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SOURCES OF SALINITY TO THE MUSSELSHELL RIVER, MUSSELSHELL COUNTY, MONTANA

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*Front photo: Delphia–Melstone Canal informational sign near Musselshell, Montana.
Photograph by Matthew Smith.*

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ABSTRACT

The Musselshell River is the sole source of irrigation water in Musselshell County, Montana. However, high levels of salinity occasionally make the river an unsuitable source of irrigation water. Salinities that approach or exceed the irrigators' threshold of 3,000 µS/cm occur in some years during early spring and late fall. At the request of the Musselshell Watershed Coalition, the Montana Bureau of Mines and Geology Ground Water Investigation Program investigated the groundwater/surface-water system along the Musselshell River in eastern Musselshell County to identify the cause of elevated river salinity.

We investigated the roles of geology, irrigation canals, and irrigation method on salt mobilization to the river at two focus sites, near Delphia and Melstone. Sixteen monitoring wells were installed and instrumented to measure groundwater level and salinity through 2020 and 2021. Groundwater and surface water were sampled seasonally for major ions and isotopes of strontium. To the extent possible, interpretations presented here account for the influence of the 2021 drought, which resulted in a foreshortened irrigation season and low river flow rates.

Elevated river salinity in the spring and late fall/winter occurs when high-salinity baseflow (groundwater discharge to the river) represents a larger fraction of river flow; this condition is associated with lower overall river flow rates. Irrigation practices that recharge groundwater increase the amount of baseflow discharged to the river during the summer and fall. In late summer and early fall of 2020, irrigation return flows increased the salinity of the Musselshell River from Delphia to Melstone by approximately 20 to 30 percent (July–September, 2020). However, the contribution of irrigation-related baseflow to river salinity does not negatively impact irrigators because of its timing: this baseflow is diluted by low-salinity conditions in the river during periods of naturally high flow rates (snowmelt–runoff) or releases of low-salinity reservoir water.

Application of irrigation water to fields and leaking irrigation canals raise the water table, and these high water table conditions dissolve available soluble salts from the soil. Those salts can then migrate to the soil surface or surface water. Marginal improvements to lower the salinity of the river could be achieved through the installation of additional center pivots (replacing flood irrigation) or lining the irrigation canals; however, these would not prevent the river from approaching 3,000 µS/cm in the early spring, when baseflow makes up a large portion of total flow in the river. Leakage from the Delphia–Melstone Canal provides low-salinity recharge water to the aquifers overlying the Fox Hills and Bearpaw geologic units. The water quality of canal leakage is similar to the naturally occurring levels of salinity in groundwater of the Fort Union Formation. These aquifers are not currently used for drinking water or stock water, but the water table aquifers provide subirrigation to crops in areas hydraulically downgradient of the canals.

INTRODUCTION

The Musselshell River runs 340 mi through central Montana. The mainstem begins near the town of Martinsdale and flows east and then north to its confluence with the Missouri River and the Fort Peck reservoir (fig. 1). The river is the sole source of irrigation water in Musselshell County. However, in some years, the river's salinity levels at certain times can make it unsuitable for irrigation. The salinity of irrigation water controls crop production and soil health (Hanson and others, 2006). The salinity at which there are adverse effects to crop production and soil structure is dependent upon the crop, soil type, and water chemistry. Along the Musselshell River, the irrigators have set that threshold at 3,000 μS/cm and have implemented a volunteer-based citizen-monitoring network to better understand the timing and controls on river salinity (MWC, 2021). Volunteers measure the river salinity throughout the growing season from Two Dot to below Melstone. Since their monitoring began in 2011, the river has exceeded the 3,000 μS/cm benchmark during the spring (April and/or May) of 2011, 2012, 2015, 2016, 2020, and 2021 (MWC, 2021). The Musselshell Watershed Coalition approached the Montana Bureau of Mines and Geology (MBMG) Ground Water Investigation Program (GWIP, 2022) to investigate the groundwater contribution to the river salinity and the potential agricultural controls on mobilization of salt to the river. Irrigators may use this information to identify techniques, such as canal lining and pivot installation, that will minimize salt mobilization and improve irrigation efficiency.

Leakage from irrigation canals and the application of irrigation water can mobilize salts held naturally in the soil and from applied agricultural amendments (Hanson and others, 2006). Agricultural amendments in use along the Musselshell River can include manure from livestock operations, fertilizers (primarily on corn fields), and herbicides (e.g., Roundup; oral commun., Landon Krogstad, Rangeland Management Specialist, NRCS Musselshell Field Office, October 31, 2022). Raising the groundwater level brings more native soil-salts into contact with the groundwater. Additionally, infiltration of applied irrigation water can dissolve available salt in the soil and transport agricultural amendments to the groundwater (fig. 2).

While in some agricultural settings canal leakage and applied irrigation water can mobilize salt from the soil into the groundwater, in others leakage and irrigation return provide a diluting effect, lowering the salinity of the groundwater (Meredith and others, 2009). When concerns about the contribution of groundwater salinity to surface water arise, identifying geologic settings where canal leakage mobilizes salts may guide efforts to line canals. Similarly, if the leaching fraction (irrigation water applied in excess of evapotranspiration demand) of applied irrigation water mobilizes salt to the groundwater, installing efficient irrigation systems—such as sprinklers and pivots—should reduce that leaching fraction and the associated mobilized salt. These two solutions were evaluated for predicted efficacy if implemented along the Musselshell River.

Purpose and Objectives

To achieve the goal of the Musselshell Watershed Coalition to further their understanding of natural and agricultural controls on river salinity, this study focused on two main objectives:

1. Document the groundwater quality and groundwater/surface-water interactions along the Musselshell River, and

2. Determine if canal leakage and/or applied irrigation mobilize salinity to groundwater.

The groundwater/surface-water interaction (objective 1) determines possible salt contributions from groundwater to the river. Identifying salinity mobilized through irrigation practices (objective 2) delineates the agricultural component of groundwater salinity.

Study area location

This project focused on the approximately 30-mi reach of the Musselshell River through Musselshell County serviced by the Delphia–Melstone irrigation canal (figs. 1, 3). The two focus areas represent the major geologic units underlying the Musselshell River in the study area: the Tongue River (sandstone) Member of the Fort Union Formation at Delphia and the Fox Hills sandstone and Bearpaw shale at Melstone.

Hydrologic Setting

The Musselshell River has its headwaters in the Little Belt, Castle, and Crazy Mountains. From the confluence of the North Fork and South Fork at Martinsdale (elevation 4,700 ft), the river flows 340

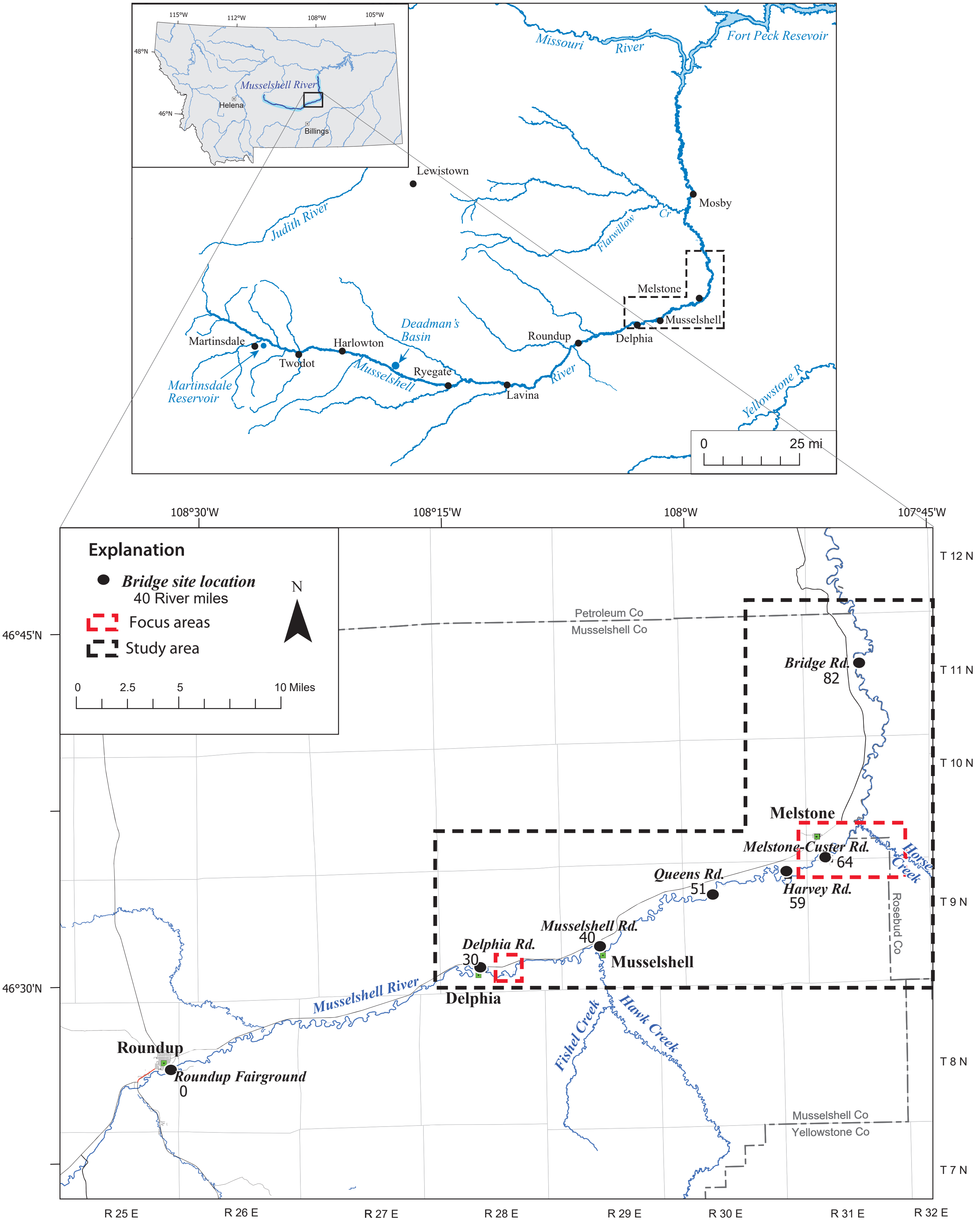


Figure 1. Study site location. The study area encompassed the irrigated land along the Delphia–Melstone Canal in Musselshell County. Seven bridges over the Musselshell River, from Roundup to the county line, were included in the monitoring network. Two focus areas were chosen for detailed study.

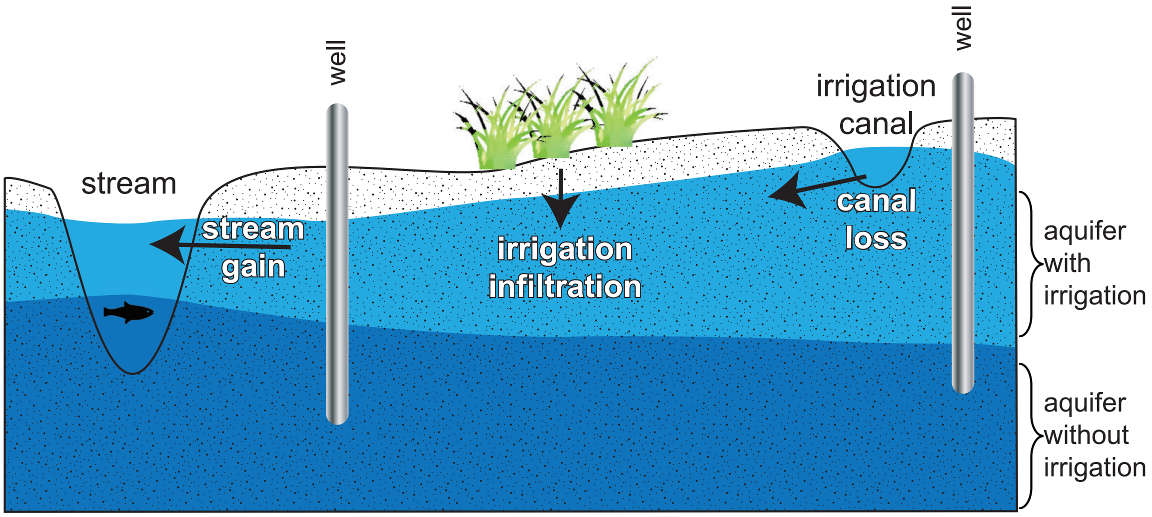


Figure 2. Irrigation and groundwater conceptual schematic. Irrigation practices can recharge groundwater through canal seepage and infiltration of applied irrigation water in excess of evapotranspiration (crop) demand. Recharge from irrigation raises the water table, which increases the aquifer storage and potentially creates or increases baseflow to streams. The example presented in this schematic illustrates a stream that loses flow to groundwater initially but transitions to gaining groundwater under the influence of irrigation-related recharge.

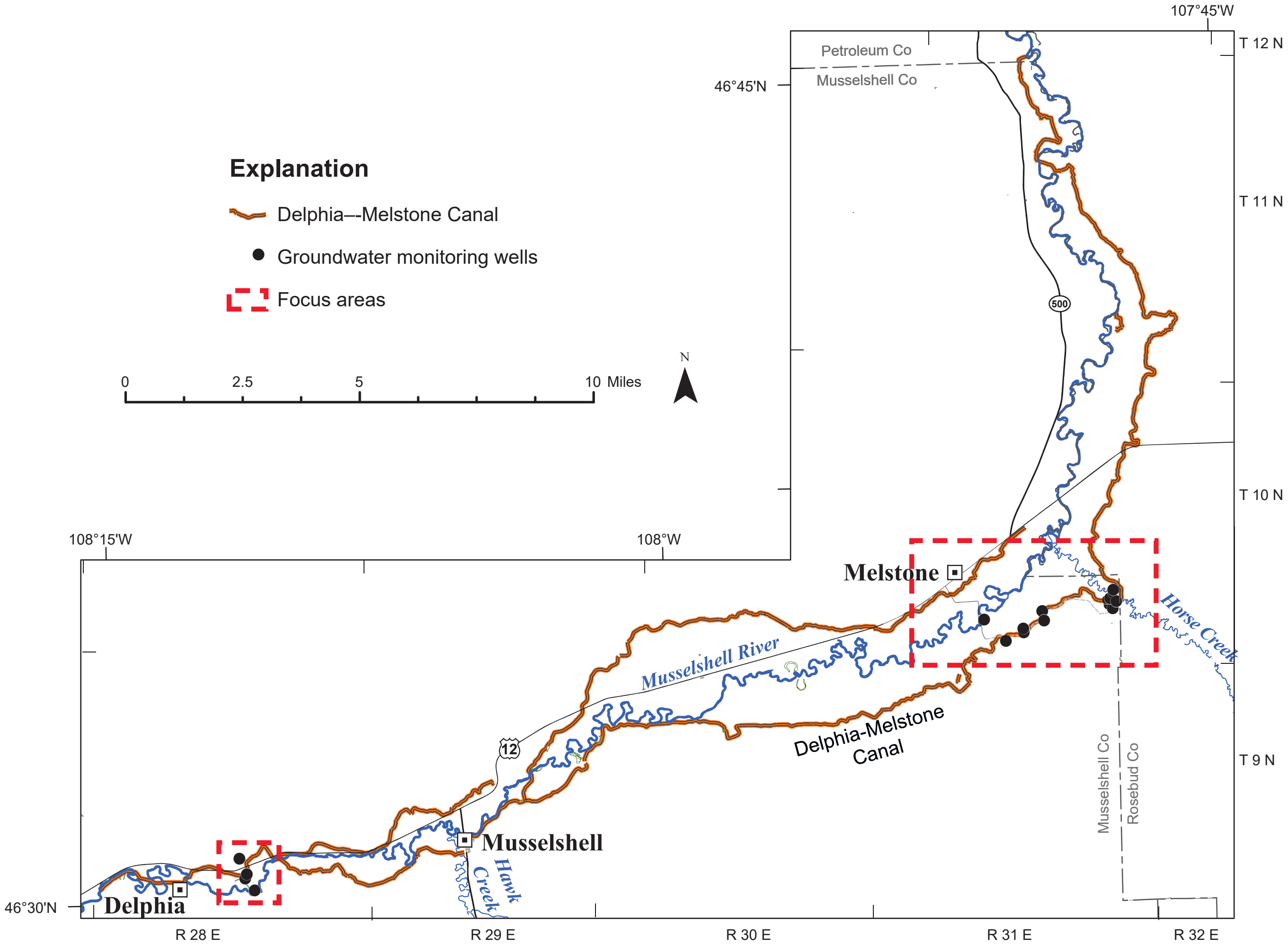


Figure 3. Site location. The Delphia–Melstone Canal runs on the north and south side of the Musselshell River, servicing 50 irrigators who irrigate over 6,000 acres. Focus sites for this study were chosen near the towns of Delphia and Melstone.

mi to its mouth at Fort Peck Reservoir (elevation 2,250 ft).

The Musselshell River average monthly discharge at Roundup varies between 64 cubic feet per second (cfs) in January to 701 cfs in June (Gage 06126500; USGS, 2021). Flow rates in 2020 were close to average—the high-flow event in May did not result in flood conditions (fig. 4). In contrast, the river discharge in 2021 followed a trend similar to the lower 25th quartile of flow rates measured over the past 73 years. As a result of low river discharge, the Delphia–Melstone Canal stopped supplying water to irrigators in mid-July 2021, whereas it would have typically continued through September.

In the Musselshell River Valley, irrigators use a combination of flood, side-roll sprinkler, and center pivot irrigation methods (fig. 5). The narrow river valley created by the resistant sandstone of the Fort Union Formation (fig. 6), near the towns of Delphia and Musselshell, does not lend itself to the large areas needed for pivot irrigation; therefore only flood irrigation is used. Where the valley widens in the more readily eroded shales of the Bearpaw, irrigators use a combination of irrigation methods (figs. 5, 6). Irrigated crops are predominantly alfalfa, small grains such as wheat and barley, hay grasses, and corn. Applied irrigation water is generally diverted from the Musselshell River into canals but is also pumped directly from the river. From Martinsdale to Fort Peck Reservoir (fig. 1), the river supplies nearly 85,000 acres on 250 farms and ranches with irrigation water (MWC, 2021). The Delphia–Melstone Canals run from the town of Delphia to the Musselshell–Petroleum County line. The system consists of 3 canals and 2 diversions from the Musselshell River that service 50 irrigators and 6,085 acres of irrigated land (fig. 5; DMWUA, 2021). In areas where the groundwater table is within

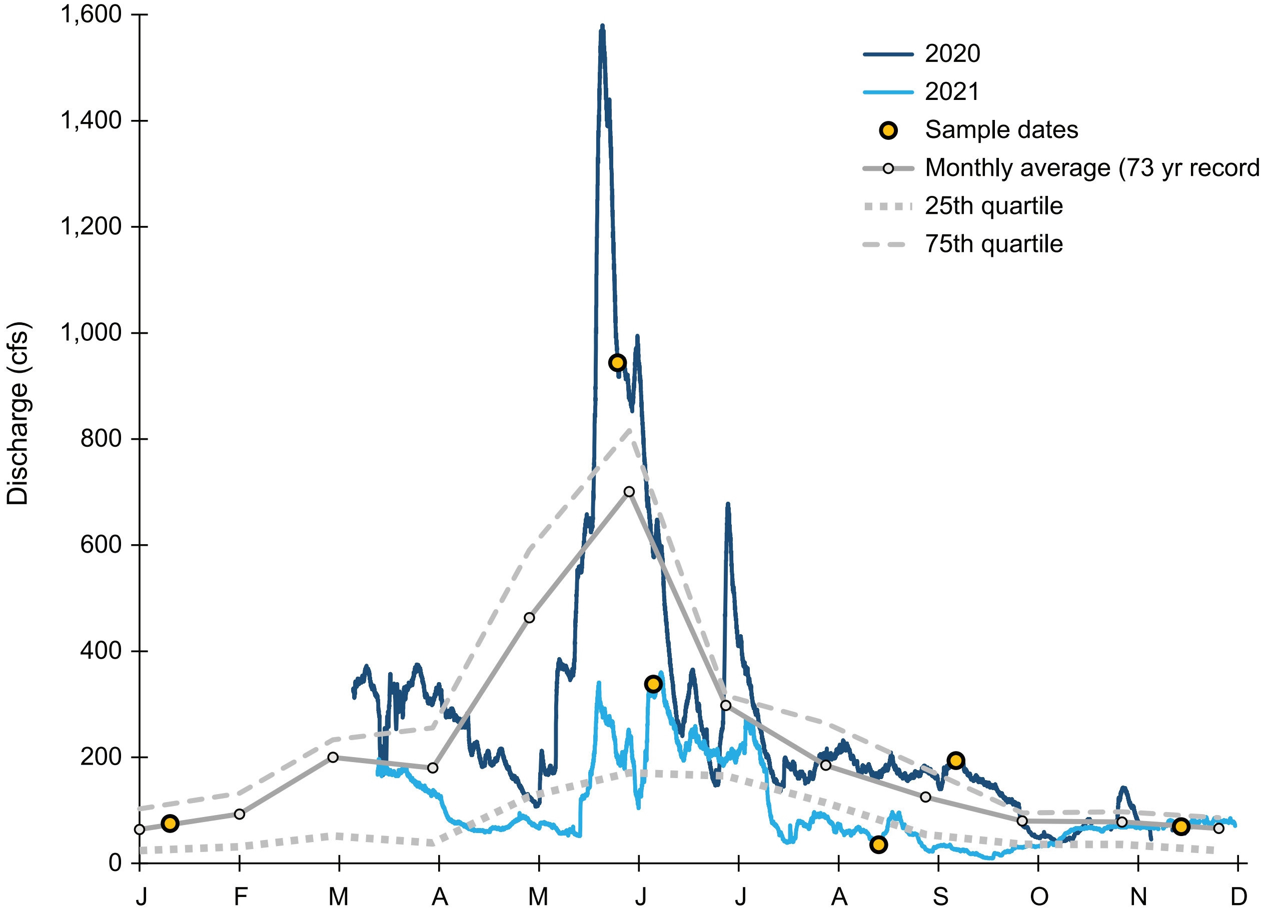


Figure 4. Musselshell River discharge. The Musselshell River, gaged by the USGS at Roundup (Gage 06126500; USGS, 2021), averages 64 cfs in January and 701 cfs in June (period of record 1947–2020). High flows occur during spring snowmelt, as was seen in 2020; however, the drought conditions in 2021 led to below average discharge throughout the year. River samples collected for this project coincided with high flow, low flow, and August/September, when elevated irrigation return flow was expected.

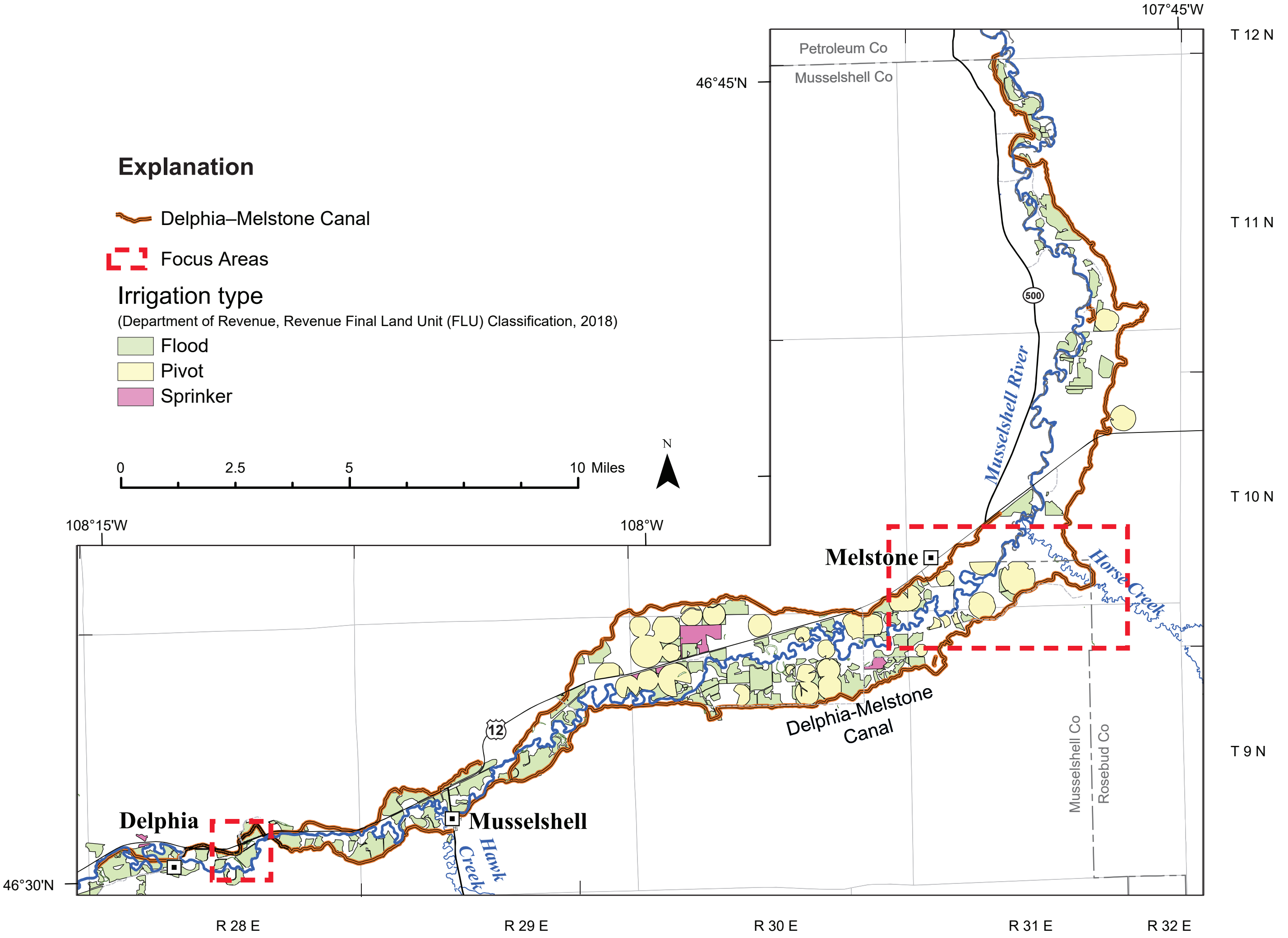


Figure 5. Irrigation along the Musselshell River. Irrigators in Musselshell County depend upon the Musselshell River as their only source of irrigation water. From Delphia to the county line, 4,700 acres are flood irrigated, 3,500 are pivot irrigated, and 300 are sprinkler irrigated. Of these approximately 8,500 irrigated acres, 6,085 acres are irrigated from the Delphia–Melstone Canal. Remaining acres are irrigated directly from the river.

the rooting zone during the growing season, agricultural fields are referred to as "subirrigated." This condition occurs in locations where the water table is naturally near the surface, such as the river's alluvial plain, or where the water table is artificially elevated, such as below leaking irrigation canals. The subirrigated field included in this study is not also irrigated from the surface (e.g., not flood or pivot irrigated). This report refers to "unirrigated" fields as those fields where irrigation water is not, and has never been, applied to the soil surface through flood, sprinklers, or pivots. The unirrigated fields included in this study are not subirrigated.

Hydrogeologic Setting

The bedrock underlying the Musselshell River as it passes by the towns of Delphia and Musselshell is the Tongue River Member of the Tertiary Fort Union Formation (fig. 6). The Fort Union Formation is composed of interbedded sandstone, shales, and coals. The Tongue River Member is a massive sandstone interbedded with carbonaceous shale, siltstone, and coalbeds (Porter and Wilde, 1999; Wilde and Porter, 2000; Vuke and Wilde, 2004). The Tongue River sandstone is generally an adequate aquifer for stock and domestic uses but can require treatment for human consumption.

From the town of Melstone to the northern project boundary, the primary bedrock unit underlying the river is the Cretaceous Bearpaw shale (fig. 6). Massive shale units such as the Bearpaw (thickness ranges from 1,100 to 1,318 ft) have low transmissivity and porosity and are therefore generally poor aquifers (Porter and Wilde, 1999; Wilde and Porter, 2000; Vuke

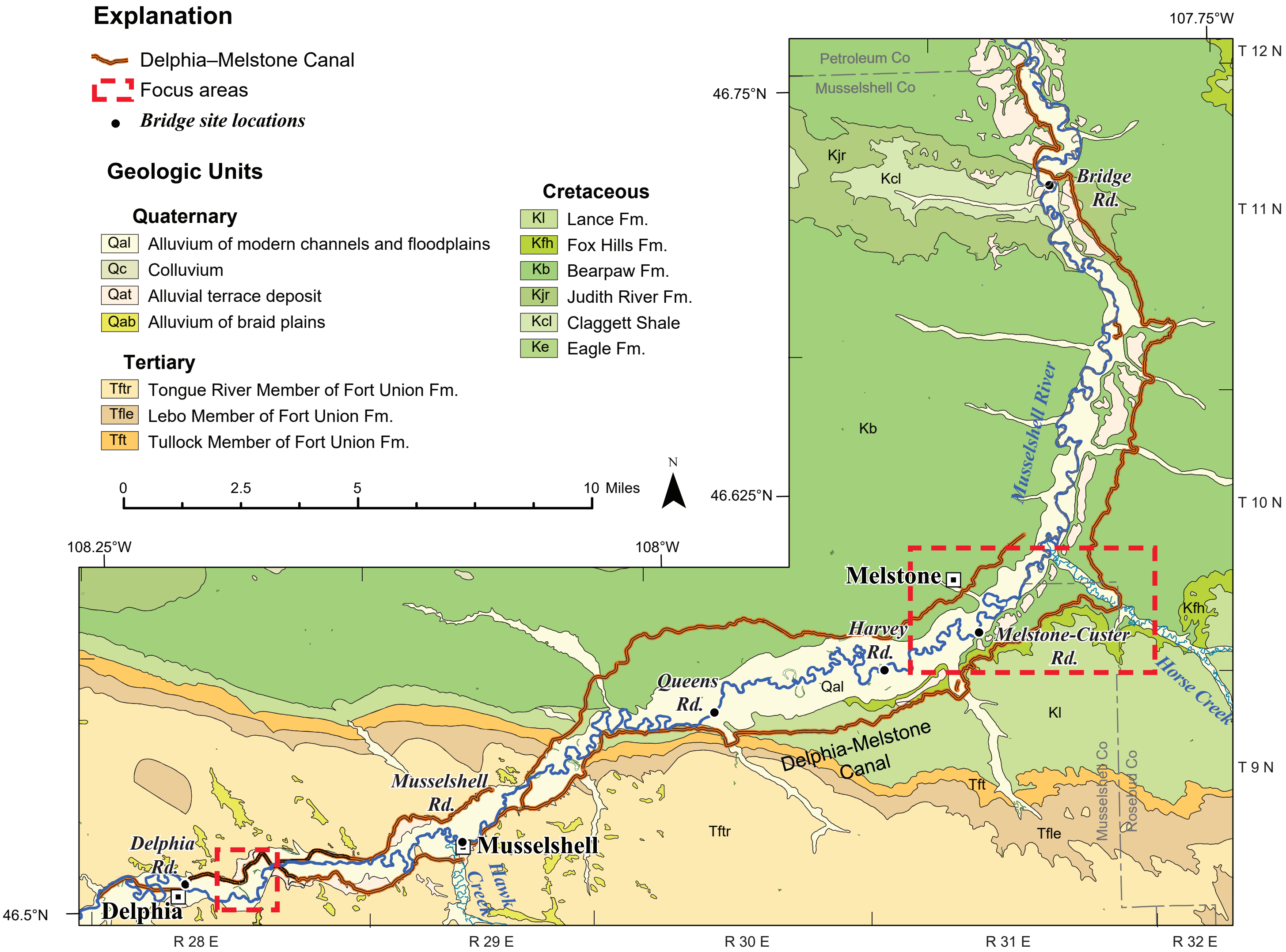


Figure 6. Geology of the study site. The Musselshell River crosses two major geologic units within the study area: the Tertiary Fort Union Formation—primarily the Tongue River member sandstone—and the Cretaceous Bearpaw shale. Focus areas within the study site were chosen at Delphia and Melstone to investigate the role of geology on the river salinity.

and Wilde, 2004). Although the Bearpaw Shale is not an aquifer as defined by Freeze and Cherry (1979) because it does not “transmit significant quantities of water under ordinary hydraulic gradients,” it is the sole source of groundwater for much of this study area, supplying groundwater recharge to stock reservoirs and springs. Because of this locally important contribution to water supply, the Bearpaw shale is considered an aquifer for the purposes of this project.

Transitioning from the Fort Union to the Bearpaw, the river crosses the Cretaceous Fox Hills and Lance Formations (fig. 6). The Hell Creek Formation is stratigraphically equivalent to the Lance Formation and the nomenclature is used interchangeably in central and eastern Montana. The Lance and Fox Hills Formations consist mainly of light brown to gray sandstone. The units are interbedded with medium gray shale and thin coalbeds. The basal sandstones are channel deposits that have eroded into the underlying Bearpaw Shale. The combined Lance and Fox Hills Formations are about 400 to 450 ft thick (Porter and Wilde, 1999; Wilde and Porter, 2000; Vuke and Wilde, 2004).

Sandstone and shale geologic units generally differ in aquifer properties. While sandstone can have hydraulic conductivities (a measure of how easily water moves through the medium) of 10^{-4} to 1 ft/d, shale tends to be much less conductive with hydraulic conductivities ranging from 10^{-7} to 10^{-3} ft/d (Weight and Sonderegger, 2001). Water wells in Musselshell County illustrate this difference: 275 wells in the Ground Water Information Center (GWIC) database are noted as completed in the Fort Union or Tongue River (predominantly sandstone) aquifer, but there are no reported wells in Musselshell County completed in the Bearpaw shale, outside of the monitoring wells installed for this study (MBMG, 2021).

Climate

The average precipitation from 1971 to 2021 for Melstone is 15.0 in per year with peak monthly precipitation occurring in May at approximately 3 in (fig. 7; DRI, 2022). Precipitation was 1.7 in below average (total of 13.3 in) during the first year of the study, 2020. Below-average rainfall in fall and winter of 2020 continued through 2021 (fig. 7). Total precipitation during 2021 was 7.6 in, which is 7.4 in below the 50-yr average (DRI, 2022).

The potential evpotranspiration demand in central Montana is much greater than the typical annual precipitation. The calculated potential evapotranspiration at the Lower Musselshell AgriMet station near Melstone (USBR, 2022) for water years 2020 and 2021 (measured October through September) was 50.03 and 48.94 in, respectively. The annual crop water demand ranged from 17.2 to 38.4 in. in 2020 and from 19.3 to 39.0 in. in 2021, for spring grains (low range demand) and alfalfa (high range demand; USBR, 2022).

The west and mountain west of the United States, including Montana, experienced drought conditions during the second year of the study, 2021. Over 98 percent of Montana was classified as in severe drought; eastern Montana, including the study area, experienced extreme-to-exceptional drought conditions (fig. 8; NOAA, 2021). NOAA defines extreme drought as periods when crops are not harvested, winter pasture is opened for grazing, soil exhibits cracks, and fields are bare. MBMG field staff observed all these conditions in Musselshell County.

Previous Investigations

Canal loss rates in Musselshell County were investigated at the county scale by the Musselshell Watershed Coalition (Lange and Friedman, 2017). Synoptic measurements of canal flow rates were collected five times along the Deadman's Basin and Delphia–Melstone irrigation canal systems throughout the 2017 irrigation season. Canal loss calculated for sections of the Delphia–Melstone Canal coincide with this project's study area at one location near Delphia [the reach between Lange and Friedman (2017) sites DC2 and DC3] and one location near Melstone [the reach between Lange and Friedman (2017) sites SC4 and SC5].

Lange and Friedman (2017) determined that the canal near Delphia lost between 2.6 cfs/mi (May 24th, 2017) to 0.75 cfs/mi (July 5th, 2017). Flow measurements on August 16th found the canal gained 1.1 cfs/mi. The canal near Melstone also transitioned between a losing and gaining system through the irrigation season. Based on results from May and June measurements, Lange and Friedman (2017) added an additional flow measurement site (SC4a) between sites SC4 and SC5 in early July. This allowed them to identify a gaining reach between Melstone Fields A and B (see Focus Areas). Loss measurements from sites SC4 to SC4a ranged from 1.6 cfs/mi (July 5th) to 3.7 cfs/mi (July 20th). Calculated gain between sites SC4a and SC5 ranged from 4.3 cfs/mi (July 5th) to 7.0 cfs/mi (July 20th). The Delphia–Melstone Canal diverted approximately 17 cfs from the river near Delphia and 61 cfs from the river near Melstone (Lange and Friedman, 2017). Per-mile loss was, therefore, approximately 10 percent of the diverted flow for both reaches of the canal. Error associated with the measurements was not provided; however, the narrative description indicated that irrigation withdrawals on the canal were difficult to quantify.

The Musselshell Watershed Coalition has organized a volunteer-based salinity monitoring program of the Musselshell River since 2011 (MWC, 2021). From Two Dot (upstream) to the Flatwillow Creek confluence (downstream; fig. 1), volunteers record the specific conductance (SC) of the river approximately weekly to biweekly from April through September. The data are hosted on the Montana State University Extension website and are plotted against river flow rates measured at USGS gages. The monitoring program was implemented to allow for more informed water management decisions along the Musselshell River. These salinity measurements provide an important historical record to compare trends in SC with the seasonal flows.

The Montana Department of Environmental Quality (MT DEQ) evaluated the water quality of the Musselshell River from 2015 to 2017 (MT DEQ, 2018). The investigators analyzed samples from the river and its tributaries for nutrients, metals, salinity, *Escherich-*

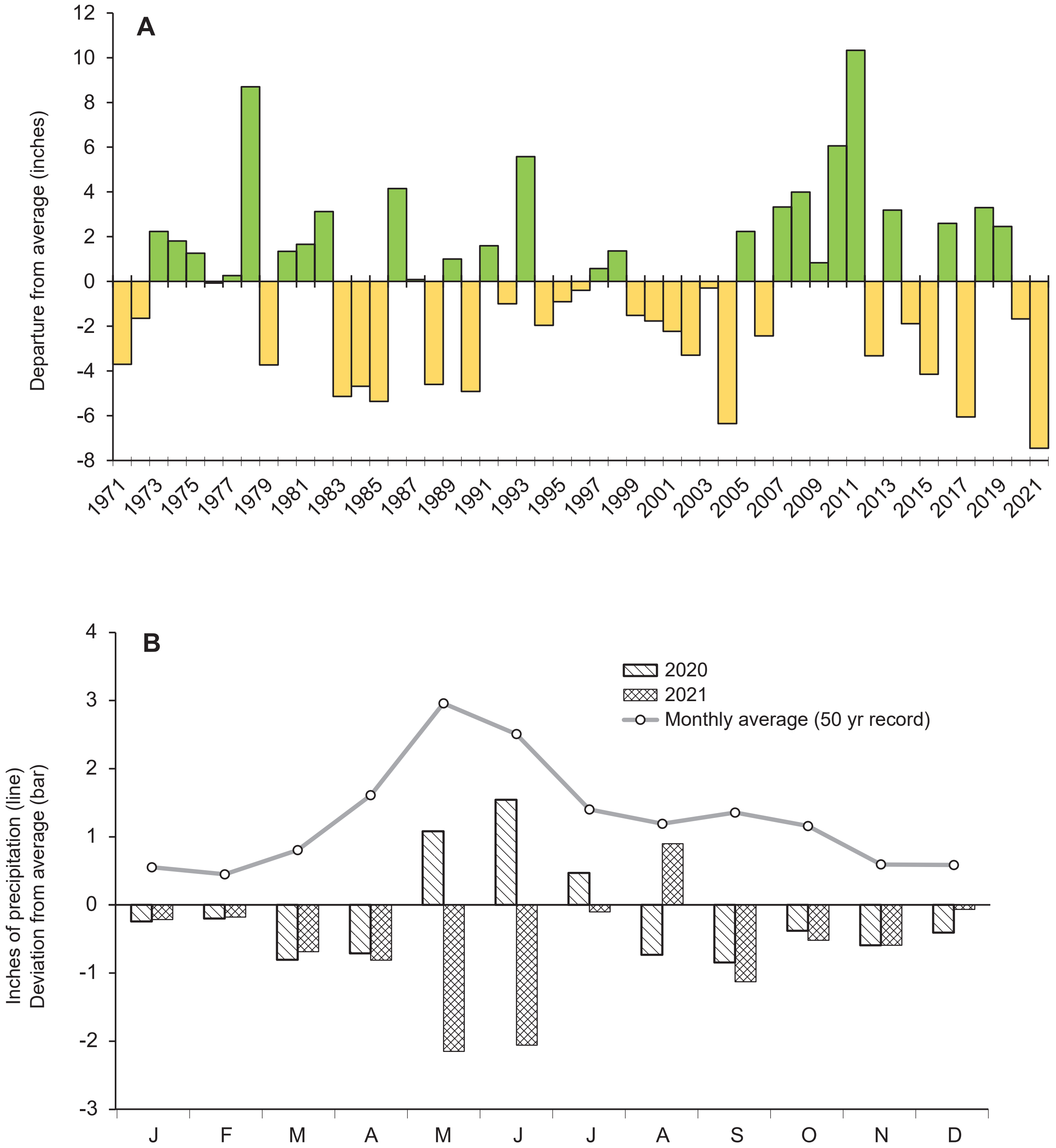


Figure 7. Deviation from average precipitation. Precipitation was below average during both of the study years, 2020 and 2021 (A). The average annual precipitation from 1971 to 2021 in Melstone (Station 245596; DRI, 2021) is 15 in per year, with peak monthly precipitation of about 3 in occurring in May. The year 2020 was below average for every month aside from May, June, and July. Below-average precipitation continued through 2021 (B).

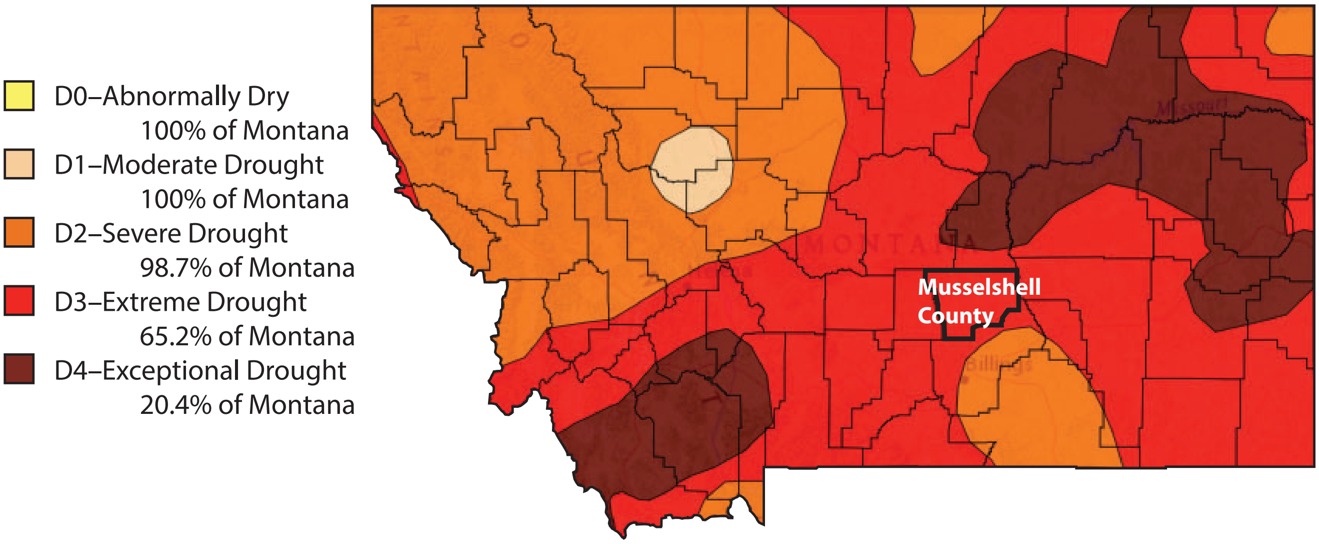


Figure 8. Summary of 2021 drought. Musselshell County, like much of the western United States, experienced extreme drought conditions in 2021 (September conditions; modified from NOAA, 2021).

ia coli, and sediment. The highest measured SC of the river was 4,000 µS/cm; however, some of the tributaries to the river exceeded 10,000 or 20,000 µS/cm (e.g., North Willow Creek, Painted Robe Creek, Dovetail Creek, and Crooked Creek; outside of this project's study area). MT DEQ monitored one tributary within the study area of this project, Hawk Creek. The SC of Hawk Creek ranged from 2,930 to 3,115 µS/cm (four sample dates); flow rates varied from 0 to 2.40 cfs (six measurements; median value 0.85 cfs). The authors concluded that management of the storage reservoirs along the Musselshell River (e.g., Martinsdale Reservoir and Deadman's Basin; fig. 1) play a part in moderating the salinity of the river by storing low-salinity spring flows for later release. Releasing low-salinity reservoir water buffers the salinity of the river during low flows in late summer, when the river typically experiences higher salinity (MT DEQ, 2018).

These studies considered canal loss and river salinity separately. Prior to the work presented here, there have been no investigations into whether canal loss influences river salinity or how applied irrigation influences the groundwater system in the area. Similarly, there have been no previous investigations into groundwater salinity and its potential contribution to river salinity.

METHODS

Fieldwork began in June 2019 with collection of groundwater-level and salinity measurements as monitoring wells were installed. The primary study period extended from January 2020 through September 2021.

The general approach to field data collection was driven by the two objectives:

> *Objective 1. Determine the spatial and temporal patterns of groundwater interactions with the Musselshell River.*

Nested monitoring wells were installed in the Musselshell River alluvium and underlying bedrock to monitor hydraulic conditions and water exchange among the bedrock, alluvium, and the river.

> *Objective 2. Identify the role of irrigation in salinity mobilization.*

Wells were installed upgradient and downgradient from irrigation canals to measure the influence canal leakage has on the water table elevation and groundwater quality. Soil moisture and electrical conductivity were measured in the soil profile of unirrigated fields, flood-irrigated fields, and pivot-irrigated fields to assess the effect of applied irrigation water on groundwater. Soil cores from these fields were analyzed for the distribution of salt through the profile.

Groundwater and surface water were sampled seasonally to identify water-quality trends related to seasonal irrigation. These data were also used to assess relationships between salinity levels and the hydraulic connections between groundwater and the canal and river.

Data Management

All information related to monitoring sites, including location, drill logs, water-level measurements, and sample results, is stored in the Ground Water Information Center (GWIC) database hosted by the Montana Bureau of Mines and Geology (MBMG, 2021). Monitoring sites are identified in the database by a GWIC identification number; numbers are included in appendix A.

Focus Areas

Two focus areas were chosen to represent the major geologic units the Musselshell River crosses in the study area: the Tongue River (sandstone) Member of the Fort Union Formation at Delphia and the Fox Hills sandstone and Bearpaw shale at Melstone. At both sites, wells were installed in the Musselshell River alluvium and underlying bedrock to measure hydraulic gradients between the groundwater and the river (figs. 9, 10). Wells upgradient and downgradient from the canal were installed on four fields (fig. 11) to measure the groundwater response to canal leakage.

The Melstone focus area (fig. 9) encompasses the influences of a subirrigated field on Fox Hills/Bearpaw contact (Field A), a center pivot on Fox Hills/Bearpaw contact (Field B), a center pivot on Fox Hills sandstone (Field C), and leakage from the Delphia–Melstone Canal as it crosses these formations. The Fox Hills overlies the Bearpaw and the contact between these two units falls within the fields in the Melstone area (fig. 9, cross-section).

The Delphia focus area (fig. 10) encompasses Delphia–Melstone Canal leakage and a flood-irrigated field (Delphia Field). At this site, colluvium and alluvium overlie the Fort Union sandstone (fig. 10 cross-section).

Groundwater Monitoring

We installed 11 wells at the Melstone focus area (fig. 9) and five monitoring wells at the Delphia site (fig. 10 and appendix A). Wells were instrumented with an In-Situ Inc. AquaTroll 200 datalogger that recorded water level and SC hourly. Field technicians visited wells monthly to manually measure water levels and SC with a Heron Conductivity Plus downhole water level/SC meter. This method, measuring SC at the depth of the well screen, varies from the purging method for measuring SC as described in Gotkowitz (2022) and served as a check against the SC values recorded by the AquaTroll 200. Measurements were verified with sample collection that included purging (see Groundwater and Surface-Water Sampling).

Well nomenclature

Well names are acronyms that describe their location within the study area (table 1; figs. 3, 9, and 10). The first letters, D, M, A, B, and C, stand for the locations Delphia, Melstone, and irrigated Fields A, B, and C, respectively. The second letters, U, R, and C, refer to upper (unirrigated land), river (near the Musselshell River), and canal (near the Delphia–Melstone irrigation canal), respectively. The last letter identifies the well as part of a shallow (S) and deep (D) pair or upgradient (U; upper) or downgradient (L; lower) from the canal. On Melstone Field A, the nested wells below the canal (ACL wells) are also distinguished by their relative depth: shallow (S), middle (M), and deep (D; table 1; appendix A).

Surface-Water Monitoring

Bridges crossing the Musselshell River, from Roundup to the Musselshell–Petroleum County line, were visited twice monthly (fig. 1). Depth to water and SC were measured from surveyed points on seven bridges. The Delphia–Melstone Canal stage was measured at two locations (fig. 9, D-M Canal site 307593 and fig. 10, D-M Canal site 304690) using water-level/SC data loggers installed in stilling wells anchored to the canal walls.

Synoptic flow rates of the Musselshell River were measured using a Teledyne StreamPro Acoustic Doppler Current Profiler (ADCP) in September and November of 2020 and August 2021 (appendix B). River stage less than 1 ft during drought conditions in August 2021 required switching to a Swoffer handheld, propeller-driven current meter to measure flow rates under 5 cfs. Discharge measurements were made at the bridges used during the bimonthly monitoring (fig. 1). Attempts to measure flow rates in the river in the spring of 2020 were hampered by the river's high

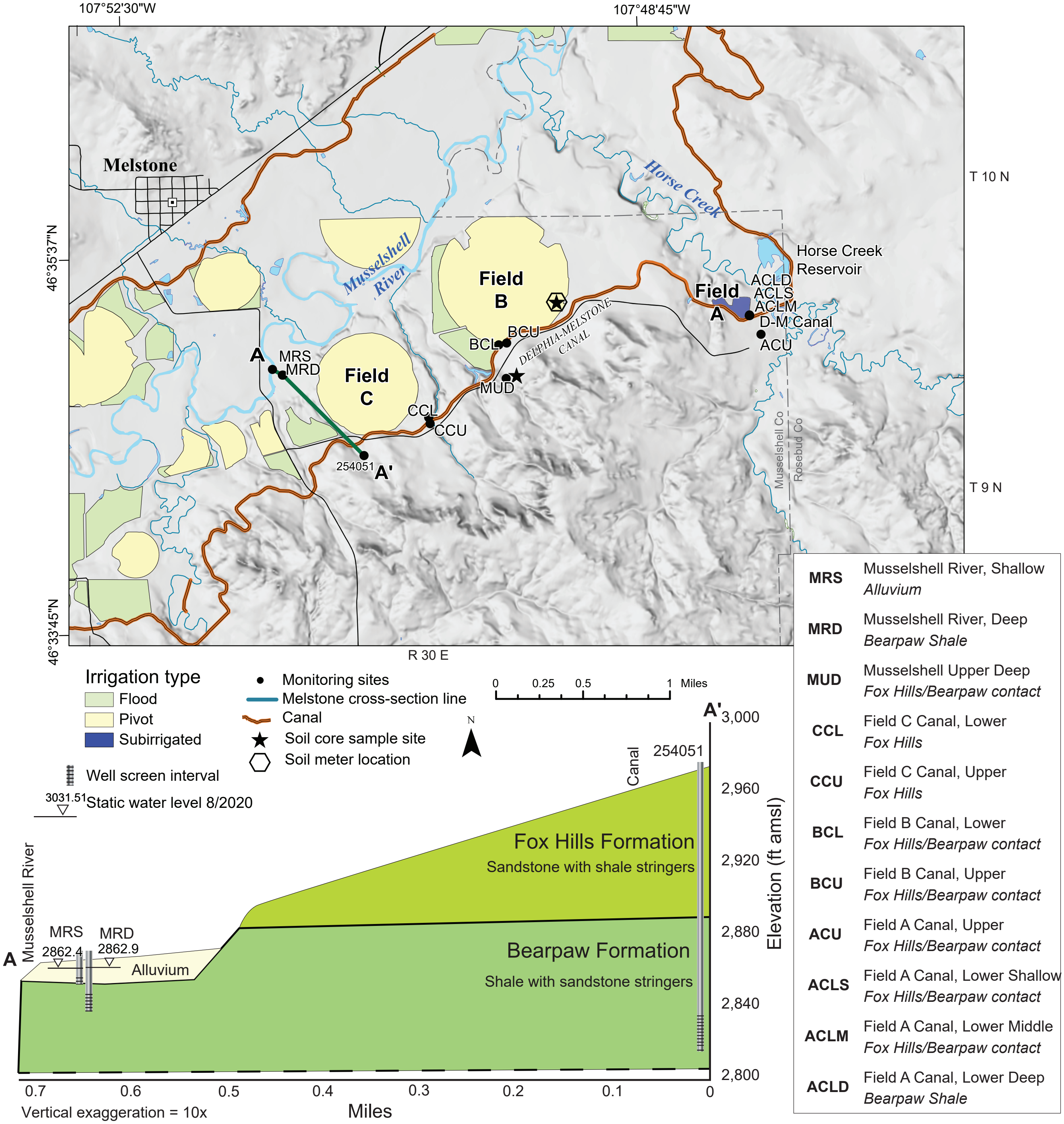


Figure 9. Melstone focus area. The Melstone focus area includes three irrigated fields: Field A, a subirrigated field on Fox Hills; Field B, a pivot-irrigated field on the Fox Hills/Bearpaw contact; and Field C, a pivot-irrigated field on Fox Hills. A nested set of shallow and deep monitoring wells monitor hydraulic gradients between the groundwater system and the river downgradient from Field C (MRS and MRD). Private well 254051 is identified by its GWIC identification number.

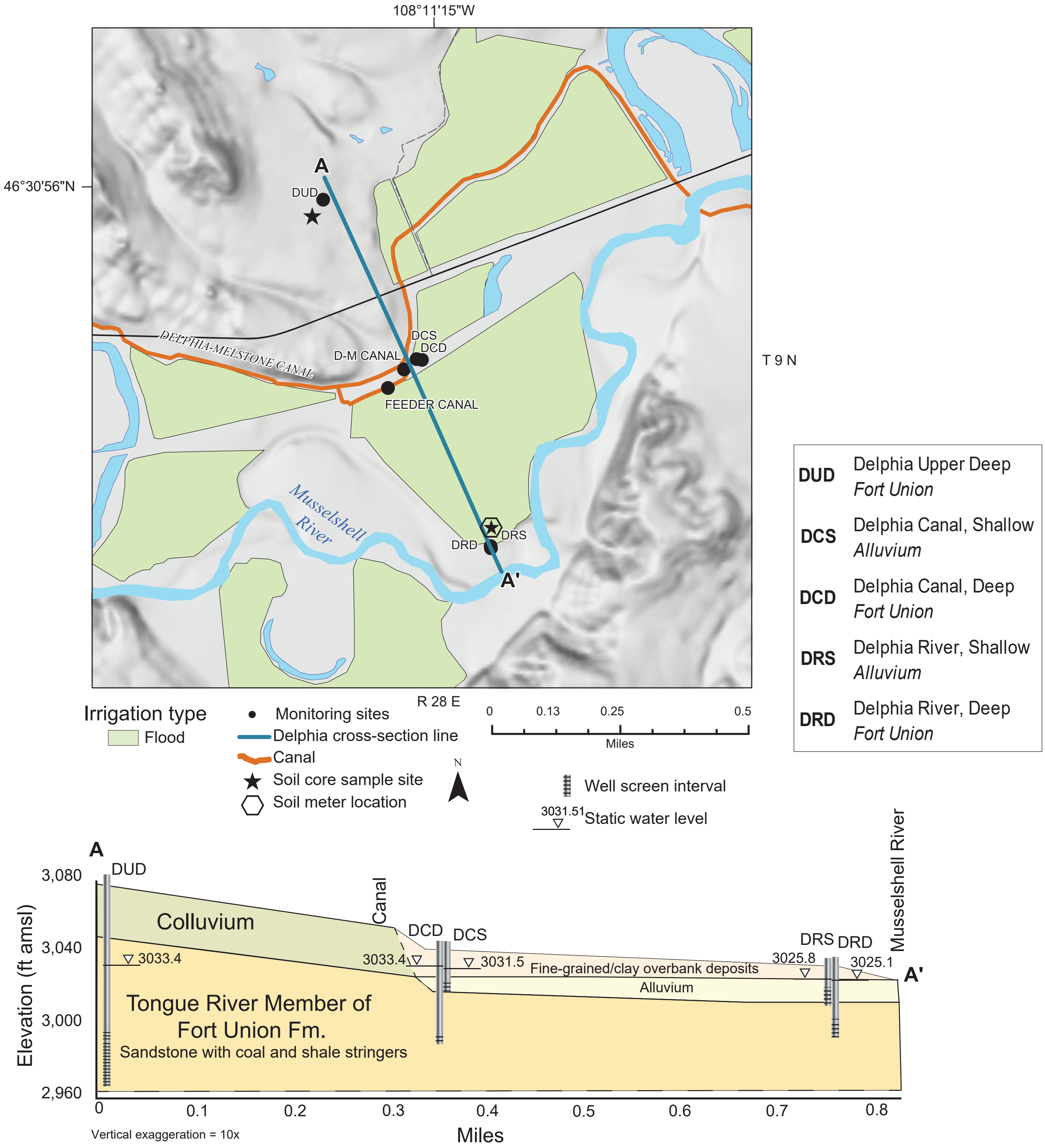


Figure 10. Delphia focus area. The Delphia focus site includes a flood-irrigated field on Fort Union geology and a nested pair of shallow and deep monitoring wells (DRS and DRD, respectively) that measure the groundwater connection to the river.

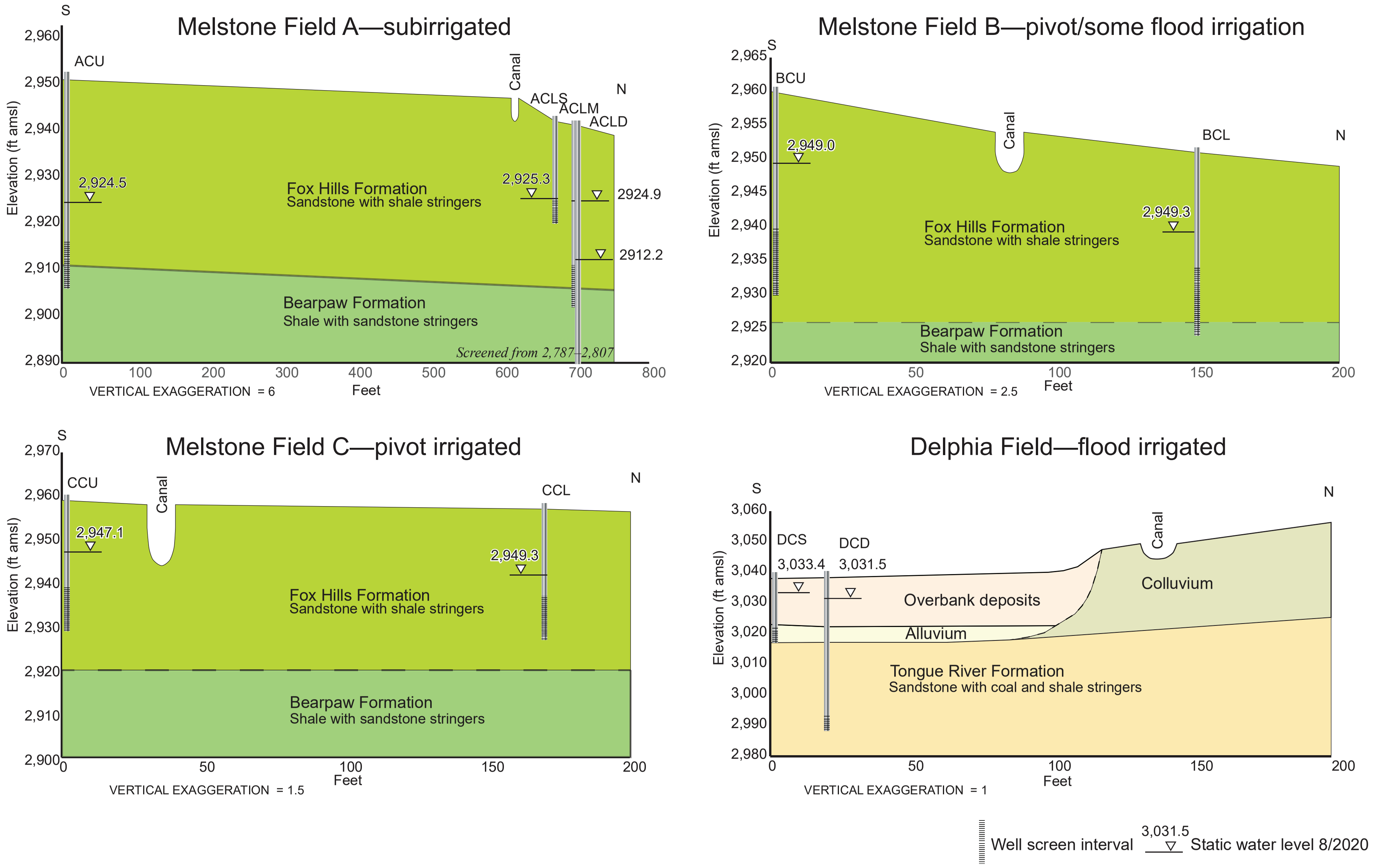


Figure 11. Field cross-sections. The effect of irrigation canals on groundwater quantity and quality was measured by wells installed along the canal at the four monitored fields in the Melstone focus area (Fields A, B, and C) and at the Delphia focus area. Well DUD, not shown, represents the upgradient groundwater on the Delphia Field. The elevation of the Bearpaw shale at Field C was established by the contact in the MUD monitoring well.

Table 1. Groundwater monitoring well summary.

Gwic ID	Site Name	Aquifer	Total Depth (ft)
Delphia Focus Area			
Wells near the river			
303461	DRD * Delphia river, deep	Fort Union	50
303456	DRS * Delphia river, shallow	Alluvium	18
Wells near the canal			
303536	DUD * Delphia upper, deep	Fort Union	108
303465	DCD * Delphia canal, deep	Fort Union	50
303471	DCS * Delphia canal, shallow	Alluvium	21
Melstone Focus Area			
Wells near the river			
303621	MRD * Melstone river, deep	Bearpaw	30
303622	MRS * Melstone river, shallow	Alluvium	15
Wells near the canal			
303623	MUD * Melstone upper, deep	Fox Hills/Bearpaw	60
301883	ACU * Field A canal upper	Fox Hills/Bearpaw	45
301861	ACLD * Field A canal lower, deep	Bearpaw	160
301868	ACLM * Field A canal lower, middle	Fox Hills/Bearpaw	39
301866	ACLS * Field A canal lower, shallow	Fox Hills/Bearpaw	22
303537	BCU * Field B canal upper	Fox Hills/Bearpaw	30
303593	BCL * Field B canal lower	Fox Hills/Bearpaw	27
303538	CCU * Field C canal upper	Fox Hills	30
303539	CCL * Field C canal lower	Fox Hills	29

levels of suspended sediment, which prevented accurate Doppler measurements.

Flow rates in the Delphia–Melstone Canal were measured using the Swoffer in water less than 2 ft deep and the ADCP in water deeper than 2 ft. Synoptic flow measurements were made in August and September of 2020 and in May 2021 (appendix C). Repeat measurements in August and September 2021 were not possible because drought conditions resulted in the canal being turned off in July.

Reported flow rate error (appendices B and C) is based on the instrument used. The ADCP generates percent error based on the standard deviation of measured flows (minimum 10 measurements). Handheld flow meter error was based on Sauer and Meyer (1992), which states Swoffer error is approximately five percent under good conditions and eight percent or higher in poor conditions with significant vegetation.

Groundwater and Surface-Water Sampling

Groundwater and surface-water sample collection followed the established MBMG standard operating procedures (Gotkowitz, 2022). Groundwater samples were collected in spring and summer of 2020 and 2021. Sample collection timing was chosen to represent the highest and lowest points on the hydrograph: in late summer during irrigation season and in spring prior to the start of irrigation.

Grab samples of the Musselshell River were collected in winter, spring, and late summer of 2020 and 2021 from the seven bridges used for monitoring (fig. 1). Sample collection timing was chosen to represent baseflow (winter), peak flow (spring), and maximum irrigation return from groundwater to the river (late summer; fig. 4). Upstream samples representing the river before it enters the study area were collected in Roundup. Canals were sampled at stage-monitoring points during the spring and summer, if flowing. All samples were analyzed for the standard MBMG Laboratory (Butte) analytical suite, which includes major ions, trace metals, nutrients, and isotopes of oxygen and deuterium (appendix D, Groundwater; appendix E, Surface Water).

Samples were also analyzed for strontium isotope ratios and strontium concentration because strontium has been shown to effectively fingerprint waters based on geologic source and quantify contributions when waters from geologically distinct aquifers or surface water are mixed (Meredith, 2016). Analyses were performed by the University of North Carolina, Charlottesville Isotope Laboratory (appendix F). Stable isotopes of strontium are measured as the ratio of the heavy to light isotope: $^{87}Sr/^{86}Sr$. Analytical precision is 0.000008–0.000015 (2-σ absolute error).

Salinity Measurement

The concentration of dissolved constituents in groundwater and surface water (the salinity) was measured in two ways. Field measurements of the conductivity of the water—the SC measured in µS/cm—is an indirect method that correlates the conductivity of the water to the dissolved constituents. Water-quality laboratory analyses measure total dissolved solids (TDS), measured in mg/L, which sums the dissolved constituents as a direct measure of salinity. Musselshell County irrigators define their irrigation risk using an SC benchmark (3,000 µS/cm) because it can be measured in the field.

There is a positive, linear correlation between higher conductivity (higher SC) and higher dissolved constituents (higher TDS). In the study area, the relationships can be approximated as:

For groundwater (appendix D, fig. D1):

$$\text{TDS (mg/L)} = 0.8*\text{SC (mS/cm)}. \qquad \text{eq. 1}$$

For the Musselshell River (appendix E, fig. E1):

$$\text{TDS (mg/L)} = 0.7*\text{SC (}\mu\text{S/cm)}. \qquad \text{eq. 2}$$

The relationship is defined up to 3,000 µS/cm for the river (38 samples) and up to 9,000 µS/cm for groundwater (69 samples). The specific linear relationships from least-square regressions between TDS and SC for groundwater and surface water in the study area are outlined in appendix D, fig. D1, and appendix E, fig. E1, respectively. These values are consistent with the conversion factors calculated from the MT DEQ dataset, which resulted in 0.73*SC for SC <1,500 µS /cm, 0.81*SC for SC between 1,500 and 5,000 µS/cm, and 0.91*SC for SC greater than 5,000 µS/cm (MT DEQ, 2018).

Soil Measurements

Probes that measure soil moisture (as a percent), soil temperature, and soil–water salinity (as SC) were installed in spring 2021 at three depths on the Melstone area pivot-irrigated Field B (fig. 9) and flood-irrigated Delphia Field (fig. 10). Attempts to monitor soil moisture on unirrigated fields at Melstone and Delphia (near wells MUD and DUD) were unsuccessful due to moisture levels too low at all depths to register on the meter. The probes were installed using a direct-push Geoprobe to core a hole in the soil to the installation depth of 2, 5, or 10 ft; the probe was pushed into the undisturbed soil at the bottom of the hole, and the hole was backfilled with soil from the immediate vicinity. On Field B, the soil was too hard to push the probe fully into the undisturbed soil without damaging the probe. The probe was pushed approximately 3 in into the soil until refusal and the hole was carefully backfilled with native soil. Each set of nested probes was attached to a data logger that recorded hourly measurements.

Soil cores were collected to 20 ft on the Delphia Field, Field B, and on the unirrigated fields near wells MUD and DUD (figs. 9, 10). Samples from approximately every 2 ft of core were analyzed by Energy Laboratories in Billings for saturated paste extract analysis of specific conductance and cation and anion concentrations (appendix G). Intervals of less than 2 ft were analyzed if color or texture changes were observed in the core. The saturated paste extract method involves saturating the soil sample with distilled water until the pore space is filled. This is usually about twice the water content of the soil's field capacity. The water is then extracted under vacuum and analyzed for electrical conductivity (i.e., specific conductance) and chemical constituents (Hanson and others, 2006).

RESULTS

Groundwater and Surface-Water Elevations

The gradient (difference in hydraulic pressure) between groundwater elevation and surface-water elevation determines which direction water will flow, provided there is a subsurface pathway. Water at higher pressure (higher elevation) flows toward lower pressure (lower elevation); the elevation difference controls where and when a stream gains flow from, or loses flow to, underlying groundwater. Groundwater elevations measured 170 ft from the river near Melstone (wells MRD and MRS) and 250 ft from the river near Delphia (wells DRD and DRS) are similar to the Musselshell River elevations measured at the bridges at Melstone–Custer Road and Delphia Road, respectively (fig. 12). In both locations, the bedrock aquifer and the shallow alluvial aquifer generally follow the trend of the river stage.

At the Melstone site (fig. 12A), the river and groundwater elevations, as measured in both MRS (15 ft deep; alluvium) and MRD (30 ft deep; Bearpaw shale), are similar throughout the study period. The magnitude and timing of water-level changes in the shallow aquifer (MRS) are similar to those of the river, indicating a close connection between the shallow groundwater and the river at this site. Sampling MRD, a well completed in the Bearpaw shale, caused the well to go dry, as shown by water levels in August 2020 and March and September 2021. The water level recovered to pre-sampling levels over a 2-mo period after each sampling event. Throughout the study, river elevations were within a foot of the shallow groundwater elevation. While the river may occasionally be gaining groundwater or losing water to the alluvium, the magnitude of the elevation difference is small and therefore the flux between the two waters will be minimal.

At the Delphia site (fig. 12B), groundwater elevation in both the shallow (DRS, 18 ft deep; alluvium) and deep (DRD, 50 ft deep; Fort Union sandstone) aquifer are generally similar to or above the river elevation. The groundwater elevation ranged from approximately 1 ft to 5 ft higher than the river elevation. The groundwater is likely contributing baseflow to the river at this site. The groundwater levels mirror one another; however, the shallow alluvial-aquifer water level is consistently higher than that of the deeper, Fort Union aquifer.

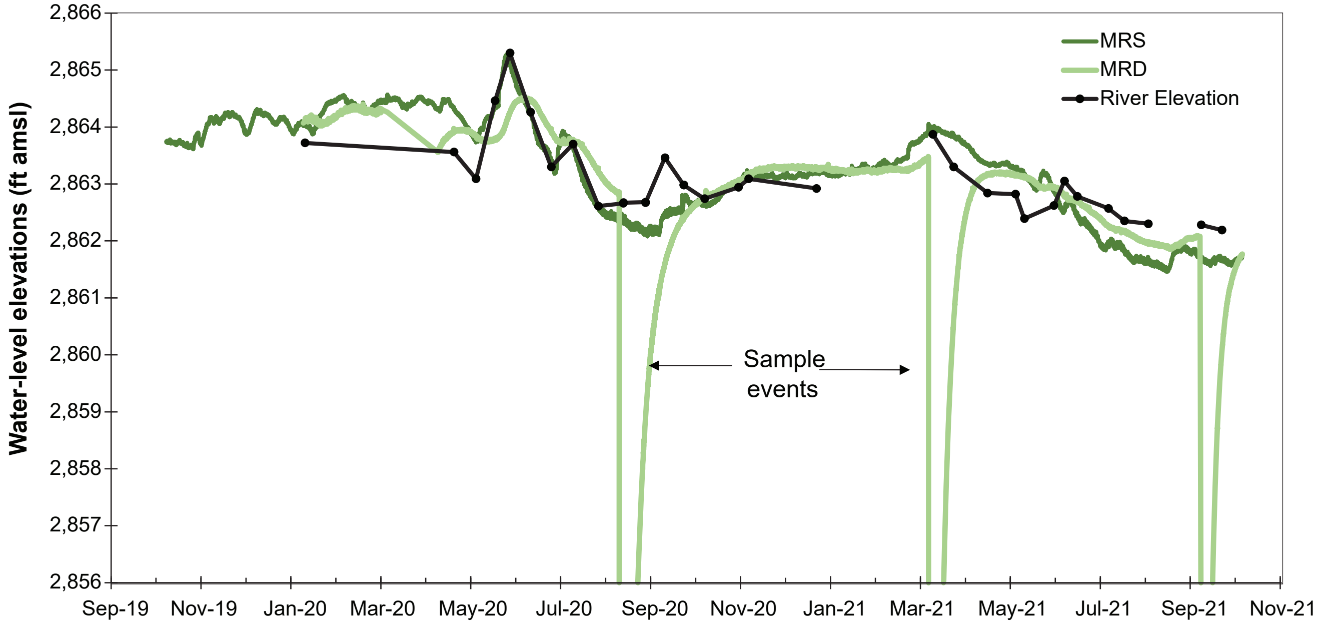
Shallow groundwater levels within 150 ft of the Delphia–Melstone Canal respond quickly to the presence of water in the canal (fig. 13). The canal water elevation was approximately 15 ft higher than the groundwater elevation in wells ACU and ACLM on Melstone Field A and approximately 5 ft higher than the groundwater monitored at Delphia (DUD and DCS; figs. 11, 13). The higher elevation in the canal creates a gradient from the canal to the groundwater.

Water levels increased in upgradient and downgradient wells near the canal within 48 h after water began flowing in the canals. Upgradient water levels respond to the pressure of the mounding water below the canal; upgradient groundwater geochemistry is distinct from the canal water (see Groundwater and Surface-Water Chemistry section). When canals are shut off, groundwater levels fall and continue declining until the canals carry water again. The groundwater response to canal use demonstrates that the canals recharge shallow groundwater. Water levels in well ACU show a slower, dampened response that may be driven by regional recharge or canal leakage. The influence of canal leakage at ACU may be dampened because of the distance, approximately 600 ft from the canal (whereas the other monitoring wells are 50 to 150 ft from the canal; fig. 11), and the low transmissivity of the aquifer.

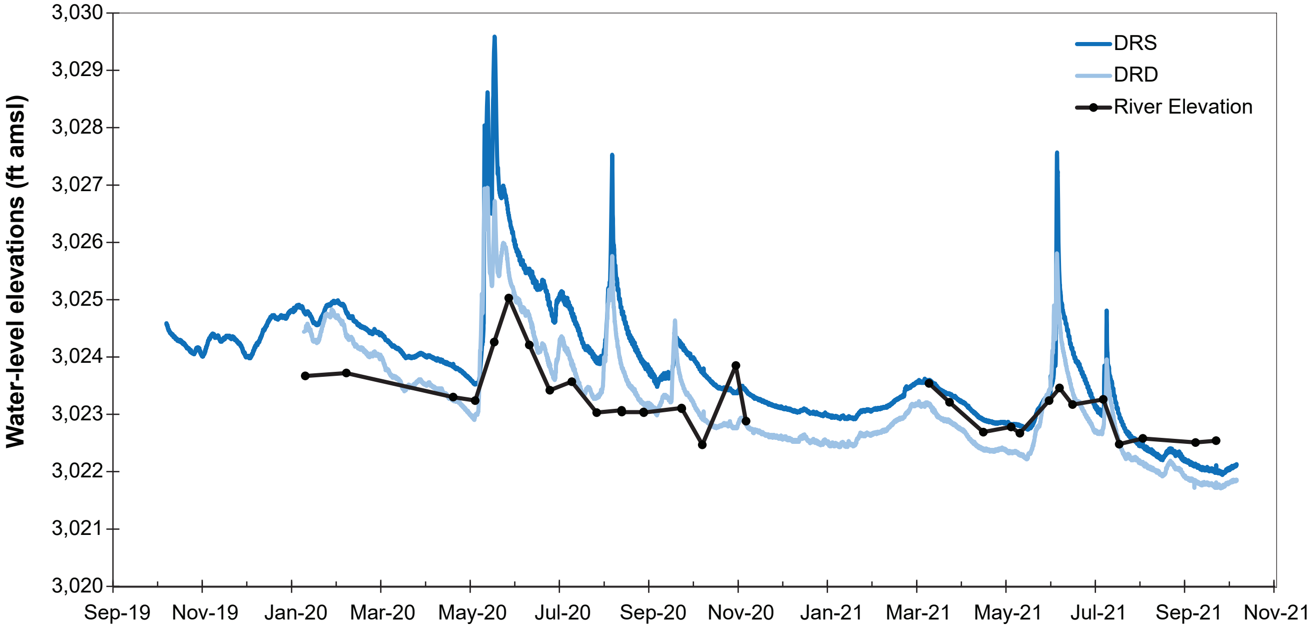
Surface-Water and Groundwater Quality

The Musselshell River is balanced-cation–sulfate type or sodium–magnesium–sulfate water type; in general, the water becomes more dominated with sodium, magnesium, and sulfate with higher salinities (fig. 14; appendix E, table E1, fig. E2). The Bearpaw (wells ACLD, MUD, and MRD) and Fox Hills (wells ACU and BCU) aquifers are sodium–sulfate type. Fort Union aquifer groundwater (wells DUD, DCD, and DRD), is sodium–sulfate–bicarbonate type (fig. 14). When the river salinity increased in the November 2020 samples, and during the drought of 2021, the river chemistry became more dominated by sodium and sulfate (appendix E, fig. E2), illustrating the increasing influence of groundwater baseflow on the river's chemistry when river flow rates are low.

Major ion chemistry of shallow groundwater downgradient from the canals (ACLM, BCL, and CCL), and in one upgradient well (CCU), reflects the influence of the leaking canal. Groundwater near the



A. Melstone River Site



B. Delphia River Site

Figure 12. River and groundwater elevations at Melstone (A) and Delphia (B). Groundwater elevations in the Melstone focus area (A) follow the river elevations. The low transmissivity of the Bearpaw aquifer (well MRD) results in long recovery times of approximately 2 mo after each sampling event. Groundwater elevations in the Delphia focus area (B) are generally close to or higher than the river elevations, indicating a potentially gaining river reach. Absence of measured river elevations in winter months is due to ice cover on the river.

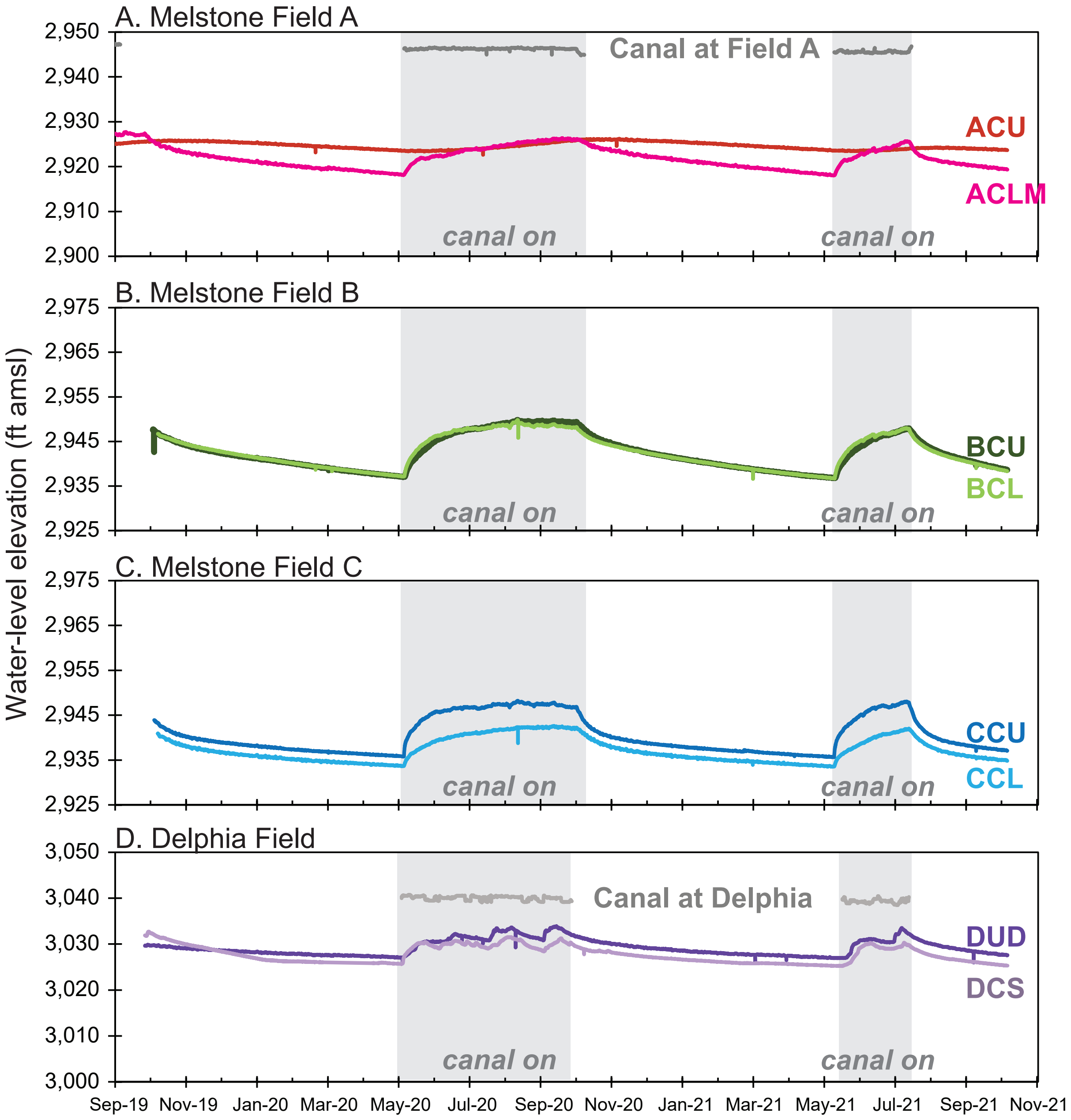


Figure 13. Groundwater elevations above and below the canal. Canal water elevations at Melstone Field A and at the Delphia Field are higher than the nearby groundwater. Groundwater elevations near the Delphia–Melstone Canal respond within 48 h to the presence of water in the canal, with the exception of ACU, which peaks in October and only varies by 3 ft. The higher canal elevation and the subsequent groundwater response to the presence of water in the canal indicate canal loss is a source of groundwater recharge. The canals were on for an abbreviated duration in 2021 due to drought conditions.

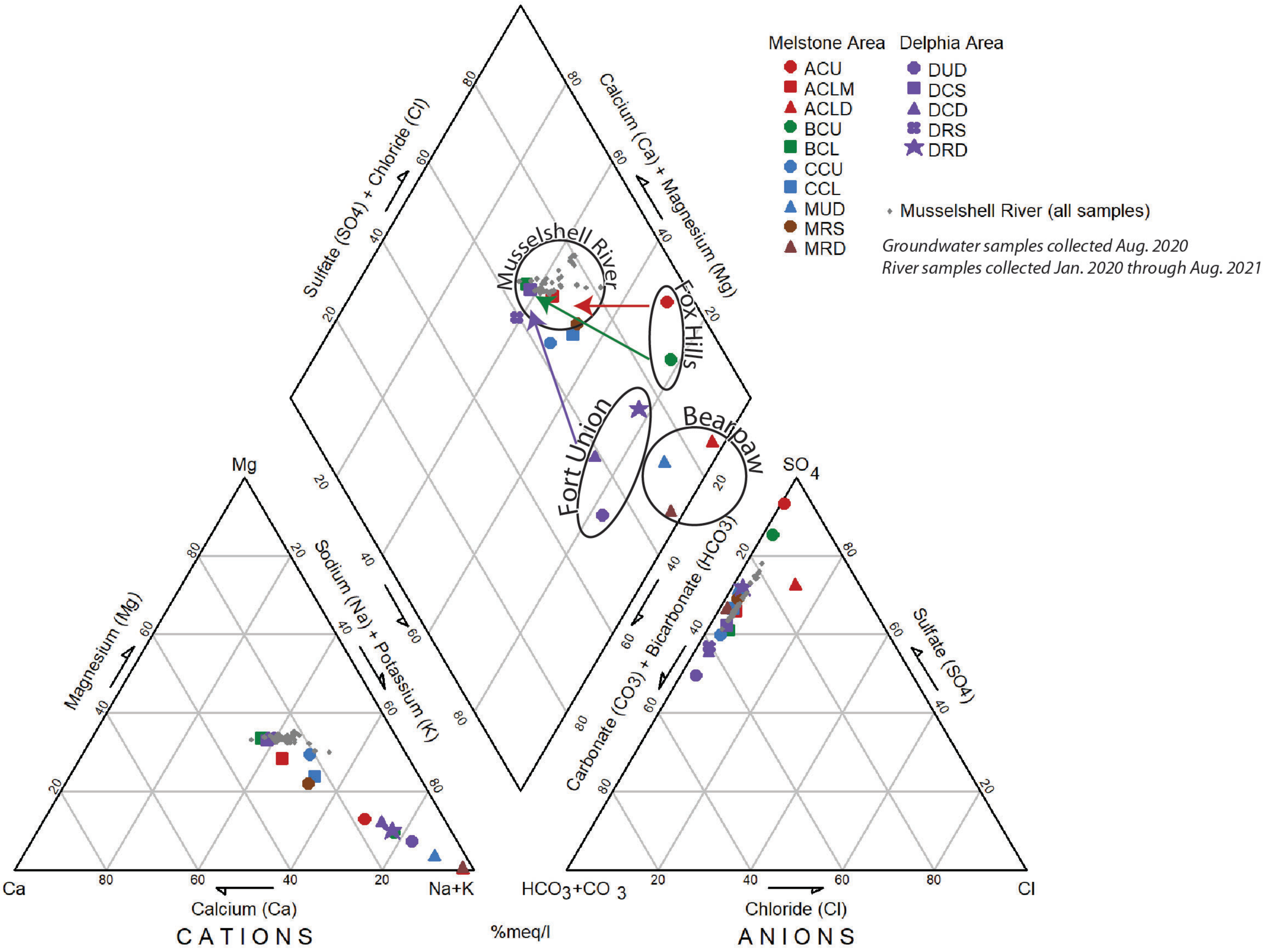


Figure 14. Piper diagram of groundwater and surface water. The major ion geochemistry of the Fort Union, Fox Hills, and Bearpaw aquifers is distinct. Shallow aquifers near the irrigation canal (wells ALCM, BCL, CCU, CCL, and DCS) and the river (wells MRS and DRS) are geochemically similar to the river; the shift in groundwater chemistry caused by mixing of surface water in shallow aquifers is shown by arrows.

canal is more geochemically similar to the Musselshell River, the source of irrigation water, than to the underlying bedrock aquifers (arrows in fig. 14 show this shift from bedrock chemistry). Alluvial groundwater near the river, sampled from wells MRS and DRS, is also geochemically similar to the river, showing the river provides recharge to these alluvial aquifers. Groundwater sampled from wells MRS, CCU, and CCL, while falling near the geochemical signature of surface water, also shows a component of the underlying sodium–sulfate type water of the bedrock aquifer (fig. 14).

Alluvial groundwater SC was measured in the shallow river monitoring wells MRS and DRS. The groundwater SC was consistently higher than the SC of the river (fig. 15). Groundwater contribution to the river, therefore, would tend to increase the salinity of the river. The salinity of the river approached the salinity of the groundwater during low river flow rates in the spring and winter. As surface-water flow rates drop, groundwater baseflow becomes an increasingly large component of the overall flow—driving both higher salinities and sodium–sulfate-dominated chemistry. Through the summer, river flow rates and chemistry are also partially controlled by releases from upgradient reservoirs (MT DEQ, 2018).

Major ion composition of the river samples collected at Delphia Road Bridge and Melstone–Custer Road Bridge (fig. 1) are similar except for samples collected in September 2020 and June and August 2021 (fig. 16, appendix E, fig. E2). The major ion composition of samples collected on these dates became more dominated by sodium and sulfate in

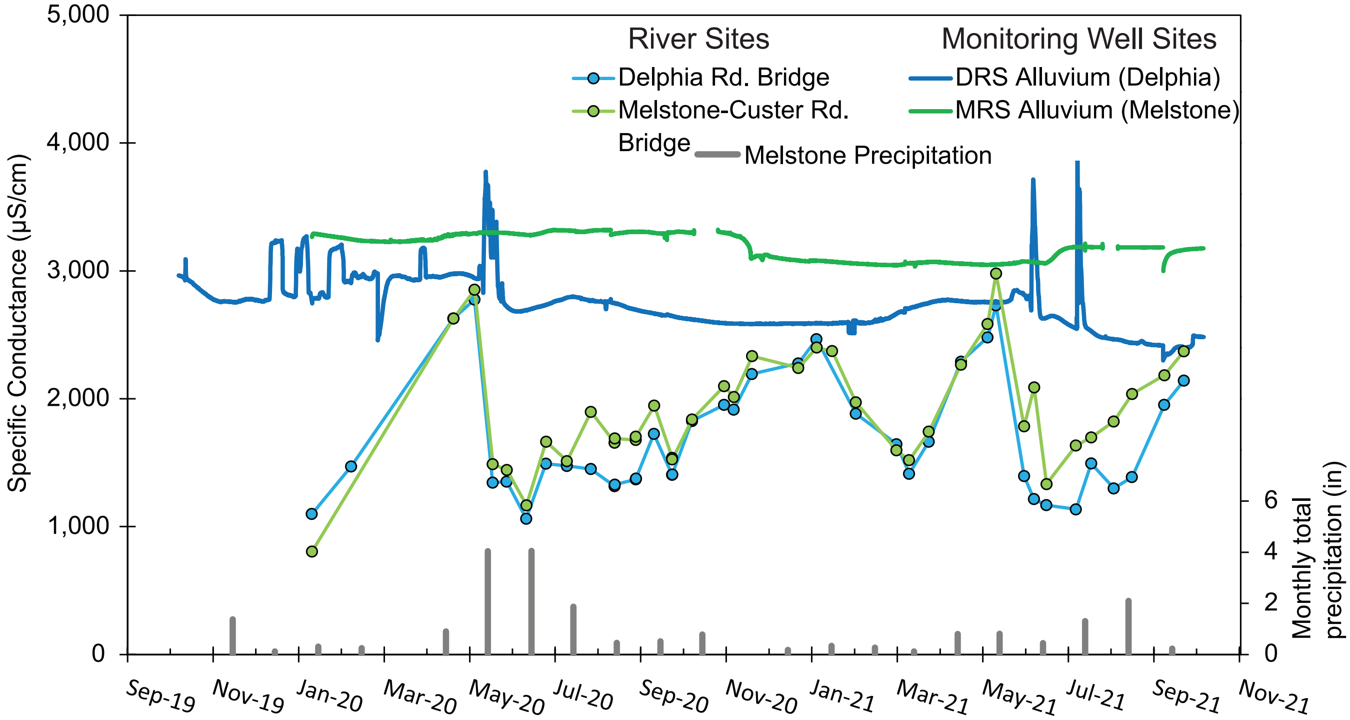


Figure 15. River and alluvial-groundwater salinity. With few exceptions, the shallow groundwater along the Musselshell River has higher SC than the river. Groundwater discharge to the river would tend to increase its salinity. River salinity approaches groundwater salinity levels during times of high groundwater levels in the spring (e.g., May 2020) and during low river flow rates in the winter (e.g., January 2021). Changes in river and groundwater salinity do not appear to correlate to local precipitation measured at Melstone (DRI, 2022).

downgradient samples, reflecting the contribution of sodium–sulfate baseflow.

Through the winter months, the river salinity at Delphia and Melstone is similar; however, during the summer, the salinity at Melstone is consistently higher than at Delphia by approximately 20 to 30 percent (figs. 15, 16). This increase in salinity is observed between Delphia and Melstone, where the majority of irrigation occurs (fig. 5). It is not apparent upgradient from Delphia nor downgradient from Melstone (appendix E, fig. E3). These findings indicate groundwater baseflow to the reach of the Musselshell River serviced by the Delphia–Melstone Canal is bolstered by irrigation return flow, which increases the salinity of the river.

Musselshell River discharge in the summer and fall of 2021 was below average (fig. 4), which allowed the influence of a small amount of sodium–sulfate groundwater baseflow to have a larger impact on the overall chemistry of the river. The effect of evaporation on shallow streams may also account for some of these changes; however, if evaporation was the primary force of geochemical change, the percent chloride composition of the anions would have increased downgradient. There were no changes in percent chloride concentration from upgradient to downgradient samples (fig. 14). This suggests that evaporation was not a dominant force in increasing river salinity in late 2021; rather it was due to an increasing relative contribution of groundwater baseflow.

Nitrate concentrations in groundwater and surface-water samples were all below the drinking water standard of 10 mg/L (appendix E; EPA, 2021). Most samples were below 1.0 mg/L, with the exception of samples collected from wells ACU, BCU, and BCL. Nitrate concentrations in samples from the Field B wells ranged from below detection to 2.28 mg/L; samples collected from well ACU contained nitrate at concentrations ranging from 4.36 to 8.57 mg/L. Because of its overall low groundwater concentrations in the study area, nitrate is not a useful tracer of groundwater/surface-water interaction for this project.

Irrigation water leaking from the Delphia–Melstone Canal changes the salinity (measured as SC) of the downgradient shallow groundwater—the nature of these changes is dependent upon the underlying

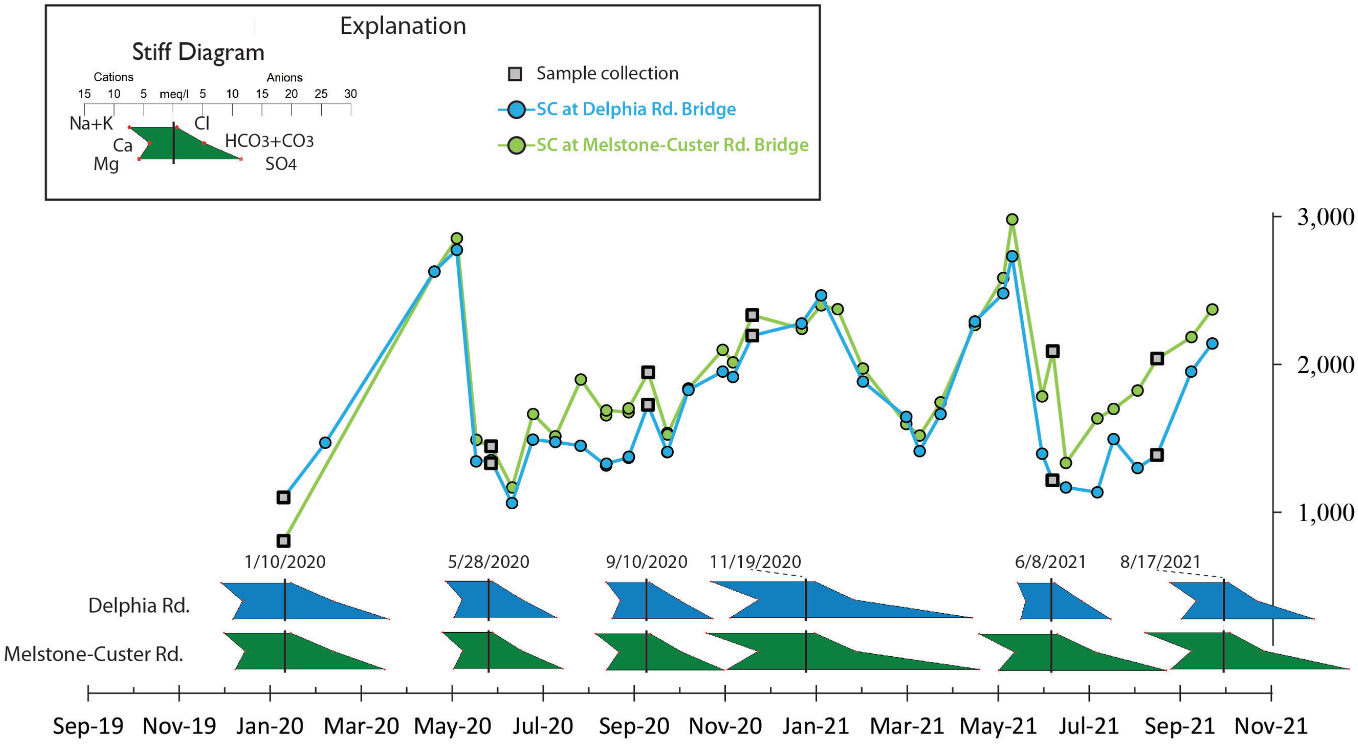


Figure 16. Downstream Stiff diagrams of the Musselshell River. Major ion geochemistry of the Musselshell River is generally similar at Delphia Road and Melstone-Custer Road, except during the summer and early fall. Irrigation return flow and groundwater baseflow, which is sodium–sulfate-dominated, can make a measurable difference when the river flow rate is low. The increased groundwater discharge due to irrigation returns accounts for the increase in salinity from Delphia to Melstone during the summer and early fall months.

geology (fig. 17). Shallow groundwater, downgradient from the canal in Melstone Fields A and B [wells ACLM (39 ft deep) and BCL (27 ft deep), respectively], has salinity similar to the canal water (figs. 17A, 17B). Irrigation water salinity is highest when the canals are first put to use in the spring—this is likely due to hydration of the canal mobilizing salts left through evaporation. These peaks in irrigation water salinity are also seen, although dampened, in wells ACLM and BCL approximately 1 mo after the canal begins carrying water. The upgradient groundwater at the base of the Fox Hills on Melstone Fields A and B [ACU (45 ft deep) and BCU (30 ft deep)] had the highest salinities in this study, ranging from 7,000 to 9,000 µS/cm (figs. 17A, 17B). Recharge to shallow groundwater from canal leakage lowers salinity in downgradient groundwater through dilution.

In contrast, the effect of leaking canals on Field C and on the Delphia Field is less dramatic (figs. 17C, 17D; note the change in y-axis). The upgradient well on Field C (CCU; 30 ft deep) is less than 50 ft from the canal (fig. 11). It has similar salinity (fig. 17C) and geochemistry (fig. 14) to the irrigation water, which suggests it is recharged by canal leakage. While the downgradient well at Field C (CCL; 29 ft deep) has a similar salinity to the underlying bedrock (well MUD), most of the year (fig. 17C) the major ion chemistry is closer to upgradient groundwater (CCU) than underlying bedrock groundwater (MUD; fig. 14). This result (similar chemistry but higher salinity) implies mobilization of local salts in groundwater downgradient from the canal. At Delphia, the salinity of the irrigation water is similar to that of the bedrock groundwater (fig. 17D); however, the geochemistry of the shallow groundwater is closer to that of surface water than to the underlying bedrock (DUD; fig. 14). Mixing of the irrigation water and bedrock groundwater does not appear to change the overall salinity of the groundwater underlying the Delphia Field.

Surface-Water Discharge Measurements

Measurements of gain and loss along the Musselshell River were inconclusive (appendix B). Changes in flow rate were within the measurement error of the ADCP. Direct withdrawals from the river for irrigation could not be quantified from public right-of-

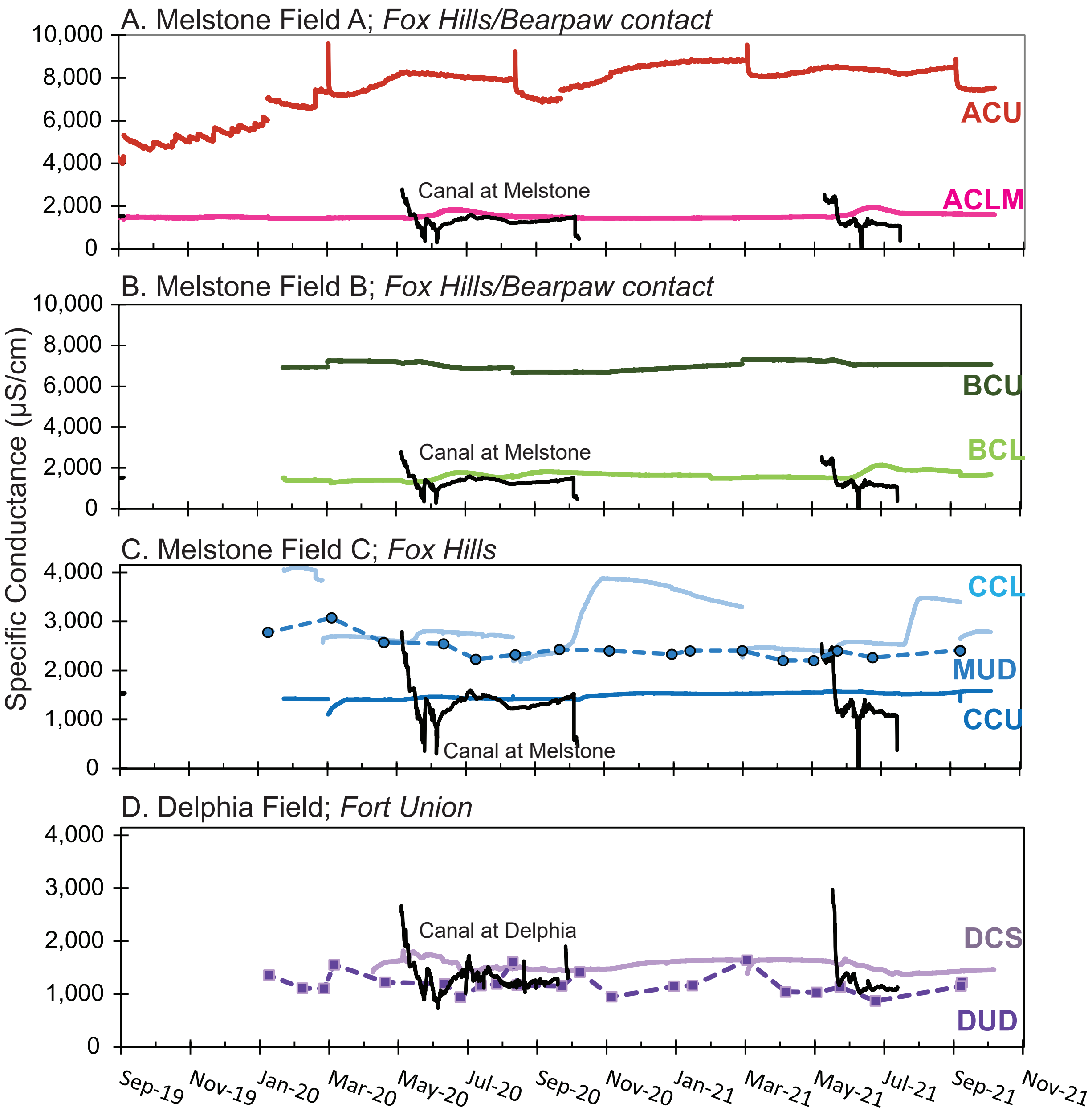


Figure 17. Groundwater salinity above and below the canals. The salinity of the shallow groundwater below the canal at Fields A and B (charts A and B; Fox Hills/Bearpaw sandy-shale aquifer) matches the canal water, including mirroring the small perturbations in irrigation-water salinity. Salinity spikes in well ACU are caused by pumping the well to collect samples. This pulls in higher salinity groundwater from the aquifer. Well CCU (chart C; Fox Hills sandy-shale aquifer) is upgradient of, but close to, the canal (fig. 11). Groundwater in well CCU has similar salinity to irrigation water. The groundwater near the canal at Delphia (chart D; Fort Union sandstone aquifer) has an SC similar to the canal water, so canal leakage has a minimal impact on the shallow groundwater salinity. Note the different y-axes scales. Solid lines represent SC measured by transducers; dashed lines represent SC measured during field visits.

way, which also complicated identification of gaining and losing river reaches.

Changes in flow along canal reaches were also generally within measurement error (appendix C). When loss was measured it ranged from 1.1 to 2.9 cfs per mile, which is within the typical published loss rates for canals in Montana (Metesh, 2012) and similar to those found by Lange and Friedman (2017).

Soil Moisture and Chemistry

Saturated paste analysis for specific conductivity (fig. 18) and major ion concentrations of soluble salts (appendix G) in soil cores illustrate the effect of irrigation upon movement of salts through the soil profile. The pivot-irrigated Melstone Field B and the flood-irrigated field at Delphia have lower salinities compared to nearby unirrigated soils at well sites MUD and DUD (fig. 18). Specific conductivity of the soils at the flood-irrigated Delphia site is consistent through the soil profile to a depth of 20 ft. This indicates that the irrigation practices at this site regularly create saturated conditions that dissolve and mobilize soluble soil salts through the profile, causing an overall reduction in soil salt over time.

While the pivot-irrigated site, Melstone Field B, also has a lower salinity as compared to the nearby soils at MUD, it has distinct peaks in salinity at 6 ft and 14 ft below ground surface (fig. 18). Field B was flood irrigated prior to installation of the pivot. The pivot was installed between 2009 and 2011, based on historical imagery in Google Earth. Flood irrigation may likely have created a salinity profile similar to that at the Delphia field. The subsequent 10 yr of pivot irrigation, which applies irrigation water to meet the evapotranspiration demand, may account for the accumulation of salt at 6 ft, below the typical rooting depth of alfalfa of 4 ft (Hanson and others, 2006). Alfalfa was cultivated on Field B during this study.

Unirrigated soils near wells MUD and DUD have higher overall total salinity as compared to irrigated

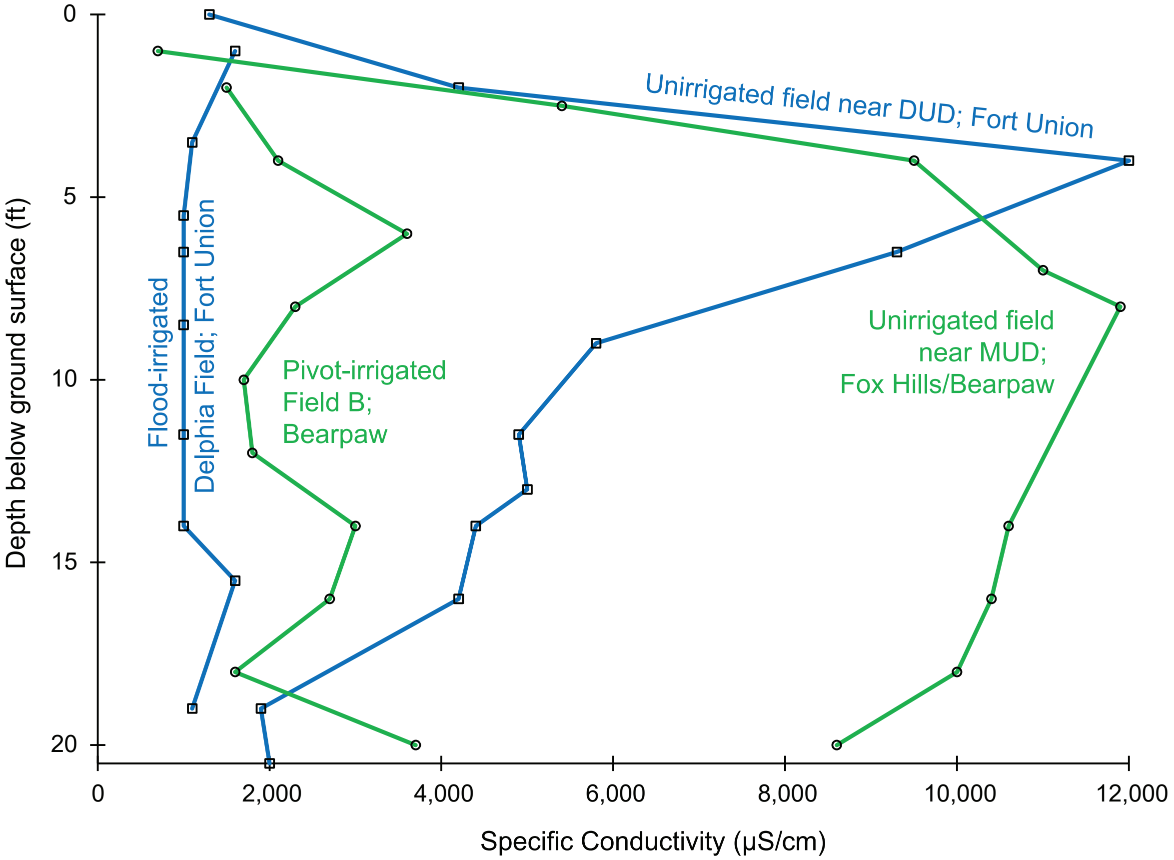


Figure 18. Soil salinity profile. Saturated paste analyses of soil cores from unirrigated soils near wells DUD (Delphia: Fort Union geology) and MUD (Melstone: Fox Hills–Bearpaw contact) indicate more available soluble salts compared to historically irrigated fields, such as the flood-irrigated field at Delphia (Fort Union) and the pivot-irrigated Field B (Melstone: Fox Hills–Bearpaw). Core locations are shown in figures 9 and 10.

soils, with peaks in salinity between 4 and 8 ft below ground surface (fig. 18). The salinity of the soil and colluvium sourced from Fort Union sandstone and shales at the DUD well site drops quickly with depth after the peak at 4 ft, the average maximum depth of infiltration of precipitation (Hanson and others, 2006). Soil salts accumulate at the average depth of precipitation infiltration where evapotranspiration causes the salt to precipitate. In contrast, the salinity of the Fox Hill–Bearpaw core at the MUD site peaks remains high through the cored depth. Compared to the Fort Union geology, these results indicate there are more naturally occurring soluble salts in the Fox Hills/Bearpaw Formations. This difference in geologic sources accounts for the higher levels of groundwater salinity measured in the Melstone study area (underlain by Fox Hills–Bearpaw units) compared to the Delphia site (underlain by Fort Union).

Measurements of soil moisture, soil–water salinity, and soil temperature from irrigated areas during the 2021 irrigation season partially support the findings of salinity distribution in the soil cores (fig. 19). Application of irrigation water increased the percent soil moisture to 5 ft below ground surface on the flood-irrigated Delphia site and to 2 ft on the pivot-irrigated Melstone Field B. The 2021 irrigation season was not typical in that the drought caused irrigators to stop irrigating in July; in average years, irrigation continues through September. With the additional irrigation water applied in a typical year, infiltration may extend deeper in the soil profile to match the 5 ft or greater infiltration depths predicted by the soil cores (fig. 18). Soil meters installed on the unirrigated fields near MUD and DUD did not register any soil moisture (and therefore no conductivity) during the drought conditions of 2021.

A slight increase in soil moisture was measured at the deepest soil measurement probe, 10 ft, after the first application of flood irrigation on the Delphia site. The soil moisture trend at the deepest measurement probe at Field B, 8 ft, appears to be an annual cycle driven by regional recharge. Soil–water salinity increases correlated to these increases in soil moisture, indicating that application of irrigation water mobilizes soil-salts (figs. 19A, 19B). Temperature trends on both fields appear to be dominated by annual climate signals (figs. 19C, 19F); however, the addition of irrigation water on the Delphia site also caused the soil temperature to increase (fig. 19C).

Strontium Isotopes

Strontium isotopes in groundwater are the result of rock–water interactions. The ratio of strontium-87 to strontium-86 ($^{87}Sr/^{86}Sr$) is determined by the rubidium-87 concentration and age of the aquifer matrix. Geologically distinct aquifers are likely to provide groundwater with measurably distinct strontium isotope ratios. Strontium isotope ratios can be measured with great precision (0.000008–0.000015), which makes them useful tracers of groundwater discharge to surface water in some settings. In particular, baseflow may be identified by changes in the strontium isotope ratio when the volume of groundwater discharge to surface water is too low to be detected through surface-water discharge measurements (gain/loss studies) or changes in major ion composition (Meredith, 2016).

The groundwater and surface-water samples collected during this study had strontium isotope ratios ranging from 0.7077 to 0.7114, with strontium concentrations that varied from less than 1 mg/L to over 9 mg/L (fig. 20; appendix F, table F1, table F2). Similar to the patterns in the major ion geochemistry, the Fort Union, Fox Hills, and Bearpaw aquifers had unique strontium isotope fingerprints. Also similar to the major ion geochemistry, shallow groundwater below the canals and near the river had strontium isotope ratios and concentrations similar to those of surface-water samples collected from the Musselshell River and the Delphia–Melstone Canal (fig. 20), indicating the mixing of surface water and groundwater (the isotopic shift from bedrock is shown by arrows in fig. 20).

The strontium isotope ratio and its concentration, formed by the mixing of two waters with distinct isotope ratios, is described by the equation:

$$\frac{^{87}Sr}{^{86}Sr}_{mixed}[Sr]_{mixed} = \frac{^{87}Sr}{^{86}Sr}_{endmember1}[Sr]_{endmember1}f_{endmember1} + \frac{^{87}Sr}{^{86}Sr}_{endmember2}[Sr]_{endmember2}(1 - f_{endmember1}), \qquad \text{eq. 3}$$

where $^{87}Sr/^{86}Sr$ refers to the isotope ratio and [Sr] refers to the dissolved concentration of strontium in the water sample. In the context of groundwater mixing near canals, canal leakage (subscript “endmember1”) mixes with the bedrock groundwater (subscript “end-

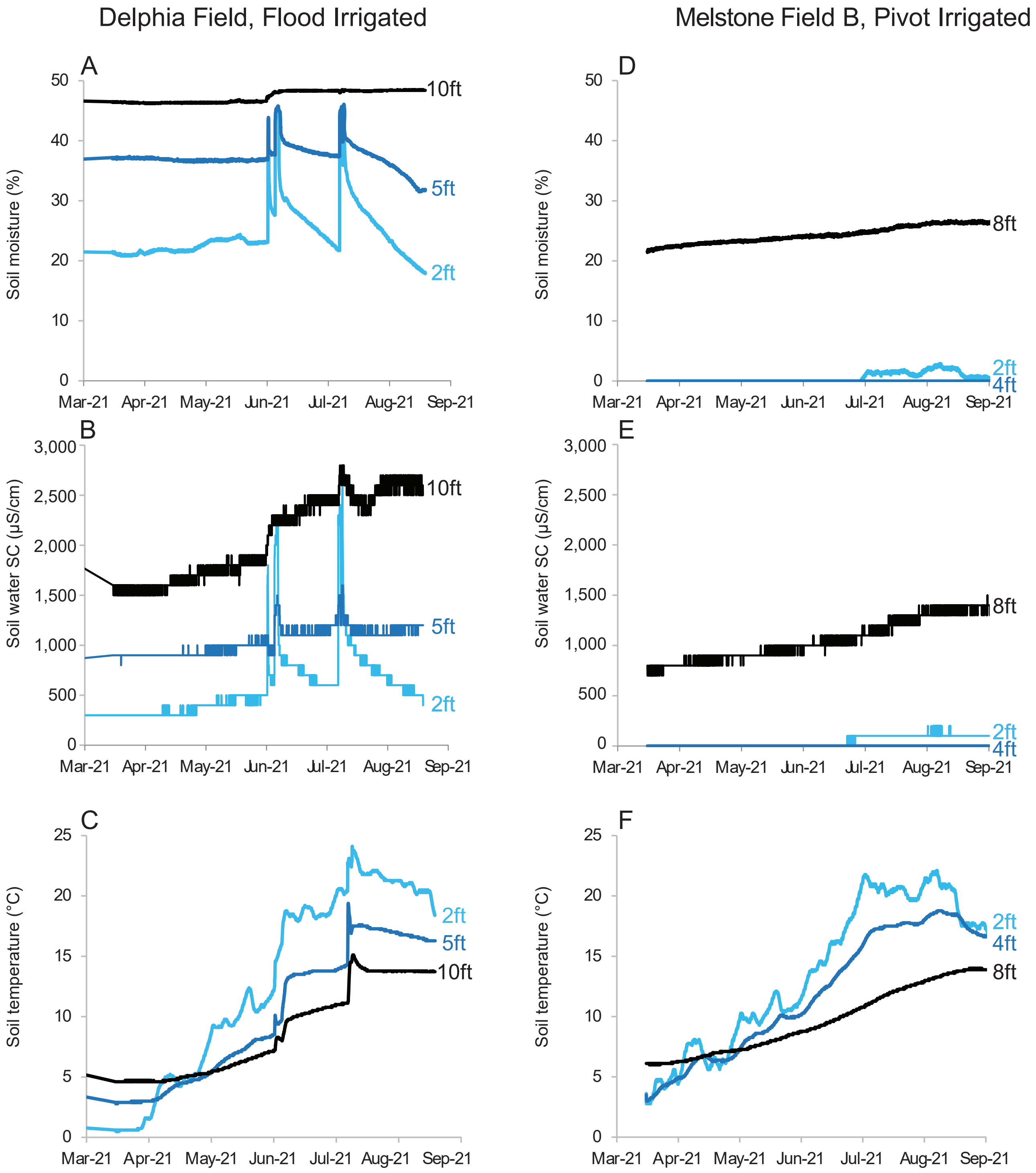


Figure 19. Soil moisture, SC, and temperature profiles. While the 2021 irrigation year was foreshortened due to drought, spring and early summer irrigation rates were typical. Infiltration of flood irrigation water was evident, in both moisture and increased salinity, to 5 ft below ground surface on the Delphia field (charts A and B); however, at Melstone Field B, infiltration of water was only evident within the first 2 ft below ground surface (D). Soil salinity reported here in specific conductance (SC) is equivalent to the unit electrical conductivity (EC) typically used in soil science (Hanson and others, 2006).

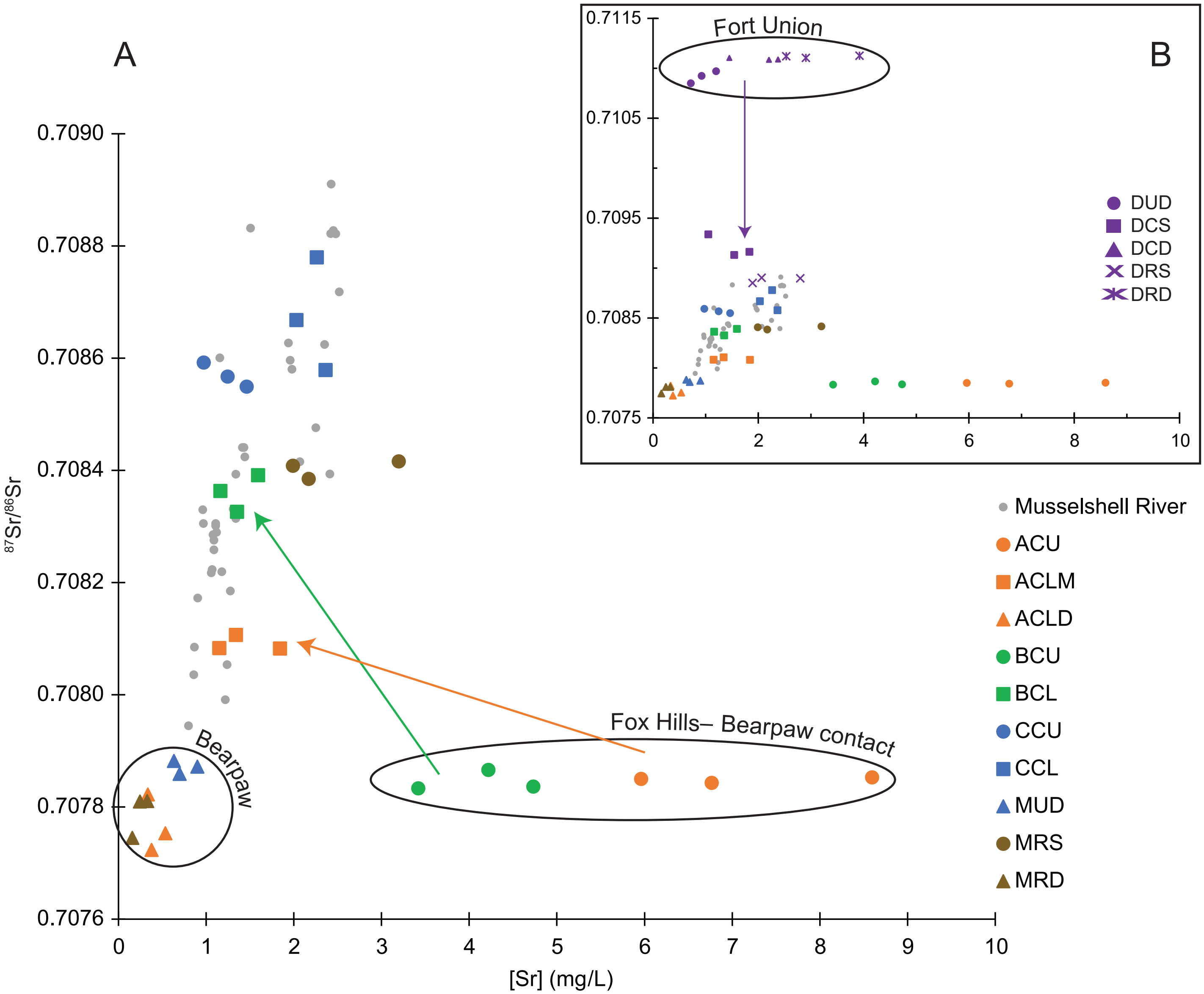


Figure 20. Strontium isotope chart. Each aquifer has a unique strontium isotope ratio and concentration fingerprint. As was seen in the major ion geochemistry, shallow aquifers below canals and along the river have a strontium isotope fingerprint similar to that of the river. Arrows indicate changing strontium isotope ratios in groundwater upgradient of the canals to downgradient, below the canals. The Fort Union aquifer strontium isotope ratio is displayed on a broader scale (graph B) to preserve detail.

member2”) to create the downgradient groundwater (subscript “mixed”). The fraction of the canal water present in the downgradient water is represented by the term “f” (appendix F, table F3). This equation only considers two waters mixing. In the calculations presented, the infiltration of precipitation or snowmelt is assumed to be negligible.

Where the river loses flow to the alluvial aquifer, river water (endmember1) mixes with bedrock groundwater (endmember2) to create the alluvial aquifer groundwater (mixed). The fraction of the river water in the alluvial sample is represented by the term “f” (appendix F, table F3). This, again, assumes only two main sources of recharge to the alluvium.

At locations where groundwater discharges to the Musselshell River, groundwater baseflow (endmember1) mixes with the upstream river samples (endmember2) to create the downstream river sample (mixed). The fraction of groundwater baseflow present in the downstream sample is represented by the term “f” (appendix F, table F3).

In the Melstone focus area, the shallow groundwater downgradient from the Delphia–Melstone Canal is almost entirely from canal leakage (figs. 21A, 21B, 21C). On Field A and Field B (figs. 21A, 21B), the fraction of irrigation water in the downgradient, shallow groundwater was 95 and 93 percent, respectively (appendix F, table F3). Groundwater below the canal at Field C (fig. 21C) had a strontium isotope signature higher than both the upgradient groundwater (above the canal) and the canal water. While the salinity is similar to the upgradient Fox Hills bedrock aquifer water, the geochemistry and isotope ratios are dissimilar. At this site, the introduction of canal water may be mobilizing local soil-salts or applied agricultural amendments, causing a shift upward in the strontium isotope ratio. At the Delphia site, canal leakage accounts for approximately half of the shallow groundwater downgradient from the canal (below the canal; fig. 21D; appendix F, table F3).

Strontium isotopes indicate the alluvial groundwater at Melstone (fig. 21C) is a mixture of the underlying Bearpaw shale aquifer and the river water, dominated by over 80 percent river water. In contrast, the alluvial aquifer at Delphia is approximately half Fort Union aquifer groundwater and half river water and/or leakage from the canal (fig. 21D).

For both the shallow groundwater below the canals and the alluvium, the low-transmissivity shale aquifer at Melstone provides little water to the shallow aquifer in comparison to canal leakage and river water. The higher-transmissivity sandstone of the Fort Union aquifer contributes more water into the mixing zones.

The Fort Union aquifer also contributes baseflow to the river. As the river crosses the sandstones of the Fort Union, from Roundup to Queens Road Bridge, the strontium isotope ratio of the river increases toward the high 0.7114 ratio characteristic of Fort Union groundwater (fig. 22). During January, September, and November of 2020, the change in strontium isotope ratio slowed or stopped downstream of the town of Musselshell, where the river flows past the Fort Union and into the Bearpaw (fig. 22, Queens Bridge). Although the continued change in June 2021 toward higher strontium ratios downriver of Queens Road Bridge is not well understood, it may result from surface flow, or near-surface flow through the soil, to the river that mobilized soluble salts in the soil and/or agricultural amendments. For June 2021 calculations of the rate of baseflow contribution, only the end members at Roundup and Queens Road, and the river miles between them, were considered.

In general, based on the strontium analyses, the Fort Union aquifer contributes between 0.2 and 0.5 cfs per mile to the Musselshell River (fig. 22; appendix F, table F3) and varied between 7 percent (September 2020 and June 2021) and 22 percent (November 2020) of total flow (appendix F, table F3). However, this method is less successful in estimating baseflow from the Bearpaw shale aquifer because it is a mixing endmember where strontium isotopes are not an appropriate tracing/mixing tool. The strontium concentration of the Bearpaw shale is low compared to the surface water with which it is mixing; the average strontium concentration of samples collected from well MRD is 0.24 mg/L, whereas the average strontium concentration in the river is 1.5 mg/L. For example, in September 2020, to result in a difference of 0.0003 in the strontium isotope ratio, the Bearpaw shale would have to contribute 4 cfs per mile from the Melstone–Custer Bridge to Bridge Road Bridge. This is an order of magnitude more than the estimated baseflow from the Fort Union aquifer (fig. 22) and is unlikely given the low transmissivity of the Bearpaw shale.

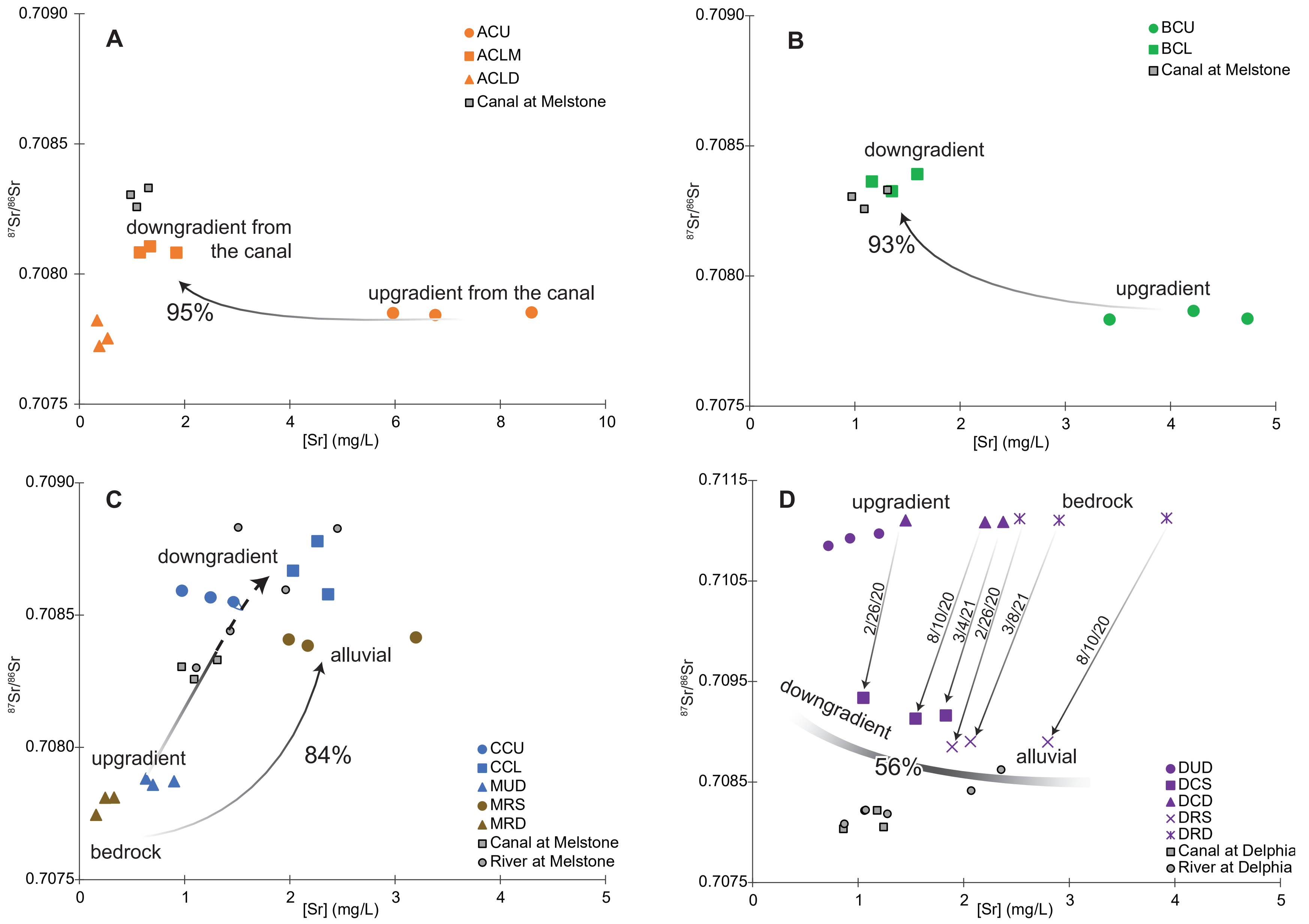


Figure 21. Strontium in groundwater mixing. The strontium isotope ratio and strontium concentration of shallow groundwater downgradient of the canals at Melstone Fields A, B, and C and Delphia (charts A, B, C, and D, respectively) is a mixture of strontium from the canal water and groundwater from the underlying bedrock aquifer. Shallow alluvial groundwater is a mixture of groundwater from the underlying bedrock aquifer and the river water (charts C and D). Percentages presented are averages of the two endmembers; detailed calculations are presented in appendix F, table F4. No percent contribution was calculated for Field C below the canal because a third source of strontium, likely shallow soluble soil salts or applied agricultural amendments, is also contributing to the strontium isotope ratio. The river contribution to alluvial groundwater below Field C was calculated as 84

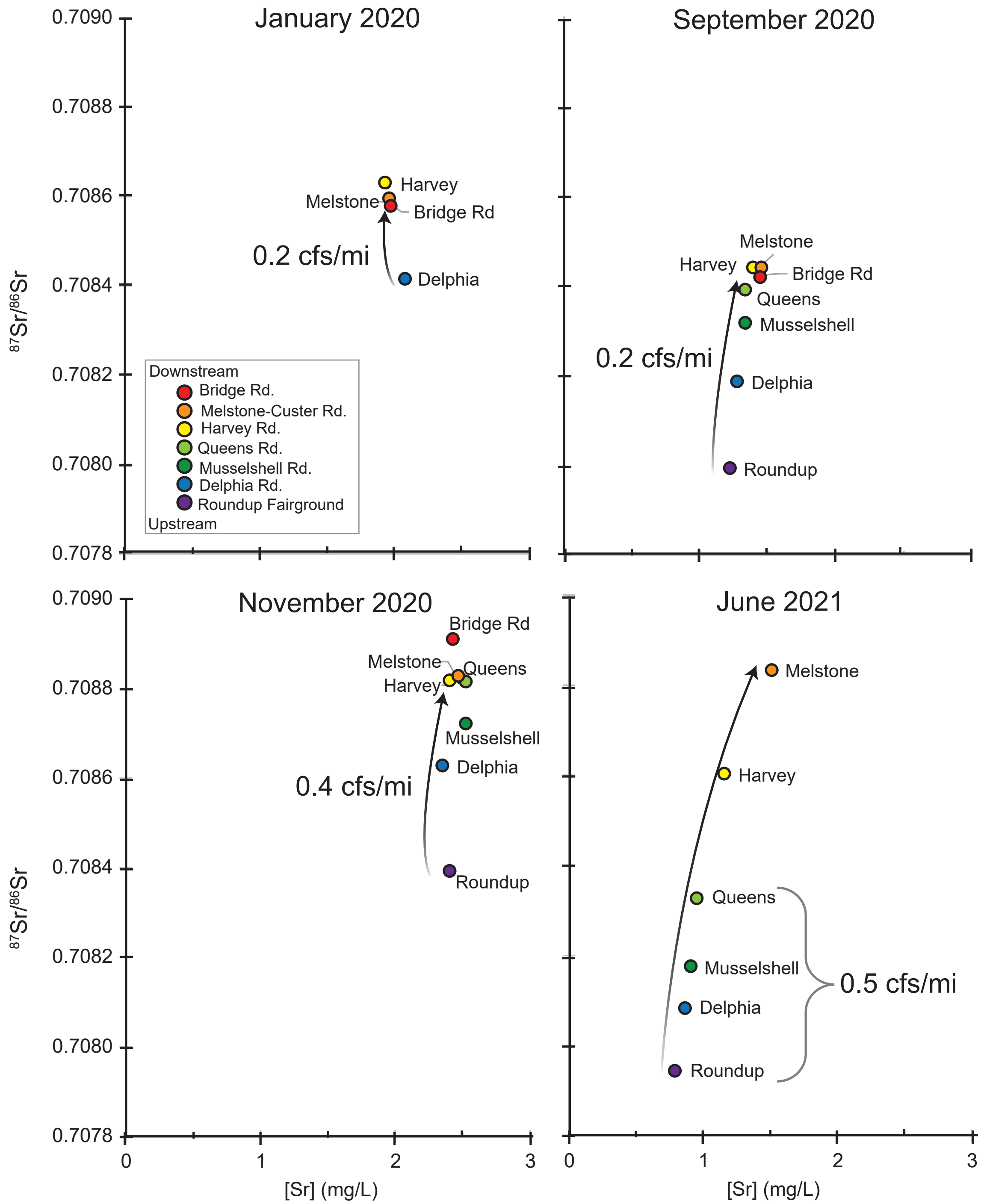


Figure 22. Strontium in surface-water mixing. Fort Union groundwater baseflow contributes approximately 0.2–0.4 cfs per mile to the Musselshell River, with the exception of samples collected in June 2021, which result in a calculated contribution of 0.5 cfs per mile (appendix F, table F4).

DISCUSSION

Objective 1. Groundwater Contribution to the Musselshell River

Traditional methods of estimating groundwater gain and loss to surface water by measuring changes in stream discharge along a reach were not successful along the Musselshell River because changes in streamflow were within measurement error and direct pumping withdrawals could not be quantified. Instead, we used alternative direct and indirect measures to estimate groundwater contributions to the Musselshell River.

Evidence that the Musselshell River gains groundwater from the Fort Union aquifer near Delphia includes: (1) groundwater elevations in the alluvium and the Fort Union aquifer at Delphia are generally higher than the elevation of the river (fig. 12B), (2) increasing sodium and sulfate in downstream river samples from sodium–sulfate groundwater baseflow (fig. 16), and (3) isotopic evidence of increasing contributions from the Fort Union aquifer to the river (fig. 22). Based on strontium isotope mixing calculations, we estimate the Musselshell River gains groundwater baseflow from the Fort Union aquifer at a rate of 0.2 to 0.5 cfs/mi.

Groundwater elevations in the alluvial aquifer near Melstone suggest a connection between the Musselshell River and the alluvium, but also that the river is generally neither gaining nor losing (fig. 12A). Although strontium isotopes were not a useful approach in this setting, major ion chemistry showed that during fall and early winter, the chemical composition of river water is increasingly dominated by sodium and sulfate. This indicates groundwater baseflow from the Fort Union and Bearpaw is of sufficient volume during low-flow conditions to alter surface-water quality.

The Musselshell River is a source of recharge to alluvial groundwater at Delphia and Melstone as evidenced by the similarity of the major-ion geochemistry (fig. 14) and strontium isotope ratios in the river and shallow groundwater (fig. 20). Major ion and isotope geochemistry suggest that groundwater in the alluvium overlying the Bearpaw shale near Melstone contains over 80 percent river water (figs. 14, 21C) with only a small contribution from the underlying bedrock aquifer. In contrast, the alluvium overlying the more transmissive Tongue River member of the Fort Union Formation is recharged approximately half from the river and half from the sandstone aquifer. These calculations assume that the river and bedrock aquifers are the only major sources of water to the alluvium.

Groundwater discharge to the river increases the salinity of the river at times when the river flow rate is low and there are no upstream releases from reservoirs (figs. 15, 23A). Alluvial groundwater measured in wells DRS and MRS was consistently more saline than the river, with few exceptions. Groundwater contributions from the Fort Union and Bearpaw aquifers to the river increase the relative abundance of sodium and sulfate in the river. Despite the sodium-dominated groundwater contributions, the sodium adsorption ratio, an estimate of the sodium hazard to irrigated soils, was under 5 except for the two samples collected at Bridge Road Bridge during the height of the 2021 drought (June and August 2021; appendix E). Musselshell River water, therefore, does not pose a sodium hazard for most soils (Hanson and others, 2006).

The peaks in river salinity in 2020 and 2021 occur when river flows are lowest. This pattern of the highest river salinity occurring before the peak in river discharge is observed during years where the Musselshell River has a distinct high spring flow (e.g., 2014, 2015, and 2020; appendix H; MWC, 2021). The increase in the proportion of groundwater discharge to total river flow causes the river salinity to increase toward that of the groundwater (~3,000 µS/cm; fig. 23A). High river flow rates dilute the river salinity to levels seen throughout the summer (~1,500 µS/cm). Upgradient reservoirs are filled during high spring flows with low-salinity water. The salinity and flow rate of the river in the summer are partially controlled by releases from upgradient reservoirs (MT DEQ, 2018), and this lessens the effect of relatively saline baseflow.

Objective 2. Identify Irrigation Sources of Salinity Mobilization

Canal leakage is a source of recharge to shallow groundwater at all four monitored fields. Groundwater levels at these sites respond within 2 d to the presence of water in the canal (fig. 13). Major ion and isotope geochemistry results also indicate canal leakage; shallow groundwater downgradient from the canals is more geochemically similar to the irrigation water carried by the canal than to underlying groundwater in the bedrock aquifer (figs. 14, 21).

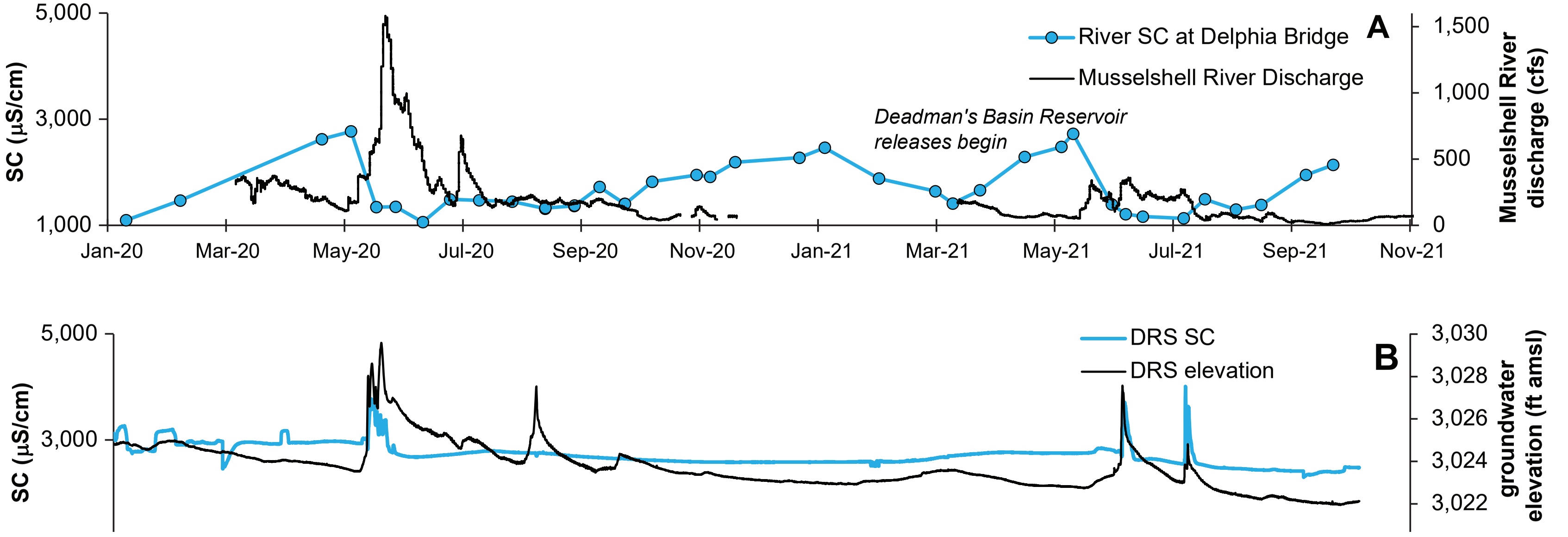


Figure 23. River discharge and groundwater elevation relationship to SC. River salinity (measured as SC at the Delphia Rd. bridge; chart A) is highest in the spring and winter when Musselshell River discharge is at its lowest (Gage 06126500 at Roundup; USGS, 2021). These data show the seasonality of baseflow in the river hydrograph. The river salinity becomes more similar to groundwater salinity (~3,000 µS/cm) during this time because of the higher proportion of baseflow in the river, until high river discharge decreases river salinity. When groundwater levels rise (chart B), either due to precipitation recharge or applied irrigation water, the groundwater salinity also increases.

Though there is a groundwater-level response to canal leakage, the SC of the downgradient groundwater is relatively constant throughout the year and does not change seasonally with canal leakage (fig. 17). At Melstone Fields A, B, and C, this is attributed to low groundwater flux from the underlying bedrock aquifer to the shallow groundwater, due to low bedrock aquifer transmissivity. On the Delphia field (fig. 17D), the salinity of the native groundwater is similar to that of the canal water.

Irrigation on the Delphia Field and Melstone Field B mobilized the available soluble salts, moving them downward through the soil profile, resulting in significantly less available salt within 10 ft of the surface as compared to fields that have never been irrigated (figs. 18, 19, 23). The uniformity of salinity on the flood-irrigated Delphia Field implies regular saturation to the sampled depth (20 ft), suggesting irrigation is a source of recharge to the groundwater, which, at well DRS, is typically between 6 and 8 ft below ground surface.

In comparison, the salinity peaks in the soil profile of pivot-irrigated Melstone Field B indicate that the profile is not regularly saturated to the sampled depth of 20 ft (fig. 18). The transition to pivot irrigation on Field B approximately 10 yr ago appears to be causing an accumulation of salt at the deepest point of infiltration, 6 ft below ground surface. The core was dry to 20 ft when it was collected in March 2021, approximately 400 ft downgradient from the canal. Water levels near the canal are higher: wells BCU and BCL are approximately 75 ft on either side of the canal and water levels vary from 10 to 20 ft below ground surface (BCU) and 2 to 14 ft below ground surface (BCL; MBMG, 2021). Pivot irrigation, therefore, does not appear to be a source of groundwater recharge, nor does it provide irrigation return flow by way of groundwater baseflow in this setting. However, MBMG field personnel noted irrigation water flowing from the edge of Field B and accumulation of salt at the edge of the field. These observations indicate that applied irrigation water may mobilize salt that reaches the river through overland flow rather than through a groundwater pathway.

Despite irrigated soils having much lower levels of available salt than unirrigated soils, application of irrigation water mobilizes salt into the soil water (fig. 19B). The SC increase of the soil water is proportional to the amount of infiltrating irrigation water on both the Delphia Field and Field B (fig. 19). Infiltration of irrigation water is mobilizing soluble salt held in the soil, potentially to the groundwater. On the Delphia Field, infiltrating irrigation water peaked at 2,500 µS/cm, similar to the salinity of the groundwater. The difference in flood and pivot irrigation, as a source of recharge to groundwater, is evident in the total depth of observed infiltration. Given that the short 2021 irrigation season is not representative of typical irrigation rates, the pivot-applied irrigation water was only evident to 2 ft of depth (fig. 19D, Melstone Field B), while two applications of flood irrigation (fig. 19A, Delphia Field) infiltrated to 5 ft. In typical years (that is, non-drought conditions), the maximum infiltration depth would likely be deeper on both fields, but the depth of infiltration from the pivot would likely remain less than that from flood irrigation. Soil type also plays a role in maximum infiltration depth; soils formed on Fort Union sandstones are sandier than the clay-rich soils formed on Bearpaw shales. The narrow river valley through the sandstone unit does not lend itself to the large areas needed for a center pivot, and fields for direct comparisons of irrigation type and soil type are difficult to find. As more pivots are installed, such comparisons may be possible.

CONCLUSIONS

The high salinity in the Musselshell River during some years in the spring is not irrigation related, but is a function of the seasonal dominance of baseflow as a component of the river hydrograph, availability of salts, and salinity of the groundwater derived from natural soil and bedrock sources.

In late summer and early fall, irrigation return flows increase the salinity of the Musselshell River from Delphia to Melstone by approximately 20 to 30 percent (July–September 2020; figs. 15, 16). However, this increase occurs when the river is typically at its lowest salinity and therefore does not cause the river to approach the 3,000 µS/cm irrigation threshold.

High salinities in the river during late fall and winter are caused by groundwater baseflow representing a larger fraction of the river hydrograph. The river chemistry is more dominated by sodium, magnesium, and sulfate during low flows, indicating the increasing influence of groundwater baseflow. Irrigation practices increase the amount of baseflow during late fall and winter, but the higher salinity does not occur at a time when the river is being used for irrigation.

Soil profiles record the history of salt mobilization. Unirrigated soils overlying Fort Union, Fox Hills, and Bearpaw geologic units both have high levels of available soluble salts; however, the soils associated with the Fox Hills and Bearpaw have more salt available at depth compared to the Fort Union soils. Irrigated soils have lower levels of soluble salts throughout the profile as compared to never-irrigated soils. However, the application of irrigation water still mobilized salts to the groundwater on the flood-irrigated Delphia Field.

RECOMMENDATIONS

Although installation of additional center pivots or lining canals might reduce the amount of irrigation recharge to groundwater and subsequent rate of groundwater baseflow in fall and winter, these improvements would not impact the usability of the river for irrigation because most of the increased salinity from irrigation return flow occurs through summer and fall, when the river salinity is low, or in the winter, when the river is not used for irrigation. Lining canals or installing pivots is unlikely to improve the river salinity in a consequential way. Canal lining and pivot installations will affect local conditions, such as reducing muddy conditions below leaking canals, and advance other desired outcomes, such as improving soil condition through managed irrigation or conservation of irrigation water.

Installation of pivot irrigation appears to mobilize fewer salts downward through the soil profile, as illustrated by the soil core from Melstone Field B (fig. 18). More efficient application of water leaves an accumulation of salt below the rooting zone. However, edge-of-field seepage of irrigation water can cause salt accumulation at the soil surface.

Lining canals preserves irrigation water for downgradient users. However, unintended negative consequences to fields near the canals may occur if canals are lined. Along the Delphia–Melstone Canal, canal leakage generally provides low-salinity water that dilutes shallow groundwater that is naturally saline. This dilution may benefit crops, especially on subirrigated fields (e.g., Melstone Field A). Fields near canals may also benefit from higher water levels, allowing for subirrigation of crops. In the Melstone focus area, canal leakage provides a source of low-salinity groundwater to shallow systems that would otherwise be dry or highly saline (e.g., Field A); however, landowners (e.g., Field C) report excess leakage has caused problems with muddy conditions below the canal. The hydrologic benefits and consequences associated with canal leakage can be assessed in light of local conditions when considering lining canals.

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