

HYDROGEOLOGIC INVESTIGATION OF THE EAST FLATHEAD VALLEY, FLATHEAD COUNTY, MONTANA

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Montana Bureau of Mines and Geology

¹Currently employed by the University of Wisconsin, Platteville

²Retired from Montana Technological University



Cover Photo: The Swan Range on the east side of the study area. Photo by James Berglund.

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Ground Water Investigation Program**

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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 on the MBMG website (<https://www.mbmgt.mtech.edu/>) under the Ground Water Investigation Program.

Products of the East Flathead Groundwater Investigation include:

- This Interpretive Report, which presents interpretations of the data and summarizes the project results. This report focuses on the study purpose: to evaluate the effects of groundwater pumping from the basin-fill aquifers on surface-water and groundwater availability.
- A Roto-Sonic Drilling Report (Smith and Bobst, 2025), presenting data collected using roto-sonic drilling at two sites, and incorporating that data into a cross-section to provide regional context.
- A Groundwater Modeling Report (Berglund and others, 2024), which combines water budget information with observed groundwater and surface-water behavior to develop calibrated steady-state and transient MODFLOW-based numerical groundwater flow models for the East Flathead Valley study area. These models provide insight into the groundwater system, and were used to test various scenarios to understand the types of hydrologic effects that might be expected from different future stresses.
- An Aquifer Test Report (Myse and others, 2023), summarizing the results of three aquifer tests conducted in the East Flathead study area.

MBMG's Groundwater Information Center (GWIC) online database (<https://mbmgtgwic.mtech.edu/>) provides a permanent archive for the data from this study, including aquifer test reports, aquifer test data, stream stage, stream discharge, groundwater elevations, temperature measurements, and water-quality results. The sites monitored for this study are accessible in GWIC (go to 'Project Data,' 'GW Investigation Program,' 'East Flathead'). Appendices A, B, and C of this report list the GWIC ID numbers for sites used in this study.

ABSTRACT

Population growth and commercial/industrial development in the Flathead Valley of northwestern Montana has raised concerns that increased groundwater use from the unconsolidated basin-fill aquifers may affect surface-water and groundwater availability. To address these concerns in the East Flathead area, the Montana Bureau of Mines and Geology (MBMG) conducted groundwater and surface-water monitoring and aquifer tests. These data were used to aid in understanding the groundwater system, and to develop calibrated groundwater models. Water-quality samples were also collected to aid in understanding hydraulic connections between aquifers and surface waters.

We found that while the shallow and deep aquifers are separated by confining layers throughout much of the study area, there is hydraulic communication between these aquifers in some areas, particularly in the southeast portion of the study area, near Jessup Mill Pond. For example, an aquifer test conducted near Jessup Mill Pond showed that pumping from the deep aquifer noticeably affected groundwater levels in the shallow aquifer, and environmental tracers tritium, $^4\text{He}/\text{Ne}$, and sulfur hexafluoride (SF_6) had similar values in the shallow, intermediate, and deep aquifers. Where fine lacustrine confining layers are relatively thick, aquifer tests showed no measurable response in the shallow aquifer from pumping the deep aquifer, and environmental tracer concentrations were noticeably different. Groundwater modeling also showed that the groundwater flow into Jessup Mill Pond (~23 cfs) could not be obtained from the shallow aquifer alone unless unrealistically high hydraulic conductivity values were used.

Groundwater flow modeling was used to aid in understanding the groundwater system, and to evaluate four scenarios. These models were developed based on an understanding of the distribution of hydrogeologic units and a groundwater budget. The models were calibrated to observed groundwater elevations and stream flow rates. The water budget showed that domestic and irrigation wells accounted for about 3% and 11% of groundwater outflows from the area, respectively. Modeling twice the amount of 2020 groundwater pumping for residential uses (from 2,153 to 4,306 acre-ft/yr) indicated a simulated maximum reduction in August groundwater outflow to the Flathead River of 0.7 cfs after 20 years. Doubling irrigation pumping (from 6,679 to 13,358 acre-ft/yr) resulted in a simulated 2.1 cfs reduction in groundwater outflow to the Flathead River after 20 years. Simulating a 1-year-long drought caused a maximum reduction in August groundwater outflow to the Flathead River of 2.2 cfs, and simulating a 5-year-long drought resulted in a 4.6 cfs maximum reduction.

The hydraulic connection between the shallow and deep aquifers indicates that groundwater pumping from either layer will cause stream depletion. The magnitude, timing, and location of that depletion will depend on the location and depth of pumping, and operational details such as pumping schedules.

INTRODUCTION

Background

Ongoing residential and agricultural development in the East Flathead area of northwestern Montana has raised concerns that increased groundwater use may affect surface water and groundwater availability. This study provides a greater understanding of the interconnection between the area's aquifers and surface water. The study area (figs. 1, 2) covers approximately 93 mi² east of the Flathead River, and generally includes the northern portion of the valley that was described as the east side aquifers by LaFave and others (2004).

Flathead County had one of the fastest growing populations in Montana from 2010 to 2020, with an estimated growth rate of 14.8% (<https://www.census.gov/quickfacts/flatheadcountymontana>). Population growth often results in increased groundwater withdrawals. The effects of groundwater withdrawals on surface water for the study area are not well understood. Understanding interconnections between aquifers and between groundwater and surface water is necessary to evaluate how surface waters will be affected by new groundwater withdrawals.

Within the study area, groundwater is used for irrigated agriculture, individual homes, public water supply (PWS) systems, the Creston National Fish Hatchery, and industrial and commercial uses. There continue to be proposals for new large subdivisions, irrigation wells, and commercial uses. A lack of information on how groundwater and surface waters are connected has caused recent Department of Natural

Resources and Conservation (DNRC) water rights decisions to be contentious.

Purpose and Scope

The purpose of this project was to evaluate interconnections between aquifers and between groundwater and surface waters to better understand the effects of pumping from the shallow and deep aquifers on surface-water and groundwater availability. To achieve this objective, we monitored groundwater levels and stream flows, collected water-quality samples, conducted aquifer tests, and installed wells and borings. This fieldwork was carried out from June 2019 to December 2021. Previous work and these monitoring data were used to develop a conceptual model for the study area, which was then implemented as numerical groundwater flow models. These models were used to test a limited set of potential future development and drought scenarios to aid in understanding the types of effects that may be expected for different types of changes in groundwater pumping or droughts. These models are also intended to aid groundwater management in the area.

Location and Physiography

The Flathead Valley is an intermontane basin in northwest Montana. The study area covers a portion of the Flathead Valley, and is bounded by the Swan Range on the east and the Flathead River on the west (fig. 2). The Flathead River at Columbia Falls (USGS station 12363000) had an average annual flow of 9,736 cubic feet per second (cfs) from 1951 to 2022, with mean monthly discharges ranging from 5,230

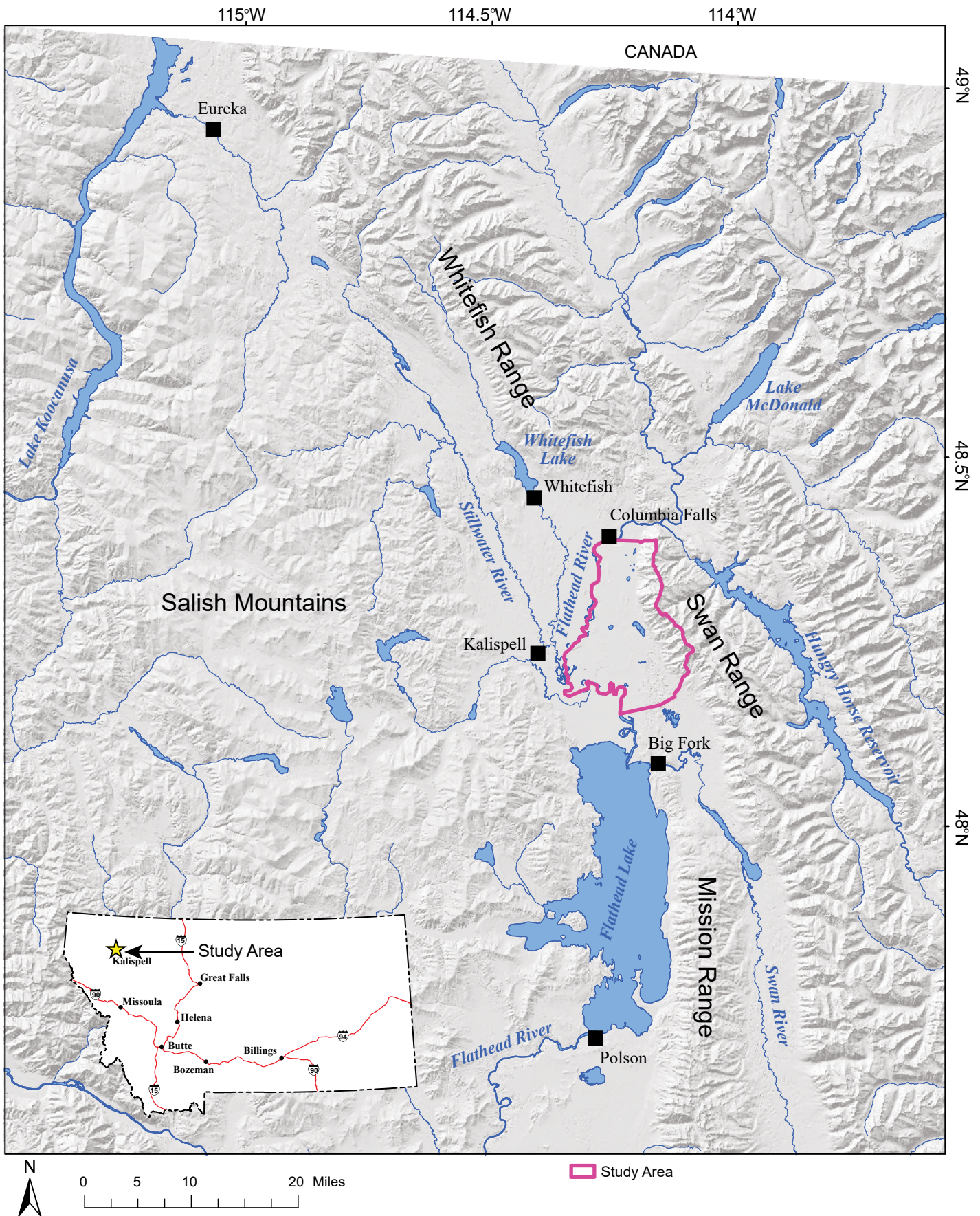


Figure 1. The East Flathead groundwater investigation was conducted on the east side of the Flathead Valley in north-west Montana.

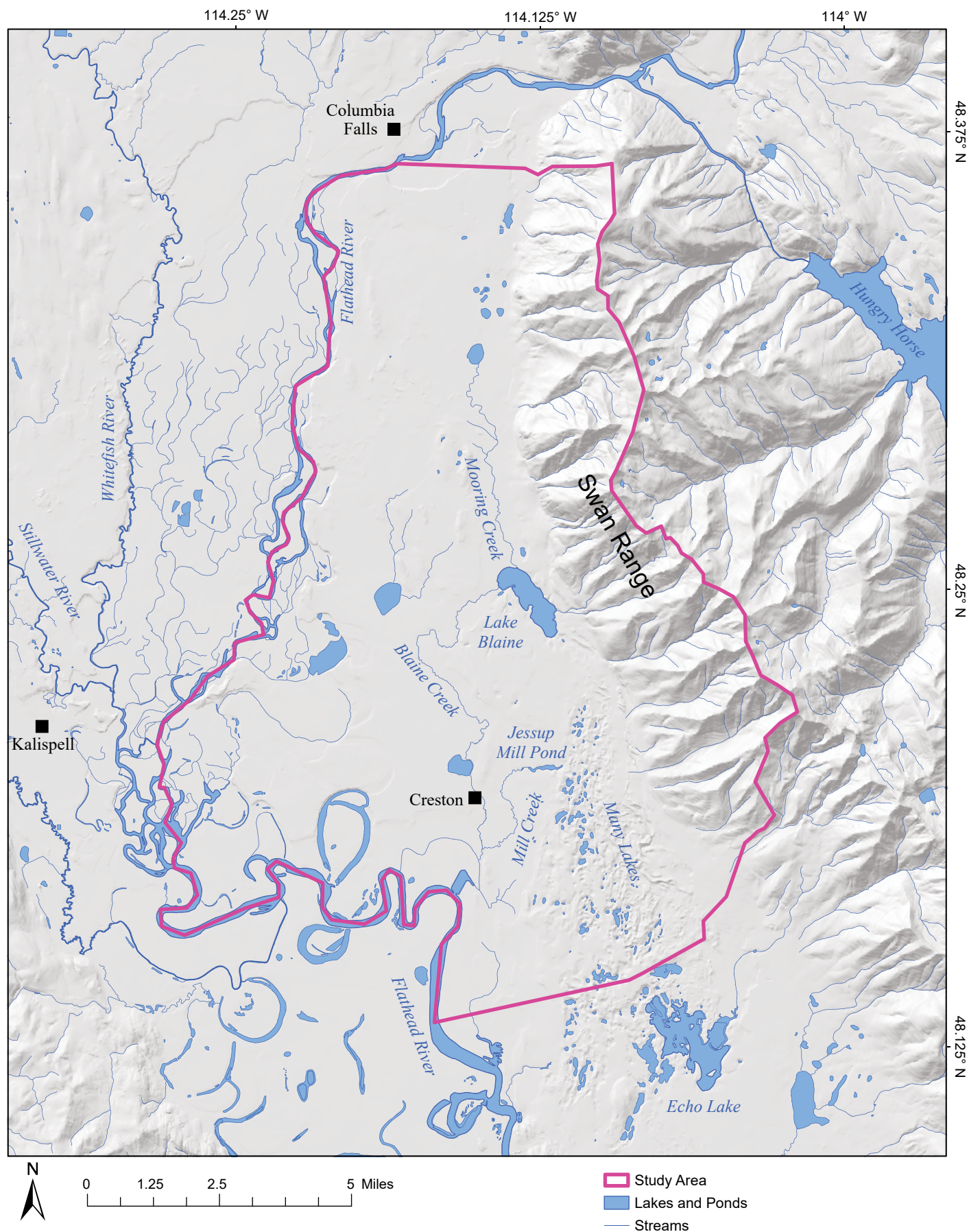


Figure 2. The study area extends east to west from the crest of the Swan Range to the Flathead River. From north to south the study area extends approximately from south of Columbia Falls to about 3 miles south of Creston.

cfs (September) to 24,900 cfs (June). Other important surface-water features include Mooring Creek, Lake Blaine, Jessup Mill Pond, and Mill Creek (fig. 2). Land surface elevations in the study area range from 2,889 feet above mean sea level (ft-amsl) along the Flathead River at the south end of the study area to 7,424 ft-amsl at the peak of Doris Mountain in the Swan Range.

Previous Investigations

There have been several studies of the geologic and hydrogeologic conditions in the Flathead Valley. Alden (1953) provided the first geomorphic interpretation of the valley and provided insight into its geology. Witkind (1977) mapped major active faults and seismicity in and near Bigfork. Stickney (1980) investigated seismicity and conducted gravity mapping. Surface geology and structure for the Kalispell 1° x 2° quadrangle were mapped by Harrison and others (1992). Smith (2004g) described the subsurface geology, relationships of specific geologic features, and the geologic timeline of the formation of the valley.

Konizeski and others (1968) described the hydrogeology of the Flathead Valley prior to widespread drilling and adoption of irrigation wells. Noble and Stanford (1986) described the unconfined aquifers in the valley. The USGS included the Flathead Valley in their evaluation of intermontane basins of the northern Rocky Mountains (Briar and others, 1996; Kendy and Tresch, 1996). Uthman and others (2000) described the subsurface geology and installed monitoring wells along a transect in the northern portion of the valley, some of which are still monitored by the MBMG's Ground Water Assessment Program (GWAP) as part of the state-wide long-term network.

MBMG's Ground Water Characterization Program (GWCP) conducted a regional study of the Flathead and Mission Valleys north and south of Flathead Lake. This study produced multiple publications about the area's hydrogeology and geology (LaFave and others, 2004; LaFave, 2004a,b; Smith, 2004a–f; Smith and others, 2004a,b; Patton and others, 2003; McDonald and LaFave, 2004; Waren and Patton, 2007).

MBMG's Ground Water Investigations Program (GWIP) investigated the hydrogeologic characteristics of the deep alluvial aquifer in the Flathead Valley (Rose and others, 2022), and the detailed stratigraphy at one site where drilling extended into the low-perme-

ability Tertiary sediments underlying the deep aquifer (Bobst and others, 2022).

Climate

Long-term average precipitation values reported by the PRISM climate group (Parameter-elevation Regressions on Independent Slopes Model; PRISM Climate Group, 2022; <https://prism.oregonstate.edu/>) show that normal precipitation for the period from 1991 to 2020 ranges from about 15 in/yr in the valley bottom to 70 in/yr at the top of the Swan Range.

Temperature data from 1985 to 2021 at the Creston Agrimet Station (U.S. BOR, 2024) in the valley bottom (fig. 2) shows that the mean annual temperature is 45°F. Mean monthly temperatures over the same time period ranged from 26°F (January and December) to 66°F (July).

The Noisy Basin SNOTEL station (USDA, 2024), in the Swan Range, shows that for water years 1979 to 2023, total annual precipitation ranged from 46 to 102 in/yr, with a median of 71 in/yr and the interquartile range extending from 61 to 76 in/yr. During the field data collection period for this study, annual precipitation totals were 58.1 in/yr in water year 2019, 65.2 in/yr in 2020, and 57.8 in/yr in 2021. As such, the study period was relatively dry in the Swan Range.

For water years 1991 to 2023, total annual precipitation at the Creston Agrimet Station (U.S. BOR, 2024) ranged from 11.4 to 21.6 in/yr, with a median of 16.4 in/yr and the interquartile range extending from 13.8 to 19.2 in/yr. During the field data collection period, annual precipitation totals were 15.2 in/yr in water year 2019, 16.1 in/yr in 2020, and 16.4 in/yr in 2021. As such, the study period was slightly dry in the valley bottom.

Land Use

Land use within the study area includes irrigated and dryland agriculture, residential development, and minor commercial uses. Since the mid-1970s irrigated agriculture has been shifting from flood irrigation, using surface-water sources, to sprinkler and pivot irrigation using groundwater sources (Kendy and Tresch, 1996; Rose and others, 2022; R. Noble, written commun., 2025). Residential development is increasing with population growth, and much of the new development is in areas previously used for agriculture. Water for residential developments is supplied by either individual domestic wells or PWS wells.

Hydrogeologic Framework

The Flathead Valley is the southernmost expression of the Rocky Mountain Trench, which extends over 1,000 mi north into the Yukon Territory in Canada (Garland and others, 1961; Harrison and others, 1992). The Rocky Mountain Trench formed by extension where the bedrock beneath the valleys dropped relative to the surrounding terrane along normal faults, such as along the west flank of the Swan and Mission Ranges (fig. 1).

Bedrock in this area is composed of the Piegan and Ravalli Groups of the Belt Supergroup, which are primarily siltite, metacarbonates, quartzite, and mafic sills (Smith, 2004a; Lonn and others, 2020). These units are referred to as Belt bedrock in this report. Belt bedrock is exposed in the Swan Range on the east side of the study area, and in the nearby Salish, Whitefish, and Mission Ranges (figs. 1, 3).

A thick layer of unconsolidated basin-fill sediments overlie the downdropped Belt bedrock west of the Swan Range Front (table 1, fig. 3). These Tertiary to Quaternary sediments are up to 3,000 ft thick (Smith, 2004b). Based on a well drilled in the southern Flathead Valley (Bobst and others, 2022), and similar sediments encountered in other intermountain basins in western Montana, the Tertiary sediments are interpreted to function as a basal aquitard in the Flathead Valley.

The Quaternary deep aquifer overlies the Tertiary sediments (LaFave and others, 2004; Rose, 2018; table 1) and is interpreted to be glacial outwash mostly composed of silt, sand, gravel, and cobbles. The clasts are dominantly composed of siltite, which is consistent with a Belt bedrock source. This aquifer is a primary source of water in the Flathead Valley, and it is used for municipal water supplies, irrigation wells, and domestic wells. Wells in the deep aquifer may produce over 3,000 gpm.

The deep aquifer is generally overlain by glacial till and lake sediments (table 1). These lower permeability sediments comprise the confining layer. Smith (2004d) mapped thinner confining units (<100 ft) in some parts of the study area (fig. 4).

Intermediate aquifers, composed of lenticular deposits of sand and gravel, occur within the confining layers in some areas. Smith (2004d) mapped areas

where the deep and intermediate aquifers are interfingering (fig. 4). At the surface there are areas of sandy glacial lake sediments, interpreted to be near-shore deltaic deposits (Smith, 2004a). Similar near-shore facies would have been deposited throughout the time that a glacial lake filled the valley. These sediments may provide a hydraulic connection between the deep aquifer and shallow aquifers in portions of the study area.

A variety of sediments from the modern depositional environment typically cover the confining layer, and form the shallow aquifers (table 1). These shallow aquifers are in direct communication with surface waters (Konizeski and others, 1968; Noble and Stanford, 1986; Smith, 2004a; LaFave and others, 2004).

Groundwater elevation and water-quality data suggest that the deep aquifer receives substantial recharge along the east side of the Flathead Valley (Parrett and Hull, 1984; LaFave and others, 2004). It is also notable that while the Swan Range to the east receives up to 70 in of precipitation per year, most of the mountain creeks draining that area cease to flow at the mountain front (fig. 2). This indicates that mountain front recharge along the eastern side of the valley is likely quite high.

METHODS

Data Management

Data collected for this investigation are archived in the MBMG's Ground Water Information Center (GWIC) database, which is accessible online at <https://mbmggwic.mtech.edu>. GWIC includes information on well completions, groundwater elevations, water chemistry, aquifer tests, and other data. Groundwater and surface-water site numbers presented in the text and figures of this report can be correlated with GWIC ID numbers listed in appendices A, B, and C.

Monitoring and Sampling

Field data were collected from June 2019 to December 2021. Data collected by previous MBMG studies were also incorporated where applicable, particularly water-quality data. Monitoring and sampling were conducted in accordance with MBMG standard operating procedures (SOPs; Gotkowitz, 2023).

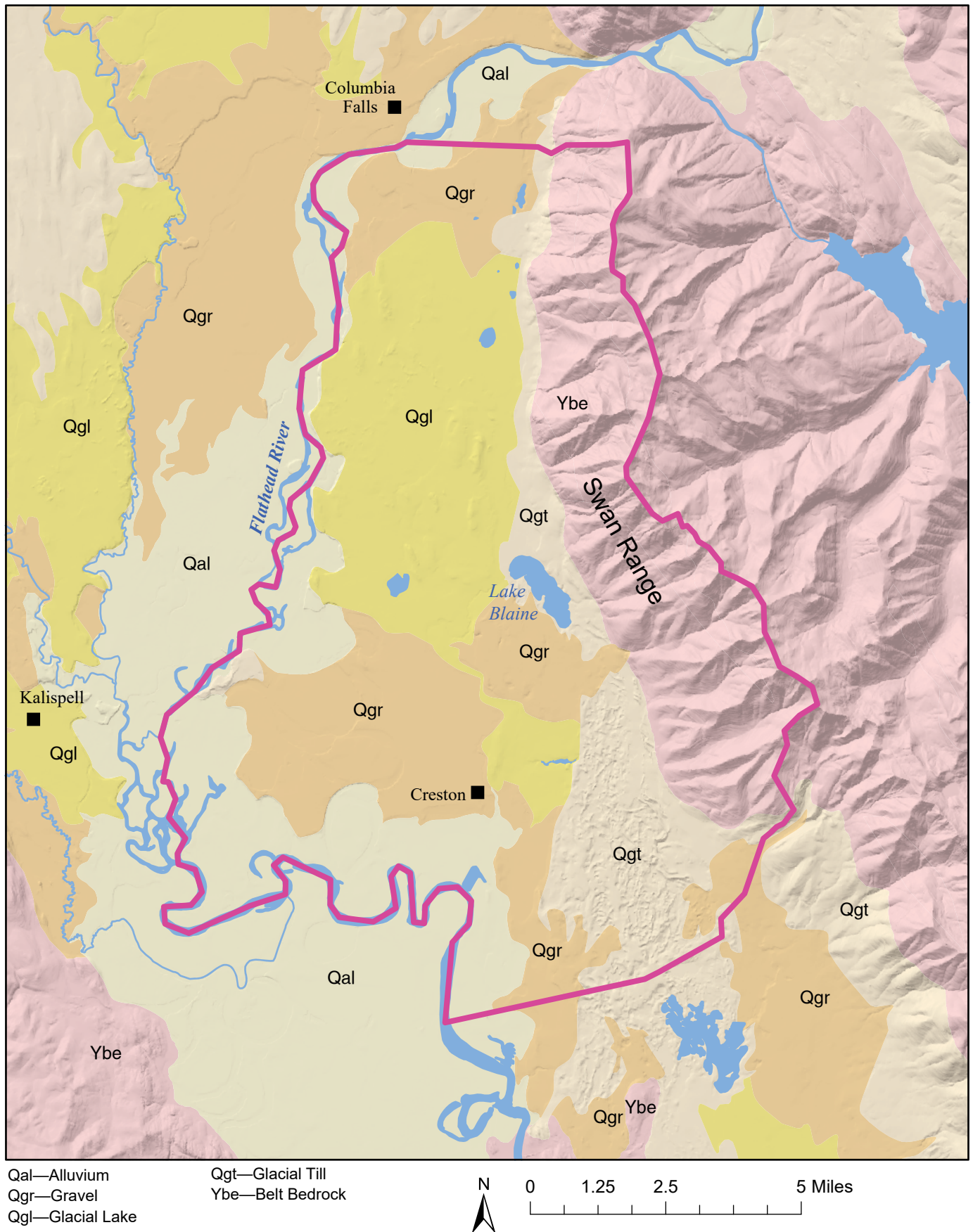


Figure 3. Generalized geologic map of the East Flathead study area modified from the statewide geologic map of Montana (Vuke and others, 2007). For a more detailed geologic map of the area see Smith (2004a), which is the basis of the units in table 1.

Table 1. Hydrostratigraphy of the East Flathead Valley, with comparison to recent MBMG publications; based on the units from Smith (2004a).

Geologic Age		Geologic Units ¹	Geologic Interpretation ³	Hydrogeologic Units					
Period	Epoch			LaFave and others, 2004	Rose, 2018	This Study (East Flathead)			
Quaternary	Holocene	Lake Deposits (Q _{lk})	Outwash, eolian sand sheets and dunes, fluvial, alluvial, lacustrine, and alluvial fan deposits.	Shallow Aquifer	Shallow Aquifer	Shallow Silt	Shallow Aquifers	Mountain-Front Deposits	
		Eolian Deposits (Q _e)							
		Alluvial Fan Deposits (Q _{af})							
		Landslide Deposits (Q _{ls})							
		Alluvium (Q _{al})							
		Older Alluvium (Q _{ao})							
	Pleistocene	Glacial Outwash Deposit (Q _{go})	Most deposited from suspension in distal positions in lake that was initially pro-glacial; few gravels deposited from melting ice; subaqueous outwash fan deposits near recessional moraines; higher lacustrine deposits were abandoned successively as the lake receded.	Confining Unit	Lacustrine-Till Aquitard	Intermediate Aquifers	Fine Lacustrine Aquitard	Sandy Lacustrine Sediments	
		Glacial Esker Deposits (Q _{ge})							
		Glacial Outwash Deposit (Q _{go})	Intermediate Alluvium; englacial or subglacial alluvial deposits that are encased in till.	Intermediate Aquifers		Confining Unit	Deep Aquifer	Shallow Deep Aquifer	Deep Aquifer
		Glacial Esker Deposits (Q _{ge})							
		Glacial Till, Ablation Deposits (Q _{glie})	Massive Diamicton: mostly till deposited subglacially by lodgment and melt-out processes; surface is marked by englacial or subglacial eskers, supraglacial ablation deposits, drumlins, and moraines.	Bedded Diamicton: flow till and debris flow deposits; typically reworked in ice contact environments.		Confining Unit	Deep Aquifer	Shallow Deep Aquifer	Deep Aquifer
		Glacial Ice-Contact Deposits (Q _{gic})							
Glacial Till (Q _{gl})	Outwash deposited during glacial advance; may include some intraglacial alluvium.	Tertiary Sediments	Tertiary Sediments	Tertiary Sediments	Tertiary Sediments				
Glacial Outwash Deposits, Older (Q _{goo})									
Tertiary	Oligocene	Tertiary Sediments (T _s)	Tertiary Sediments: Brown and orange medium- and coarse-grained pebbly sandstone; pebble and cobble conglomerate; carbonaceous shale and carbonized wood; gray, yellow, and orange mudstone; and orange clayey gravel (diamicton); gravel clasts of argillite, quartzite, and siltstone are mostly well rounded; sandstone and conglomerate beds have channelized, erosional bases. May include strata of the Kishenehn Formation and Paola gravel.	Tertiary Sediments	Tertiary Sediments	Tertiary Sediments	Tertiary Sediments		
	Eocene								
Middle Proterozoic		Belt Supergroup (Y _{be})	Belt Bedrock: Composed mostly of siltite, metacarbonates, and quartzite.	Bedrock	Bedrock	Bedrock	Bedrock		

Note. These units/colors do not directly correlate with figure 3. Not to scale.
¹See Smith (2004a) for areal exposure of geologic units, and fig. 8 for schematic cross-sections. All units are not present at all locations.
²Geologic Age based on Dawson and Constenius (2018).
³Modified from Smith (2004a).

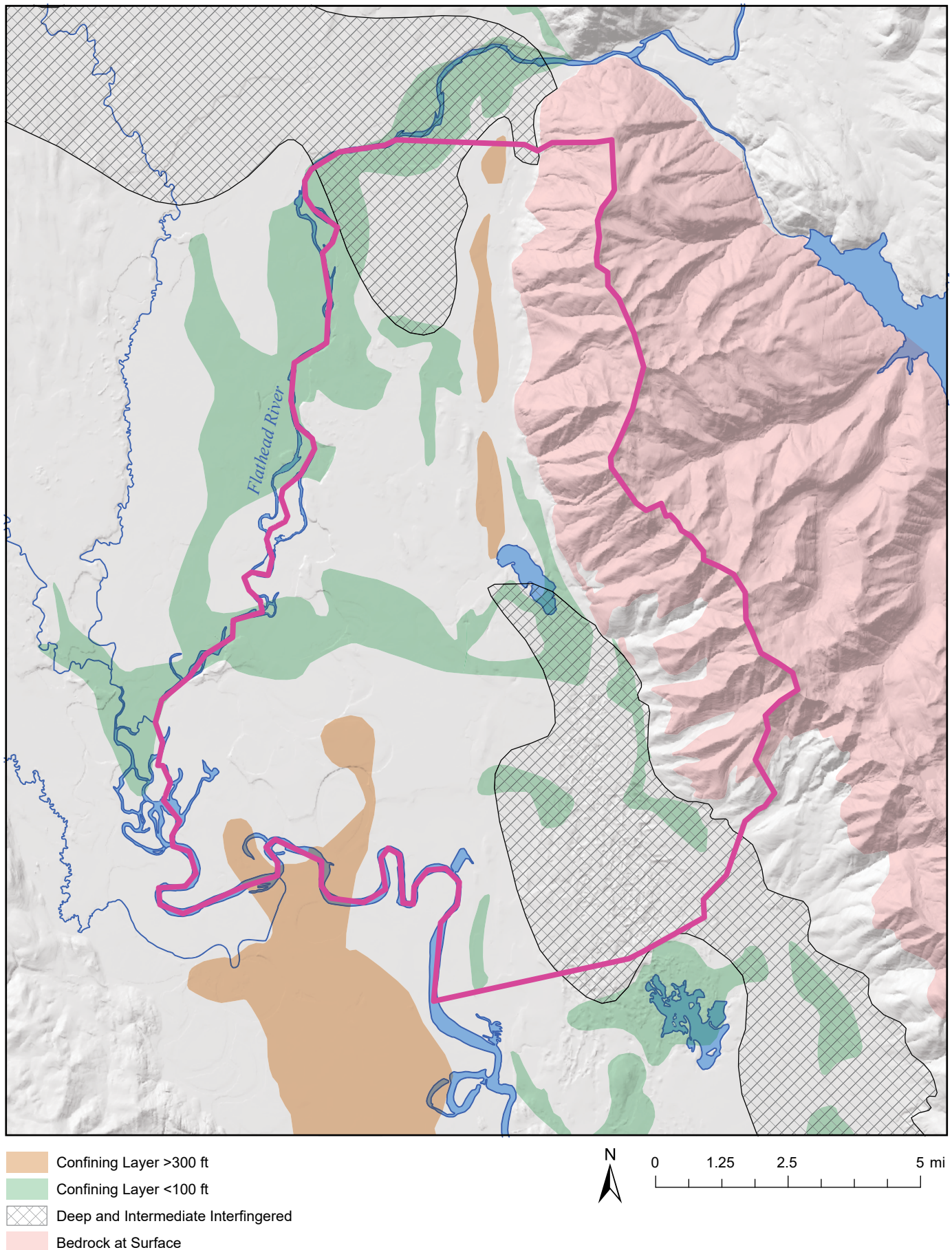


Figure 4. Smith (2004d) identified areas where the confining unit was, thick (>300 ft) and thin (<100 ft), and areas where the deep and intermediate aquifers appeared to be interfingered.

Groundwater

Static groundwater elevations were monitored in a network of 144 wells (fig. 5; appendix A, table A1). The wells were monitored for different durations depending on landowner permissions, but most sites were monitored from January 2020 to September 2021. Fourteen wells and two roto-sonic borings were installed for this study, to improve coverage, define stratigraphy, and conduct aquifer tests. Most wells were monitored monthly using an electronic sounder (e-tape), and 29 wells had pressure transducers installed to record water level and temperature hourly. Some of the wells are monitored as part of the MBMG's long-term GWAP network (appendix A, table A1; fig. 5). Measuring point elevations were determined by survey or using lidar data (1σ vertical accuracy = 0.1 ft; Watershed Sciences, Inc., 2010). The groundwater elevations were used to develop potentiometric surface maps, evaluate vertical hydraulic gradients, evaluate seasonal patterns in hydrographs, and provide calibration targets for the groundwater models (Berglund and others, 2024).

Groundwater-quality data from 82 wells were evaluated. Samples were obtained from 31 wells in the monitoring network during this study, mainly during two synoptic sampling events in June and September, 2020. The samples were analyzed for major ions, trace elements, nutrients, and water isotopes (δD and $\delta^{18}O$; appendix D, table D1). The samples were collected and preserved following MBMG SOPs (Gotkowitz, 2023), and analyzed by the MBMG Analytical Laboratory following quality assurance protocols (Timmer, 2020). Water-quality data were also obtained from the Ground Water Information Center database (<https://mbmggwic.mtech.edu>) from previous MBMG work in the area. This included 14 wells that were in the monitoring network and 37 wells that were not part of the monitoring network for this study (appendix C, table C1; fig. 6; appendix A, table A1). The water-quality data were used to compare different hydrogeologic units, which can indicate hydraulic communication between the units, and to evaluate overall water quality.

Water-Quality Data Analysis

We evaluated parameters for which stakeholders have expressed concern (nitrate), or where there were exceedances of drinking water regulatory standards (iron and arsenic) or human-health guidelines (manga-

nese). For these parameters, 20 to 58% of the samples had concentrations that were below the analytical detection limit (DL). These “censored” concentrations do not provide discrete numerical values; however, they do provide a constraint, or an upper limit, for the non-detect samples. Estimates of the overall shape of the probability distribution function for each parameter, and the associated summary statistics, are affected by the treatment of censored values (Helsel, 2012; Helsel and others, 2020). Therefore, we applied methods to account for censored values while compiling summary statistics (Helsel, 2012). Regression on Order Statistics (ROS) estimate the probability distribution function for a parameter based on the values measured above the detection limit, the proportion of samples below the detection limit, and the distribution type (e.g. lognormal). ROS were calculated in R (R Core Team, 2020) using the NADA and NADA2 packages (Helsel, 2012; Lee, 2020; Julian and Helsel, 2021). The cenCompareQQ function from NADA2 (Julian and Helsel, 2021) was used to evaluate if the normal, lognormal, or gamma distribution best fit the data. For the parameters we evaluated the lognormal distribution fit best, so it was used for the ROS analysis.

Environmental Tracers

Environmental tracers were analyzed to assess the time since groundwater recharge and the degree of aquifer confinement, with samples collected from 15 wells (appendix D, table D5, fig. D1). In 2020 two wells with different depths were sampled in each of three areas (north, central, and south), with samples being collected in June and September. This included sampling for tritium (3H), noble gases (helium, nitrogen, argon, neon, krypton, and xenon), and sulfur hexafluoride (SF_6 ; September only). Additionally, there was one round of sampling in 2021, from shallow, intermediate, and deep wells at three sites in the southern part of the study area where aquifer tests had been conducted (Myse and others, 2023). The 2021 samples were analyzed for tritium and noble gases. The environmental tracer samples were analyzed by the University of Utah Noble Gas Lab (Salt Lake City, UT), and sample collection and preservation were conducted in accordance with their SOPs (<https://noble-gaslab.utah.edu/how-to.php>).

Tritium is a naturally occurring radioactive isotope of hydrogen with a half-life of 12.43 yr (Lindsay and others, 2019). It is directly incorporated into the water

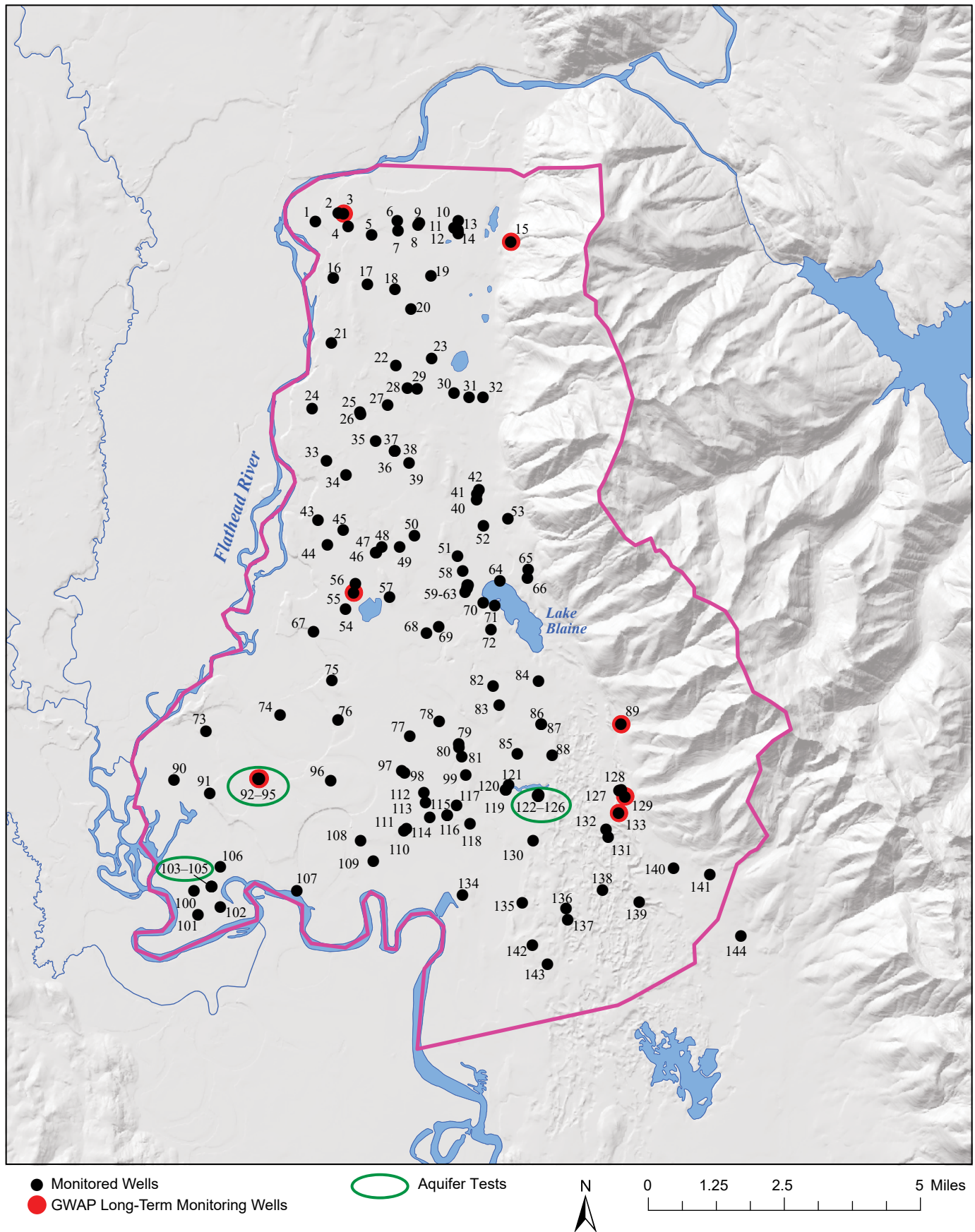


Figure 5. There were 144 wells monitored during this study. Well details, including GWIC IDs are included in appendix A.

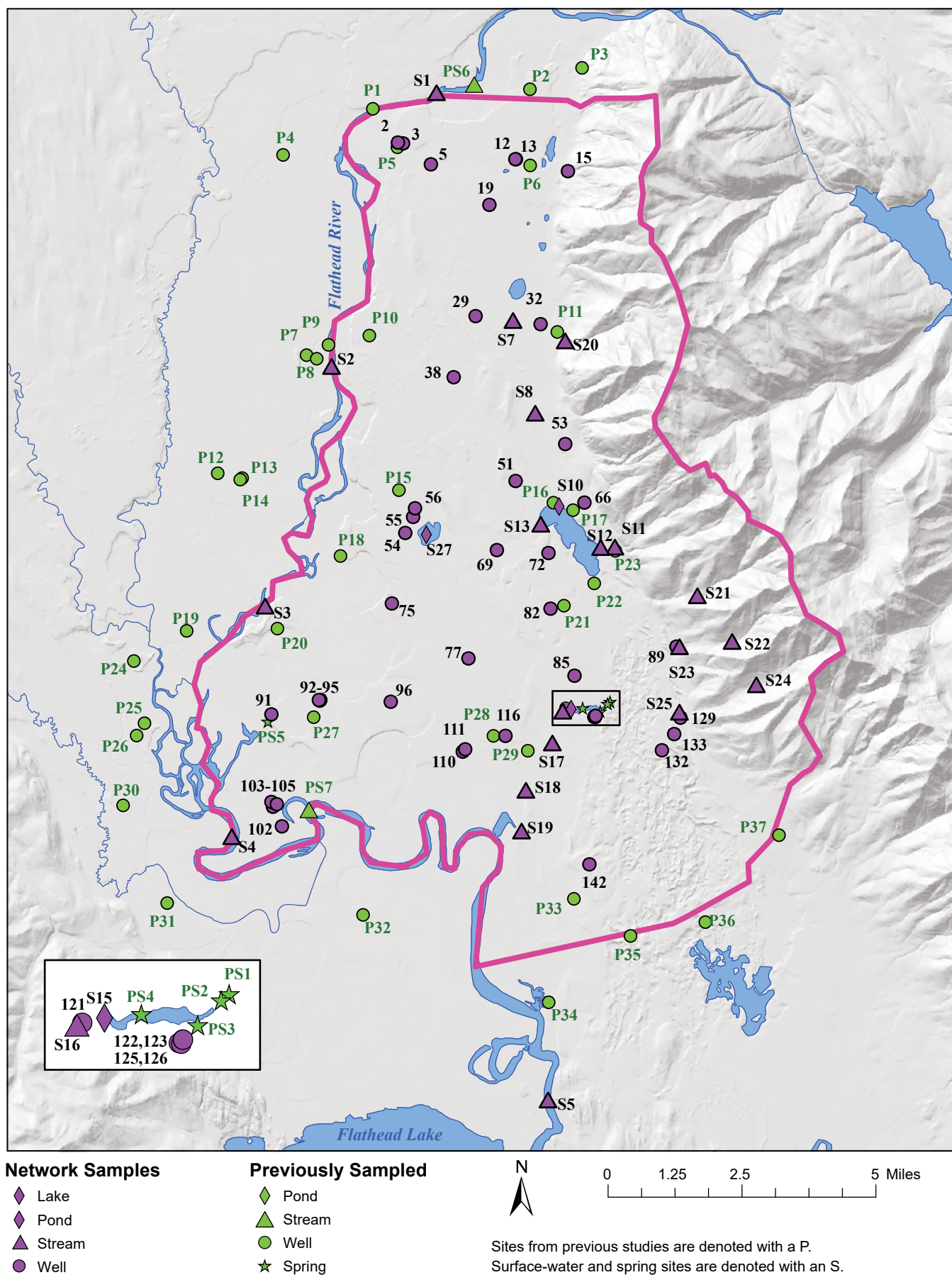


Figure 6. Groundwater and surface-water sampling sites from our network and from previous studies in the area. Site details, including GWIC IDs, are in appendices A, B, and C. Site S6 (Flathead Lake at Polson) is not shown on this map. Inset box shows the sites near Jessup Mill Pond.

molecule, and can be used to evaluate the time since groundwater was recharged. Atmospheric testing of nuclear weapons between 1952 and 1963 released large amounts of tritium into the atmosphere. Due to its short half-life, this “bomb-pulse” tritium has been steadily decreasing towards natural concentrations. Lindsay and others (2019) suggest that waters with less than 0.3 tritium units (TU) can be classified as premodern (pre-1952), waters with greater than 2.9 TU are modern, and waters with between 0.3 and 2.9 TU are mixtures of modern and premodern waters.

The ratio of helium-4 (^4He) to neon (Ne) provides an indication of excess ^4He accumulation in a groundwater sample (i.e., terrigenic ^4He ; Gardner and others, 2012). Terrigenic ^4He is produced by the release of alpha particles during natural radioactive decay (e.g., decay of ^{235}U to ^{231}Th) of aquifer sediments along with crustal and mantle degassing (Castro and others, 1998; Torgersen and Clarke, 1985; Zhao and others, 1998). It is assumed that the only source of Ne is the atmosphere and it is incorporated into the water during recharge. In shallow unconfined aquifers $^4\text{He}/\text{Ne}$ is generally similar to the atmosphere (~ 0.3). The accumulation of ^4He in groundwater depends on the residence time, the degree to which the aquifer is confined (cannot outgas), and the geochemistry of the aquifer matrix.

SF_6 is a synthetic chemical that has been detectable in the atmosphere since the early 1960s, and its concentration is steadily increasing (Chambers and others, 2019). By knowing the solubility of SF_6 in water, the approximate temperature during recharge, and assuming piston flow, the concentration of SF_6 in groundwater can be used to estimate the age of the water (Darling and others, 2012). Potential complicating factors include lag from movement through the unsaturated zone, uncertainty in the recharge pressure or temperature due to mountainous terrane, incorporation of excess air, groundwater mixing, and loss of SF_6 due to degassing, sorption, or microbial decay (Darling and others, 2012).

Surface Water

We monitored 16 surface-water sites for stage, discharge, temperature, and water quality (fig. 7; appendix B). At 13 sites a staff gage and stilling well were installed and surveyed. Stage and temperature were measured hourly using pressure transducers installed in the stilling wells. Discharge measurements were

obtained manually during ice-free periods in 2020 and 2021 at approximately 2-week intervals during spring runoff (April–June), and approximately monthly during the summer and fall (July–October). Manual discharge and stage measurements allowed stage-discharge rating curves to be developed.

The DNRC monitored six sites and the U.S. Geological Survey (USGS) monitored five sites in or near our study area (fig. 7; appendix B, table B1). We used the data from these sites when possible.

We collected water-quality samples at 21 sites (fig. 6; appendix B, table B1). The samples were analyzed for major ions, trace elements, nutrients, and water isotopes (appendix D, table D1). The samples were collected and preserved following MBMG SOPs (Gotkowitz, 2023), and analyzed by the MBMG Analytical Laboratory following quality assurance protocol (Timmer, 2020). Water-quality data from a previous MBMG study (Rose and others, 2022) was used at site 15, we used USGS water-quality data at sites 4 and 6 (appendix B), and data from sampling 5 springs and 2 stream sites during previous studies was also used (appendix C).

Characterizing Hydrogeologic Units

Distribution of Hydrogeologic Units

Rockworks 17 (RockWare, 2015) was used to develop a three-dimensional model of the distribution of hydrogeologic units in the study area. This model was based on previous geologic work in the area (Uthman and others, 2000; LaFave and others, 2004; Smith, 2004a–g; Rose, 2018), and lithologic logs from water wells in MBMG’s GWIC database (<https://mbmggwic.mtech.edu>). Details of modeling the hydrogeologic units are included in the groundwater modeling report (Berglund and others, 2024).

Based on the initial geologic model, 10 wells were installed to clarify lithologies in areas with conflicting reports. Roto-sonic coring was subsequently conducted at two locations to obtain high-resolution lithologic information (Smith and Bobst, 2025). A detailed cross-section (fig. 19 in Smith and Bobst, 2025) was developed between the roto-sonic sites, supplemented with lithologic logs from GWIC to better understand the framework of the aquifers and confining units in the southern portion of the study area.

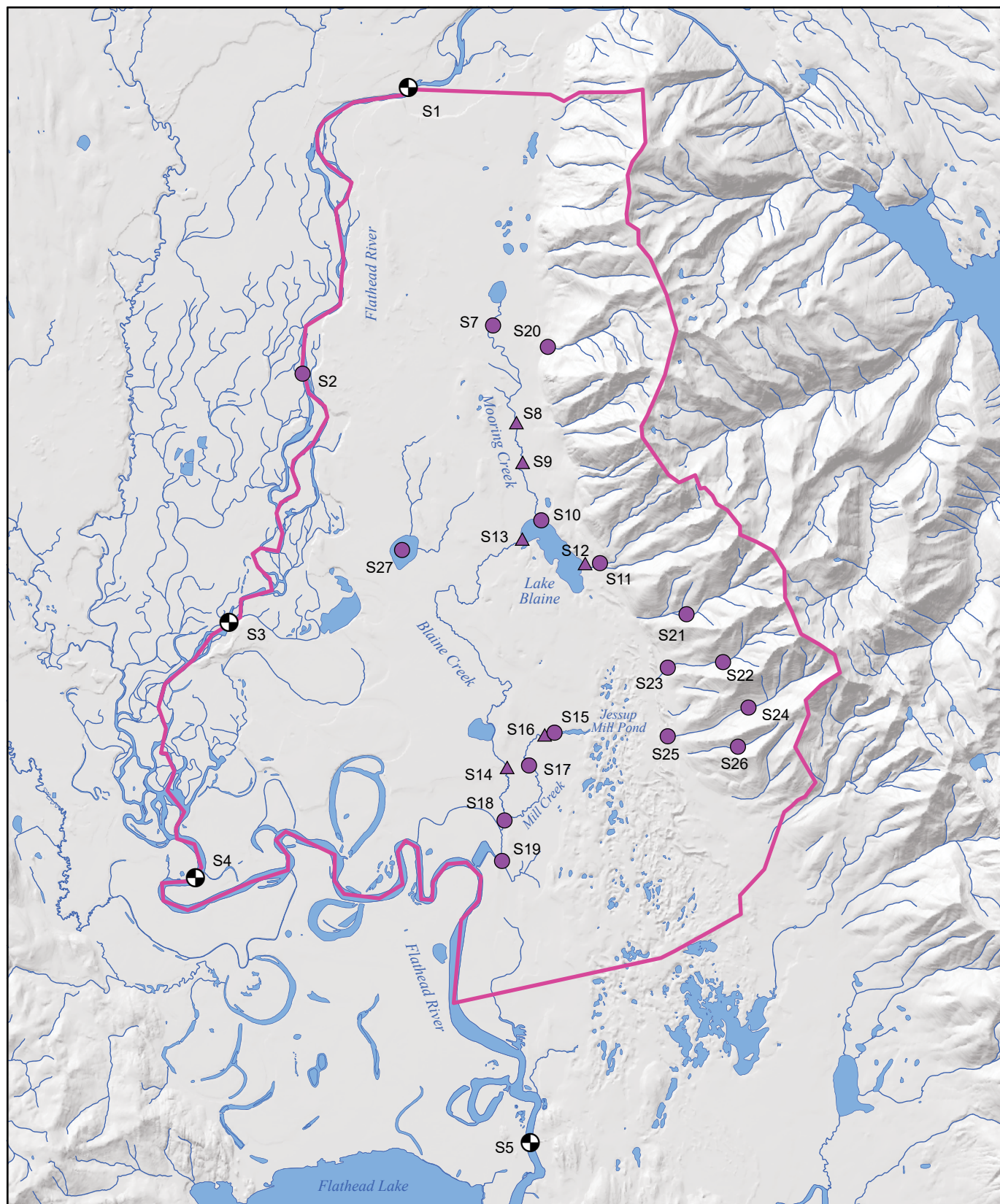


Figure 7. The surface-water monitoring network consists of 16 MBMG sites, 6 DNRC sites, and 5 USGS sites. Site details, including GWIC IDs, are in appendix B. Site S6 (Flathead Lake at Polson; USGS) is not shown on this map.

Aquifer Properties for Hydrogeologic Units

To define reasonable ranges of aquifer properties for each of the hydrogeologic units, we reviewed aquifer test reports submitted to DNRC for water rights applications in the study area, and literature values for the sediment types present (Berglund and others, 2024). We also conducted two aquifer tests for this study, and compiled and analyzed data from a previously unpublished aquifer test (fig. 5; Myse and others, 2023).

Numerical Groundwater Modeling

Groundwater models provide a framework for synthesizing different types of field information (e.g., observed groundwater elevations and stream gains/losses), water budget estimates, and geologic models, with an understanding of groundwater flow processes (Anderson and others, 2015). We imported the hydrogeologic unit model from RockWorks into Groundwater Vistas (GWV, version 8.15) as a graphical user interface (Environmental Simulations Incorporated, 2020). GWV was used to develop MODFLOW-2005 groundwater flow models (version 1.12.00; Harbaugh, 2005).

The details of groundwater modeling are documented in Berglund and others (2024), and are summarized here. The models used four layers, with the deepest (layer 4) representing the deep aquifer, the shallowest (layer 1) representing the shallow aquifers, and the middle layers (layers 2 and 3) representing a mixture of lacustrine aquitard, sandy lacustrine sediments, intermediate aquifers, and till. The grid cells were 500 ft x 500 ft horizontally, with thicknesses based on the hydrogeologic model. We developed a preliminary groundwater budget for the basin-fill sediments in the study area based on monitoring data, remote sensing, and other sources of information. That groundwater budget was used to define model boundary conditions and provide flux targets for calibration. Observed groundwater elevations were also used as calibration targets. A steady-state version of the model was developed and calibrated to groundwater elevations and flux targets. Calibration of the steady-state model included a sensitivity analysis. The steady-state model was converted to a transient model by applying time-varying boundary conditions, adding storage parameters, and calibrating to dynamic groundwater elevations (hydrographs) at monitoring wells. Once

the transient model reasonably replicated past observations, it was used to predict the effects of hypothetical scenarios. The modeled scenarios included:

1. Doubled 2020 residential groundwater pumping amounts,
2. Doubled 2020 irrigation groundwater pumping amounts,
3. A 1-yr-long drought, and
4. A 5-yr-long drought.

For each of these scenarios, the changes in groundwater elevations and effects to surface waters (stream depletion) were quantified relative to a baseline 20-yr transient model that used the same transient stresses as the calibrated transient model. A predictive uncertainty analysis was conducted to evaluate the uncertainty associated with the model predictions.

RESULTS AND INTERPRETATIONS

Hydrostratigraphy and Aquifer Properties

The stratigraphy of the East Flathead Valley is complicated due to structural deformation, multiple periods of glacial advances and retreats, changing depositional systems (e.g. glaciers, fluvial deposits from the ancestral and modern Flathead River, and from streams along the Swan Mountain Front), and partial erosion of previously deposited materials. This results in aquifers and aquitards that are heterogeneous, and not necessarily continuous, even over short distances.

Bedrock

The study area is underlain and bounded on the east by bedrock from the Belt Supergroup (Y_{be} , table 1; figs. 3, 8). These units are composed primarily of siltite, metacarbonates, and quartzite (Harrison and others, 1992; Kendy and Tresch, 1996; Smith, 2004a). Belt rocks are exposed in the Swan Range, the Whitefish Range, the Mission Range, and the Salish Range surrounding the Flathead Valley (fig. 1). Belt rocks are also exposed in the southern Flathead Valley, northwest of Bigfork, where the northern end of the Mission Range extends into the valley (surface exposure shown at the southern end of fig. 3). This northern extension of the Mission Range bisects the deep aquifer in the south end of the study area (fig. 8B). The primary porosity and permeability of these units are low;

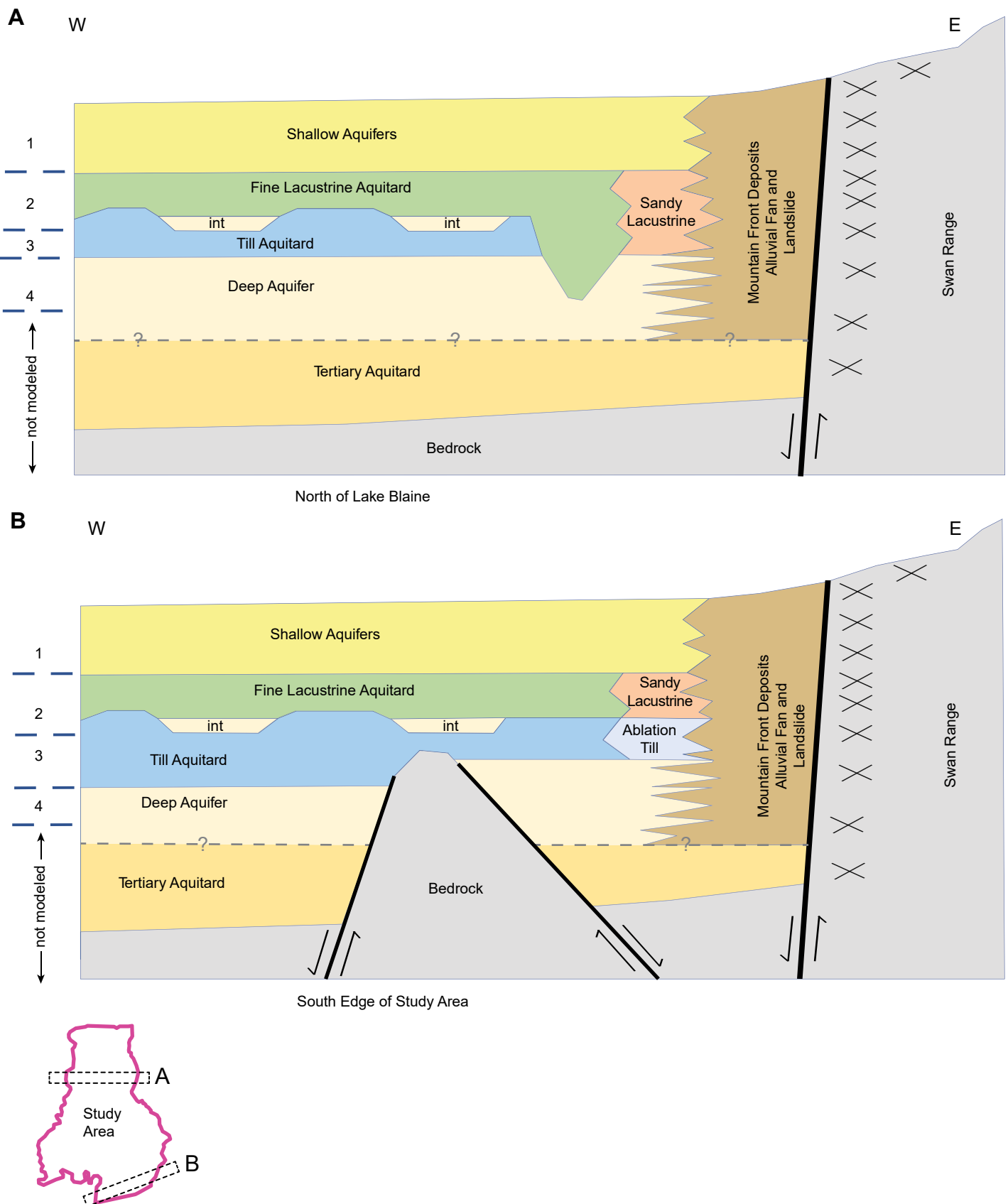


Figure 8. Schematic diagram of hydrogeologic units in the East Flathead area (not to scale). Model layers are indicated by the numbering on the left side. The distribution of hydrogeologic units is complex in this area, with the fine lacustrine “trench” being a strong influence in the north (A), and the bedrock high (north end of the Mission Range) important in the south (B). Intermediate aquifer is denoted as “int.” General areas of cross-sections shown on inset map.

however, fracturing creates secondary permeability that allows these units to store and transmit groundwater. The productivity of wells completed in the bedrock depends on the number of fractures the well bore intersects, the aperture of those fractures, and the degree to which the fractures are interconnected to a larger fracture network (Driscoll, 1986). Reported yields from bedrock wells in the Flathead Valley generally range from 0.5 to 50 gpm, with an average of about 9 gpm (Konizeski and others, 1968; Kendy and Tresch, 1996; Rose and others, 2022). In the Swan Range south of the study area there is a well (GWIC 148733) completed in fractured bedrock that has a reported yield of 200 gpm and it becomes flowing artesian during some years (R. Noble, written commun., 2025), demonstrating the steep gradient toward the valley and the potential productivity of highly fractured bedrock aquifers.

Tertiary Sediments

Tertiary sediments (T_s , table 1, fig. 8) underlie the Flathead Valley, between the bedrock of the Salish Mountains to the west, and the Swan Range to the east. These units are dominated by mudstone, and contain some lenses of sand and gravel. The Tertiary sediments are interpreted to function as a basal aquitard in the Flathead Valley (LaFave and others, 2004; Bobst and others, 2022). A well completed in these sediments was purged for sampling, and a pumping rate of 0.4 gpm resulted in 75 ft of drawdown (Bobst and others, 2022).

Mountain Front Deposits

The mountain front deposits are a complex accumulation of sediments deposited near the Swan Range Front. They include coarse-grained sediments eroded from the steep mountain block mixed with till and other glacial deposits. Holocene alluvial fans (Q_{af}) and landslides (Q_{ls}) near the land surface were deposited across the till and, by analogy, are expected to also occur at depth. While these sediments are heterogeneous, they contain sand and gravel and are relatively coarse grained and permeable. Notably, these sediments are sufficiently permeable to allow infiltration of stream flow along the Swan Range Front, which explains why streams cease to flow once they cross the mountain front. The infiltration of streams along the mountain front provides recharge to both the shallow and deep aquifers (table 1, fig. 8). Monitored wells identified as being completed in these deposits (appendix A, table A1) had yields ranging from 3 to 20 gpm.

Glacial Deposits

The Flathead Lobe of the Cordilleran ice sheet advanced across the Flathead Valley during the Pleistocene, about 20,000 to 15,000 years ago (Porter and others, 1983). The glacier terminated at the south end of Flathead Lake, forming the Polson terminal moraine. This most recent glaciation covered and modified sediments from previous glaciations, so that the existing sediments dominantly reflect the last glacial advance and retreat. The glacial sediments in the Flathead Valley include those laid down as stratified drift in front of the glacier as it advanced, ice-proximal deposits formed near the glacier, and lacustrine sediments deposited as the glacier retreated. The compactness, grain sizes, and sorting of the sediments are important for evaluating aquifer properties.

Stratified Drift—The Deep Aquifer

The deep aquifer is composed of silty sand, sand, and gravel, and occurs in the subsurface in much of the Flathead Valley (Smith, 2004g; Rose and others, 2022; Bobst and others, 2022). It also outcrops along the Flathead River east of Columbia Falls (Erdman, 1947). These sediments are interpreted to be glaciofluvial outwash deposits, deposited prior to the Flathead Lobe of the Cordilleran ice sheet advancing across the valley. The deep aquifer is typically the most productive hydrogeologic unit in the study area, with variable aquifer properties, both geographically and stratigraphically. Clast lithologies represent Belt bedrock sources. The upper portion of the deep aquifer is commonly rich in silt (Smith, 2004g; Rose, 2018), suggesting accumulation of sediment in ice-marginal or proglacial lake environments directly in front of the advancing Flathead Lobe (Rose, 2018; Smith, 2004g; Anderson, 1989; Eyles and others, 1988). Wells monitored for this study completed in the deep aquifer (appendix A, table A1) have a median yield of 50 gpm and an interquartile range from 30 to 100 gpm. Yields of over 3,000 gpm have been reported for some wells completed in the deep aquifer.

Results from 25 aquifer tests performed on the deep aquifer within the Flathead Valley (summarized in Berglund and others, 2024) also reflect the variability in sediment types. Reported hydraulic conductivity (K) values vary from 1.7 to 1,287 ft/d, with an interquartile range from 37 to 214 ft/d, and a geometric mean of 65 ft/d. This is consistent with the range ex-

pected for sediments ranging from silty sand to gravel (Heath, 1984). The deep aquifer is approximately 800 ft thick in the south-central Flathead Valley (Bobst and others, 2022). A 900-ft-deep well that produced over 1,000 gpm was recently drilled in the southern portion of the East Flathead Study Area (GWIC 336290; R. Noble, written commun., 2025); the deep aquifer is at least 622 ft thick at that site.

Ice-Proximal Deposits

Deposits formed on, in, under, and adjacent to glaciers are complex due to dynamic changes in meltwater and sediments inputs over short distances and times (Fetter, 1994; Maizels, 1995). For instance, meltwater production, which affects sorting, may show strong daily and seasonal variations. The major ice-proximal deposit types in the Flathead Valley are basal till, ablation till, and glacial-fluvial deposits.

Till Aquitard. The till aquitard (table 1) is a basal till deposited beneath the glacier, and is mainly composed of massive, commonly compact diamicton (Smith, 2004a). It is typically water-saturated in the subsurface but produces little water to wells and functions as an aquitard in the study area (Smith, 2004a). The glacial till is a relatively thick and continuous unit in the central portion of the Flathead Valley, where it was not eroded by subglacial water discharge and post-glacial streams (fig. 8). In the northern portion of the study area, west of the Swan Range Front, and in the southwest portion of the study area, north-to-south-oriented troughs cut through the basal till and into the underlying deep aquifer (fig. 4 denoted as the confining layer >300 ft; Smith, 2004d). In these areas the till is not present (Smith, 2004g). The troughs were likely eroded subglacially and were subsequently filled with fine-grained lacustrine sediments (described below; Smith, 2004g).

Ablation Till. Ablation till (table 1; fig. 8) forms from the melting of stagnant glacial ice. As a glacier stagnates, meltwater reworks till and other ice-contact deposits, resulting in typically convoluted mounds of stratified drift. This unit is common in the Many Lakes area in the southeastern portion of the study area, south of Lake Blaine (fig. 2), and it forms characteristic knob and kettle topography (Smith, 2004a). The unit is dominated by pebble and cobble conglomerate, with lesser amounts of diamicton, sand, silt and clay, and stratified drift. Although the stratification causes

vertical variations in sediment types, the ablation till is typically productive for water wells (Smith, 2004a), with reported median yields of 25 gpm (LaFave and others, 2004). Lake elevations in the Many Lakes area fluctuate seasonally with changes in groundwater elevations (LaFave and others, 2004), suggesting that the lakes are recharged by and discharge through the ablation till.

Glacial Fluvial Sediments (Intermediate Aquifers). Glacial till (table 1) is often reworked by meltwater, resulting in deposition of glacial fluvial sediments. Sand and gravel layers were deposited along with the glacial till (Smith, 2004a), and form intermediate aquifers, stratigraphically above the deep aquifer, but below the modern shallow aquifers. While these are not present in all locations, and are typically thin (<~20 ft), they are locally important for domestic water supplies. Reported yields for wells identified as completed in the intermediate aquifer for this study (appendix A, table A1) had a median yield of 20 gpm, with an interquartile range from 15 to 33 gpm. These units are interpreted as being englacial or subglacial alluvium (table 1; Smith, 2004g). There are areas where the intermediate aquifers are reported to be interfingered with the deep aquifer (fig. 4; Smith, 2004d). Groundwater elevation monitoring and water-quality results (see below) also indicate that the intermediate aquifers can be (1) isolated lenses, (2) connected to the deep aquifer, or (3) connected to the shallow aquifer. The nature of these connections depends on the site-specific stratigraphy.

Results from 17 aquifer tests performed in wells completed in the intermediate aquifers indicate that K values range from 7.9 to 1,180 ft/d, with an interquartile range from 57 to 402 ft/d and a geometric mean of 129 ft/d (Berglund and others, 2024). These values are similar to or somewhat higher than K values in the deep aquifer, indicating that these sand and gravel layers can be relatively well sorted; however, the intermediate aquifers are thinner than the deep aquifer. These K values are consistent with the range expected for sediments ranging from sand to gravel (Heath, 1984).

Lacustrine Sediments

Lacustrine, or lakebed sediments, were deposited during and after the retreat of the Flathead Lobe of the Cordilleran ice sheet (Smith 2004a,g). Lacustrine units have been mapped as fine glacial lacustrine sediments (Q_{gl} in Smith, 2004a), and sandy glacial lacustrine

sediments (Q_{gls} in Smith, 2004a). These units were deposited in proglacial environments and grade into glacial fluvial deposits. As the glacier retreated, its influence was reduced, resulting in finer sediments.

Glacial lakes that occupied parts of the Flathead Valley include both Glacial Lake Missoula and ancestral Flathead Lake. Glacial Lake Missoula developed behind a glacier ice dam on the Clark Fork River near the present Idaho/Montana border, and existed until about 14,000 years ago, with many episodes of filling and draining (O'Connor and others, 2020). Radiocarbon (^{14}C) age determinations of lacustrine sediments cored using roto-sonic techniques for this project, in the southwestern part of the study area (well 105; fig. 5), date to 15,821–15,566 calendar years before present (Smith and Bobst, 2025). This age suggests Glacial Lake Missoula inundated at least part of the Flathead Valley, leaving behind lacustrine deposits that are more than 250 ft below the current land surface.

Fine Lacustrine Sediments. Fine lacustrine sediments were deposited in low-energy environments, generally further from the glacier and the shore, and in deeper water. The fine lacustrine deposits are found at elevations up to 3,050 ft-amsl. These sediments are particularly thick where troughs were subglacially eroded through the till and into the deep aquifer, and then filled with fine lake sediments. A single slug test conducted in the fine lacustrine sediments in the Flathead Valley (Bobst and others, 2022) showed that groundwater elevations recovered very slowly, with an estimated K value of 0.0007 ft/d. While that site is outside of the study area, the results still inform our understanding of this unit. At that site the deep aquifer was also pumped, and the best-fitting solution for that test was based on a non-leaky confining layer (Theis, 1935; Bobst and others, 2022). Two aquifer tests were also conducted by the MBMG for this study, where pumping was from the deep aquifer, and the deep aquifer was overlain by fine lacustrine sediments. Pumping for these aquifer tests was from wells 95 and 103 (fig. 5; Myse and others, 2023). For these tests the best-fitting solution was leaky confined (Hantush, 1960), but with low leakage values, and wells in the overlying shallow aquifers showed no measurable response to pumping. This unit functions as a slightly leaky aquitard.

Sandy Lacustrine Sediments. Lacustrine sediments on the eastern side of the study area (fig. 8) contain

more sand and gravel, suggesting they were deposited closer to shore, in a more energetic shallow water environment, and nearer fluvial inputs to the lake. These sandy lacustrine deposits are interpreted as being deltaic, partly based on the roto-sonic coring conducted for this project (Smith and Bobst, 2025). There is a gradational contact between the deep-water fine lacustrine deposits and near-shore sandy lacustrine deposits (Smith and Bobst, 2025). A 72-h constant-rate aquifer test was conducted at well 125 (fig. 5), where the deep aquifer is overlain by sandy lacustrine sediments (Myse and others, 2023). During that test groundwater levels in the shallow aquifer responded to pumping the deep aquifer. The sandy lacustrine sediments allow noticeable flow between the deep and shallow aquifers despite these sediments being less permeable than the overlying and underlying units, and partially confining the deep aquifer. Smith (2004a) reports that these units are locally productive for water wells. This unit functions as a low-productivity aquifer, and allows for flow between the shallow and deep aquifers.

Shallow Aquifers

The shallow aquifers are composed of a variety of sediment types (table 1). These materials are grouped into a single hydrogeologic unit since they have a common stratigraphic location above the lacustrine and till confining layers, typically are unconfined, have a direct hydraulic connection to surface waters, and are often able to supply sufficient water for domestic wells. Shallow aquifers occur along stream valleys where Holocene alluvial deposits are thick enough to be partially saturated, such as along the Flathead River floodplain and its tributaries. Sheet-like deposits of outwash, sandy lacustrine deposits, and ablation till also contain shallow, unconfined aquifers. The lateral boundaries of each unit often coincide with where they are incised into the subjacent confining unit.

Aquifer test results from the shallow aquifers (Berglund and others, 2024) reflect the variability of sediment types. Eight aquifer tests conducted in the shallow aquifers showed K values ranging from 3.2 to 655 ft/d, with the interquartile range from 12.1 to 514 ft/d and a geometric mean of 53 ft/d. These values are consistent with sediments ranging from fine sand to gravel (Heath, 1984). Reported yields have a median of 30 gpm, but yields are highly variable (LaFave and others, 2004).

Overall, the drop in the elevation of Ancestral Flathead Lake due to spillway erosion represents a shoreline recession, where deep water lacustrine sediments were replaced by near-shore lacustrine sediments, which were reworked and replaced by fluvial sediments. As such, the contacts between these units are gradational. These units also grade into the mountain front deposits along the east side of the Swan Range. The glacial outwash sediments (table 1) are interpreted as being deposited primarily by braided streams draining the increasingly distant ice sheet. As the elevation of Ancestral Flathead Lake dropped, streams eroded into the older deposits, and alluvial deposits were emplaced in broad sheets on top.

Windblown eolian sediments were deposited on top of the glacial outwash, and across the landscape (shallow silt; table 1). These sediments are fine sand to silt sized and are interpreted as sand dunes and sand sheets. These units show wind-ripple cross-laminations and large-scale sand flow cross-stratification. The Glacier Peak ash (tephra) occurs near the base of this unit and has been dated at 13.7–13.4 cal ka B.P. (Kuehn and others, 2009). This unit is not known to produce water and is often above the groundwater table.

Groundwater Flow

Flathead Lake provides an important control on groundwater elevations in the Flathead Valley. Prior to construction of the Seli's Ksanka Qlispe' Dam near Polson in 1938 (fig. 1), the natural annual low pool elevation of modern Flathead Lake was about 2,880 ft-amsl (USGS site Flathead Lake at Polson MT; site S6, appendix B). Lake elevations now depend on management of the dam. Average daily lake elevations from the USGS (site S6) show that from 1999 to 2022 the mean elevation was held between 2,892 and 2,893 ft-amsl over the summer, from June 6th to October 6th. The average pool elevation declined through the fall and winter, reaching an average minimum of about 2,885 ft-amsl in March. The lake elevation then increased during the spring runoff from snowmelt waters.

Deep Aquifer

Groundwater elevations in 66 wells completed in the deep aquifer were monitored for this project. Groundwater elevations from 82 wells monitored by the MBMG from previous investigations were used to

increase data density both within the study area and beyond the extents of the study area. This allowed the potentiometric surface to be extended beyond the study area to provide a more complete view of groundwater flow through the deep aquifer (fig. 9). The most recent groundwater elevations for each well from previous studies were measured between 1996 and 2015. Since all wells were not measured at the same time, the average measured groundwater elevation was used to represent long-term average conditions. Based on the GWAP long-term monitoring wells (fig. 5; appendix A), seasonal variations in static groundwater levels are up to about 10 ft in the valley fill sediments. While the error introduced by using the average values rather than synoptic values may cause slight changes in the potentiometric surface (fig. 9), the general shape of the surface would be similar.

The deep aquifer potentiometric surface (fig. 9) shows that groundwater flows into the study area from the Swan Range in the east, and through the Swan Valley in the southeast. Near the center of the south side of the study area, a bedrock high (the north end of the Mission Range) creates a boundary within the deep aquifer, so that water from the Swan Valley flows north into the study area before turning to the south. Groundwater exits the study area to the west and southwest boundaries, flowing towards Flathead Lake on the west side of the bedrock high.

Smaller scale variations in the deep aquifer potentiometric surface also provide information on the local flow systems. Groundwater contours deflect to the southwest near Lake Blaine, reflecting recharge in that area. The contours deflect to the northeast, south of Lake Blaine, reflecting the convergence of groundwater flow from the Lake Blaine area and from the Swan Valley, and groundwater discharge from the deep aquifer to the shallow aquifer.

Shallow Aquifers

Thirty-three wells were monitored in the shallow aquifers during this study, and the averages of measured groundwater elevations were used to develop a potentiometric surface (fig. 10). The shallow potentiometric surface shows that groundwater flow is generally from the Swan Range toward the Flathead River. The 2,950 ft contour reflects groundwater discharge to Jessup Mill Pond and Mill Creek. A notable difference between the shallow and deep aquifers is that the bed-

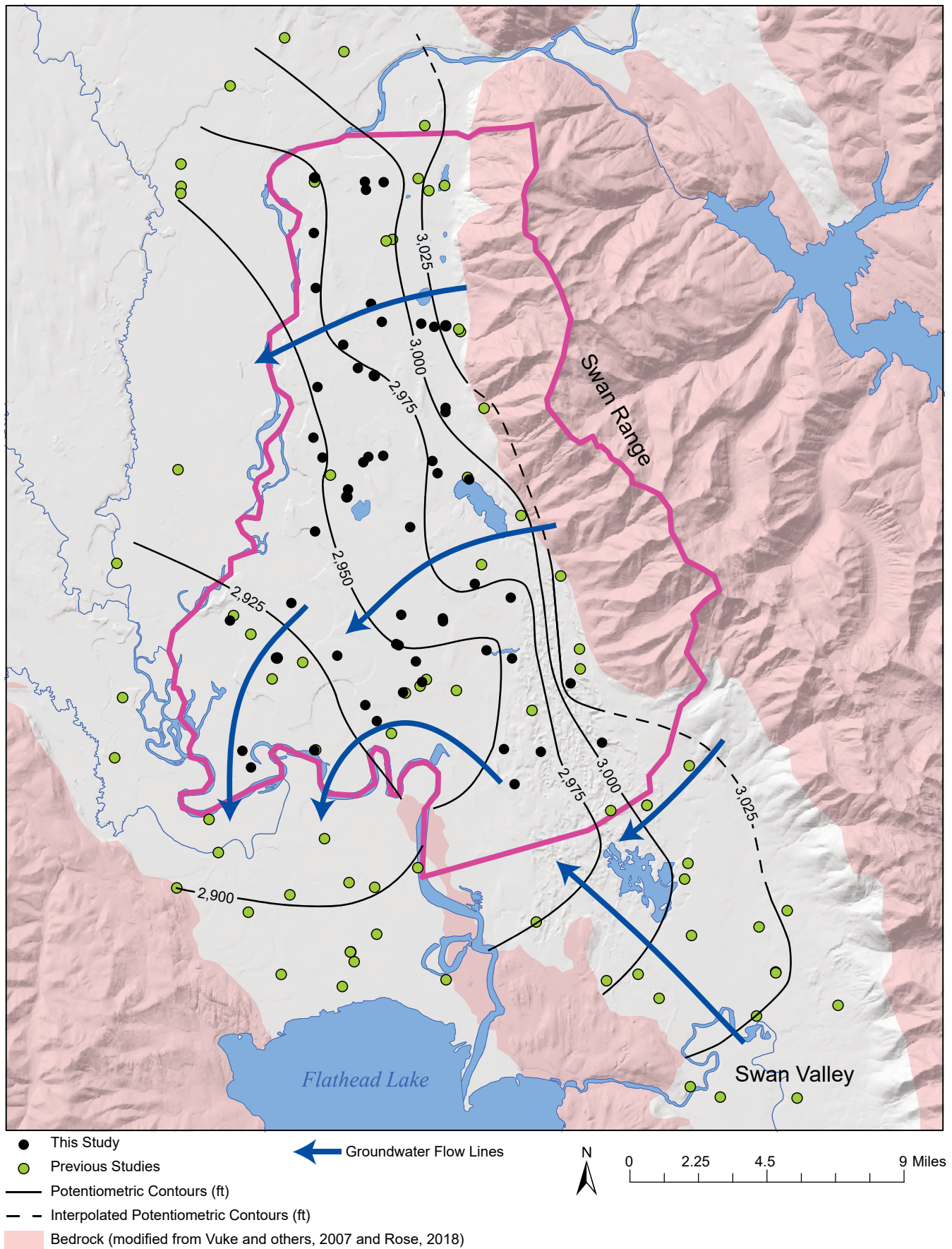


Figure 9. Deep aquifer potentiometric surface based on average groundwater elevation readings from wells during this study, and from previous MBMG monitoring in the area. Groundwater generally flows into the study area from the Swan Range and Swan Valley, and flows out towards Flathead Lake. Flow is around the bedrock high at the north end of the Mission Range (fig. 1).

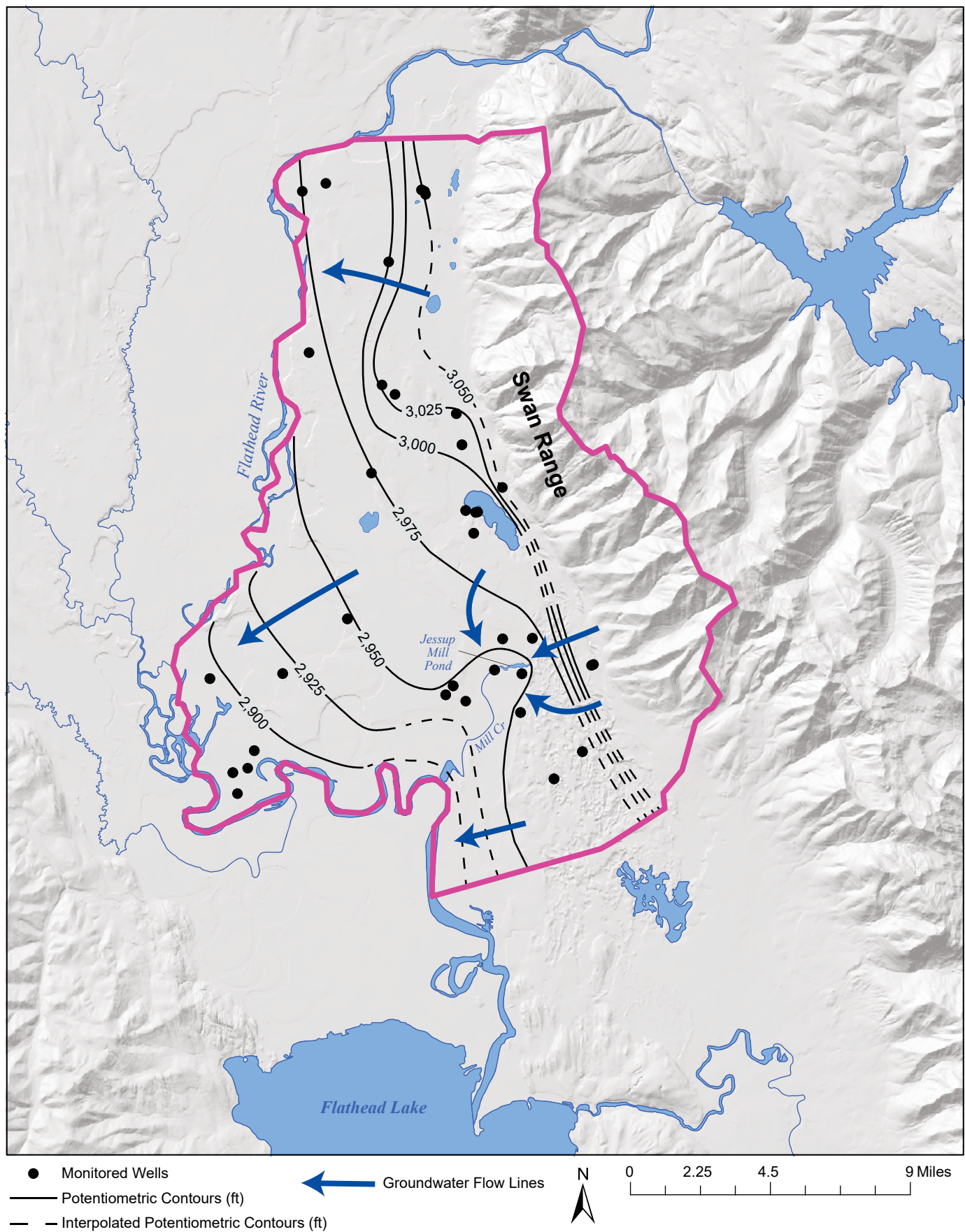


Figure 10. The shallow potentiometric surface based on monitoring during this study shows that flow is generally from the Swan Range to the Flathead River. The trough in the south suggests outflow to Jessup Mill Pond and Mill Creek.

rock high that bisects the deep aquifer near the south end of the study area is not present in the shallow aquifers, so groundwater flow in the shallow aquifer is to the west rather than to the north in the southeast portion of the study area.

Vertical Gradients

Vertical hydraulic gradients were evaluated by comparing groundwater elevations in the shallow and deep aquifers from the calibrated steady-state model, and in 18 areas with monitored wells completed in different hydrogeologic units (fig. 11; appendix A, table A2, fig. A1). The intermediate aquifer groundwater elevations may be similar to the shallow aquifer, similar to the deep aquifer, or between the shallow and deep aquifers (fig. 12). This suggests that the intermediate aquifer may be directly hydraulically connected to the shallow aquifer, the deep aquifer, or neither, depending on the site-specific stratigraphy. The type of lithologic connections at a site are not readily apparent from drillers' logs. Comparisons also show that while groundwater elevations in the different aquifers were similar in most areas, the shallow and deep aquifer have more pronounced differences in the northeast and south portions of the study area.

Shallow groundwater elevations are up to 59 ft higher than those in the deep aquifer in the northeastern portion of the area (fig. 11), indicating a downward gradient (maximum downward gradient of 0.25). This may represent a perched shallow aquifer in that area, reflecting a continuous confining layer.

Deep aquifer groundwater elevations were observed to be up to 28 ft higher than in the shallow aquifers (maximum upward gradient of 0.21) in the southern portion of the area near Jessup Mill Pond and Mill Creek (figs. 2, 11). In this area, groundwater flow paths converge from the north and south, and flow in the deep aquifer is constrained by the bedrock high. This area is also known to have flowing artesian wells. Since groundwater discharges from the shallow aquifer to Jessup Mill Pond, Mill Creek, and the Flathead River, there is an upper limit on groundwater elevations in the shallow aquifer in that area.

Seasonal Groundwater-Elevation Variations

Groundwater hydrographs capture the dynamic behavior of the aquifer system in response to the seasonality of recharge and pumping. Two major pat-

terns were identified in the hydrographs: "asymmetrical" and "plateau." These patterns are similar to the "runoff response" and "pumping response" patterns identified by LaFave and others (2004) for analysis of hydrographs in the broader Kalispell area. The type of seasonal hydrograph appears to depend on the well's geographic location (fig. 13), but, somewhat surprisingly, was not correlated with well depth (Berglund and others, 2024).

A pumping response plateau-type hydrograph is generally observed away from the mountain front (fig. 13). Groundwater elevations are generally consistent from September to June (plateau), which is attributed to well locations that are relatively isolated from snowmelt recharge. There is a sharp drop in groundwater elevations in July and August due to irrigation pumping. This pattern is observed in both pumped and non-pumped wells, indicating that it is a regional phenomenon. This pattern is most pronounced in the northern portion of the study area, where fine-grained lacustrine deposits fill a trough north of Lake Blaine and limit the hydraulic connection to mountain front recharge (figs. 4, 13). Due to generally drier conditions in 2021, pumping for irrigating crops and yards began earlier, and the summer drawdown was more pronounced.

Along the Swan Range Front, groundwater elevations showed a runoff response asymmetrical-type hydrograph (fig. 13), with peak water elevations occurring from June to August followed by a gradual decline until the pattern repeats. Wells closest to the mountain front have the earliest peaks in the spring, while wells further from the mountain front peak later in the summer, as shown best in the southeast part of the study area (fig. 13). This pattern is attributed to short duration, intense recharge from snowmelt along the mountain front, resulting in a sharp rise in water elevations. Groundwater elevations gradually declined after the peak until the onset of snowmelt the next spring. The snowpack was greater in 2020 than in 2021, so the magnitude of the peak was generally greater in 2020.

Two wells (wells 73 and 90) near the Flathead River also show an asymmetric response (figs. 5, 13), with the timing corresponding to the changing stage of the Flathead River. This response, while similar to the asymmetric pattern at the mountain front, is likely driven by the river stage. The similar response in wells

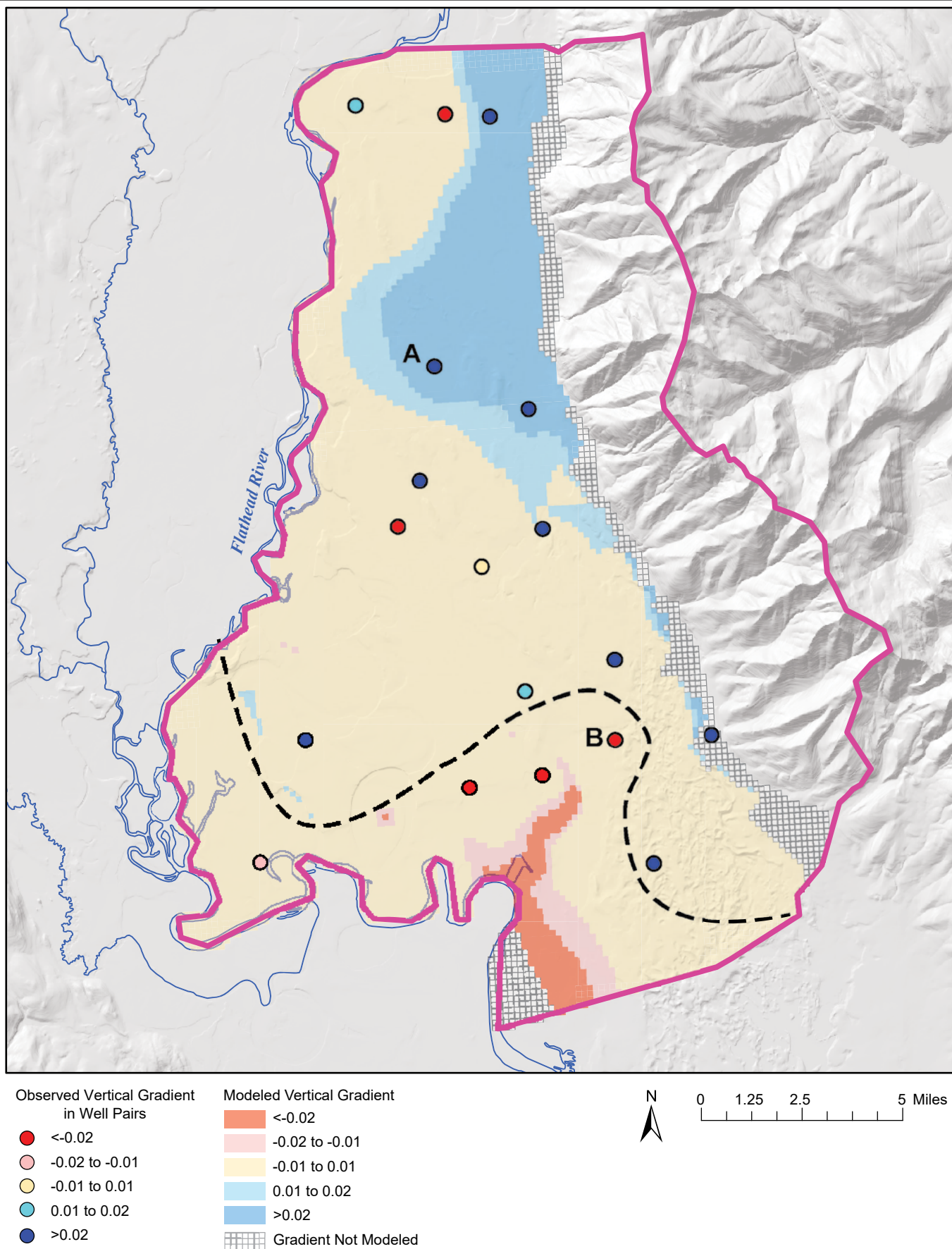


Figure 11. Average observed vertical groundwater gradients in well pairs (appendix A) and modeled steady-state head gradients between layers 1 and 4 (colored shading). Dashed line shows the boundary between a generally downward gradient (positive values) in the north and east, and a generally upward gradient (negative values) in the south. Labeled sites (A and B) have hydrographs shown in figure 12.

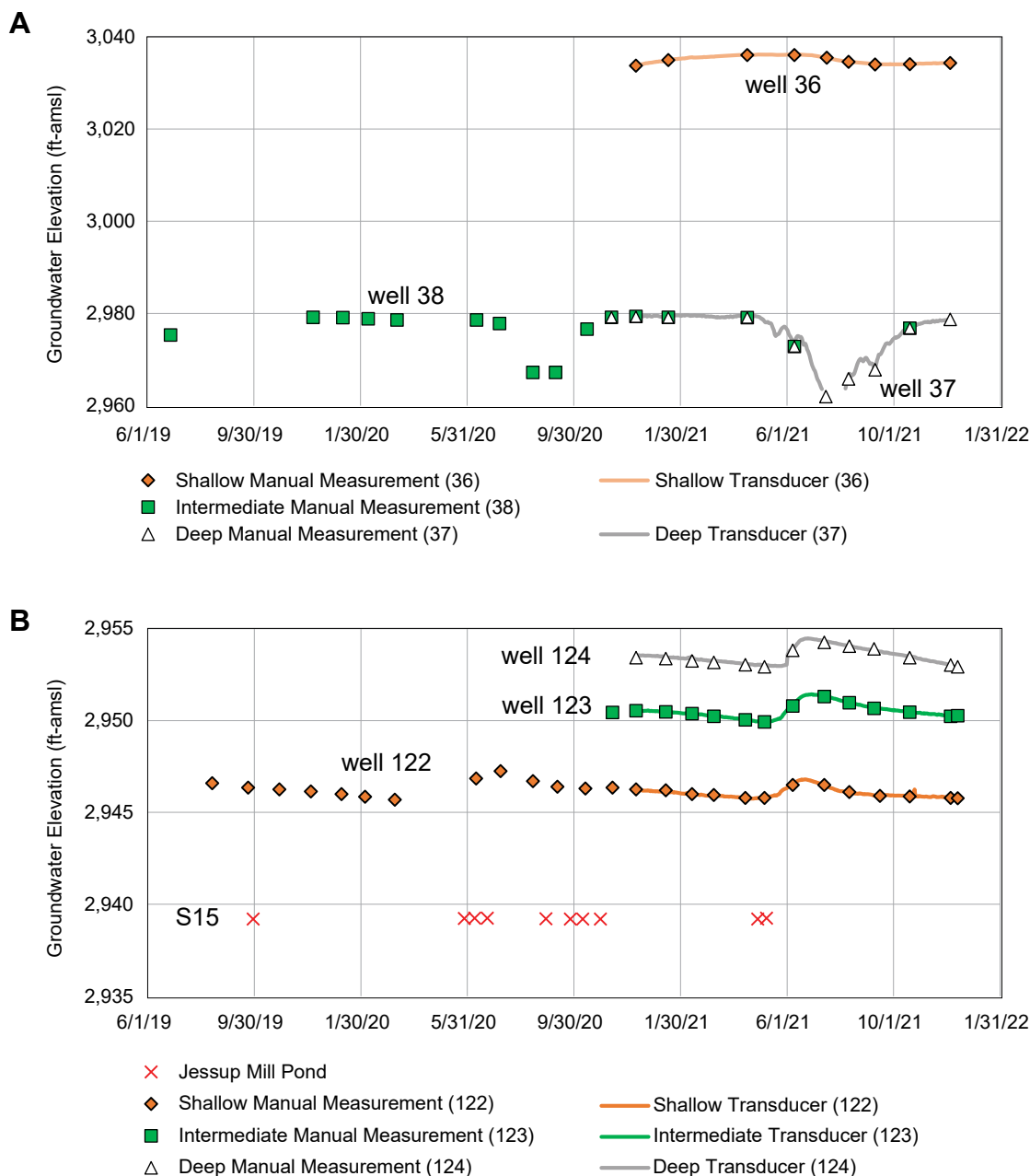


Figure 12. Vertical groundwater gradients and seasonal hydrograph patterns varied in the shallow, intermediate, and deep aquifers depending on their location within the study area. Locations of well groups are shown on fig. 11 (denoted by A and B). Well numbers (appendix A) are in parentheses in the legends. A downward groundwater gradient from the shallow to deep aquifers is shown in A, while an upward gradient is indicated in B. Note that the groundwater elevation in the intermediate aquifer is similar to that of the deep aquifer in A while it is between the groundwater elevations of the shallow and deep aquifer in B.

completed in the shallow and deep aquifers suggests a hydraulic connection in this area, which has also been mapped as having a thin confining layer (Smith, 2004d; fig. 4).

Some wells display mixed patterns, such as a double peak, with two maxima occurring around November and June with declines in between (fig. 13). These are interpreted to be a combination of the types above, where there is a noticeable response to both snowmelt recharge and summer pumping.

Water Chemistry

The analytical results from this study show that the water quality in the study area is generally good, with total dissolved solids (TDS) concentrations generally less than the secondary maximum contaminant limit (MCL) of 500 mg/L. However, there were a few exceedances of drinking water regulatory standards (iron and arsenic) or human-health guidelines (manganese), which are discussed in subsequent sections.

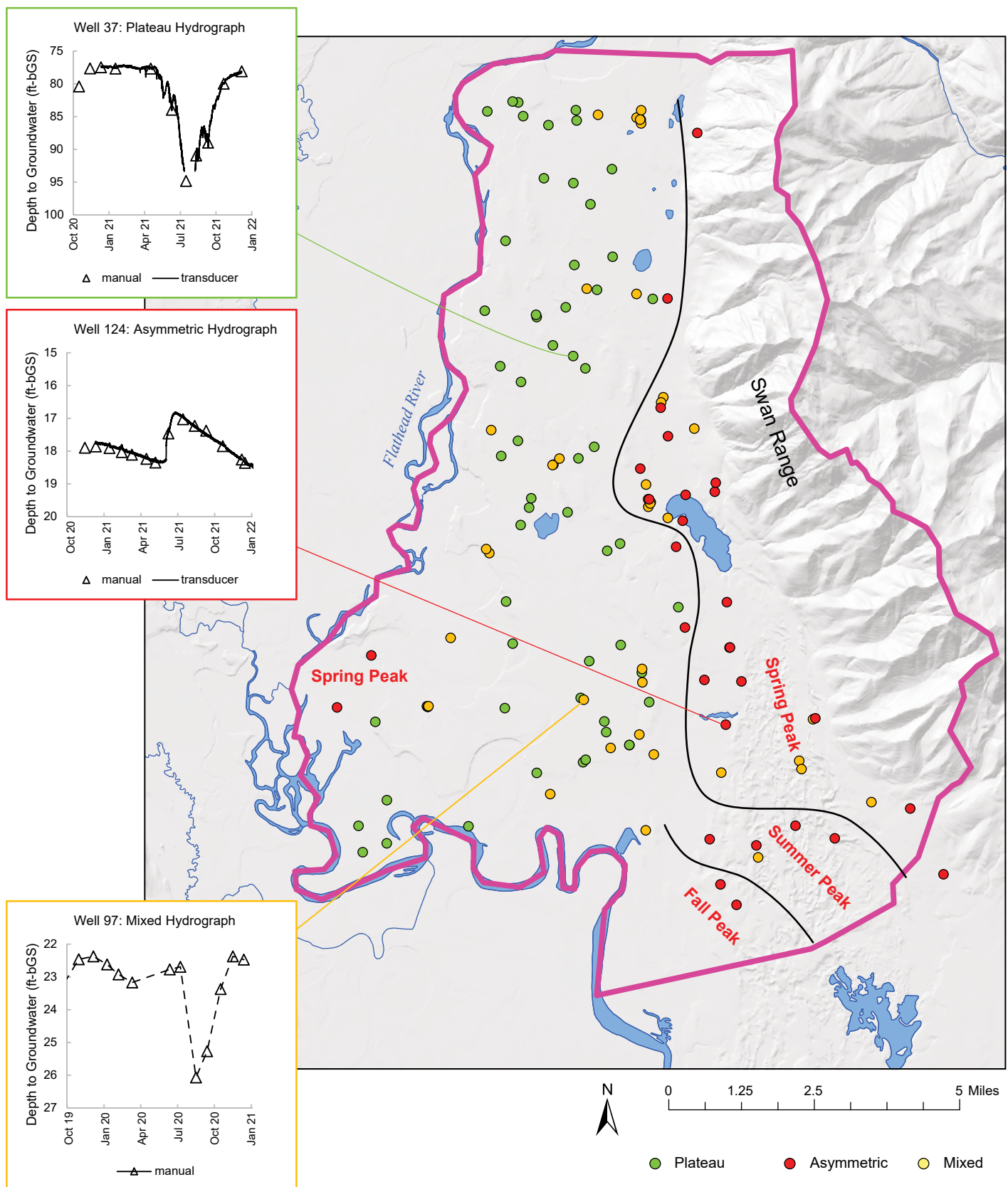


Figure 13. Well hydrographs showed different seasonal patterns depending on their locations. Seasonal patterns were not correlated with well depth or the aquifer the well is completed in.

According to the U.S. EPA (<https://www.epa.gov/radon/health-risk-radon>, accessed 10/30/25), radon is the second leading cause of lung cancer in the U.S., after smoking. Radon in water is a concern primarily due to it being released to the air, such as during showering. Although we did not sample for radon in this study, previous sampling in the area has shown that radon is relatively high (LaFave and others, 2004). Previous MBMG sampling from wells (29 samples from 18 sites; appendices A, C) shows that radon concentration ranged from 119 to 6,160 pCi/L, with a median of 640 pCi/L. The proposed MCL of 300 pCi/L was exceeded in 86% of the samples, and at 89% of the sites. We found that the 9 samples from bedrock wells had a median concentration of 817 pCi/L (ranging from 718 to 6,160 pCi/L), while samples from unconsolidated units ($n = 20$) had a median of 475 pCi/L (ranging from 119 to 1,590 pCi/L). Interestingly, some wells that were sampled multiple times (e.g., well 55) showed considerable variation (in this case from 119 to 690 pCi/L), but with no apparent trend.

Major Ions

Major ion composition was examined for groundwater and surface-water samples to identify if there were differences in water chemistry among the shallow, intermediate, and deep aquifers, and surface-water sources (i.e., streams, ponds, lakes, and rivers). Stiff diagrams use the major ion composition to “type” water. Water type is based on the percentage of milliequivalents per liter (meq/L) from each of the major cations (Ca, Mg, Na, and K) and anions (HCO_3 , SO_4 , and Cl). For example, in a Ca-type water, Ca contributes more than 50% of the cation meq/L. In a Ca-Mg-type water, Ca and Mg would each contribute between 25 and 50% of the cation meq/L, while Na and K each contribute <25%. For a mixed cation water type, Ca, Mg, and Na would each contribute between 25 and 50% of the cation meq/L.

For figures 14 to 17, which illustrate water type, we used the results from the most recent sample at each site since there were not substantial differences between sampling events. For this reason, the number of samples from the text will not match the number of sites shown on the figures. We also used the most recent results to evaluate concentrations of nitrate, iron, manganese and arsenic (fig. 18). Analytical results are summarized in appendix D. GWIC numbers for all sampled sites are included in appendices A, B, and

C, and additional analytical results are available from GWIC (<http://mbmggwic.mtech.edu/>).

Groundwater

This and previous studies collected a total of 152 groundwater-quality samples in and near the study area (appendix A, table A1; appendix C). The TDS of groundwater samples ranged from 79 to 1,052 mg/L; however, samples from one site (P6; intermediate aquifer) had much higher TDS values (856 and 1,052 mg/L). When those values are removed the range is from 79 to 542 mg/L, with a median of 210 mg/L. The samples from wells completed in bedrock generally had the lowest TDS (median of 160 mg/L), while samples from the other aquifers were similar to each other with median values from 199 to 216 mg/L (appendix D, table D2).

The relatively low TDS (generally <500 mg/L) indicates that silicate weathering is likely the dominant process contributing ions to the water (Hounslow, 1995), consistent with the weathering of the dominant siltite of the Belt bedrock (Lonn and others, 2020). The groundwater samples had HCO_3 (in meq/L) to SiO_2 (in millimole/L) ratios between 8 and 63, with a median of 23. This relatively high ratio (generally >10) indicates that carbonate dissolution is also an important process (Hounslow, 1995). This is consistent with the weathering of subordinate metacarbonates of the Belt bedrock (Lonn and others, 2020).

Most of the groundwater samples were either Ca-HCO_3 (62%) or Ca-Mg-HCO_3 (29%) types (figs. 14–16). The major-ion chemistry for the different aquifers largely overlapped (fig. 16), suggesting weathering of similar Belt or Belt-derived materials, and/or groundwater mixing between aquifers. Samples with higher Na (sites 13, 132, P6, and P23; fig. 16) occurred near the mountain front (figs. 14–15). Sources of sodium include geothermal waters (Smith and Icopini, 2016) possibly along the Swan Mountain Front, cation exchange with sodic clays (Van Voast and Reiten, 1988), and septic system effluent (Harman and others, 1996).

Surface Water

This and previous studies obtained 52 water-quality samples from 31 surface-water sites (figs. 6, 16, 17). TDS values ranged from 70 to 366 mg/L, with the lowest values from S11 (Hemler Creek; fig. 17), and the highest values from S27 (an unnamed pond with

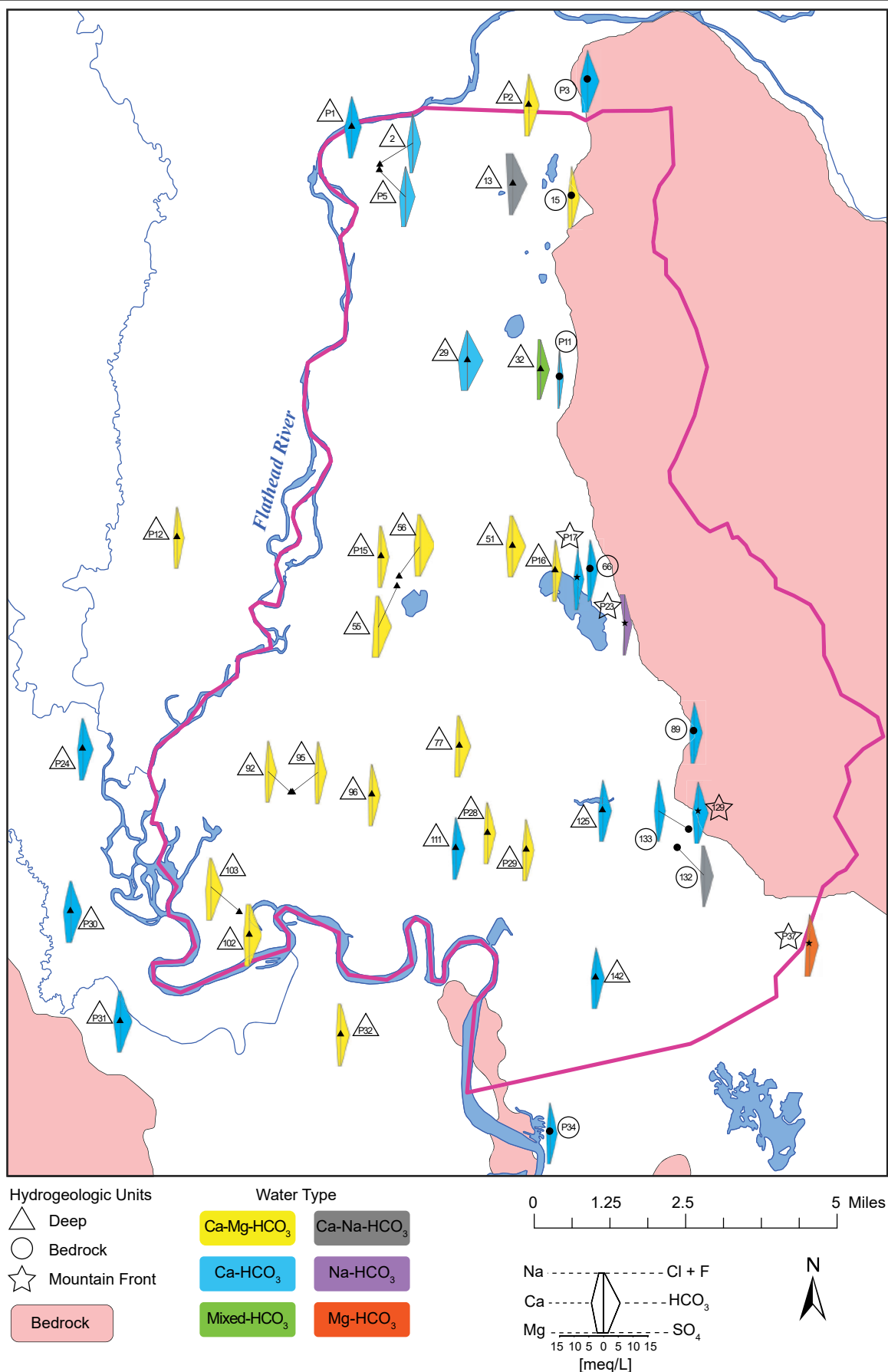


Figure 14. Groundwater Stiff diagrams for the bedrock, deep, and mountain front aquifers show that most waters are Ca-HCO₃ or Ca-Mg-HCO₃. Samples with higher relative concentrations of Na or Mg occurred near the Swan Mountain Front. Well numbers are shown in the hydrogeologic symbol next to each Stiff diagram.

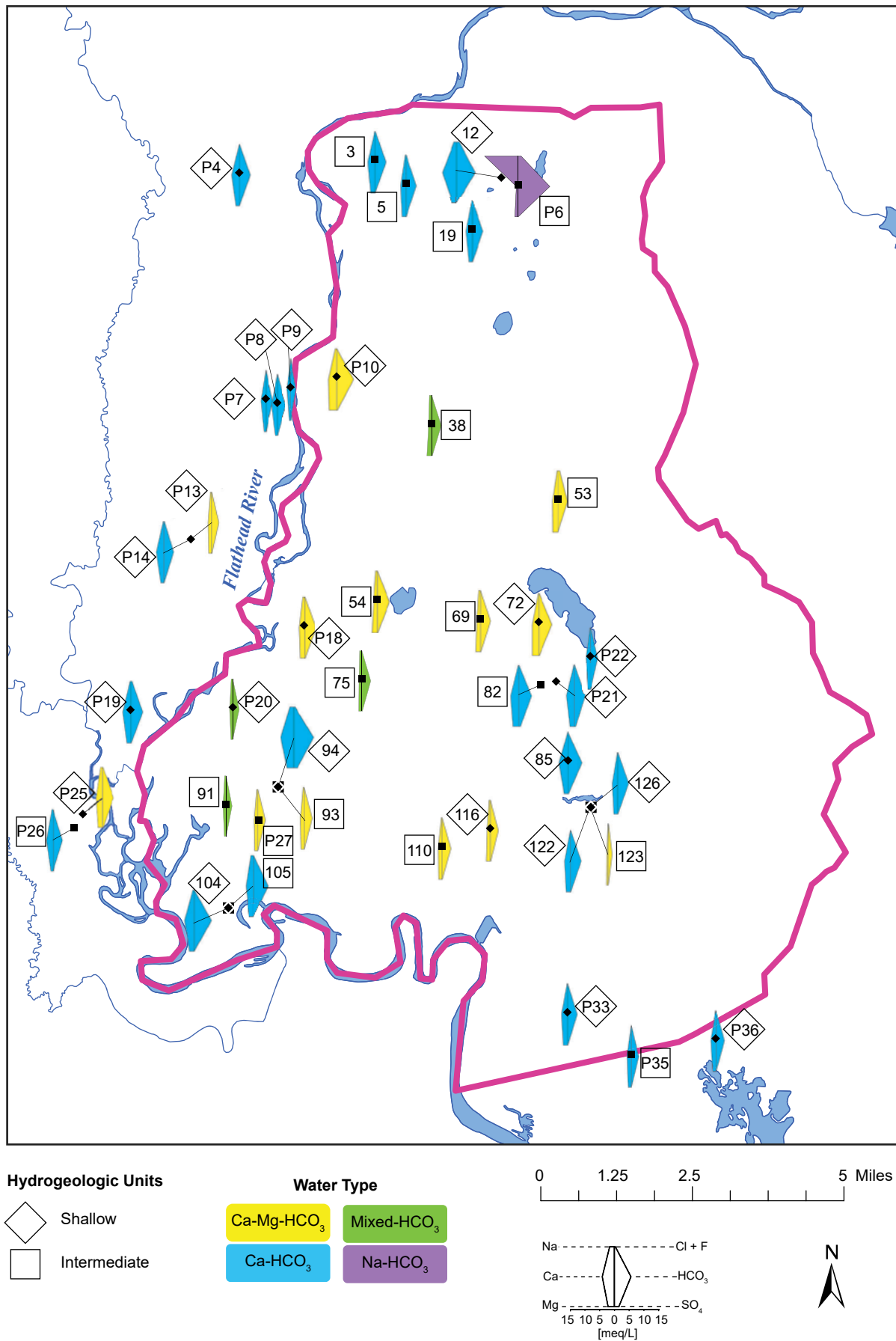


Figure 15. Groundwater Stiff diagrams for the intermediate and shallow aquifers show generally higher TDS than in the deeper zones, and a more heterogeneous distribution of water types (compared to fig. 14). Well numbers are shown in the hydrogeologic symbol next to each Stiff diagram.

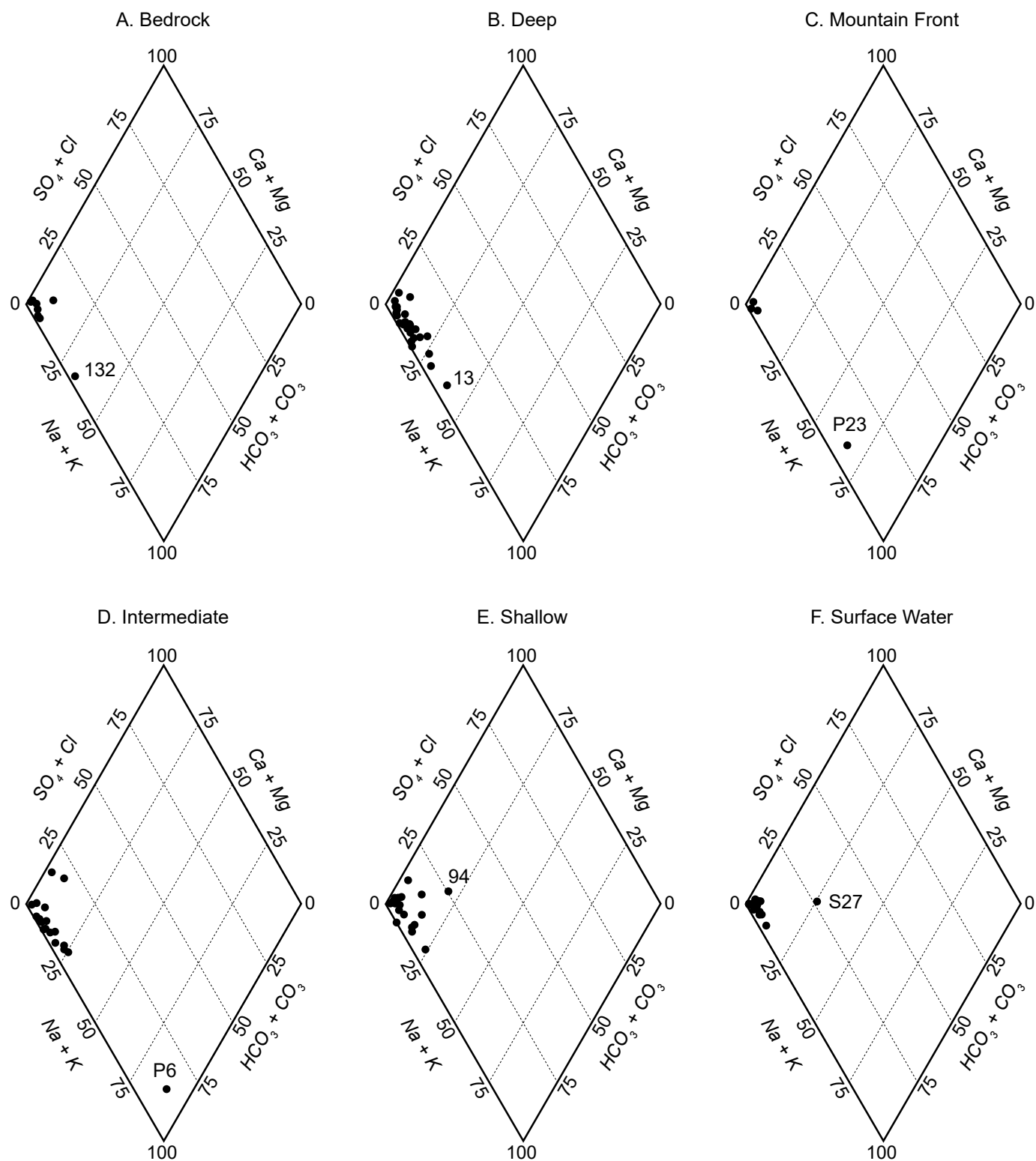


Figure 16. Water type in the study area was primarily calcium-bicarbonate or calcium-magnesium-bicarbonate (A-E). Some groundwater samples near the mountain front were relatively enriched in sodium (A-E; figs. 14 and 15). Surface waters were also primarily calcium-bicarbonate or calcium-magnesium-bicarbonate (F and fig. 17).

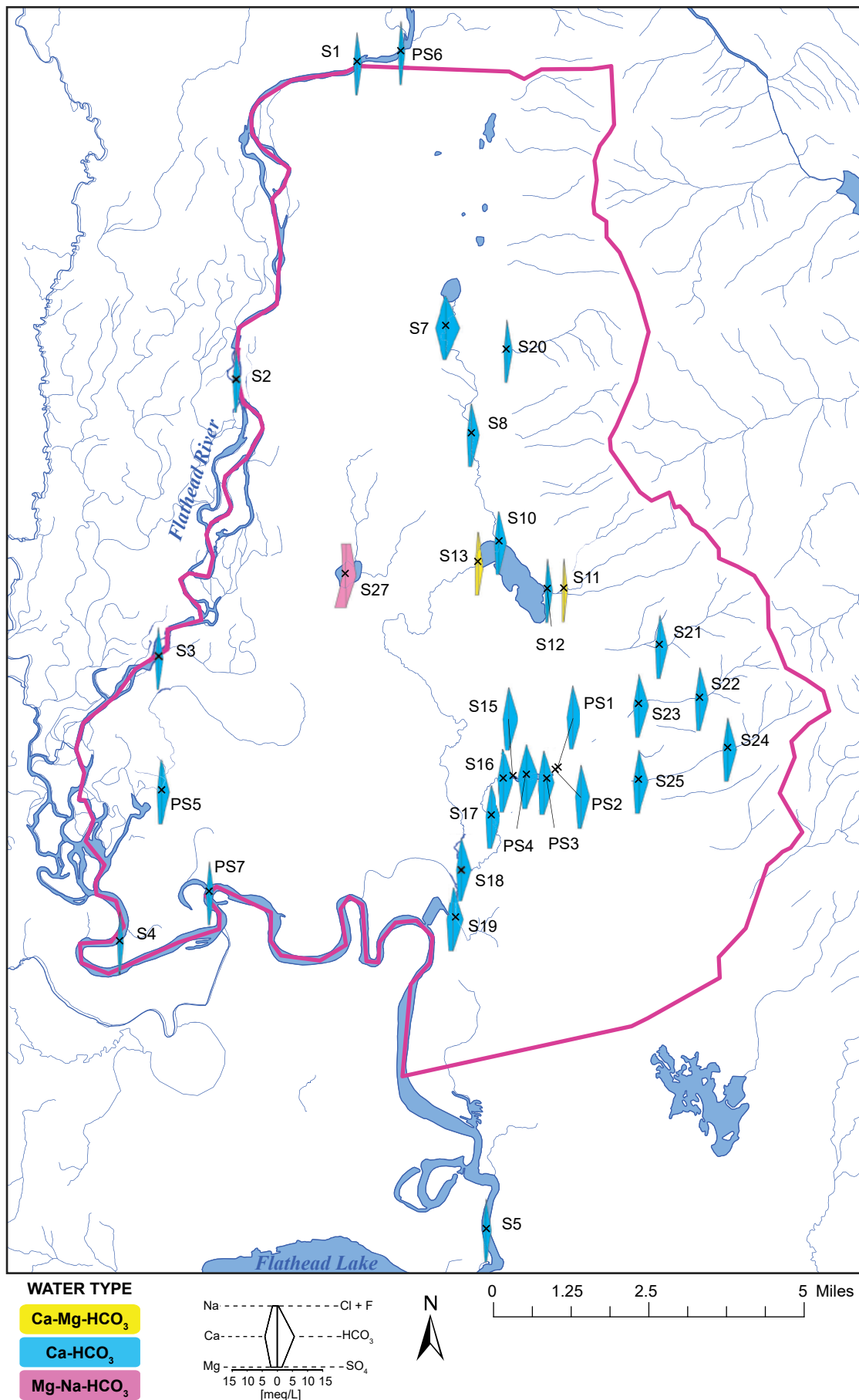


Figure 17. Surface-water samples showed that most waters were Ca-HCO₃ type, with slightly higher relative Mg concentrations near Lake Blaine. The unnamed pond (S27) shows a distinctly different chemistry, suggesting evaporative concentration and calcite precipitation.

no outlet; fig. 17). Surface-water types were mostly Ca-HCO₃ (48 samples; 92%) or Ca-Mg-HCO₃ (2 samples; 4%) (figs. 16, 17). Two samples from site S27 had a distinctly different Mg-Na-HCO₃ water chemistry (figs. 16, 17), which appears to result from evaporative concentration and precipitation of calcite; efflorescent calcite deposits were observed near this pond.

Nitrate, Iron, Manganese, and Arsenic

Stakeholders expressed concerns about groundwater nitrate concentrations; in addition, there were exceedance of drinking water standards or human health guidelines for iron, manganese, and arsenic.

Therefore, we evaluated those parameters in this section, while results for other parameters are available from GWIC (appendices A–C).

The drinking water maximum contaminant level (MCL) for nitrate is 10 mg/L. This standard was set by the Montana Department of Environmental Quality (MDEQ) to prevent health effects, such as blue baby syndrome (MDEQ, 2019). The nitrate results from groundwater and surface water ranged from non-detect (23% of the samples; DL ≤ 0.1 mg/L) to 3.6 mg/L (fig. 18). All nitrate results were below the MCL (table 2). Results prior to 2009 were not included in this evalu-

Table 2. Summary of water-quality results for NO₃, Fe, Mn, and As based on Regression on Order Statistics (ROS).

		Estimated Percentiles from ROS								
		<i>n</i>	<i>n</i> >DL	5%	10%	25%	50% (median)	75%	90%	95%
Nitrate (NO ₃ ; mg/L)	Overall	112	86	0.02	0.03	0.10	0.10	0.20	0.30	1.29
	Bedrock	8	8	0.10	0.10	0.10	0.20	0.23	0.30	0.30
	Deep	23	14	0.02	0.03	0.04	0.10	0.10	0.20	0.20
	Mountain Front	1	1	nc	nc	nc	nc	nc	nc	nc
	Intermediate	20	12	0.01	0.01	0.03	0.10	0.10	0.23	1.42
	Shallow	14	11	0.03	0.03	0.10	0.35	1.10	2.68	3.28
	Surface Water	46	40	0.06	0.07	0.10	0.10	0.20	0.20	0.30
Iron (Fe; mg/L)	Overall	204	125	0.0003	0.0006	0.0028	0.012	0.06	0.29	0.80
	Bedrock	19	6	0.0005	0.0006	0.0010	0.002	0.01	0.01	0.03
	Deep	44	34	0.0006	0.0009	0.0050	0.027	0.21	0.94	3.21
	Mountain Front	6	3	0.0001	0.0001	0.0001	0.004	0.06	0.99	1.45
	Intermediate	29	23	0.0034	0.0054	0.0124	0.044	0.12	0.25	0.28
	Shallow	54	42	0.0006	0.0010	0.0055	0.012	0.05	0.43	0.81
	Surface Water	52	17	0.0003	0.0004	0.0012	0.004	0.01	0.03	0.06
Manganese (Mn; mg/L)	Overall	201	85	0.00001	0.00002	0.0001	0.001	0.011	0.19	0.28
	Bedrock	19	1	nc	nc	nc	nc	nc	nc	nc
	Deep	44	24	0.00044	0.00079	0.0020	0.0077	0.155	0.28	0.28
	Mountain Front	6	1	nc	nc	nc	nc	nc	nc	nc
	Intermediate	29	20	0.00012	0.00020	0.0010	0.0040	0.059	0.24	0.26
	Shallow	54	18	3.35E-07	1.11E-06	1.37E-05	0.0002	0.004	0.17	0.37
	Surface Water	49	21	2.03E-05	4.39E-05	0.0001	0.0007	0.005	0.01	0.02
Arsenic (As; mg/L)	Overall	114	91	0.05	0.07	0.20	0.28	0.52	1.11	2.22
	Bedrock	9	6	0.27	0.28	0.32	0.39	0.47	0.50	0.54
	Deep	25	20	0.06	0.07	0.21	0.26	0.74	1.85	2.09
	Mountain Front	0	0	nc	nc	nc	nc	nc	nc	nc
	Intermediate	20	17	0.03	0.04	0.21	0.26	0.36	2.99	10.22
	Shallow	14	9	0.01	0.01	0.03	0.22	0.71	5.94	8.91
	Surface Water	46	39	0.12	0.15	0.24	0.30	0.52	0.61	0.87

Note. Highlight indicates exceedance of MDEQ MCL, SMCL, or human-health guidelines. DL, detection limit. *n*, number of samples analyzed; *n*>DL is the number of results above the DL. nc, indicates that we did not have at least 3 concentrations above the DL, so a distribution could not be calculated. ROS estimates the shape of a parameter's distribution based on the detected values and the distribution type. As an example of how to read this table, iron in the deep aquifer had a median concentration of 0.027 mg/L, and 10% of the samples were above 0.94 mg/L. Also see Helsel (2012).

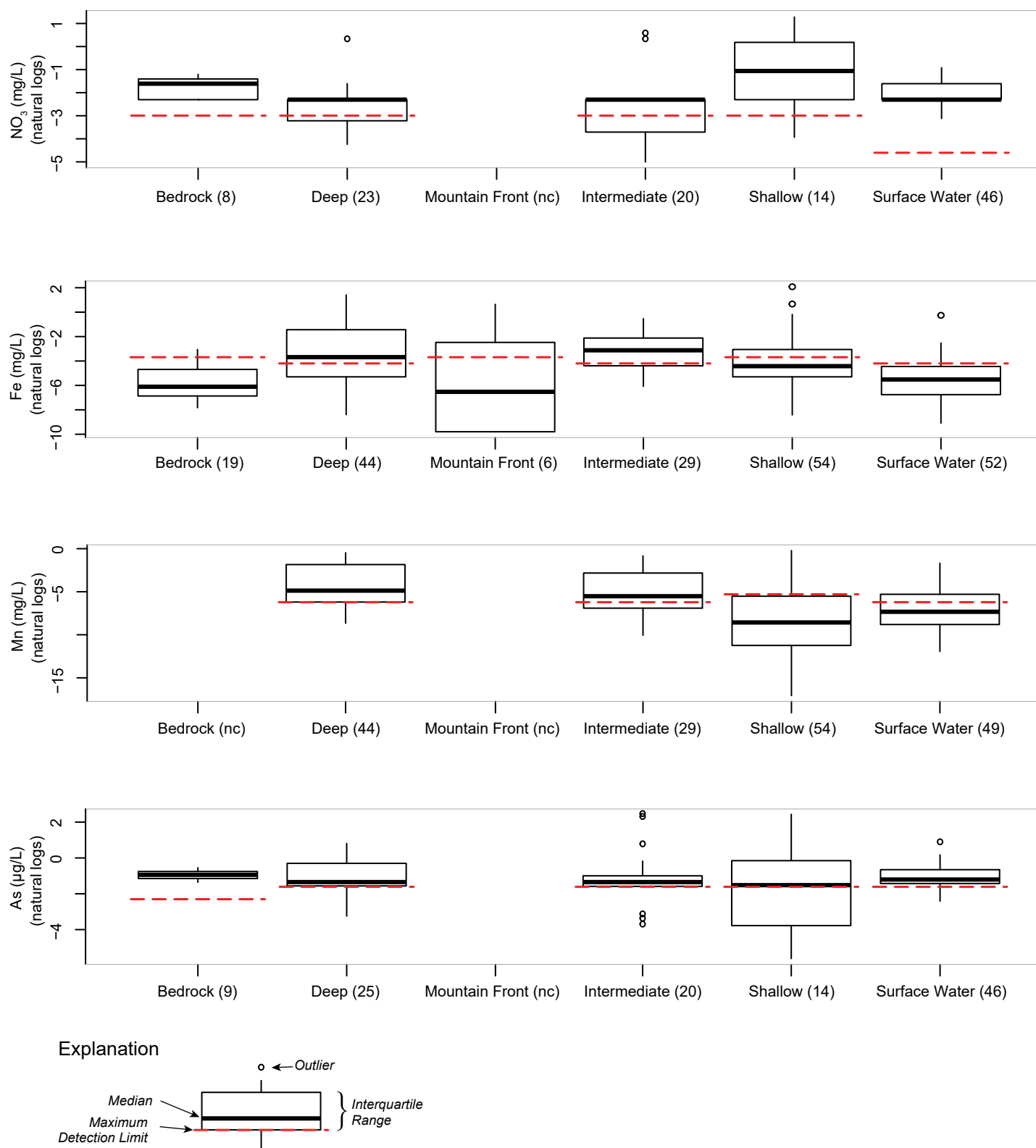


Figure 18. Concentrations of nitrate, Fe, Mn, and As in the hydrogeologic units and surface waters. Boxplots summarize analytical results for each constituent for each hydrogeologic unit. At least three values above the detection limit (DL) are needed for each group to allow estimation of the distribution for regression on order statistics (ROS); therefore, distributions could not always be calculated, and are denoted as "nc" (not calculated). Values in parentheses indicate the number of samples used, or indicate "nc."

ation since the detection limits were substantially higher. Nitrate concentrations were the highest in the shallow aquifers (fig. 18), consistent with nitrate being introduced from surface sources, such as septic systems or fertilizer. There was no apparent geographic pattern to the higher concentrations.

Iron (Fe) has a secondary MCL (SMCL) of 0.3 mg/L. SMCLs are set by MDEQ to be protective for aesthetic considerations, such as taste, color, and odor, even though the constituents are not considered to present a risk to human health. Iron was non-detect in 39% of the samples (DL ranged from 0.001 to 0.025 mg/L). The highest iron concentration was in the shallow aquifer, at 8.0 mg/L. Twenty of the 204 samples (10%) at 12 of 113 sites exceeded the SMCL. ROS estimated median Fe concentrations were highest in the intermediate aquifers, followed by the deep aquifer, and the shallow aquifers (fig. 18, table 2). Iron concentrations appear to be somewhat higher in the southern portion of the study area.

Drinking water that contains elevated manganese (Mn) is an aesthetic and potential human-health concern. It stains plumbing fixtures and laundry, and can impart a bitter taste to water (EPA, 2004, 2023; MDEQ, 2021). Emerging research indicates manganese in drinking water may be linked with memory, attention, and motor skill problems; children younger than 6 years old are particularly susceptible (Bouchard and others, 2007; ATSDR, 2012; Avila and others, 2013; Montana DEQ, 2021; Hanson and LaFave, 2022). Because of these human-health concerns, the MDEQ recommends that drinking water contains less than 0.1 mg/L for those 6 yr old and under, and less than 0.3 mg/L for those older than 6 yr. These MDEQ human-health guidelines for manganese are not regulatory standards. Measured Mn was non-detect for 58% of the samples (DL ranged from 0.001 to 0.005 mg/L). The maximum measured value was 0.8 mg/L from the shallow aquifer. Thirty-three of the 201 samples (16%) at 23 of 111 sites exceeded the human-health guidelines for those under 6 yr old (0.1 mg/L), and 8 samples (4%) at 7 sites exceeded the human-health guidelines for those over 6 yr old (0.3 mg/L). ROS estimated median Mn concentrations were the highest in the deep aquifer, followed by the intermediate aquifers (fig. 18, table 2). There was no apparent geographic pattern to the higher concentrations.

The MCL for arsenic (As) is 10 mg/L. This standard was set to prevent health effects such as liver and kidney damage (MDEQ, 2019). Arsenic concentrations from groundwater and surface water ranged from non-detect (20% of the samples; DL ranged from 0.1 to 0.2 mg/L) to 11.9 mg/L (fig. 18). Three samples from two sites from the intermediate aquifers (sites 19 and P6) and one sample from the shallow aquifers (site 104) had concentrations above the MCL. A total of 178 samples from 110 sites were evaluated for the ROS analysis. Sample results from prior to 2006 were not included in the analysis since the detection limits were substantially higher, resulting in 114 samples being used. ROS estimated As concentrations were the highest in the shallow and intermediate aquifers. There was no apparent geographic pattern to the higher concentrations.

Water Isotopes

Stable isotopes of water can provide insight into sources of water and hydrologic processes. The δD and $d^{18}O$ in precipitation will vary based on factors such as distance to the ocean, elevation, and temperature. Precipitation from around the world plots along the global meteoric water line (GMWL; Rozanski and others, 1993; fig. 19). Departure from the GMWL typically indicates fractionation due to evaporation or geothermal influences. Stable isotopes of water (δD and $d^{18}O$) were analyzed for 50 groundwater samples and 41 surface-water samples within the study area (fig. 19A; appendix D, tables D3, D4).

The groundwater samples plotted near the GMWL (fig. 19), indicating that the waters originated as precipitation, and have not been noticeably altered by geothermal exchange or evaporation. The groundwater samples were generally heavier (more negative) than the surface-water samples, suggesting recharge that originated from colder sources (e.g. mountain snowpack). There was substantial overlap between the isotopic composition of groundwater from the different aquifers (fig. 19B), indicating similar sources and potential intermixing.

Most (79%) of the surface-water samples also fell near the GMWL (fig. 19A). Nine samples fell below the GMWL, following an apparent evaporation line (Bowen and others, 2018). The two samples showing the most evaporation were collected from an unnamed pond between Lake Blaine and the Flathead River (site S27; figs. 7, 19A); the major ion chemistry of this

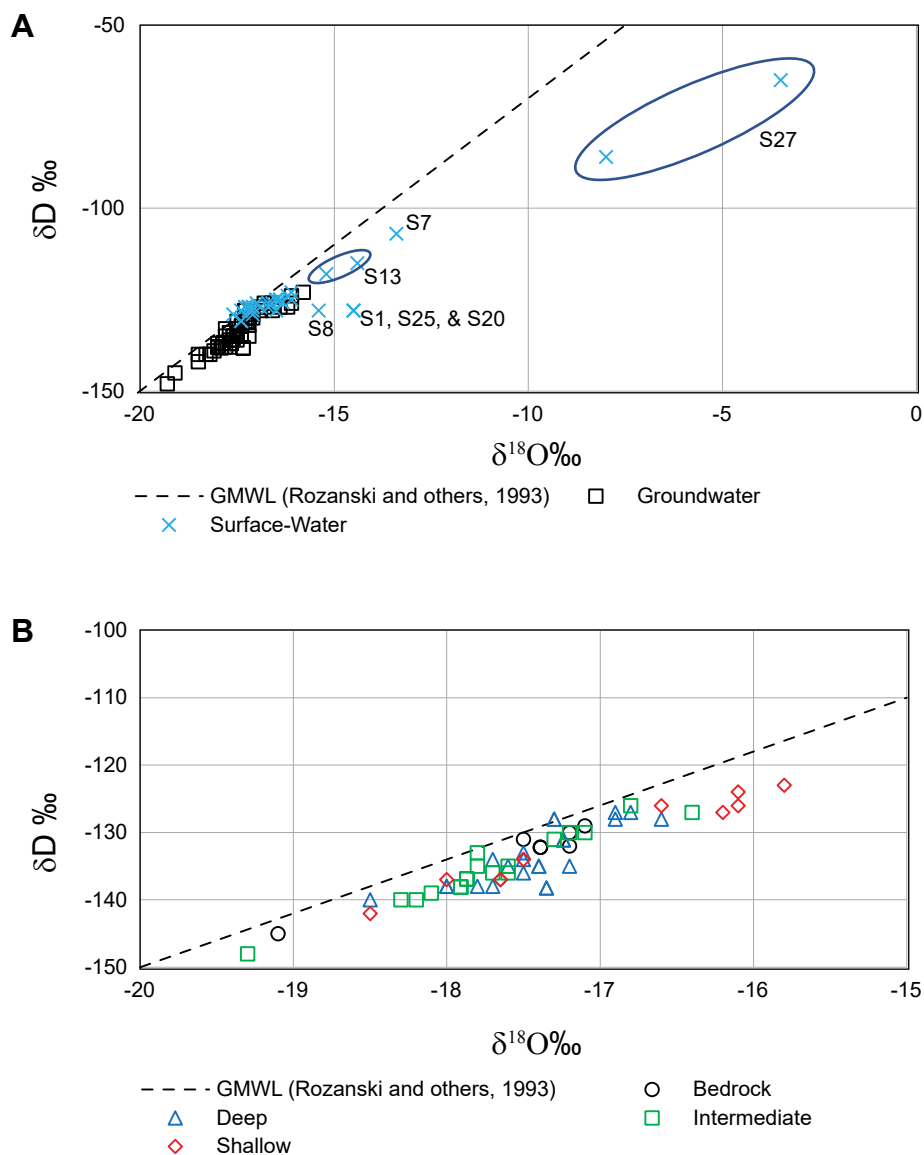


Figure 19. Stable water isotopes of all samples show that the groundwater, and most of the surface waters, fall near the global meteoric water line (GMWL; Rozanski and others, 1993). Nine of the surface-water samples (A) follow an apparent evaporation line, with the greatest effect observed at an unnamed pond with no surface outlet (S27 in A). Groundwater samples (B) show substantial overlap in the isotopic composition of waters from the different hydrogeologic units.

pond also suggested evaporation (see above). The other surface-water samples affected by evaporation were from Mooring Creek (sites S7 and S8), Blaine Creek at the Lake Blaine outlet (site S13, 2 samples), Lost Creek (site S20) and Browns Gulch (site S25) near the Swan Range mountain front, and the Flathead River at Columbia Falls (site S1; fig. 19A). The surface-water sites with multiple samples generally showed higher values in September than in June, consistent with greater evaporation in September (appendix D, table D4).

Environmental Tracers

Groundwater samples were obtained for analysis of tritium (^3H) and $^4\text{He}/\text{Ne}$ ratios (among other noble

gases) at 6 sites from 15 wells (fig. 20, see fig. 5 to correlate well numbers with location; appendix D, table D5). At three sites SF_6 was also sampled. The environmental tracers were used to assess the hydraulic connections between the different aquifers. These parameters can be used to estimate the age since water was recharged; however, age determinations assume piston flow, and the reality is that groundwaters are likely to be mixtures of water of different ages (Darling and others, 2012). As such, we interpret the results qualitatively.

At the north site (wells 12, 13; fig. 5; appendix D) the sampled wells are completed in the shallow (well

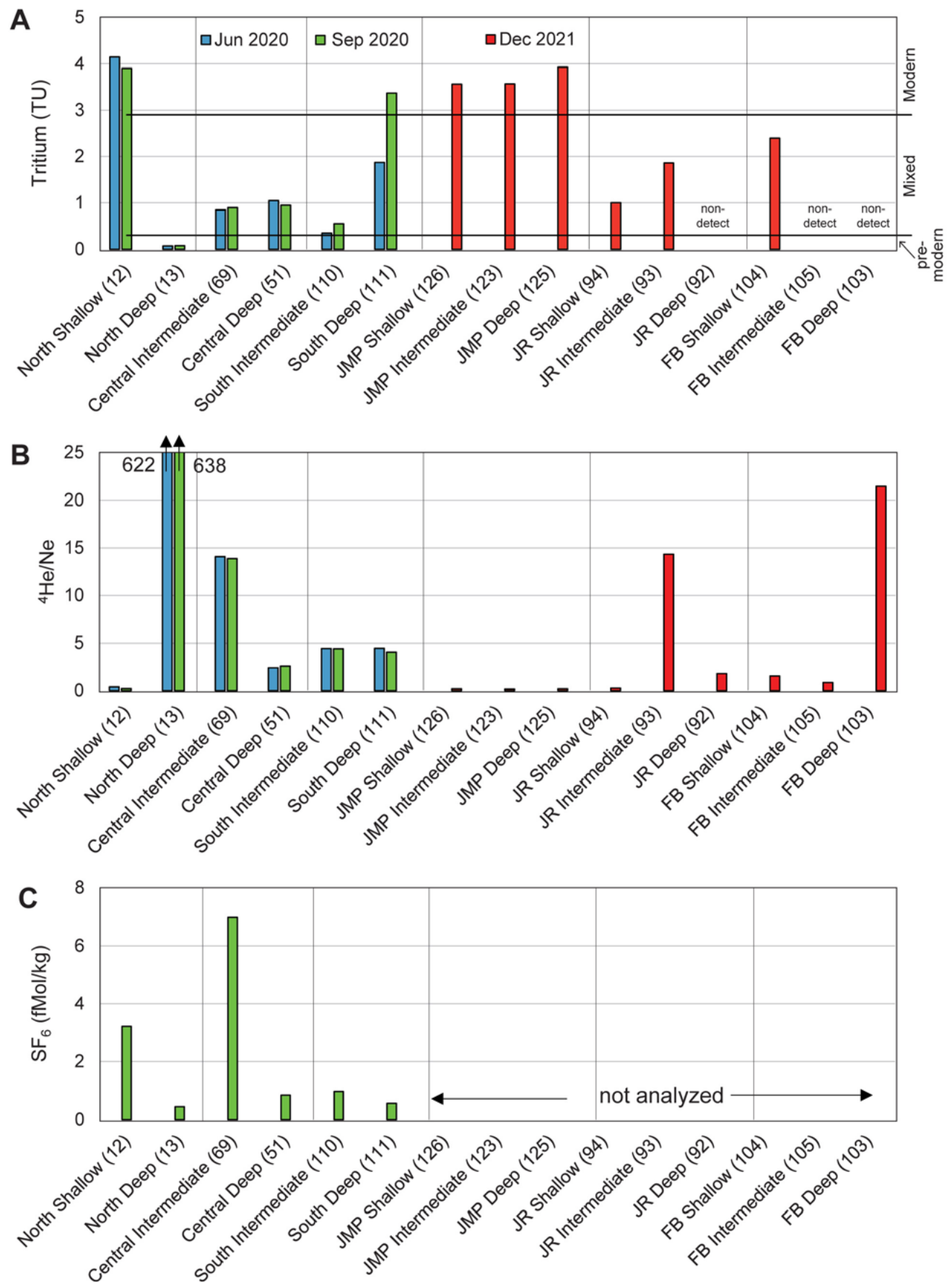


Figure 20. Tritium, $^4\text{He}/\text{Ne}$, and SF_6 results. JMP, Jessup Mill Pond; JR, Jaquette Road; FB, Foy's Bend. Values in parentheses are well numbers (appendix A; fig. 5). See text for interpretations.

12) and deep (well 13) aquifers. There is a downward gradient in this area, with groundwater elevations in the deep aquifer about 35 ft below those in the shallow aquifer. Results of sampling at this site are consistent with the shallow and deep aquifer being separated by a competent confining layer. Tritium concentrations indicate that the water in the shallow aquifer is modern (3.9 to 4.1 TU) and the water in the deep aquifer is pre-modern (0.1 TU; fig. 20A; appendix D, table D5). The $^4\text{He}/\text{Ne}$ ratio shows that terrigenous ^4He is low in the shallow aquifer (0.2 to 0.4), but ^4He has accumulated in the deep aquifer (~620 to 640; fig. 20B). The $^4\text{He}/\text{Ne}$ ratio in the deep aquifer at this site was much higher than any other sample. Similar to the tritium results, SF_6 is elevated in the shallow aquifer (3.22 fMol/kg) relative to the deep aquifer (0.45 fMol/kg), indicating young and old water, respectively (fig. 20C).

At the central site (wells 51, 68, and 69, fig. 5; appendix D), the wells are completed in the intermediate (well 69) and deep (wells 51, 68) aquifers. The sampled wells (51, 69) are 1.3 miles apart, which may complicate interpretation of these results. Groundwater elevations in wells 68 (not sampled) and 69, which are close to each other, show that the intermediate aquifer groundwater elevations are about 3 ft higher than the deep aquifer in this area, indicating a slight downward gradient. The interpretation of results from wells 51 and 69 differ depending on the parameter evaluated. Tritium concentrations are similar in both wells (0.9 to 1.0 TU for all samples), and are classified as a mixture of modern and premodern water (fig. 20A). The $^4\text{He}/\text{Ne}$ ratios show that terrigenous ^4He is higher in the intermediate aquifer (13.9 to 14.1) than in the deep aquifer (2.4 to 2.6; fig. 20B), which may suggest that the intermediate aquifer is bounded by confining units so there is less outgassing, while the deep aquifer is a more active flow system. Contrary to the $^4\text{He}/\text{Ne}$ results, SF_6 concentrations are high in the intermediate aquifer (6.98 fMol/kg) and low in the deep aquifer (0.85 fMol/kg; fig. 20C). The SF_6 concentration in the intermediate aquifer at this site (well 69) is higher than all other samples. Since tritium is incorporated into the water molecule, the similar tritium concentrations suggest that the groundwaters in these aquifers are of similar age; however, the mechanisms of transport and retention of dissolved ^4He and SF_6 appear to be different.

At the south site (wells 110, 111, fig. 5; appendix D) wells were sampled in the intermediate and

deep aquifers, respectively. Groundwater elevations in the deep aquifer were about 10 ft higher, indicating an upward gradient. Tritium concentrations in the intermediate aquifer (0.4 to 0.6 TU) were lower than in the deep aquifer (1.9 to 3.4 TU), with the water in the intermediate aquifer on the low end of mixed, while water in the deep aquifer is mixed to modern (fig. 20A). This suggests that flow is less active in the intermediate aquifer, likely due to bounding confining layers. $^4\text{He}/\text{Ne}$ ratios were similar in both aquifers (4.1 to 4.5 for all samples), and above atmospheric levels (fig. 20B), suggesting that although the water in the deep aquifer appears mixed to modern based on tritium, some ^4He is being retained. SF_6 concentrations are relatively low in both aquifers (0.57 to 0.98 fMol/kg; fig. 20C), indicating that although the deep aquifer water is mixed to modern based on tritium, it does not have high SF_6 concentrations.

Three wells were installed in the shallow, intermediate, and deep aquifers at a site near Jessup Mill Pond in the southeast part of the study area (wells 123, 125, 126; figs. 2, 5; appendix D). Roto-sonic drilling at this site showed that the confining layer is dominated by sandy deltaic lake sediments (Smith and Bobst, 2025). Aquifer testing also showed a slight but measurable groundwater elevation drop in the shallow aquifer from pumping in the deep aquifer (Myse and others, 2023). Groundwater elevations in these wells show an upward gradient, with the deep aquifer about 7 ft higher than the shallow aquifer (fig. 12B). The tritium in all three wells was similar and classified as modern (3.6 to 3.9 TU for all samples; fig. 20A). The $^4\text{He}/\text{Ne}$ ratio was low for all wells (0.2 for all samples; fig. 20B), indicating little accumulation, and that the aquifers are interconnected.

In the southwest part of the study area three wells installed during a previous GWIP investigation (Rose and others, 2022) on Jaquette Road were sampled (wells 92–94; fig. 5; appendix D). Groundwater elevations in the deep aquifer were about 7 ft lower than in the shallow and intermediate aquifers, indicating a downward gradient. During aquifer testing there was no response to pumping from the deep aquifer in the shallow aquifer, but the intermediate well showed a delayed response (Myse and others, 2023). Tritium concentrations were higher in the intermediate aquifer (1.9 TU) than in the shallow aquifer (1.0 TU), but both were classified as mixed (fig. 20A). Tritium was

below the detection limit (<0.06 TU) and classified as premodern in the deep aquifer (well 93; fig. 20A). $^4\text{He}/\text{Ne}$ ratios were higher in the intermediate aquifer (14.3; fig. 20B) than in the shallow (0.3) or deep (1.8) aquifers, likely due to bounding confining layers, and a lack of ^4He retention in the deep aquifer.

Further to the southwest we sampled three wells at the Foy's Bend site (wells 103–105; fig. 5). Groundwater elevations in the deep aquifer were about 8 ft higher than in the shallow and intermediate aquifers, indicating an upward gradient. During aquifer testing at this site there was no response to pumping from the deep aquifer in either the shallow or intermediate aquifers. The confining layer at this site is 477 ft thick and dominated by fine lacustrine sediments. The intermediate well was completed in the borehole created by roto-sonic drilling in a thin sand bed within the confining layer (Smith and Bobst, 2025). Tritium at this site was only detected in the shallow aquifer (2.4 TU; fig. 20A) and $^4\text{He}/\text{Ne}$ ratios were higher in the deep aquifer (21.4; fig. 20B) than in the shallow (1.6) or intermediate (0.8) aquifers. This is consistent with a competent confining layer.

Overall, the results from the environmental tracer sampling showed that in areas where the confining unit is thick (e.g., the north site and the Foy's Bend site), the deep aquifer is hydraulically separated from the shallow aquifers, and therefore, surface waters. Where the confining unit is thin or composed of more permeable sediments (e.g., the Jessup Mill Pond site), the shallow and deep aquifers are hydraulically connected. Between these end members the connections between the shallow, intermediate, and deep aquifers are variable, and depend on the local stratigraphy.

Numerical Groundwater Models

The details of groundwater modeling are documented in Berglund and others (2024), and are summarized here. Results from groundwater modeling also support the concept that in some areas the confining layers are thin or absent. To achieve model calibration near the Swan Range Front, relatively permeable sediments were needed to route mountain front recharge away from the front, and evaluation of well logs in the area supported the inclusion of this unit. Groundwater flux to Jessup Mill Pond and groundwater heads near the Flathead River required hydraulic connection between the deep and shallow aquifers to achieve

model calibration. As such, simulated pumping from either the shallow or the deep aquifer in the East Flathead area results in stream depletion; however, the timing and magnitude of this depletion depend on the location, site-specific stratigraphy, and development details.

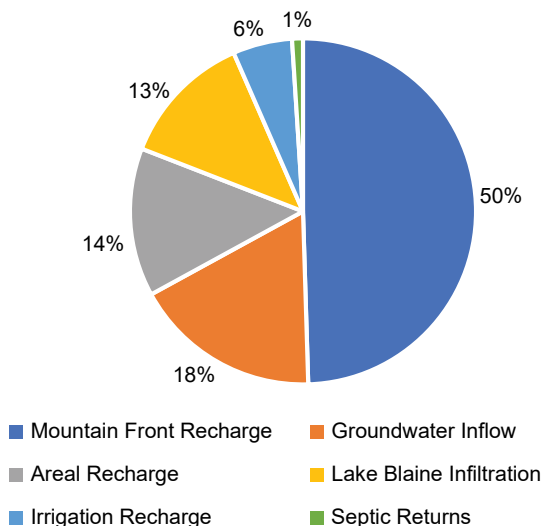
Modeled Groundwater Budget

A preliminary groundwater budget for the valley-fill aquifers (including both the shallow and the deep aquifers) was developed based on monitoring data, remote sensing, climatic data, and other information (Berglund and others, 2024). This preliminary budget was incorporated into the modeling effort and refined based on other sources of data, such as hydrostratigraphy, observed groundwater elevations, and observed surface-water gains and losses. The model-derived budget is summarized here; for details see Berglund and others (2024).

The total amount of water moving through the groundwater system was estimated to be about 70,000 acre-ft/yr. Groundwater flows into the basin-fill aquifers from a variety of sources (fig. 21). Mountain front recharge, which includes groundwater inflow from the Swan Range bedrock (figs. 9, 10) and infiltration of streams at the mountain front, provides 50% of the modeled inflow. Groundwater flows into the deep aquifer along the southeastern edge of the study area from the Swan Valley (fig. 9), and provides 18% of the total inflow. Areal recharge from infiltration of precipitation (14% of inflow) occurs throughout the study area. Recharge also occurs as infiltration from Lake Blaine (13%), irrigation recharge (6%), and septic returns (1%). Note that the percentages do not sum to 100% due to rounding.

Outflows from the model domain include groundwater discharge (outflow from the study area to adjacent aquifers), surface waters, pumping wells, evaporation from groundwater-fed lakes, and groundwater evapotranspiration by riparian vegetation (fig. 21). Groundwater flows out of the study area to the west and south, as depicted on the potentiometric surface maps (figs. 9, 10), and accounts for 42% of outflows. Discharge to Jessup Mill Pond, Mill Creek, and Mooring Creek accounts for 35% of the outflow. Groundwater also discharges to the Flathead River (6%). Domestic, commercial, and irrigation wells pump water from the aquifers, and account for 14% of total outflow.

Inflows



Outflows

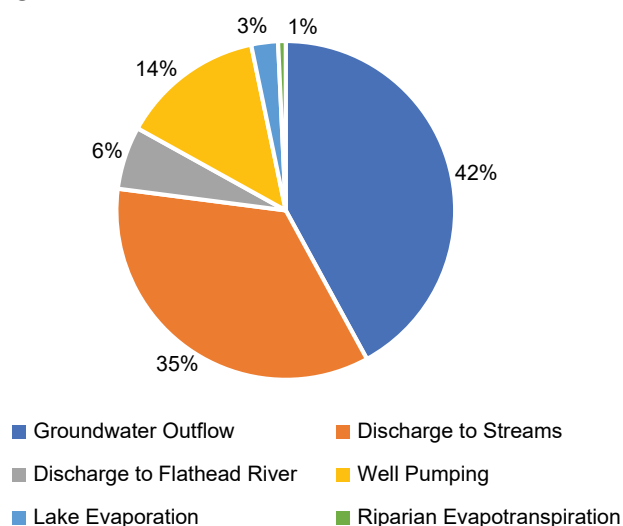


Figure 21. A summary of the modeled average annual groundwater budget for the study area (for details see Berglund and others, 2024). The majority of the inflow is from mountain front recharge. The outflow is dominated by groundwater outflow to the south and east, and discharge of groundwater to surface waters.

Lake evaporation (3%) and riparian evapotranspiration (1%) were relatively minor sinks.

Model Scenarios

The results from modeling scenarios are summarized below with a more complete discussion in the groundwater modeling report (Berglund and others, 2024). All scenario results are relative to the baseline 20-yr transient model, which uses the same transient stresses as the calibrated transient model. Estimated predictive uncertainty was about 10%, so the results of the scenarios should be viewed with this uncertainty in mind.

Scenario 1—Double Residential

For this scenario, groundwater withdrawals from domestic and PWS wells were doubled, an increase in pumping from 2,153 to 4,306 acre-ft/yr. Rather than hypothesize about future areas of development and well completions, we simply doubled the rates from the existing residential supply wells. This resulted in an average drop in August groundwater elevations at the end of the 20-yr model run of up to 0.7 ft. Simulated August groundwater discharge to Jessup Mill Pond (the largest receptor) was reduced by 0.6 cfs (37 acre-ft/mo; fig. 22; table 3).

Scenario 2—Double Irrigation

Simulated withdrawals for irrigation wells were doubled from 6,679 to 13,358 acre-ft/yr for this sce-

nario. Again, we did not speculate on the details of future development, but simply doubled the rates for existing irrigation wells. This resulted in an August average drop in groundwater elevations at the end of the 20-yr model run of up to 1.5 ft. Groundwater discharge to Jessup Mill Pond was reduced by 1.7 cfs (106 acre-ft/mo; fig. 22; table 3).

Scenario 3—1-yr-Long Drought

Mountain front recharge along the Swan Range Front and areal recharge were reduced by 25% for 1 year for this scenario, which is a reduction from 40,480 to 30,361 acre-ft/yr. This was intended to simulate an approximate 20-yr drought. The greatest effects occurred during the drought year, when average August groundwater elevations dropped by as much as 2.7 ft, and August groundwater discharge to Jessup Mill Pond was reduced by 2.2 cfs (133 acre-ft/mo; fig. 22). Ten years after the simulated drought, average August groundwater levels were still up to 2.1 ft lower than baseline, and August discharges to Jessup Mill Pond were 0.03 cfs less than baseline (2 acre-ft/mo; fig. 22).

Scenario 4—5-yr-Long Drought

This scenario was implemented similar to scenario 3, except that the reduced recharge was maintained for 5 consecutive years. The greatest effects occurred during the last drought year, when average groundwater elevations dropped by as much as 3.7 ft, and ground-

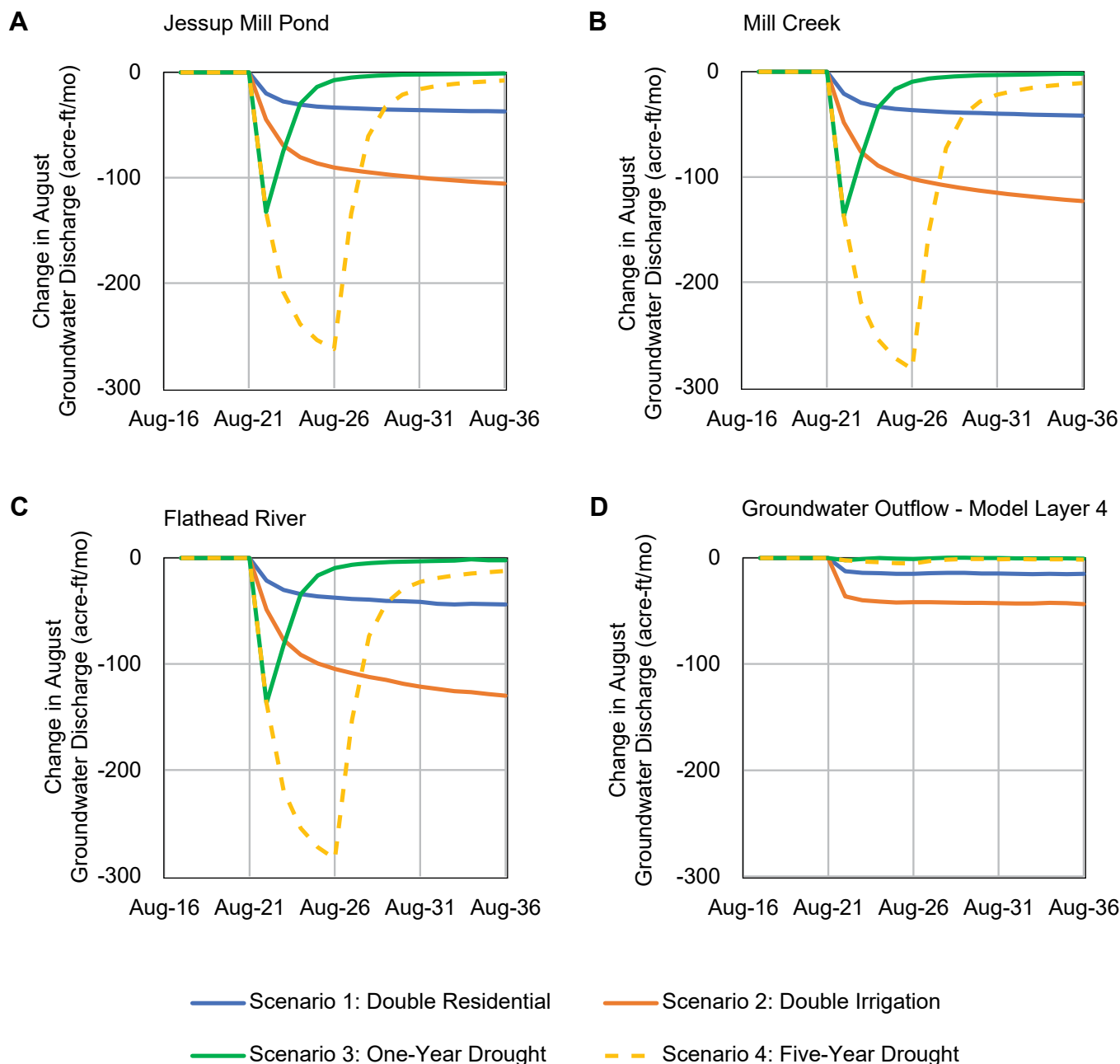


Figure 22. Changes in groundwater fluxes during August for different receptors due to the pumping and drought scenarios. Results for selected times are also in table 3. While the greatest short-term effects were generally due to the drought scenarios, the greatest long-term effects were from increased residential and irrigation development.

water discharge to Jessup Mill Pond was reduced by 4.3 cfs (263 acre-ft/mo; fig. 22). Ten years after the simulated drought average, August groundwater levels were still as much as 2.2 ft lower than baseline, and August discharges to Jessup Mill Pond were 0.12 cfs less than baseline (8 acre-ft/mo; fig. 22).

Model Limitations

Limitations and uncertainties exist in any modeling study. These limitations are embedded in the understanding of complex hydrogeological settings, in the conceptual model design, and in model calibration and

prediction simulations, as well as the estimation of some key parameters such as recharge and evapotranspiration. There are also limitations associated with the capabilities of the existing groundwater modeling software packages to adequately represent the complexities of hydrogeological systems. As such, the predictions from a groundwater model should be viewed with this uncertainty in mind. Through the calibration process, sensitivity analysis, and uncertainty analysis we attempt to minimize this uncertainty and quantify it; however, it cannot be eliminated.

Table 3. Summary of changes from baseline in selected outflows for the tested scenarios.

Scenario	Evaluation Time	Change in Discharge (acre-ft/mo)					Change in Discharge (ft ³ /s; cfs)				
		Jessup Mill Pond	Mill Creek ¹	Flathead River ²	Groundwater Outflow		Jessup Mill Pond	Mill Creek ¹	Flathead River ²	Groundwater Outflow	
1—Double Residential	August 2036	-37.2	-41.5	-43.9	-15.1		-0.60	-0.68	-0.71	-0.25	
	August 2036	-105.6	-122.8	-130.0	-43.4		-1.72	-2.00	-2.11	-0.71	
2—Double Irrigation	August 2022	-132.8	-136.9	-136.9	-2.1		-2.16	-2.23	-2.23	-0.03	
	August 2023	-75.3	-81.9	-82.1	-1.2		-1.22	-1.33	-1.34	-0.02	
	August 2027	-4.9	-6.4	-6.6	-0.3		-0.08	-0.10	-0.11	-0.01	
	August 2032	-1.8	-2.5	-2.8	-0.3		-0.03	-0.04	-0.05	-0.01	
4—5-yr Drought	August 2026	-262.6	-282.6	-283.4	-5.3		-4.27	-4.60	-4.61	-0.09	
	August 2027	-134.4	-151.8	-152.8	-2.8		-2.19	-2.47	-2.49	-0.05	
	August 2031	-16.0	-21.6	-22.7	-1.4		-0.26	-0.35	-0.37	-0.02	
	August 2036	-7.6	-10.8	-12.2	-1.7		-0.12	-0.18	-0.20	-0.03	

¹Mill Creek includes reduced flux from Jessup Mill Pond in addition to reduced flux to Mill Creek itself.²Flathead River includes reduced flux to Jessup Mill Pond and Mill Creek, in addition to reduced flux to Flathead River itself.

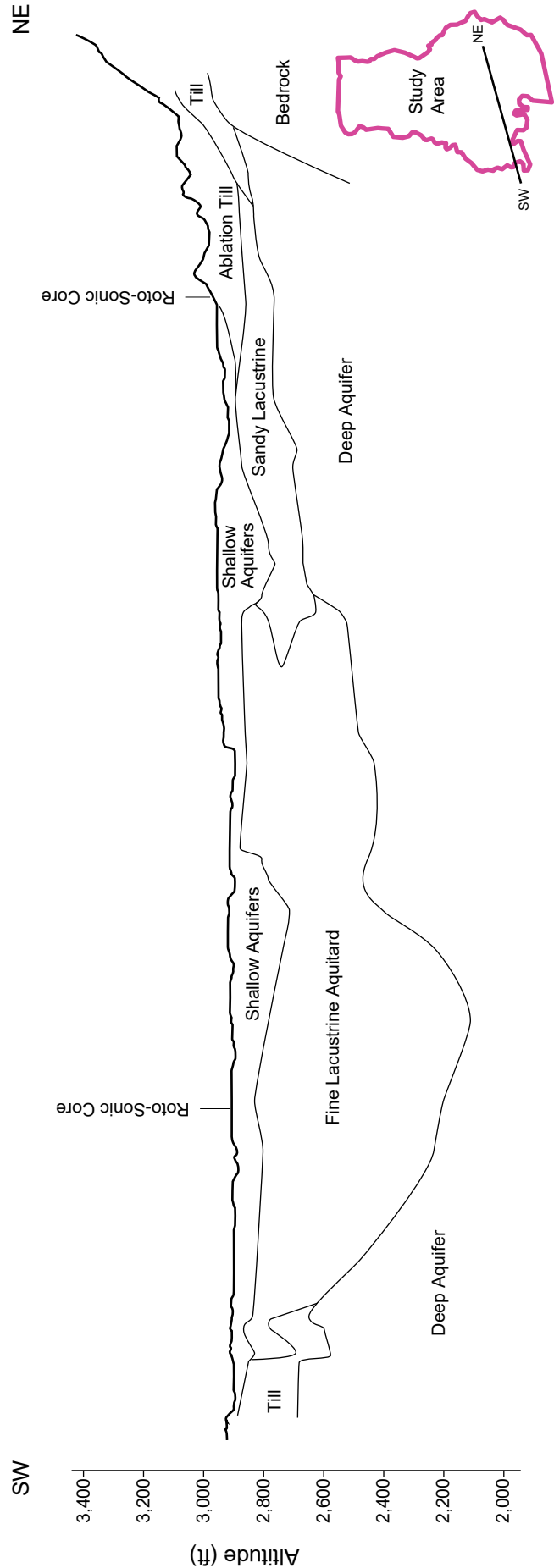


Figure 23. Cross-section based on wells cored using roto-sonic and GWIC logs (details in Smith and Bobst, 2025).

DISCUSSION

Hydraulic Communication between the Shallow and Deep Aquifers

There is hydraulic communication between the shallow and deep aquifers in some parts of the East Flathead study area. This communication is highly dependent on the site-specific stratigraphy. The aquifers appear to be hydraulically separated north of Lake Blaine. South of Lake Blaine the shallow and deep aquifers generally appear to be connected in areas where the confining layer is less than 100 ft thick, or where the intermediate and deep aquifer interfinger (Smith, 2004d; fig. 4). In areas where the confining layer is more than 300 ft thick (Smith, 2004d; fig. 4), such as near Foy's Bend (wells 103–105; fig. 5), the shallow and deep aquifers are separated. Where the confining layer is identified as between 100 and 300 ft thick the connection is variable and depends on the local stratigraphy.

North of Lake Blaine there is a divergence in groundwater elevations in the shallow and deep aquifers along the Swan Range Front, and extending out into the valley. This indicates an extensive and continuous confining layer in that area, even though the confining layer is identified as thin and interfingered in some areas. Environmental tracers and groundwater modeling also suggest that there is separation of the shallow and deep aquifers in the northern portion of the study area.

Connections between the shallow and deep aquifers are clearest near Jessup Mill Pond and Mill Creek, south of Lake Blaine, where the confining layer is identified as thin and there is interfingering between the deep and intermediate aquifers (figs. 2, 4). In this area an aquifer test, environmental tracers, and groundwater modeling indicate groundwater flow from the deep to the shallow aquifers. Sandy lacustrine deltaic sediments (fig. 23; Smith and Bobst, 2025) are within the stratigraphic interval that includes the basal till and fine-lacustrine sediments in other parts of the valley. This suggests that subglacial or proglacial processes eroded or reworked the till in this area, and then deposited sandy-grained lacustrine sediments (Smith and Bobst, 2025). While these sediments are finer grained than the shallow and deep aquifers above and below, they provide a pathway for water movement.

Near the Flathead River, in the central part of the study area (in the vicinity of wells 73 and 90; fig. 5) where the confining layer is thin (Smith, 2004d; fig. 4), observed groundwater elevations, hydrograph patterns, and groundwater modeling also suggest that the shallow and deep aquifers are connected (Berglund and others, 2024). This indicates that the confining layers may have been eroded by past fluvial activity.

The shallow and deep aquifers show local separation in much of the study area, but in some areas they are interconnected. Therefore, increased groundwater pumping from either the shallow or deep aquifer is likely to result in surface-water depletion. The magnitude and timing of this depletion will depend on the location of the development and the project-specific details (e.g., pumping schedules).

Hydraulic Connections to the Intermediate Aquifers

Groundwater elevations and environmental tracers show that the intermediate aquifers may be isolated from both the shallow and deep aquifers, or hydraulically connected to either or both of them. Site-specific stratigraphic information from drillers' logs is not sufficient to identify interconnections between the aquifers, since even relatively thick confining layers may not be laterally extensive due to truncation against other units during deposition, or subsequent erosion.

Influence of Increased Groundwater Development Residential

The net groundwater withdrawal by domestic wells (estimated as 1,762 acre-ft/yr; Berglund and others, 2024) accounts for about 3% of the total groundwater outflow from the study area, and about 16% of groundwater pumping for all uses. Groundwater modeling (Berglund and others, 2024) showed that doubling domestic pumping rates for 20 yr would result in simulated groundwater elevations that were on average up to 0.7 ft lower. This increase in domestic pumping would also cause modeled groundwater discharge to Jessup Mill Pond to be reduced by about 0.6 cfs, which represents 2% of the average flow rate. This stream depletion resulted from pumping from the shallow, intermediate, and deep aquifers. While this stream depletion is calculable, it would be difficult to measure through monitoring.

Irrigation

The net groundwater withdrawal by irrigation wells (estimated as 6,679 acre-ft/yr; Berglund and others, 2024) accounts for about 11% of the total groundwater outflow, and about 61% of groundwater pumping for all uses. Groundwater modeling (Berglund and others, 2024) showed that doubling irrigation pumping rates would result in simulated groundwater elevations that were on average up to 1.5 ft lower than baseline conditions. Since drawdown would be focused in the areas where pumping occurs, and there are relatively few irrigation wells compared to domestic wells, the drawdown in pumping centers would be substantially greater. This would also cause modeled groundwater discharge to Jessup Mill Pond to decrease by about 1.7 cfs, which represents 6% of the average flow rate. A decrease in flow of this magnitude may be detectable through monitoring.

Climatic Influences

Decreased mountain front recharge could result from reduced precipitation, a change in precipitation from snow to rain, or increased evapotranspiration. This could potentially influence groundwater and surface-water availability in the study area more than the simulated effects of doubling domestic or irrigation pumping. Mountain front recharge accounts for about 50% of the recharge to the basin-fill aquifers in the East Flathead area (Berglund and others, 2024). A simulated 25% reduction in mountain front recharge and areal recharge for 5 years caused groundwater elevations to be as much as 3.7 ft lower, and reduced groundwater discharge to Jessup Mill Pond by up to 4.3 cfs (16% of the average flow rate).

RECOMMENDATIONS

Additional groundwater pumping from the basin-fill aquifers in the East Flathead area will result in lower groundwater elevations, and decreased groundwater outflow to surface waters. Drought conditions can reduce groundwater recharge at the Swan Range Front from stream infiltration and groundwater inflow from the bedrock. These changes in recharge also have the potential to decrease groundwater levels and groundwater outflow to surface waters.

The groundwater models developed during this study can be used to evaluate the potential stream depletion and groundwater elevation declines that may result from proposed development. The predictions

should allow for potential decreases in recharge due to climatic variability. The actual amount of development and associated consumptive use, climatic information, and groundwater-level monitoring should be used to periodically evaluate if the model is providing accurate outputs. The model should be improved over time to increase its utility. Site-specific data collection and modeling would provide more robust predictions in particular areas of interest.

Rather than relying exclusively on model-derived criteria, there should also be a network of dedicated monitoring wells in key areas with defined trigger points to guide decision making. While the amount of stream depletion is a key concern, measured groundwater levels have less uncertainty than measured stream flow, so they are preferred for change detection. Ideally the dedicated monitoring wells will be located in areas with little nearby pumping to provide an understanding of the regional response to development, and in areas near pumping to understand the maximum effects.

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APPENDIX A

MONITORED WELLS

Table A1. Wells Monitored by MBMG during the East Flathead Groundwater Investigation

GWICID	Well #	Site Name	Depth (ft)	Hydrogeologic Unit	Water Quality	GWAP ¹ Well
					Sample Collected	
85605	1	BOWERMAN BEN * FV-N-13	64	Shallow Aquifer		
148188	2	NORMILE JIM	518	Deep Aquifer	X	
148187	3	LANDWEHR, JIM * FVGS A-2	157	Intermediate Aquifer	X	X
219805	4	SCHAFF, DAVID AND SUSAN	162	Intermediate Aquifer		
85628	5	HENNEBERG THOMAS * FV-N-09	149	Intermediate Aquifer	X	
85652	6	JOHNSON MAURICE * FV-N-08	183	Deep Aquifer		
85656	7	EGAN, DUANE C	169	Deep Aquifer		
85649	8	SAMPLES HAROLD * FV-N-07	160	Intermediate Aquifer		
310812	9	TAYLOR, KAYLA	218	Deep Aquifer		
122756	10	STERNAD JEFF & NANCY * FV-N-05	210	Deep Aquifer		
85669	11	NAGEL JOSEPH * FV-N-06	40	Shallow Aquifer		
305674	12	HALLO, HAL * SHALLOW WELL	NR	Shallow Aquifer	X	
301628	13	HOLLO, HAL	240	Deep Aquifer	X	
85687	14	SUTTER MICHAEL L.	40	Shallow Aquifer		
158200	15	NICHOLS RON AND SABRINA	170	Bedrock	X	X
305482	16	FLINT, FRED	NR	Deep Aquifer		
85774	17	HOERNER, EDWARD	152	Intermediate Aquifer		
176091	18	HOPKINS RALPH L. & KENI	145	Intermediate Aquifer		
85730	19	GRAHAM, MONTY	91	Intermediate Aquifer	X	
164733	20	TUTTLE, RICHARD	145	Intermediate Aquifer		
173515	21	HOERNER, LARRY AND DEBBIE	193	Deep Aquifer		
305675	22	TIMLICK, PATRICIA	168	Deep Aquifer		
268043	23	BERRETH, MELISSA	178	Deep Aquifer		
152953	24	RILEY NICK & KATHY	78	Shallow Aquifer		
215682	25	HEATH ART AND LORETTA	180	Deep Aquifer		
83503	26	TAYLOR JACK	149	Deep Aquifer		
139610	27	BADROCK VOLUNTEER FIRE DEPT	151	Deep Aquifer		
310809	28	MOSER, JED	238	Deep Aquifer		
209308	29	PLANTS, WALTER AND SARAH	175	Deep Aquifer	X	
284671	30	SMITH, ZACK	501	Deep Aquifer		
83431	31	PIER, DAVID AND ETHEL	552	Deep Aquifer		
83435	32	LIBERTY, BRETT	340	Deep Aquifer	X	
180242	33	HOERNER, GARY AND WENDY	204	Deep Aquifer		
188169	34	KISSANE PATRICK & TERRI	173	Deep Aquifer		
291347	35	HAVEMAN, DAVID & BLAIR	198	Deep Aquifer		
310814	36	QUIGLEY, EMMETT	79	Shallow Aquifer		
310813	37	QUIGLEY, EMMETT	319	Deep Aquifer		
83538	38	QUIGLEY, EMMETT & SUSAN	200	Intermediate Aquifer	X	
83586	39	REYNEN, PETER AND KAREN	121	Shallow Aquifer		
83579	40	FRALEIGH, NOREEN AND MICHAEL	627	Deep Aquifer		
244505	41	BUNKER RAYMOND	600	Deep Aquifer		
311096	42	SAMPSON, ANDREW	4.8	Shallow Aquifer		
262175	43	HERMAN, THOMAS L.	180	Deep Aquifer		
215007	44	ENNENGA RICK P. & PEGGY S.	241	Deep Aquifer		
218164	45	MITCHELL, RYAN	200	Deep Aquifer		
310811	46	CHEROT, ROBERT	319	Deep Aquifer		
219773	47	CHEROT, ROBERT AND JESSICA	81	Shallow Aquifer		
83633	48	SANDS, TOM AND RITA	190	Deep Aquifer		
194711	49	CHEROT ROBERT AND JESSICA	219	Deep Aquifer		
274595	50	CARLBURG, TIMOTHY AND LEAH	221	Deep Aquifer		
301923	51	NEWELL CARSON	400	Deep Aquifer	X	
294592	52	HOROWITZ, ELLEN/VITALE, FRANK	8.2	Shallow Aquifer		
83571	53	KENNEY, RAY AND BARBARA	188	Intermediate Aquifer	X	
83719	54	ROUSSELLE RALPH	160	Intermediate Aquifer	X	

Table A1. Wells Monitored by MBMG during the East Flathead Groundwater Investigation

GWICID	Well #	Site Name	Depth (ft)	Hydrogeologic Unit	Water Quality	GWAP ¹ Well
					Sample Collected	
83716	55	LARSON, STEVE	338	Deep Aquifer	X	X
238895	56	SWEIGART MIKE AND SUE	221	Deep Aquifer	X	
83713	57	SHELTON, JENNIFER	194	Intermediate Aquifer		
83651	58	BUNKER RAYMOND	184	Intermediate Aquifer		
240258	59	PALMER, MARK AND TERRIE * WEST WELL	215	Deep Aquifer		
240260	60	PALMER, MARK AND TERRIE * EAST WELL	193	Intermediate Aquifer		
150702	61	ECKLEBERRY KEITH	110	Intermediate Aquifer		
305676	62	WALLER, JOHN	122	Intermediate Aquifer		
83690	63	MOORE DERRICK	100	Intermediate Aquifer		
194713	64	CONKLIN, GLENN	361	Deep Aquifer		
205926	65	MURPHY, MIC	148	Bedrock		
83662	66	BATES, GORDON AND PAM	120	Bedrock	X	
286781	67	FISHER FAMILY TRUST	200	Deep Aquifer		
132462	68	LORENTZEN, IVAN AND CONNIE	525	Deep Aquifer		
83752	69	LORENTZEN, IVAN AND CONNIE	195	Intermediate Aquifer	X	
311098	70	HEIL, DORIS (JEANIE) * LAKE BLAINE OUTLET	9	Shallow Aquifer		
209505	71	ALTENBURG, BRUCE	102	Shallow Aquifer		
83789	72	HANSEN MARVIN	119	Shallow Aquifer	X	
82262	73	STEBBINS, MICHAEL	208	Deep Aquifer		
308707	74	MASON, LAURIE	238	Deep Aquifer		
304306	75	SANTACROCE, MIKE	153	Intermediate Aquifer	X	
304311	76	TOLONEN, PAUL	NR	Shallow Aquifer		
244906	77	JOHNSTON, SCOTT	241	Deep Aquifer	X	
258145	78	LAMB, STEVE	198	Deep Aquifer		
310776	79	FENN, JAMES	300	Deep Aquifer		
304307	80	HERBOLD, MARK AND MELVA	183	Deep Aquifer		
81678	81	LAPP JASON	132	Intermediate Aquifer		
304313	82	ROTHFUSS, ED AND MARJORIE	210	Intermediate Aquifer	X	
255030	83	FOSS, KEVIN & PATTI	310	Deep Aquifer		
157098	84	PENTELUTE DANIEL	157	Intermediate Aquifer		
201436	85	BLAYLOCK, KEITH AND TRUDY	100	Shallow Aquifer	X	
310774	86	AGUE, KEITH	280	Deep Aquifer		
214653	87	47 WHITETAIL MEADOWS	160	Ablation Till		
304314	88	KAUFFMAN, DAN	80	Shallow Aquifer		
81636	89	MAYER, PAUL	75	Bedrock	X	X
194666	90	GUY, GINGER	33	Shallow Aquifer		
82288	91	SIDERIUS, TOM AND TERRY	180	Intermediate Aquifer	X	
262325	92	SMITH, KEN * MBMG_KS_3 Deep monitoring well	480	Deep Aquifer	X	X
262323	93	SMITH, KEN * MBMG_KS_1_ Intermediate monioring well	217	Intermediate Aquifer	X	X
262324	94	SMITH, KEN * MBMG_KS_2 Shallow monitoring well	66	Shallow Aquifer	X	X
82279	95	SMITH, KEN	486	Deep Aquifer	X	X
304310	96	ASA, TONY	295	Deep Aquifer	X	
301129	97	WALLER, AMY	260	Deep Aquifer		
81675	98	HUBBARD GEORGE	225	Deep Aquifer		
143314	99	REBUCK NED J	178	Intermediate Aquifer		
166458	100	SIDERIUS, BILLY JEAN	43	Shallow Aquifer		
86672	101	SACRISON, HANS AND LEANNA	214	Shallow Aquifer		
194672	102	BORGEN, BOB AND LUANN	719	Deep Aquifer	X	
318263	103	QUIGLEY, EMMETT AND SUE	640	Deep Aquifer	X	
318265	104	QUIGLEY, EMMETT AND SUE	50	Shallow Aquifer	X	
318266	105	QUIGLEY, EMMETT AND SUE	300	Intermediate Aquifer	X	
298493	106	SIDERIUS, CORY AND AMBER	58	Shallow Aquifer		
81861	107	ROBOCKER, CATHRYN (JEAN)	531	Deep Aquifer		
148762	108	WALLER JOHN & AMY	420	Deep Aquifer		

Table A1. Wells Monitored by MBMG during the East Flathead Groundwater Investigation

GWICID	Well #	Site Name	Depth (ft)	Hydrogeologic Unit	Water Quality	GWAP ¹ Well
					Sample Collected	
296866	109	WALLER, AMY	220	Intermediate Aquifer		
81781	110	MAST SILAS B.	166	Intermediate Aquifer	X	
152923	111	MAST MYRON	499	Deep Aquifer	X	
304304	112	ADDINGTON, TRAVIS AND LINDA	353	Deep Aquifer		
304312	113	MCGOUGH, BOB AND MAUREEN	281	Deep Aquifer		
131551	114	USGS * RESEARCH WELL	279	Deep Aquifer		
261280	115	LANCE, WHITT	174	Intermediate Aquifer		
81775	116	WHITT, LANCE	140	Shallow Aquifer	X	
311097	117	NELSON, ALLISON AND ANTHONY	123	Shallow Aquifer		
293105	118	STATE OF MONTANA AG EXP. STATION MSU	8	Shallow Aquifer		
300217	119	CRESTON NATIONAL FISH HATCHERY * SHORT	NR	Shallow Aquifer		
300216	120	CRESTON NATIONAL FISH HATCHERY * TALL	NR	Shallow Aquifer		
176653	121	DOI FISH HATCHERY * OBS WELL -02 1999	198	Deep Aquifer	X	
304315	122	OTTEY, MARK	51	Shallow Aquifer	X	
310816	123	OTTEY, MARK	180	Intermediate Aquifer	X	
310815	124	OTTEY, MARK	280	Deep Aquifer		
318274	125	OTTEY, MARK	300	Deep Aquifer	X	
318275	126	OTTEY, MARK	56	Shallow Aquifer	X	
310777	127	ZIELINSKI, MARK	200	Bedrock		
154810	128	HORNER-TILL SUSAN	132	Mountain Front		
81530	129	JOHNSON, LARRY AND ARLENE	171	Mountain Front	X	X
168372	130	ELIASON JASON & JAMIE	135	Shallow Aquifer		
302090	131	WACKER, MIKE AND KATHY	259	Intermediate Aquifer		
242978	132	WARD RICHARD AND LAURA	1122	Bedrock	X	
81711	133	FRANK, JERRY	340	Bedrock	X	X
242593	134	WITT LANCE	120	Shallow Aquifer		
244618	135	CHURCH OF CRESTON	200	Deep Aquifer		
241511	136	STANFILL, VERN AND ALICIA	321	Deep Aquifer		
132433	137	BATTS BOB	132	Shallow Aquifer		
302541	138	KUN, ROBERT S. AND MARILYN S.	NR	Shallow Aquifer		
81551	139	NYMAN RANDOLPH	410	Deep Aquifer		
120789	140	FEIST, KEVIN & KEHR, LIZ	110	Intermediate Aquifer		
132078	141	DISLEY, KARL AND SHARON/DANNER	390	Intermediate Aquifer		
132436	142	ROBINSON, JOHN M./TALLEY, CHERYL Y.	273	Deep Aquifer	X	
81875	143	BEDORD ALLEN & ALICE	200	Intermediate Aquifer		
304309	144	TORHEIM, HAROLD	140	Mountain Front		

¹GWAP wells are part of the MBMG's long-term statewide monitoring network implemented by the Ground Water Assessment Program, <https://www.mbmgt.mtech.edu/WaterEnvironment/GWAP>

Table A2. Well Groups used to evaluate vertical gradients for the East Flathead Groundwater Investigation

Well Group	GWICID	Well #	Site Name	Depth (ft)	Hydrogeologic Unit
A	85605	1	BOWERMAN BEN * FV-N-13	64	Shallow Aquifer
	148188	2	NORMILE JIM	518	Deep Aquifer
	148187	3	LANDWEHR, JIM * FVGS A-2	157	Intermediate Aquifer
B	85649	8	SAMPLES HAROLD * FV-N-07	160	Intermediate Aquifer
	310812	9	TAYLOR, KAYLA	218	Deep Aquifer
C	122756	10	STERNAD JEFF & NANCY * FV-N-05	210	Deep Aquifer
	85669	11	NAGEL JOSEPH * FV-N-06	40	Shallow Aquifer
	305674	12	HALLO, HAL * SHALLOW WELL	NR	Shallow Aquifer
	301628	13	HOLLO, HAL	240	Deep Aquifer
D	310814	36	QUIGLEY, EMMETT	79	Shallow Aquifer
	310813	37	QUIGLEY, EMMETT	319	Deep Aquifer
	83538	38	QUIGLEY, EMMETT & SUSAN	200	Intermediate Aquifer
E	311096	42	SAMPSON, ANDREW	4.8	Shallow Aquifer
	83579	40	FRALEIGH, NOREEN AND MICHAEL	627	Deep Aquifer
F	310811	46	CHEROT, ROBERT	319	Deep Aquifer
	219773	47	CHEROT, ROBERT AND JESSICA	81	Shallow Aquifer
G	83719	54	ROUSSELLE RALPH	160	Intermediate Aquifer
	83716	55	LARSON, STEVE	338	Deep Aquifer
	238895	56	SWEIGART MIKE AND SUE	221	Deep Aquifer
H	240258	59	PALMER, MARK AND TERRIE * WEST WELL	215	Deep Aquifer
	311098	70	HEIL, DORIS (JEANIE) * LAKE BLAINE OUTLET	9	Shallow Aquifer
	209505	71	ALTENBURG, BRUCE	102	Shallow Aquifer
I	132462	68	LORENTZEN, IVAN AND CONNIE	525	Deep Aquifer
	83752	69	LORENTZEN, IVAN AND CONNIE	195	Intermediate Aquifer
J	310774	86	AGUE, KEITH	280	Deep Aquifer
	214653	87	47 WHITETAIL MEADOWS	160	Ablation Till
K	310776	79	FENN, JAMES	300	Deep Aquifer
	81678	81	LAPP JASON	132	Intermediate Aquifer
L	262325	92	SMITH, KEN * MBMG_KS_3 Deep monitoring well	480	Deep Aquifer
	262323	93	SMITH, KEN * MBMG_KS_1 Intermediate monitoring well	217	Intermediate Aquifer
	262324	94	SMITH, KEN * MBMG_KS_2 Shallow monitoring well	66	Shallow Aquifer
	82279	95	SMITH, KEN	486	Deep Aquifer
M	310777	127	ZIELINSKI, MARK	200	Bedrock
	154810	128	HORNER-TILL SUSAN	132	Mountain Front
	81530	129	JOHNSON, LARRY AND ARLENE	171	Mountain Front
	242978	132	WARD RICHARD AND LAURA	1122	Bedrock
	81711	133	FRANK, JERRY	340	Bedrock
N	310816	123	OTTEY, MARK	180	Intermediate Aquifer
	310815	124	OTTEY, MARK	280	Deep Aquifer
	318275	126	OTTEY, MARK	56	Shallow Aquifer
O	261280	115	LANCE, WHITT	174	Intermediate Aquifer
	81775	116	WHITT, LANCE	140	Shallow Aquifer
	311097	117	NELSON, ALLISON AND ANTHONY	123	Shallow Aquifer
	293105	118	STATE OF MONTANA AG EXP. STATION MSU	8	Shallow Aquifer
P	81781	110	MAST SILAS B.	166	Intermediate Aquifer
	152923	111	MAST MYRON	499	Deep Aquifer
Q	318263	103	QUIGLEY, EMMETT AND SUE	640	Deep Aquifer
	318265	104	QUIGLEY, EMMETT AND SUE	50	Shallow Aquifer
	318266	105	QUIGLEY, EMMETT AND SUE	300	Intermediate Aquifer
R	241511	136	STANFILL, VERN AND ALICIA	321	Deep Aquifer
	132433	137	BATTS BOB	132	Shallow Aquifer

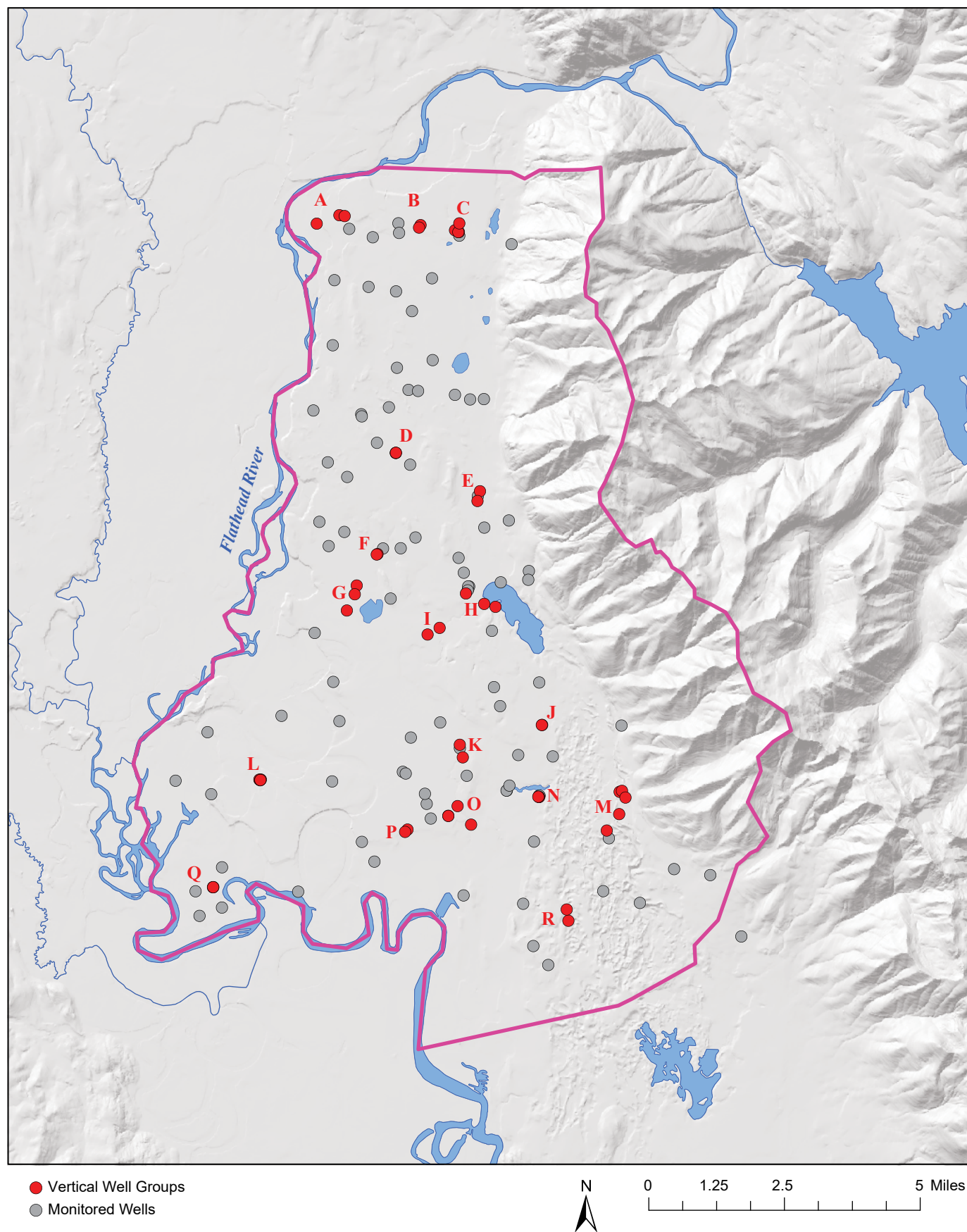


Figure A1. Well groups used to evaluate vertical gradients. See table A2 for details.

APPENDIX B

SURFACE-WATER SITES

Table B1. East Flathead surface-water sites

GWICID	Site#	Site Name	Type	Agency	Stage	Discharge	Water Quality Sample Collected
307785	1	FLATHEAD RIVER AT COLUMBIA FALLS * USGS GAUGE 12363000	STREAM	USGS		X	X
304694	2	FLATHEAD RIVER BLW PRESENTINE FISHING ACCESS	STREAM	MBMG	X		X
307792	3	FLATHEAD RIVER NEAR KALISPELL * USGS GAUGE 12363500	STREAM	USGS		X	X
321084	4	FLATHEAD RIVER AT FOYS BEND NR KALISPELL * USGS GAUGE 12366500	STREAM	USGS	X		X
307786	5	FLATHEAD RIVER NEAR BIGFORK * USGS GAUGE 12369000	STREAM	USGS			X
321083	6	FLATHEAD LAKE AT POLSON * USGS GAUGE 12371550	LAKE	USGS	X		X
307787	7	MOORING CREEK AT ELK PARK RD	STREAM	MBMG			X
307788	8	MOORING CREEK AT SAMPSONS * DNRC GAUGE 76LJ 005	STREAM	DNRC	X	X	X
321081	9	MOORING CREEK AT BLACKMER ROAD * DNRC GAUGE 76LJ 004	STREAM	DNRC	X	X	
304710	10	MOORING CREEK AT LAKE BLAINE INLET * BLW YOEMAN HALL RD	LAKE	MBMG	X	X	X
304707	11	HEMLER CREEK AT HANDKERCHIEF CREEK DR	STREAM	MBMG	X	X	X
307790	12	HEMLER CREEK * DNRC GAUGE 76LJ 003	STREAM	DNRC	X	X	X
307789	13	BLAINE CREEK AT OUTLET OF LAKE BLAINE * DNRC GAUGE 76LJ 002	STREAM	DNRC	X	X	X
321079	14	BLAINE CREEK AT MSU AG STATION * DNRC GAUGE 76LJ 001	STREAM	DNRC	X	X	
256986	15	JESSUP MILL POND	POND	MBMG	X		X
262326	16	MILL CREEK BLW CRESTON HATCHERY * DNRC GAUGE 76LJ 07500	STREAM	DNRC	X	X	X
307794	17	MILL CREEK AT HWY 35	STREAM	MBMG	X	X	X
307796	18	MILL CREEK AT RIVERSIDE ROAD	STREAM	MBMG	X	X	X
307795	19	MILL CREEK ABOVE ROSE CREEK	STREAM	MBMG			X
256831	20	LOST CREEK	STREAM	MBMG	X	X	X
302482	21	TRAIL CREEK AT PETERS RIDGE ROAD * USFS	STREAM	MBMG	X	X	X
302483	22	MILL CREEK AT PETERS RIDGE ROAD * USFS	STREAM	MBMG	X	X	X
305404	23	MILL CREEK LOWER ABV FOOTHILL DR * MBMG	STREAM	MBMG	X	X	X
302485	24	BROWNS GULCH AT PETERS RIDGE ROAD * USFS	STREAM	MBMG	X	X	X
305405	25	BROWNS GULCH LOWER ABV FOOTHILL DR * MBMG	STREAM	MBMG	X	X	X
302486	26	PETERS CREEK AT PETERS RIDGE ROAD * USFS	STREAM	MBMG	X	X	
307791	27	UNNAMED POND * BETWEEN LAKE BLAINE AND FLATHEAD RIVER	POND	MBMG			X

USGS: United States Geological Survey

DNRC: Montana Department of Natural Resources and Conservation

MBMG: Montana Bureau of Mines and Geology

APPENDIX C
PREVIOUS SAMPLING

Appendix C. Sites with water-quality data from previous studies.

GWICID	Site#	Site Name	Type	Depth (ft)	Hydrogeologic Unit
196429	PS1	JESSUP MILL POND * SPRING #14	SPRING		
256981	PS2	JESSUP MILL POND * SPRING #9	SPRING		
256983	PS3	JESSUP MILL POND * SPRING #6	SPRING		
257759	PS4	JESSUP MILL POND SPRING #22	SPRING		
255198	PS5	SIDERIUS TOM & TERRY	SPRING		
260565	PS6	FLATHEAD RIVER AT COLUMBIA FALLS AT HWY 2 BRIDGE	STREAM		
260564	PS7	FLATHEAD RIVER DEEP HOLE AT HALF MOON SLOUGH	STREAM		
85592	P1	MONTANA VETERANS HOME	WELL	238	Deep Aquifer
85468	P2	HELDSTAB, GUY/MATSON, JAMES R.	WELL	288	Deep Aquifer
40177	P3	HASSON ALEX AND MARY	WELL	165	Bedrock
127372	P4	LARSON KEVIN C	WELL	26	Shallow Aquifer
148189	P5	HOFFMAN, LARRY G. * FVGS A-3	WELL	342	Deep Aquifer
85689	P6	TURNER LORIN (BECKY) * FV-N-04	WELL	308	Intermediate Aquifer
6450	P7	BROOKS BRUCE AND NOELLA	WELL	31.4	Shallow Aquifer
156026	P8	BROOK BRUCE & NOELLA	WELL	35	Shallow Aquifer
154968	P9	RILEY NICK AND KATHY	WELL	80	Shallow Aquifer
6448	P10	USGS RESEARCH WELL * PRESSENTINE FISHING ACCESS	WELL	23	Shallow Aquifer
83424	P11	WEAVER STEVEN L	WELL	250	Bedrock
137868	P12	NUTTING, JAMI/HART, ROBERT	WELL	277	Deep Aquifer
6455	P13	MBMG RESEARCH * 84-22 * JONES	WELL	22	Shallow Aquifer
6454	P14	HELENA FLATS SCHOOL	WELL	45	Shallow Aquifer
890685	P15	EVANS FARMS	WELL	690	Deep Aquifer
702934	P16	EVANS TOM AND JULIE	WELL	422	Deep Aquifer
83666	P17	WEAVER ANDY	WELL	139	Mountain Front Deposits
125938	P18	SMITH ERIC	WELL	64	Shallow Aquifer
6419	P19	MBMG RESEARCH * 84-27 * EVERETT	WELL	23	Shallow Aquifer
81929	P20	JUKICK RICHARD	WELL	87	Shallow Aquifer
83797	P21	CAYUSE PRAIRIE SCHOOL DISTRICT 10 * WELL 01	WELL	140	Shallow Aquifer
83808	P22	VANBRUNDT DWIGHT	WELL	120	Shallow Aquifer
154870	P23	PICKENS LOIS	WELL	345	Mountain Front Deposits
82139	P24	FLATHEAD COUNTY PARK BOARD CONRAD COMPLEX	WELL	297	Deep Aquifer
130565	P25	GLENDENING MOLLIE	WELL	76	Shallow Aquifer
82381	P26	KEVIN PECINOVSKY	WELL	229	Intermediate Aquifer
139549	P27	TOELKE, DAVID/KRANTZ, CLARK	WELL	195	Intermediate Aquifer
81772	P28	BROWN, BRADLEY F AND DESIREE D	WELL	500	Deep Aquifer
81766	P29	MT AGRICULTURAL EXP STATION	WELL	407	Deep Aquifer
82558	P30	PARKS AND RECREATION	WELL	242	Deep Aquifer
258729	P31	CITY OF KALISPELL-OLD SCHOOL WELL #2 * NORTH WELL	WELL	484	Deep Aquifer
6414	P32	PLUMMER CHARLES E * 2115 LOWER VALLEY	WELL	650	Deep Aquifer
121308	P33	JAQUETH SCOTT	WELL	56	Shallow Aquifer
133079	P34	ENGELKE, GEORGE	WELL	287	Bedrock
80662	P35	HOLLINGSWORTH FRED	WELL	180	Intermediate Aquifer
150622	P36	HELGELAND, LEE AND BARBRA	WELL	43	Shallow Aquifer
81591	P37	SZABO JANET	WELL	137	Mountain Front Deposits

Note. For site locations see figure 6 in the main body of this report.

APPENDIX D
WATER-QUALITY DATA

Table D1. MBMG laboratory analytical parameters, and abbreviations.

Major Ions and Nutrients (mg/L)		Trace Elements (µg/L)	
Calcium*	Ca	Aluminum	Al
Magnesium*	Mg	Antimony	Sb
Sodium*	Na	Arsenic*	As
Potassium*	K	Barium	Ba
Iron*	Fe	Beryllium	Be
Manganese*	Mn	Boron	B
Silica	SiO ₂	Bromide	Br
Bicarbonate*	HCO ₃	Cadmium	Cd
Carbonate	CO ₃	Cerium	Ce
Chlorine*	Cl	Cesium	Cs
Sulfate*	SO ₄	Chromium	Cr
Nitrate*	as N	Cobalt	Co
Fluoride	F	Copper	Cu
Orthophosphate	as P	Gallium	Ga
		Lanthanum	La
		Lead	Pb
		Lithium	Li
		Molybdenum	Mo
		Nickel	Ni
		Niobium	Nb
		Neodymium	Nd
		Palladium	Pd
		Praseodymium	Pr
		Radon	Rn
		Rubidium	Rb
		Silver	Ag
		Selenium	Se
		Strontium	Sr
		Thallium	Tl
		Thorium	Th
		Tin	Sn
		Titanium	Ti
		Tungsten	W
		Uranium	U
		Vanadium	V
		Zinc	Zn
		Zirconium	Zr

Field Parameters		
Specific Conductivity	Field SC	µS/cm
pH	Field pH	---
Water Temperature	Temp	°C

Laboratory Parameters		
Lab Specific Conductivity	Lab SC	µS/cm
pH	Lab pH	---
Total Dissolved Solids*	TDS	mg/L

Water Isotopes		
Deuterium Fraction*	δD	per mil; ‰
¹⁸ O Fraction*	δ ¹⁸ O	per mil; ‰

mg/L, milligrams per liter (ppm);

µg/L, micrograms per liter (ppb);

µS/cm, microSiemens per centimeter at 25°C

*Parameters reported in this appendix (D).

See GWIC for other parameters: <http://mbmgwic.mtech.edu/>

Table D2. Summary of selected water-quality parameters for each HGU, based on regression on order statistics

(ROS).		TDS	Ca	Mg	Na	K	HCO ₃	SO ₄	Cl	NO ₃	Fe	Mn	As
													µg/l
Bedrock Aquifer (19) ¹	X ₂₅	151	31	11	1.7	0.5	175	3.2	0.59	0.11	0.009	-	0.46
	Median	160	33	14	2.6	0.5	189	3.9	0.65	0.21	0.011	-	0.48
	X ₇₅	174	40	16	4.9	0.6	211	5.1	1.09	0.44	0.023	-	0.58
Deep Aquifer (44)	X ₂₅	186	35	15	5.2	0.9	221	4.7	0.77	0.11	0.013	0.130	0.51
	Median	215	43	18	9.1	1.3	244	5.3	1.70	0.15	0.129	0.164	0.80
	X ₇₅	276	51	22	21.6	2.2	305	6.0	4.99	0.75	0.503	0.271	2.06
Mountain Front (6)	X ₂₅	188	33	14	2.6	0.6	202	3.6	0.71	0.20	0.046	-	0.62
	Median	199	41	18	2.7	0.7	239	3.9	0.76	0.26	0.084	-	1.01
	X ₇₅	211	50	19	3.2	0.7	253	5.8	0.78	0.27	0.992	-	1.41
Intermediate Aquifers (29)	X ₂₅	181	30	16	6.9	1.0	223	4.2	0.75	0.08	0.030	0.014	0.62
	Median	216	33	17	8.9	1.5	246	5.4	0.97	0.10	0.115	0.059	2.20
	X ₇₅	241	53	22	15.2	1.9	273	7.5	2.80	1.08	0.203	0.226	10.27
Shallow Aquifers (54)	X ₂₅	175	40	15	2.5	0.8	202	4.7	1.49	0.54	0.009	0.004	0.71
	Median	214	50	20	3.9	1.4	242	5.4	2.97	1.16	0.015	0.035	1.15
	X ₇₅	275	65	22	10.6	1.8	301	8.0	7.39	1.65	0.077	0.330	3.52
Surface Water (52)	X ₂₅	101	24	7	0.9	0.4	118	3.1	0.78	0.08	0.004	0.001	0.46
	Median	159	36	14	1.4	0.6	189	3.5	1.47	0.11	0.011	0.004	0.53
	X ₇₅	198	45	17	3.1	0.8	218	4.2	1.98	0.20	0.024	0.035	0.60

¹ Values in parenthesis next to the hydrogeologic unit (HGU) indicate the number of samples evaluated; however, the number of samples used in the analysis varied by parameter, particularly due to changes in detection limits over time.

- indicates that there were not enough values above the detection limit to calculate the statistic

X₂₅: 25th percentile; X₇₅: 75th percentile; mg/L, milligrams per liter; µg/L, micrograms per liter

Highlight indicates exceedance of MDEQ MCL, SMCL, or human-health guidelines.

Table D3. Groundwater stable-isotope results (values plotted on fig. 19 in the main body of this report).

Well Number	HGU	Depth (ft)	Sample Date	$\delta^{18}\text{O}$	δD
15	Bedrock	170	7/18/18	-17.5	-131
15	Bedrock	170	5/22/00	-17.4	-132
66	Bedrock	120	5/23/17	-17.2	-132
66	Bedrock	120	6/25/20	-17.1	-129
66	Bedrock	120	9/11/20	-17.2	-130
132	Bedrock	1,122	9/10/20	-19.1	-145
2	Deep Aquifer	518	6/17/10	-17.2	-131
13	Deep Aquifer	240	6/25/20	-18.0	-138
13	Deep Aquifer	240	9/12/20	-18.0	-138
29	Deep Aquifer	175	10/16/20	-17.2	-135
32	Deep Aquifer	340	8/12/96	-17.3	-128
32	Deep Aquifer	340	6/16/10	-17.4	-135
51	Deep Aquifer	400	6/24/20	-17.6	-135
51	Deep Aquifer	400	9/8/20	-17.5	-134
55	Deep Aquifer	338	8/5/10	-17.4	-138
56	Deep Aquifer	221	6/23/20	-17.7	-138
56	Deep Aquifer	221	9/9/20	-17.5	-136
77	Deep Aquifer	241	9/10/20	-17.8	-138
92	Deep Aquifer	480	12/14/21	-17.7	-134
96	Deep Aquifer	295	10/1/21	-17.5	-133
103	Deep Aquifer	640	12/15/21	-18.5	-140
111	Deep Aquifer	499	6/24/20	-16.9	-128
111	Deep Aquifer	499	9/8/20	-16.9	-127
121	Deep Aquifer	198	6/10/20	-16.6	-128
125	Deep Aquifer	300	12/15/21	-16.8	-127
Well Number	Hydrogeologic Unit	Depth (ft)	Sample Date	$\delta^{18}\text{O}$	δD
5	Intermediate Aquifer	149	5/22/00	-17.9	-138
19	Intermediate Aquifer	91	9/13/20	-18.3	-140
53	Intermediate Aquifer	188	9/13/20	-17.3	131
54	Intermediate Aquifer	160	6/24/20	-17.7	-136
54	Intermediate Aquifer	160	9/8/20	-17.6	-136
69	Intermediate Aquifer	195	6/24/20	-17.8	-135
69	Intermediate Aquifer	195	9/9/20	-17.6	-135
75	Intermediate Aquifer	153	6/24/20	-18.2	-140
75	Intermediate Aquifer	153	9/9/20	-18.1	-139
82	Intermediate Aquifer	210	9/8/20	-16.4	-127
91	Intermediate Aquifer	180	7/8/10	-17.9	-137
93	Intermediate Aquifer	217	12/14/21	-17.8	-133
105	Intermediate Aquifer	300	12/16/21	-19.3	-148
110	Intermediate Aquifer	166	6/24/20	-17.1	-130
110	Intermediate Aquifer	166	9/10/20	-17.2	-130
123	Intermediate Aquifer	180	12/14/21	-16.8	-126
12	Shallow Aquifer	NR	6/25/20	-16.1	-126
12	Shallow Aquifer	NR	9/12/20	-16.2	-127
72	Shallow Aquifer	120	6/25/20	-16.1	-124
72	Shallow Aquifer	120	9/10/20	-15.8	-123
85	Shallow Aquifer	100	9/9/20	-17.5	-134
94	Shallow Aquifer	66	12/14/21	-18.0	-137
104	Shallow Aquifer	50	12/15/21	-18.5	-142
116	Shallow Aquifer	140	6/6/10	-17.7	-137
126	Shallow Aquifer	56	12/15/21	-16.6	-126

Table D4. Surface-water stable-isotope results (values plotted on fig. 19 in the main body of this report).

Site Number	Water Body	Sample Date	$\delta^{18}\text{O}$	δD
S1	Flathead River	6/24/20	-17.2	-128
S1	Flathead River	9/12/20	-14.5	-128
S2	Flathead River	6/24/20	-17.2	-128
S2	Flathead River	9/11/20	-16.9	-127
S3	Flathead River	6/24/20	-16.1	-125
S3	Flathead River	9/12/20	-16.7	-127
S5	Flathead River	6/24/20	-17.1	-128
S5	Flathead River	9/10/20	-16.6	-126
S7	Mooring Creek	6/24/20	-13.4	-107
S8	Mooring Creek	6/24/20	-17.1	-129
S8	Mooring Creek	9/11/20	-15.4	-128
S10	Mooring Creek	6/24/20	-17.1	-127
S11	Hemler Creek	9/12/20	-17.2	-127
S12	Hemler Creek	6/23/20	-17.0	-126
S13	Blaine Creek	6/24/20	-15.2	-118
S13	Blaine Creek	9/12/20	-14.4	-115
S15	Jessup Mill Pond	10/19/10	-16.3	-126
S15	Jessup Mill Pond	10/19/10	-16.3	-126
S16	Mill Creek	6/10/20	-16.4	-125
S16	Mill Creek	6/23/20	-16.5	-125
S16	Mill Creek	9/10/20	-16.5	-125
S17	Mill Creek	6/23/20	-16.4	-125
S17	Mill Creek	9/10/20	-16.5	-125
S18	Mill Creek	6/23/20	-16.2	-124
S18	Mill Creek	9/10/20	-16.7	-126
S19	Mill Creek	6/24/20	-16.1	-123

Site Number	Water Body	Sample Date	$\delta^{18}\text{O}$	δD
S20	Lost Creek	7/8/10	-17.4	-131
S20	Lost Creek	6/24/20	-17.4	-128
S20	Lost Creek	9/11/20	-14.5	-128
S21	Trail Creek	6/22/20	-17.3	-127
S21	Trail Creek	9/11/20	-16.5	-128
S22	Mill Creek Upper	6/22/20	-17.2	-127
S22	Mill Creek Upper	9/11/20	-17.2	-127
S23	Mill Creek Lower	6/23/20	-17.1	-127
S23	Mill Creek Lower	9/10/20	-17.3	-127
S24	Browns Gulch Upper	6/22/20	-17.2	-127
S24	Browns Gulch Upper	9/11/20	-17.6	-129
S25	Browns Gulch Lower	6/22/20	-17.2	-127
S25	Browns Gulch Lower	9/10/20	-14.5	-128
S27	Unnamed Pond	6/25/20	-8.0	-86
S27	Unnamed Pond	9/11/20	-3.5	-65

Table D5. $^4\text{He}/\text{Ne}$, Tritium, and SF_6 results.

Site	Well Number	Hydrogeologic Unit	Total Depth	Sample Date	$^4\text{He}/\text{Ne}$	Tritium Units (TU)	TU 1- σ error	SF_6 ¹ (fMol/kg)
North	12	Shallow	~20	6/25/20	0.4	4.1	0.23	--- ²
	12	Shallow	~20	9/12/20	0.2	3.9	0.18	3.22
	13	Deep	240	6/25/20	621.8	0.1	0.02	---
	13	Deep	240	9/12/20	638.3	0.1	0.03	0.45
Central	69	Intermediate	195	6/24/20	14.1	0.9	0.06	---
	69	Intermediate	195	9/9/20	13.9	0.9	0.05	6.98
	51	Deep	400	6/24/20	2.4	1.0	0.06	---
	51	Deep	400	9/8/20	2.6	0.9	0.06	0.85
South	110	Intermediate	166	6/24/20	4.4	0.4	0.03	---
	110	Intermediate	166	9/10/20	4.4	0.6	0.04	0.98
	111	Deep	499	6/24/20	4.5	1.9	0.07	---
	111	Deep	499	9/10/20	4.1	3.4	0.15	0.57
Jessup Mill Pond	126	Shallow	56	12/16/21	0.2	3.6	0.14	---
	123	Intermediate	180	12/16/21	0.2	3.6	0.15	---
	125	Deep	300	12/16/21	0.2	3.9	0.14	---
Jaquette Road	94	Shallow	66	12/16/21	0.3	1.0	0.05	---
	93	Intermediate	217	12/16/21	14.3	1.9	0.12	---
	92	Deep	480	12/16/21	1.8	<0.06	0.02	---
Foy's Bend	104	Shallow	50	12/17/21	1.6	2.4	0.13	---
	105	Intermediate	300	12/17/21	0.8	<0.09	0.03	---
	103	Deep	640	12/17/21	21.4	<0.06	0.02	---

¹With headspace correction.²Indicates parameter was not sampled.*Note.* Sampling locations are shown on figure D1.

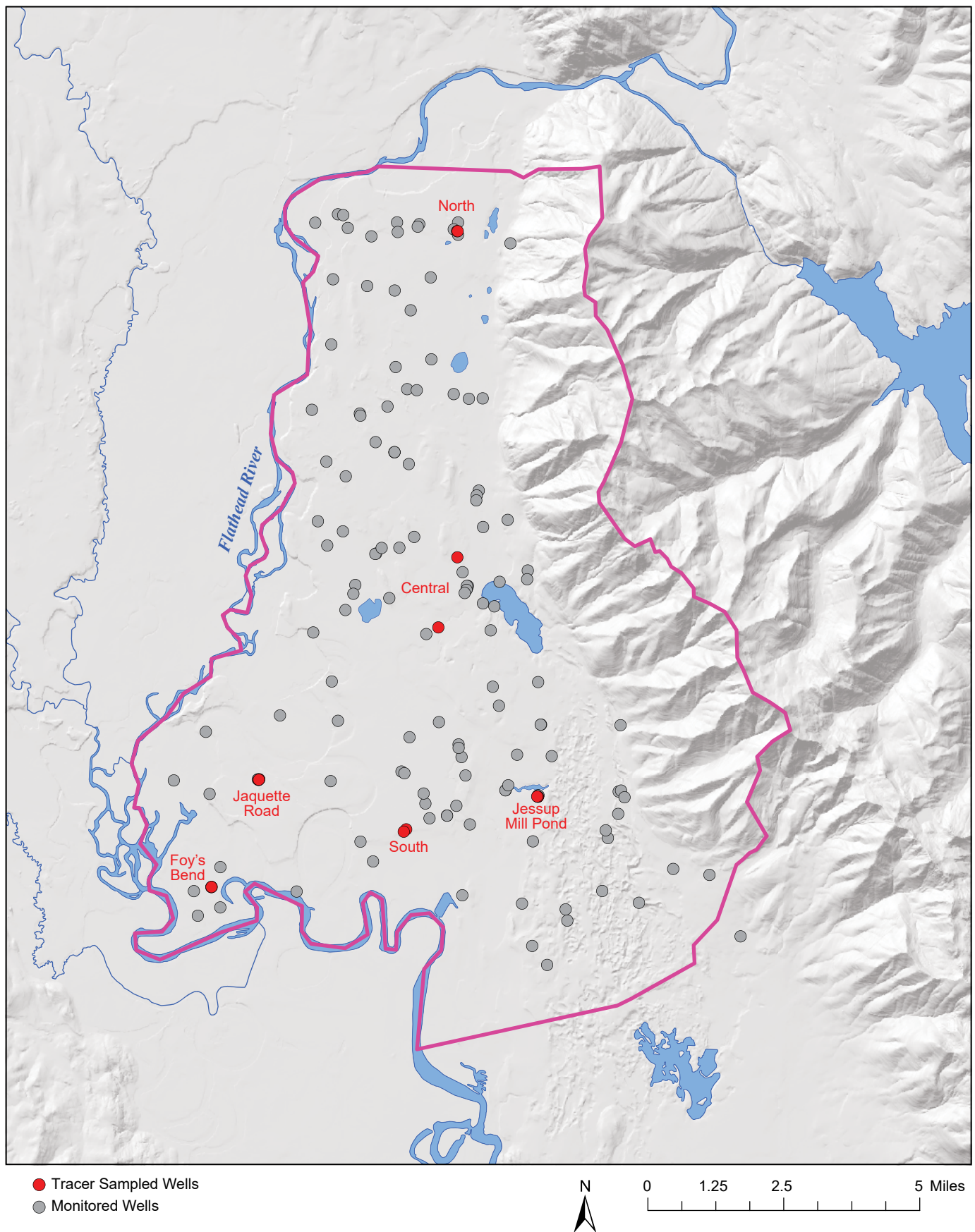


Figure D1. $^4\text{He}/\text{Ne}$, tritium, and SF_6 tracers were sampled at select wells. See table D5 for details.