFERSON RIVER AT CORBETT'S	2.1	<0.10 U	296	28.4	2.2	1.2	<0.5 U	2.4	0.24 J
278863	JEFFERSON RIVER AT PARROT CASTLE	2.4	0.24 J	304	27.3	2.2	1.2	<0.5 U	2.8	0.40 J
274566	JEFFERSON RIVER AT MAYFLOWER BRIDGE	1.5	<0.10 U	314	27.1	2.2	1.3	<0.5 U	2.7	<0.10 U
274573	JEFFERSON RIVER AT LAHOOD	1.7	<0.10 U	318	27.3	2.5	1.4	<0.5 U	2.8	0.23 J
278400	FISH CREEK AT PARROT CASTLE	2.5	0.27 J	297	28.7	2.2	1.0	<0.5 U	2.6	0.31 J
278354	SLAUGHTERHOUSE SLOUGH AT KOUNTZ ROAD	3.2	0.22 J	307	28.7	2.3	1.3	<0.5 U	2.7	0.32 J
274574	WHITETAIL AT WHITEHALL CEMETERY	3.0	<0.10 U	271	22.5	6.4	3.5	<0.5 U	1.4	<0.10 U
274885	PIPESTONE AT CAPP LANE	4.7	<0.10 U	321	26.5	7.3	2.9	<0.5 U	2.4	3.68
274564	JEFFERSON SLOUGH AT TEBAY LN	2.2	0.29 J	339	27.8	4.8	2.3	0.5 J	2.4	1.11
274564	JEFFERSON SLOUGH AT TEBAY LN	3.1	<0.10 U	336	26.3	4.9	2.2	<0.5 U	2.3	1.09
274565	JEFFERSON SLOUGH AT 359	2.8	0.25 J	343	29.7	4.5	2.1	<0.5 U	2.5	0.91
263602	BOULDER RIVER AT CANDLESTICK BRIDGE	1.4	<0.10 U	244	21.9	3.1	1.7	2.8	3.1	1.93
277129	PARSONS SLOUGH NORTH OF LOOMONT	1.5	<0.10 U	410	47.2	2.9	1.1	<0.5 U	1.4	<0.10 U
277129	PARSONS SLOUGH NORTH OF LOOMONT	1.6	0.25 J	434	55.5	3.4	1.5	1.5 J	1.2	<0.10 U
277129	PARSONS SLOUGH NORTH OF LOOMONT	2.1	0.49 J	413	52.6	3.3	1.6	1.2 J	1.1	<0.10 U
277129	PARSONS SLOUGH NORTH OF LOOMONT	1.7	0.33 J	435	49.2	3.3	1.8	2.1	1.3	<0.10 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	1.1	<0.10 U	240	33.0	2.5	1.1	<0.5 U	0.9	<0.10 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	0.9	<0.10 U	173	35.1	2.5	1.7	<0.5 U	0.6	<0.10 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	0.8	<0.10 U	161	32.8	2.0	1.7	<0.5 U	0.6	<0.10 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	1.0	<0.10 U	173	32.5	2.2	1.8	2.2	0.5	<0.10 U
277126	WILLOW SPRINGS WEST FORK AT BRIDGE	0.9	<0.10 U	176	32.2	2.1	1.9	<0.5 U	0.5	<0.10 U
279379	EAST FORK WILLOW SPRINGS	2.2	<0.10 U	272	32.6	2.7	2.0	<0.5 U	0.7	<0.10 U
279379	EAST FORK WILLOW SPRINGS	2.1	<0.10 U	261	37.3	3.0	2.5	<0.5 U	0.6	<0.10 U
279379	EAST FORK WILLOW SPRINGS	2.0	0.25 J	249	35.7	2.7	2.5	1.6 J	0.5	<0.10 U
279379	EAST FORK WILLOW SPRINGS	2.6	<0.10 U	257	34.7	2.8	2.9	<0.5 U	0.5	<0.10 U
274881	LOWER WILLOW SPRINGS	1.2	<0.10 U	234	32.2	2.3	1.5	<0.5 U	0.7	<0.10 U
274881	LOWER WILLOW SPRINGS	1.1	<0.10 U	189	37.9	2.3	2.2	<0.5 U	0.7	<0.10 U
274881	LOWER WILLOW SPRINGS	1.7	<0.10 U	188	32.9	2.3	2.2	<0.5 U	0.6	<0.10 U
274881	LOWER WILLOW SPRINGS	1.0	<0.10 U	175	31.2	2.0	2.0	<0.5 U	0.7	<0.10 U
274881	LOWER WILLOW SPRINGS	1.0	<0.10 U	183	31.5	2.1	2.1	1.5 J	0.6	<0.10 U
274579	PARROT DITCH AT HUNT'S	2.3	0.30 J	294	24.9	2.1	1.1	<0.5 U	2.9	0.21 J
277194	PIEDMONT POND	18.7	1.52	283	20.4	23.1	5.4	<0.5 U	5.5	18.10

µS/cm, microsiemens per centimeter
mg/L, milligrams per liter (ppm)
µg/L, micrograms per liter (ppb)

mcl, maximum contaminant level
smcl, secondary maximum contaminant level (aesthetic)
NR, Not Reported

U, undetected quantity below detection limit
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highlight indicates exceedance of a drinking water standard