HYDROGEOLOGY AND IRRIGATION POTENTIAL OF THE WEST CRANE AQUIFER, RICHLAND COUNTY, MONTANA

Jon Reiten and Kevin Chandler

Montana Bureau of Mines and Geology
Ground Water Investigation Program

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Front photo: Irrigation water from the West Crane aquifer has allowed production of high-value crops such as sugar beets, replacing dryland crops. Photo by Kevin Chandler, late summer 2020.

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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 agriculture. Additional program information and project ranking details are available at: http://www.mbmg.mtech.edu/ (Ground Water Investigation Program).

The final products of the West Crane aquifer study include:

- **An Interpretive Report** (this report) that presents data interpretations and summarizes the project results. The focus of this report is on defining the extent and hydrogeology of the West Crane aquifer and addressing potential changes to surface water and groundwater from increased irrigation development of the West Crane aquifer.
- **A Groundwater Modeling Report.** A groundwater modeling report is in preparation (Chandler and others, in prep.) that describes the construction of a groundwater model based on the information and data collected from the study area. The model evaluates the effects of various water-use scenarios on the West Crane aquifer as it relates to groundwater availability.

ABSTRACT

The West Crane aquifer underlies the western slopes of the Yellowstone River Valley for about 22 mi between Fox Creek (north) and Burns Creek (south) in Richland County, Montana. The aquifer occupies a buried valley eroded into the Fort Union Formation that runs parallel to the Yellowstone River Valley. Test drilling performed between 2012 and 2018 indicates the sinuous valley is about 1 mi wide, up to 300 ft deep, and the slope of the buried valley floor has a gradient similar to the modern Yellowstone River.

Seven west-to-east drainages that cross the buried valley form dry washes above the aquifer. These ephemeral streams change to perennial streams as they approach the eastern boundary of the buried valley. The basal gravel partially filling the buried valley is the most hydraulically productive sediment within the West Crane aquifer, supporting well yields up to 1,300 gallons per minute (gpm). The hydraulic conductivity (K) ranges from 360 to 1,300 ft/d. The storage coefficient (S) ranges from 0.0007 to 0.03. The overlying leaky confining unit provides a large volume of storage, which helps to maintain aquifer head.

Water quality is compatible with irrigation. The specific conductance (SC) ranges from 425 to 2,910 µS/cm. The sodium adsorption ratio (SAR) ranges from 0.1 to 48.1. Elevated SC and SAR are limited within the aquifer, and overall, the water quality is similar to other aquifers in this region that have supplied adequate water quality for irrigation over several decades.

The aquifer is recharged primarily by infiltrating snowmelt and occasional strong thunderstorms that flood the ephemeral stream washes overlying the aquifer. Smaller volumes of recharge are caused by lateral flow from bedrock aquifers, lateral flow along the bedrock surface, or infiltration of precipitation through the semi-confining sediments overlying the buried valley aquifer in the uplands between tributaries.

Hydrographs constructed from extensive data collection at monitoring wells demonstrate the aquifer response to irrigation withdrawals, recharge events, evapotranspiration, and groundwater discharge where perennial streams originate.

As of 2020, 14 irrigation wells were completed in the West Crane aquifer. Eleven of these were drilled since 2009. Aquifer tests conducted at each irrigation well have provided a better understanding of aquifer productivity and response to pumping. Increased demand for irrigation water brought on by the discovery of this aquifer prompted the Richland County Conservation District to propose this GWIP project with goals to determine the aquifer extent, hydraulic characteristics, and water quality, and to model the aquifer flow system.

INTRODUCTION

Background

The land to the west of the Yellowstone River Valley near Crane, Montana is traditionally used for grazing livestock and growing dryland crops. Low-relief upland areas between tributary valleys are split between cropland and pastures; while the tributary valleys are pastures, dryland crops are grown in the uplands. Irrigation using groundwater had never been seriously considered by the local producers. The discovery of the West Crane aquifer groundwater resource has changed the area's land-use dynamics. The high-yield aquifer provides the potential for developing irrigated cropland, thereby increasing the demand for groundwater.

Purpose and Scope

Initial irrigation development of the West Crane aquifer indicated good potential for increases in groundwater withdrawal. Acknowledging the need for more information on the development potential, the Richland County Conservation District sponsored this GWIP project, which focused on determining the physical availability of groundwater from the aquifer. Using existing and new data, we developed a conceptual model of the aquifer. Exploratory drilling and field mapping defined the aquifer boundaries and extent. Aquifer tests provided hydraulic conductivity (K), storage coefficient (S), and aquifer boundaries. Groundwater-level hydrographs were interpreted to assess sources of recharge. The project included water-quality characterization to assess the suitability of groundwater for irrigation. Many components of the water budget were developed. This information supported the development of a groundwater flow model (in preparation) to test the irrigation development potential.

Project Location

The West Crane aquifer underlies valley slopes on the west side of the lower Yellowstone River Valley from Burns Creek northward to Fox Creek (approximately 22 mi) in southern Richland County, Montana (fig. 1). It is about 1 mi wide, occupying the basal sediments of a buried valley. The aquifer parallels and has a similar overall meandering pattern as the modern Yellowstone River Valley; however, the land surface overlying the aquifer has little or no topographic expression of the buried valley. The primary study area is defined by the buried valley, but drainage basins west of the buried valley are also important because they capture precipitation and snowmelt, effectively expanding the aquifer recharge area. The land surface west of the aquifer gradually slopes upward to watershed divides, marking the extent of the basins that influence the aquifer.

Previous Investigations

Leonard (1916), Thom and Dobbin (1924), and Brown (1948) developed early descriptions and interpretations of the stratigraphy of eastern Montana and surrounding areas. Alden (1932) interpreted the surficial features and geologic history through his study of the geomorphology and glacial geology of eastern Montana. Howard (1960) described the Cenozoic history of northeastern Montana and northwestern North Dakota, which included this area. Torrey (1956) studied the groundwater resources of the lower Yellowstone River Valley. Prichard and Landis (1975) produced the first detailed geologic map of this area as part of a report on the coal deposits of the Girard coalfield. The MBMG developed geologic maps covering this area at a scale of 1:100,000, including the Glendive quadrangle by Vuke and Colton (1998) and the Sidney quadrangle by Vuke and others (2003).

Discovery of the West Crane aquifer traces back to the 1960s, when seismic shot hole drilling identified a potential source for a municipal water supply in sand and gravel deposits underlying the western part of Sidney. These deposits are about 100 ft deep and were potentially more productive than the shallow 30- to 40-ft-deep aquifer underlying the eastern part of town. Water well test drilling verified this potential and the city of Sidney has since developed seven municipal wells in the Sidney aquifer (fig. 2), which aligns with the West Crane aquifer and is likely a component of the same buried valley. Well yields range from 500 to 1,500 gpm. The buried valley is about 1 mi wide, 100 to 125 ft deep, and contains sand and gravel deposits that form a productive aquifer. The sand and gravel near the base of the buried valley is the most productive zone. This aquifer was informally named the Lower Yellowstone Buried Valley aquifer (LYBV) during the source water assessment project by Miller and others (1998). Smith (1998) mapped a narrow band of thick, unconsolidated deposits underlying the Yellowstone River Valley from the North Dakota border southwest to Fox Creek. This mapping also identi-

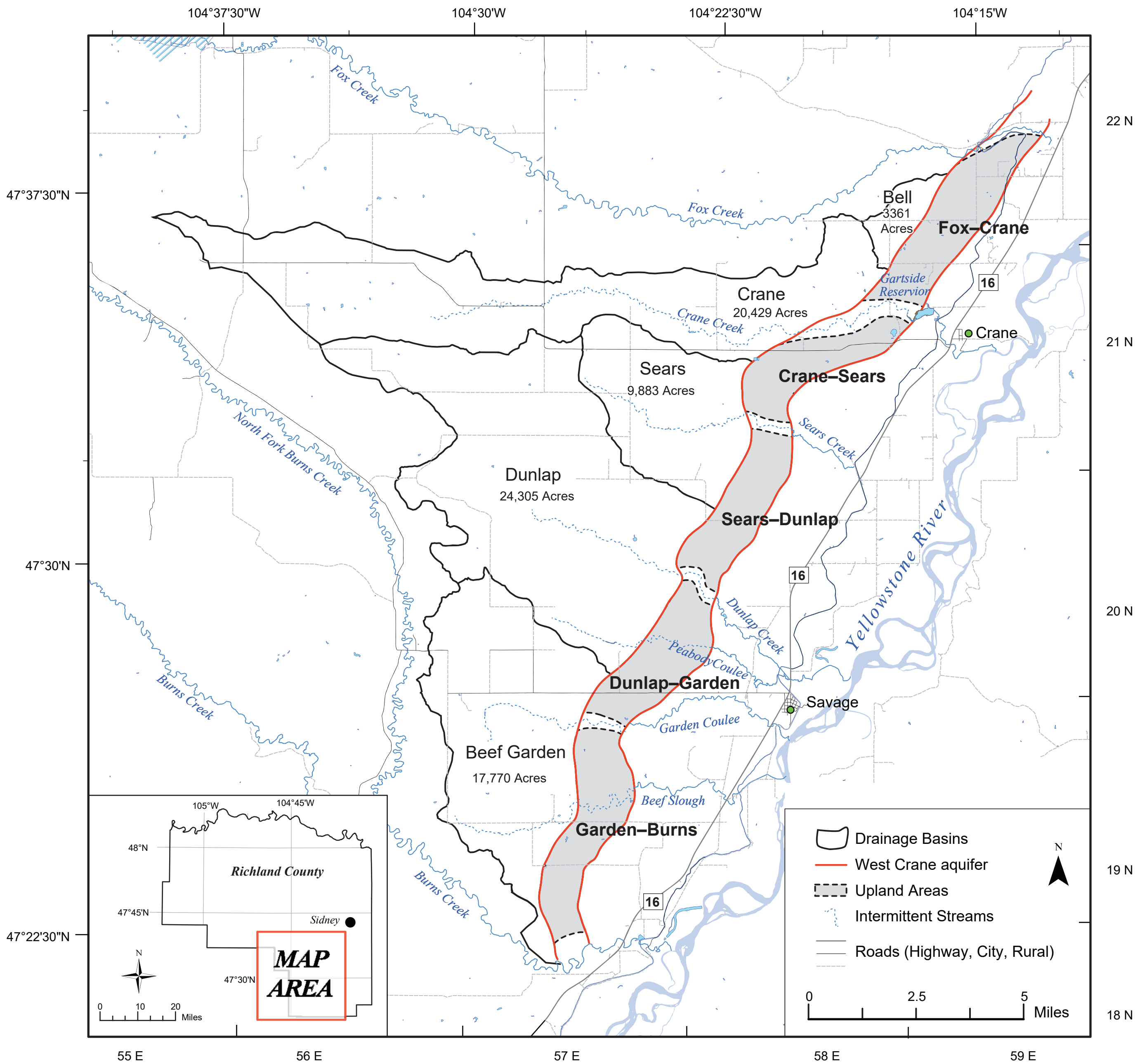


Figure 1. Project location showing the extent of the West Crane aquifer; topographically higher drainage basins are to the west, and upland or interfluve areas overlie the aquifer (shaded). The upland areas are named from south to north based on the names of bounding stream valleys: Garden–Burns, Dunlap–Garden, Sears–Dunlap, Crane–Sears, and Fox–Crane.

fied thick unconsolidated deposits that extended south about 4 mi from Fox Creek, underlying the valley slopes. These projects prompted additional investigations that eventually led to the discovery of the West Crane aquifer.

Additional test drilling during the winter of 2006–2007 in the West Crane area suggested that the LYBV extended under the valley slope and uplands south of Fox Creek to Crane Creek. This finding refined geologic mapping of several areas in the Sidney quadrangle (Vuke and others, 2003, compiled from Prichard and Landis, 1975) that showed Fort Union Formation where the buried valley has subsequently been identified.

Test drilling in the fall of 2007, as part of a Montana Department of Natural Resources (DNRC) Renewable Resource Grant (RRG) project, expanded the known aquifer extent from Fox Creek north to the North Dakota boundary near Fairview. A few test holes south of Fox Creek confirmed previous interpretations that the aquifer extended as far south as Crane Creek.

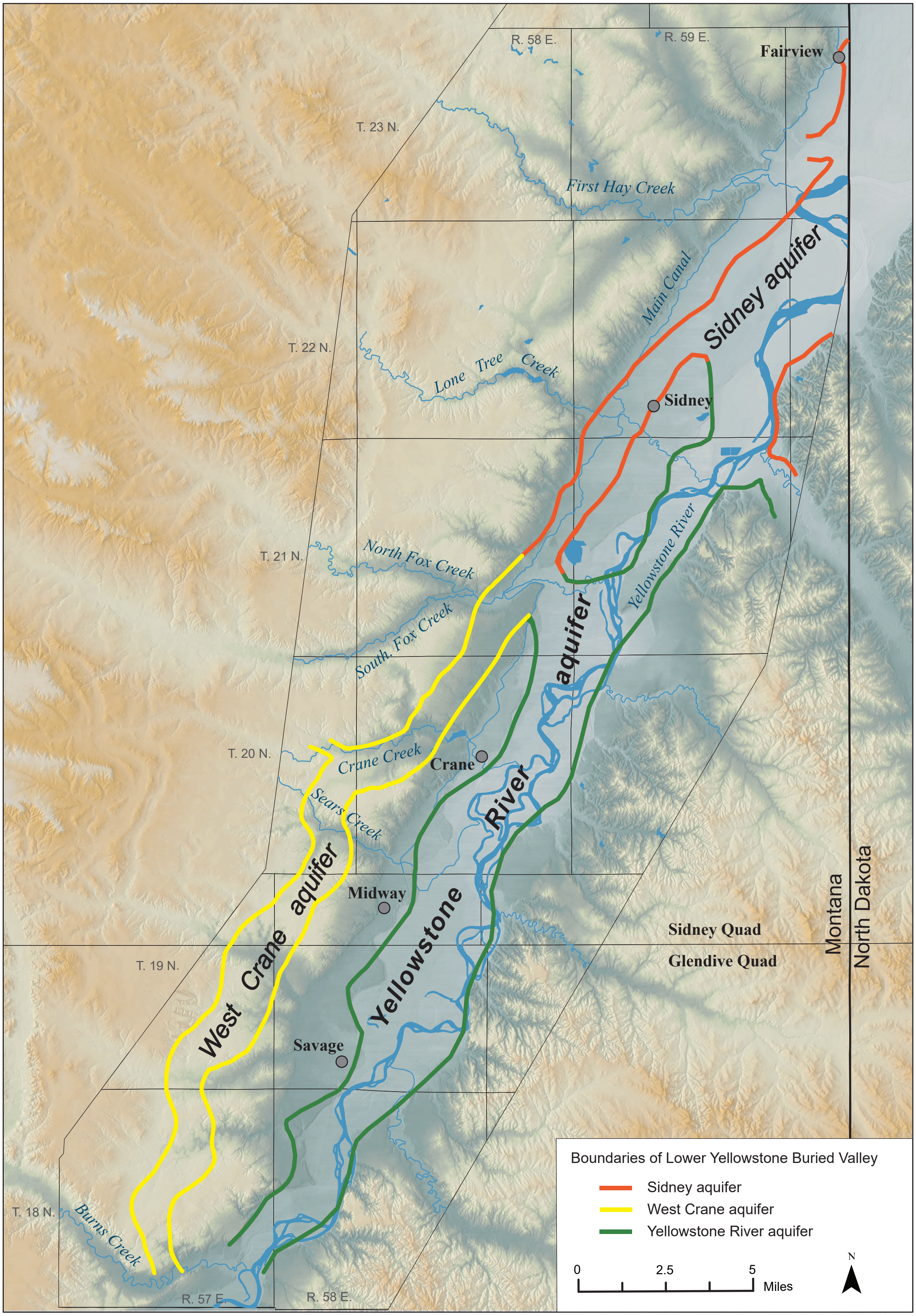


Figure 2. The Lower Yellowstone Buried Valley aquifer (LYBV) underlies the Yellowstone River Valley and western valley slopes. The LYBV comprises three distinct segments: the Sidney aquifer and Yellowstone River aquifer, both of which underlie the valley, and the West Crane aquifer, which underlies the western valley slopes.

In 2009, farmers drilled test wells in the West Crane area, speculating on irrigation potential. Constructing and testing these irrigation wells verified this potential. During the next few years, DNRC permitted three irrigation wells. Additional test drilling in 2013 extended the known southern boundary of the aquifer southward to locations west of Savage. The resulting information is published in abstracts by Reiten and Chandler (2013, 2014, 2019).

The LYBV can be divided into three aquifers (fig. 2; Chandler and Reiten, 2020). The northern part of the aquifer, the Sidney aquifer, extends from near Fairview to Fox Creek. The Sidney aquifer is recharged by deep percolation of irrigation water and leakage from irrigation canals. Another part of the LYBV aquifer underlies the valley east of Sidney, extending south to the county line. This buried valley aquifer is informally named the Yellowstone River aquifer. The southern part of the LYBV aquifer, the West Crane aquifer, extends from Fox Creek to Burns Creek. The West Crane aquifer underlies land higher in elevation than land to the east, which is irrigated using water from the Yellowstone River. Farmers and ranchers interested in expanding agricultural production have increased the demand for water resources in the West Crane area.

Regional Setting

Physiography

A triangular-shaped region that includes the watersheds of Beef Slough, Garden Coulee, Peabody Coulee, Dunlap Creek, Sears Creek, and Crane Creek influences recharge to the West Crane aquifer (fig. 1). The elevation of these watersheds gradually increases west of the aquifer, terminating at the surface-water divide located east and northeast of the North Fork of Burns Creek and south of Fox Creek. The elevation at the divide is greater than 2,700 ft above mean sea level (amsl) at the highest position in the upper reaches of the Crane Creek watershed. The land-surface elevation overlying the aquifer ranges from about 1,930 to 2,240 ft. At higher elevations west of the buried valley, the streams are intermittent (dry during some seasons when the water table drops below the elevation of the streambed) to ephemeral (dry except for periods of response to precipitation events, such as a rainstorm or snowmelt). Overlying the buried valley, the streams are ephemeral and typically form braided dry channels. To the east of the buried valley most of the streams are perennial or form permanent wetlands. These drainages are all tributaries to the Yellowstone River that cross the buried valley containing the West Crane aquifer before flowing into the Yellowstone.

Another important physiographic distinction is between the upland areas and cross-cutting drainages (fig. 1). The uplands form broad, low-relief landscapes overlying the buried valley, commonly mantled with soils developed in glacial till. These landscape features make the uplands the best targets for irrigation development from the West Crane aquifer, especially when compared to the higher relief coarser-grained soils of the tributaries and their valley slopes. These uplands have been named by the tributary drainages that segment them from south to north as Garden–Burns upland, Dunlap–Garden upland, Sears–Dunlap upland, Crane–Sears upland, and Fox–Crane upland (fig. 1).

The West Crane aquifer parallels the Yellowstone River with the basal elevation about 2,010 ft (amsl) at the southern end of the aquifer near Burns Creek (fig. 3). At the northern end of the aquifer, the basal elevation of the aquifer is about 80 to 100 ft below the land surface at Fox Creek (1,830 to 1,850 ft amsl). The uplands between tributary valleys are about 100 ft to 200 ft higher in elevation.

Geology

The Paleocene Fort Union Formation crops out along valley margins and commonly forms rugged badlands topography. This formation, and in particular the Tongue River Member, is composed of poorly consolidated interbedded layers of sandstone, mudstone, siltstone, and lignite. The Tongue River Member underlies most of the West Crane study area. In the southern part of this area near Burns Creek, the underlying Ludlow Member is at the land surface. Compared to the Tongue River, the Ludlow is generally thinner bedded, finer grained, and contains more smectite (swelling clays) that produces characteristic popcorn weathering (fig. 4). The Fort Union Formation forms the bedrock base overlain by Tertiary and Quaternary coarse-grained stream deposits and glacial till (Prichard and Landis, 1975).

Stream terraces consisting of sand and gravel of older river deposits parallel the Yellowstone River. The highest terraces are 760 ft above the modern river level west of Savage. This terrace is the oldest, with progressively younger terraces stepping down in

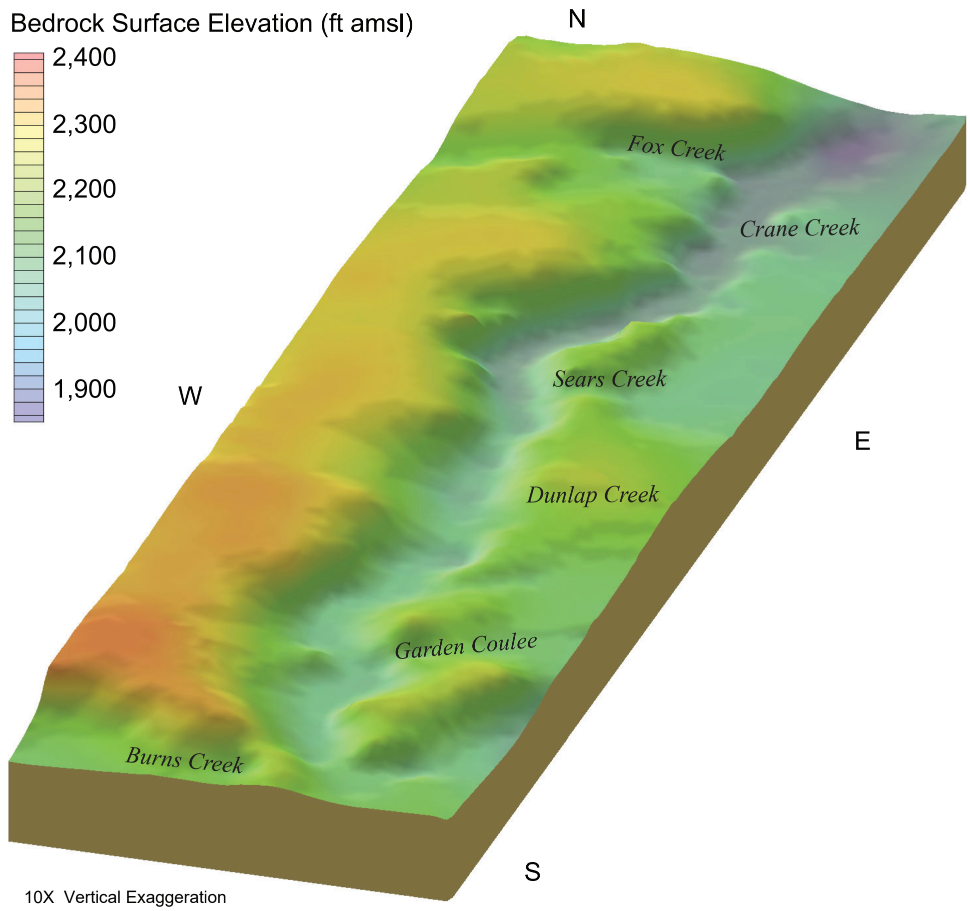


Figure 3. The buried valley bedrock surface containing the West Crane aquifer is shown in this schematic 3D image.

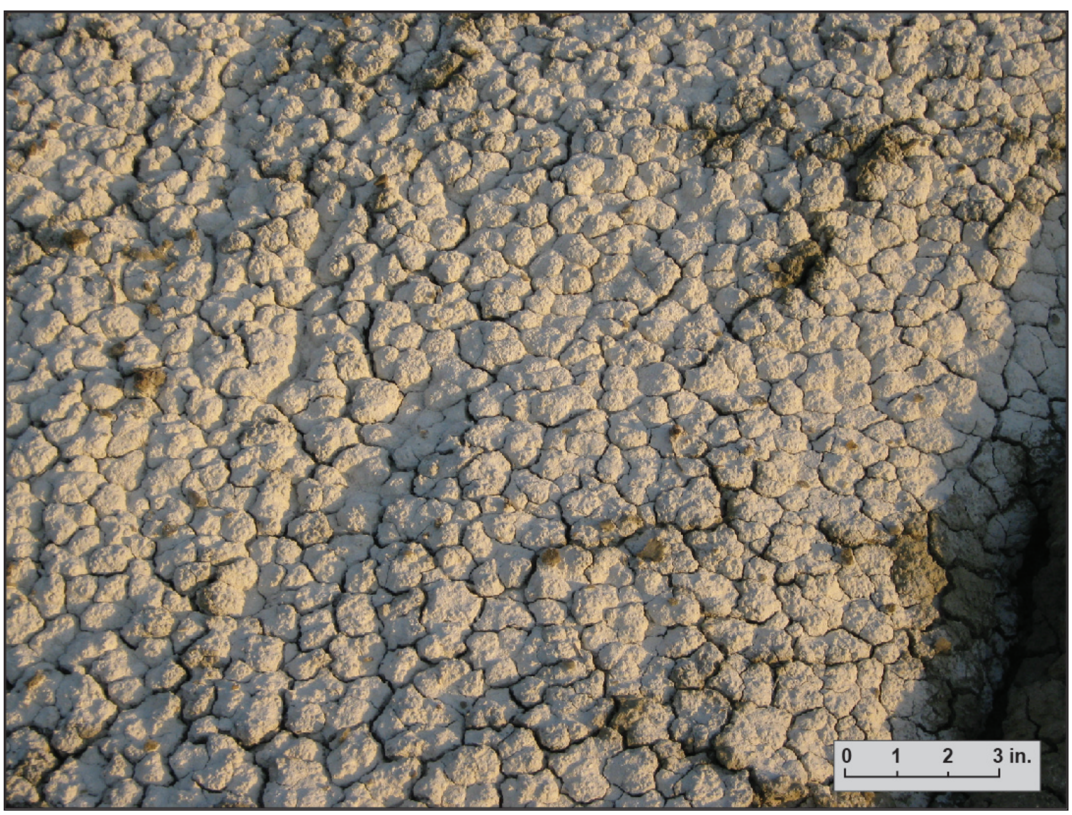


Figure 4. Popcorn texture in Fort Union sediments caused by swelling clays.

elevation eastward. The age of these terraces ranges from Tertiary to Quaternary. The buried valley appears to be the last progression of the Yellowstone River prior to major diversions of the Missouri and Yellowstone Rivers by Quaternary glaciers. The modern Yellowstone Valley to the east of the buried valley is likely to have formed following the retreat of the Late Quaternary glaciers.

Climate

Richland County has a semi-arid continental climate, characterized by cold, dry winters; cool, moist springs; moderately hot, dry summers; and cool, dry autumns. January is generally the coldest month, with an average low temperature of 2.1°F, and July the warmest month, with an average high temperature of 87.1°F (based on 1905–2012 data). At Savage, the average precipitation is 13.9 in per year (based on 1906–2020 data), with most of the precipitation falling during the growing season from May through August (fig. 5; WRCC, 2021, Savage, Montana Station 247382).

Figure 6 compares the long-term average monthly precipitation at Savage to monthly precipitation during this project (1906–2020). Exceptional rain events during September 2019 greatly exceeded the average for that month.

Irrigation Development

Irrigation development of the West Crane aquifer started in the Crane–Sears upland based on encouraging potential shown by the drilling log for monitoring well 234024, constructed in 2007. Irrigation well 284325, drilled in 2009 about 600 ft west of monitoring well 234024, produces 900 gpm. (Well number designations are described in Methods, Data Compilation and Management.) This irrigation well was first used during the 2011 growing season to supply a center pivot irrigation system. Locations of new irrigation focused on the northern part of the aquifer within the Crane–Sears and Fox–Crane areas through 2017, and appropriated 2,054 acre-ft of water (table 1). Starting in 2018, more irrigation was developed in other parts of the aquifer. By the 2020 growing season, a total of 4,561 acre-ft of groundwater had been appropriated in the West Crane aquifer.

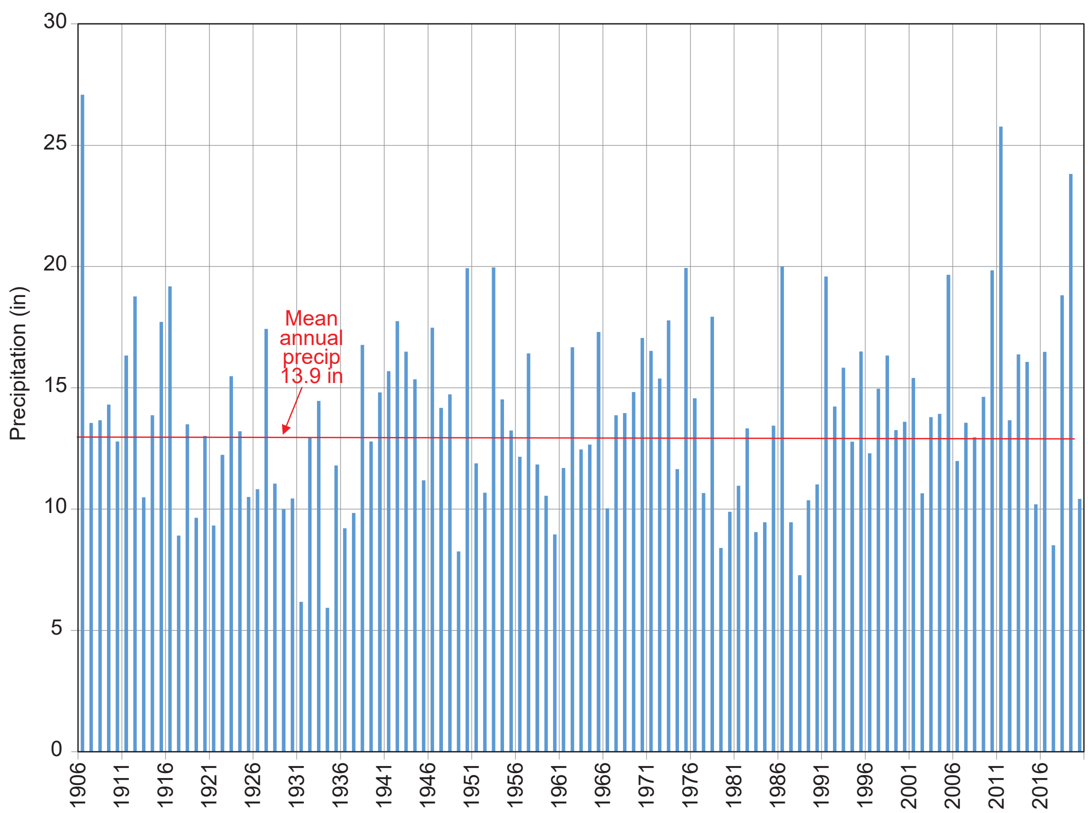


Figure 5. Annual precipitation at Savage and the long-term average (WRRC, 2021).

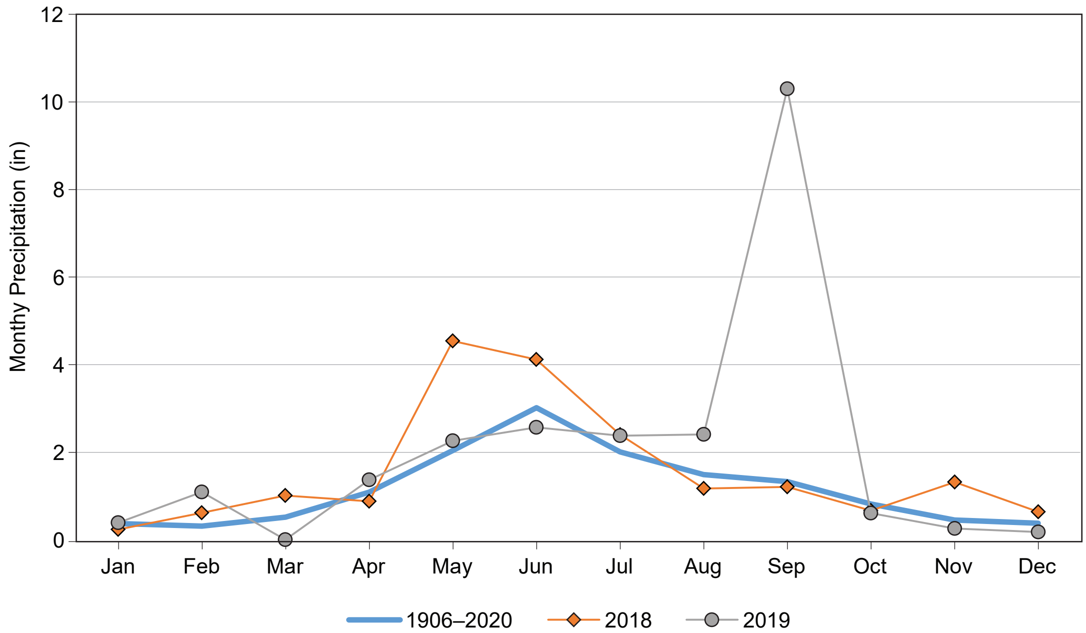


Figure 6. Comparison of monthly precipitation at Savage. Note the exceptional rain events in September 2019 compared to average precipitation.

Table 1. List of irrigation wells in the West Crane aquifer by first year used for irrigation.

Site Name	GWIC ID	Date Drilled	Year First Used	Location Latitude–Longitude	Ground-Surface Altitude (ft amsl)	Total Depth (ft)	Screened Interval (ft)	Static Water Level on Date Drilled (ft below M.P.)*	Irrigation Pumping Rate (gpm)**
KJonsson1	249505	2/25/2009	2011	47.56878 -104.32075	2,124	170	150-170	67	900
Bradley 1	253448	3/6/2009	2014	47.59730 -104.28761	2,114	180	164-174	101	800
Wyman 1	250211	3/17/2009	2016	47.57808 -104.29858	2,059	118	97-117	20	1020
Cjohnson 1	285659	9/30/2015	2017	47.60151 -104.28281	2,105	170	150-170	94	630
Cjohnson 2	285476	10/12/2015	2017	47.60530 -104.28241	2,104	180	150-180	95	900
Cjohnson 3	291010	12/13/2016	2017	47.60316 -104.28247	2,103	169	149-169	93	1010
KJonsson2	284325	8/28/2015	2018	47.57191 -104.33065	2,173	223	192-223	110	715
DJorgensen1	290760	10/28/2016	2018	47.45694 -104.40968	2,223	230	210-230	139	750
Lange 1	296426	3/3/2018	2018	47.45639 -104.42733	2,215	223	203-223	128	900
Ler1	295397	10/23/2017	2019	47.46811 -104.39520	2,114	130	110-130	38	862
Basta 1	296537	2/14/2018	2020	47.38126 -104.46094	2,193	181	171-181	115	250
Basta 1	296536	3/1/2018	2020	47.38406 -104.45614	2,192	181	171-181	111	250
Basta 1	296761	4/9/2018	2020	47.38446 -104.45562	2,193	183	173-183	112	250
JJorgensen1	303552	10/9/2019	2020	47.5132 -104.3747	2,131	260	240-260	156	1420
Lange 2	300586	1/7/2019	2020	47.44659 -104.42627	2,159	142	122-142	74	804
Basta 2	305427	10/29/2019	not yet	47.39860 -104.45836	2,229	226	206-226	154	750

*Static water level when drilled.
**Pumping rate used for irrigation.

METHODS

Data Compilation and Management

MBMG's hydrogeologists compiled and verified West Crane aquifer data including location, depth, and stratigraphy collected from 1995 to 2020. These data were used to update aquifer maps and to support hydrogeologic interpretation. The principal sources of these data are lithologic and well-completion logs, groundwater levels, water chemistry analyses, and aquifer tests reports stored in the MBMG's Ground Water Information Center database (GWIC). These data are accessible online at https://mbmggwic.mtech.edu. Appendix A lists GWIC identification numbers for groundwater and surface-water monitoring sites. Sites referred to in this report are denoted by the GWIC identification number for wells (e.g., well 242417) and for surface water (e.g., site 242228).

Drilling

Our test drilling program in 2017 and 2018 expanded on previous work (see Previous Investigations section above). We also utilized test drilling conducted during private irrigation development. Drilling was used to determine the aquifer extent and identify locations suitable for water-level monitoring. Sixty-one boreholes were drilled using a mud-rotary drilling rig (plate 1). Logs of drill cuttings describe the grain size, texture, and color of earth materials encountered. These logs were completed by MBMG hydrogeologists or licensed well drillers. Monitoring wells were constructed in 39 of these boreholes. In addition, shallow piezometers were installed in six hand-augered boreholes. All information about the monitoring wells, boreholes, and piezometers, including location and lithologic logs, is available from the GWIC database (https://mbmggwic.mtech.edu/) and in appendix A.

Geologic (Lithologic) Mapping

Plate 2A was modified from the MBMG 1:100,000-scale map of the Sidney quadrangle (Vuke and others, 2003) and the Glendive quadrangle (Vuke and Colton, 1998). Plate 2A maps the surficial geology compiled from older maps, and in some cases, field checked by MBMG geologists. The geology shown on plate 2B is based on the parent materials of the different soil series and was used to construct a surficial geologic map based on the NRCS soil survey of Richland County (USDA, 1980). Shape files from NRCS soil maps were used to classify specific geologic units based on the parent material for that soil type. Several locations were visited to provide some verification of the geologic interpretations.

Hydrogeologic Framework

Logs of drill cuttings were simplified by assigning hydrogeologic units and entered into a digital format. This process included verifying and correcting well locations and translating lithologic descriptions to major hydrogeologic units. Well logs showed heterogeneous lithologic sequences, common in glaciated terrains. The well logs indicated changes in stratigraphy between closely spaced boreholes and vertically within a single borehole. The generalization to hydrogeologic units brought consistency to the wide range of terminology used by drillers and geologists as they logged well cuttings. The generalized logs provided the information to develop stratigraphic cross-sections, construct aquifer maps, and advance the hydrogeologic conceptual model.

Water Use

We compiled irrigation water-use records for the entire project area. Nearly all of the irrigators control their pivots remotely using the AGSENSE system (www.wagnet.net). In addition to turning pivot systems on and off, AGSENSE stores daily water-use data. We installed pressure transducers and data loggers in monitoring wells close to irrigation wells. These provided data to calculate withdrawals from the aquifer to verify AGSENSE data and to monitor irrigation pivots lacking the automated systems. These data loggers recorded water levels at 15-min intervals. Water use was compiled as daily records. This information provided current and historical water-use data for the West Crane aquifer.

Monitoring Network

We surveyed the elevations and coordinates of all monitoring and irrigation wells with a Leica 1200 GNSS GPS system. The well survey utilized a base station and rover with accuracy to 1 in for altitude and latitude–longitude. Surface-water sites were located using a handheld GPS and elevations were subsequently determined from Google Earth.

Groundwater

A network of 107 monitoring, stock, and irrigation wells provided water-level data for this project (appendix A). The frequency of water-level measurements was variable; most data loggers were set to record hourly, but a 15-min interval was used in monitoring wells adjacent to irrigation wells. Water levels in irrigation wells and stock wells were manually measured, at frequencies ranging from monthly to annually, typically with a steel tape or sounder. Plate 1 shows the locations of monitoring wells.

Surface Water

We installed three cutthroat flumes in the project area (appendix A; plate 1) on Crane Creek, Sears Creek, and Burns Creek. Dunlap Creek forms a channel similar in size and gradient to Sears Creek, but we had no access to the site. A portable 90° V-notch weir was used to check streamflows on Burns and Sears Creeks as the flumes were installed. The flume on Crane Creek measures flow from a drain system installed by Montana Fish, Wildlife and Parks in the 1980s. The flume on Sears Creek measures flow near the downstream edge of the buried valley where surface flow starts. The Burns Creek flume measures flow downgradient from where the creek crosses the aquifer. Data loggers in the flume stilling wells record stages hourly.

Water Quality

The GWIC database contains 84 groundwater and surface-water analyses collected in this area (appendix B). Most samples were collected using MBMG Standard Operating Procedures (Gotkowitz, 2022). Water was purged from the wells using pumps, bailers, or airlift methods. Purging removed about three casing volumes or until temperature, SC, and pH had stabilized. Surface water was collected by pumping or grab sampling from the stream (Gotkowitz, 2022).

Aquifer Test Data

We compiled aquifer test data from 14 water-permit applications submitted to the DNRC conducted in the West Crane aquifer. These include single well tests of irrigation wells and multiple well tests where monitoring wells were available. The test data are available in GWIC with DNRC 633 reports attached to the production well record. Aquifer tests were analyzed using AQTESOLV (Duffield, 2007) and summarized in Reiten and Chandler (2021b).

RESULTS

Hydrogeologic Framework

Geology

We plotted the West Crane buried valley on the general geologic maps for the Sidney and Glendive quadrangles (plate 2A; Vuke and others, 2003; Vuke and Colton, 1998, respectively). The buried valley containing the West Crane aquifer is about 1 mi wide and 22 mi long. Based on test drilling and data compiled from other lithologic logs, the lateral boundaries of the aquifer are accurate to about ¼ mi. The Tertiary (Pliocene) to Quaternary alluvial terraces are of particular interest because they occur in the watersheds west of the buried valley. From the highest and oldest terrace, the progressively younger terraces step down in elevation eastward. The highest terraces, which vary in age from Pliocene to Quaternary, were not glaciated. Glacial till overlies other terrace deposits over much of this area, marking the extent of glaciation. Narrow bands of terrace deposits are mapped on plate 2A, overlying the Fort Union Formation and below the glacial till along drainages. Water-well logs verify that these terrace deposits are extensive on the upland areas. Hydrogeologically, the terrace deposits are important because rainfall and snowmelt can infiltrate these coarse-grained sediments and recharge underlying aquifers or flow towards the buried valley aquifer on the bedrock surface. The fine-grained pebbly clay loam texture of glacial till may delay recharge, although the relatively thin till deposits are typically fractured enough to allow recharge.

Although plate 2A illustrates the relation of the West Crane buried valley to the terrace deposits, earlier mapping did not identify where the buried valley had incised and eroded the Fort Union bedrock. The geologic map, which did not benefit from knowledge gained by drilling, shows several areas where the authors inferred the presence of Fort Union deposits. However, some of this overlying area is now known to be the buried valley, including along Fox Creek, Crane Creek, and Sears Creek. Eventually, through exploration for the buried valley, close inspection revealed outcrops previously mapped as Fort Union Formation are now recognized as Quaternary deposits. Through test drilling, we discovered that areas mapped as Fort Union at the land surface are outcrops of glacial till or other Quaternary deposits. These till and Quaternary deposits rise 100 to 250 ft above the Fort Union Formation, which lies at the base of the buried valley.

Plate 2B presents a geologic map based on the parent material shown on the soil maps of Richland and Dawson Counties (USDA, 1980), and as a result, emphasizes surficial lithologies. The main difference between the maps in plate 2 is the limited areal extent of the Fort Union Formation on plate 2B; this plate correctly shows areas where Fort Union deposits are absent over the buried valley. The soil maps show higher scale resolution of lithologic units, and as a result, thin deposits mapped on plate 2B are not shown on plate 2A. In addition, the Quaternary alluvium (Qal) is separated into coarse-grained and fine-grained alluvium on plate 2B. The coarse-grained sediments, both within the Quaternary terraces and Qal, are important hydrogeologically because they provide infiltration pathways for aquifer recharge. Wetlands lie within Qal deposits in some areas.

A radiocarbon date (Beta Analytical Laboratory number 466609) measured from bone recovered from sand and gravel of the West Crane aquifer during drilling at well 275604 suggests the stream that deposited the West Crane aquifer was active around 27,450 ± 120 BP or younger. A second radiocarbon sample (Beta Analytical Laboratory number 561010) collected from a buried peat deposit at a depth of 4–5 ft west of Gartside Reservoir (see plate 1 for location of both radiocarbon samples) suggests the deposits' age is 2,500 ± 30 BP. In several areas, groundwater discharges to wetlands, where floating sedge mats form fens. Peat develops when, during flood events, these floating sedge mats are buried by alluvial floodplain deposits. Previous test holes in this area identified several buried peat deposits, some deeper than the one that was radiocarbon dated. This suggests that groundwater has discharged in this area since Quaternary glacial meltwater incised the current tributary streams.

Hydrostratigraphy

The West Crane aquifer lies within an ancestral river valley that was incised into fine-grained Fort Union bedrock. The most productive part of the aquifer is a basal gravel or sand and gravel unit that overlies the Fort Union Formation. The aquifer ranges from less than 15 to 50 ft thick. Overlying this unit is a mixture of silty sand, till, silty clay, carbonaceous clay, and gravel forming a leaky confined unit. Glacial till caps the aquifer. These deposits completely fill the buried valley, leaving little or no surface expression of the aquifer. The confining unit that overlies the aquifer results in confined to leaky confined conditions in the West Crane aquifer.

Figures 7 and 8 are transverse cross-sections perpendicular to the axis of the buried valley (cross-section line locations are shown on plate 1). We simplified the complex mixture of lithologies for displaying cross-sections and developing the conceptual model of the groundwater flow system. Figure 7 shows the complexity and variability of lithologic units within the buried valley in a lowland setting along Sears Creek (A–A′, plate 1). Well 299171, completed in a coalbed and located just west of the buried valley, depicts the potential for groundwater to move from the coal aquifer to the buried valley aquifer. Figure 8 shows a cross-section through the Sears–Dunlap upland (B–B′, plate 1). The complex stratigraphic relationship of the leaky confining unit and the aquifer are expressions of aquifer anisotropy and heterogeneity. Post-depositional erosion of the leaky confining unit has removed over 100 ft of this material in the tributary valleys as compared to the uplands (figs. 7, 8), resulting in nearly unconfined conditions underlying the tributary valleys.

A longitudinal hydrostratigraphic cross-section of the West Crane aquifer is displayed on plate 3. The base of the aquifer is just above Burns Creek at the southern end. The northern boundary is at Fox Creek where the base of the aquifer is about 75 ft below the creek level. The aquifer continues northward as the Sidney aquifer (fig. 2).

The topography shown by the surface profile depicts areas of uplands separated by lowland valleys formed by tributary streams to the Yellowstone River (see fig. 1, plate 3). The best potential for irrigation is in the uplands. The uplands have minor topographic relief and are mantled with irrigation-compatible soils. In contrast, the low-lying areas and slopes have a more rugged topography and a gravelly surface with thin soils. Nearly all of the irrigation from the West Crane aquifer has occurred on the uplands.

Stratigraphic units on plate 3 are simplified into generalized hydrogeologic units. The following series of photographs show the physical characteristics of these hydrostratigraphic units. Low-permeability Fort

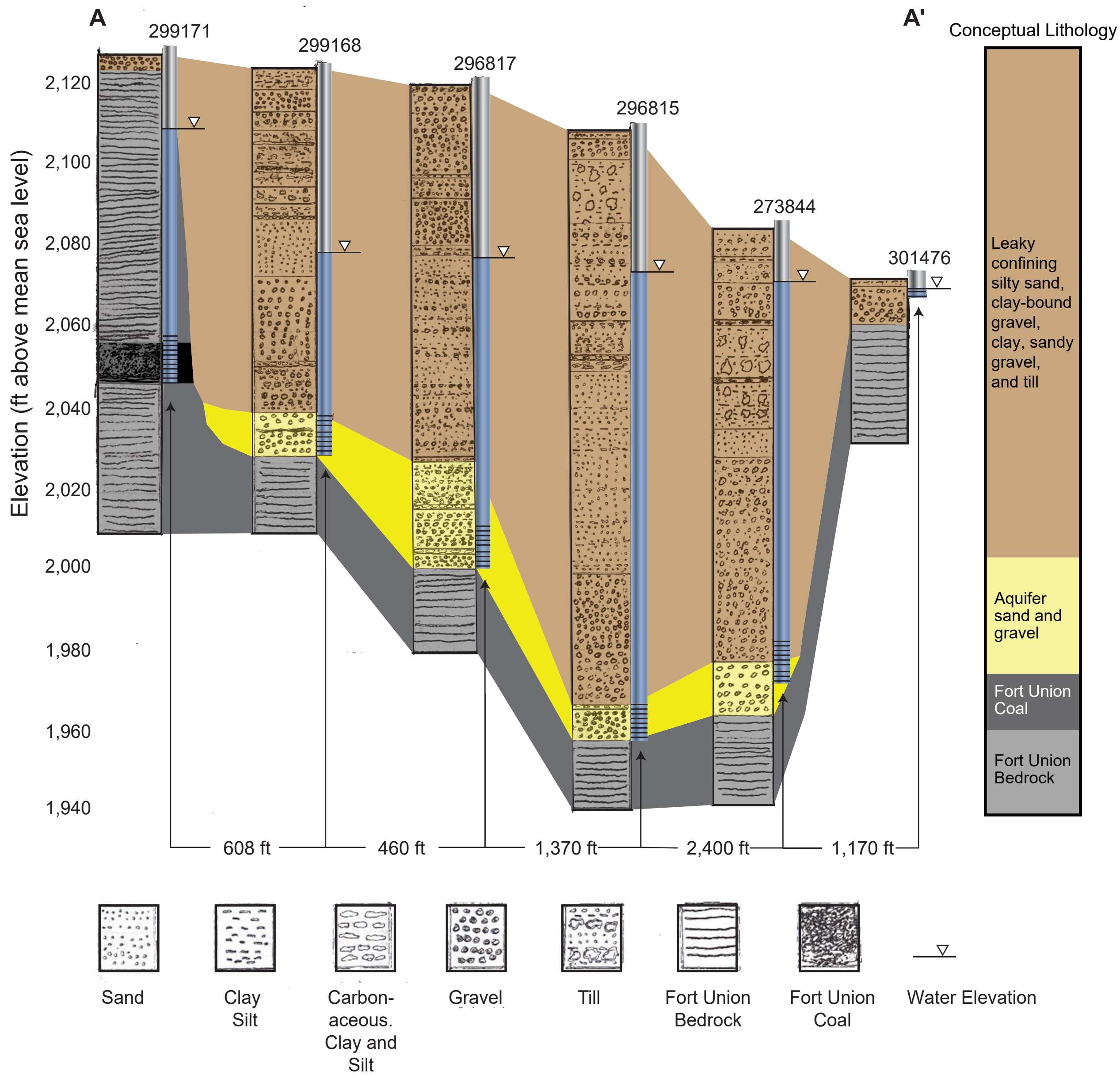


Figure 7. Sears Creek schematic cross-section showing complex lithology from individual well logs compared to simplified conceptual lithology. GWIC numbers are included above the well. Distance between borings shown in feet.

Union bedrock underlies the aquifer (fig. 9) forming the lower confining unit.

The upper confining/leaky confined unit overlying the aquifer contains layers of silty sand, sand, clay, gravel, and till (figs. 10, 11). The thickness of the upper confining/leaky confining unit ranges from 45 to 75 ft in the tributary valleys to as much as 238 ft in the uplands. Shallow gravel deposits of this unit are found from the land surface to depths up to 25 ft in the tributary valleys. These deposits are unsaturated with the exception of areas in the tributary valleys approaching the eastern or downstream edge of the buried valley. In the uplands the shallow gravel is 10 to 30 ft thick overlain by 5 to 20 ft of glacial till.

Figure 12 depicts drill cuttings typical of the aquifer. Test drilling encountered a variety of conditions related to heterogeneity of the aquifer. Hard drilling conditions are commonly referred to by well drillers as cemented zones. We interpreted that many of these hard drilling zones are areas where the gravel is tightly packed, in contrast to the easy drilling zones where the gravel is loosely packed. Although cemented gravels of the West Crane aquifer were not observed during drilling, extensive deposits of tightly cemented gravel are at the ground surface north of Burns Creek (fig. 13). This cemented gravel conglomerate underlies the south-facing valley slope above Burns Creek and appears to have very low permeability.

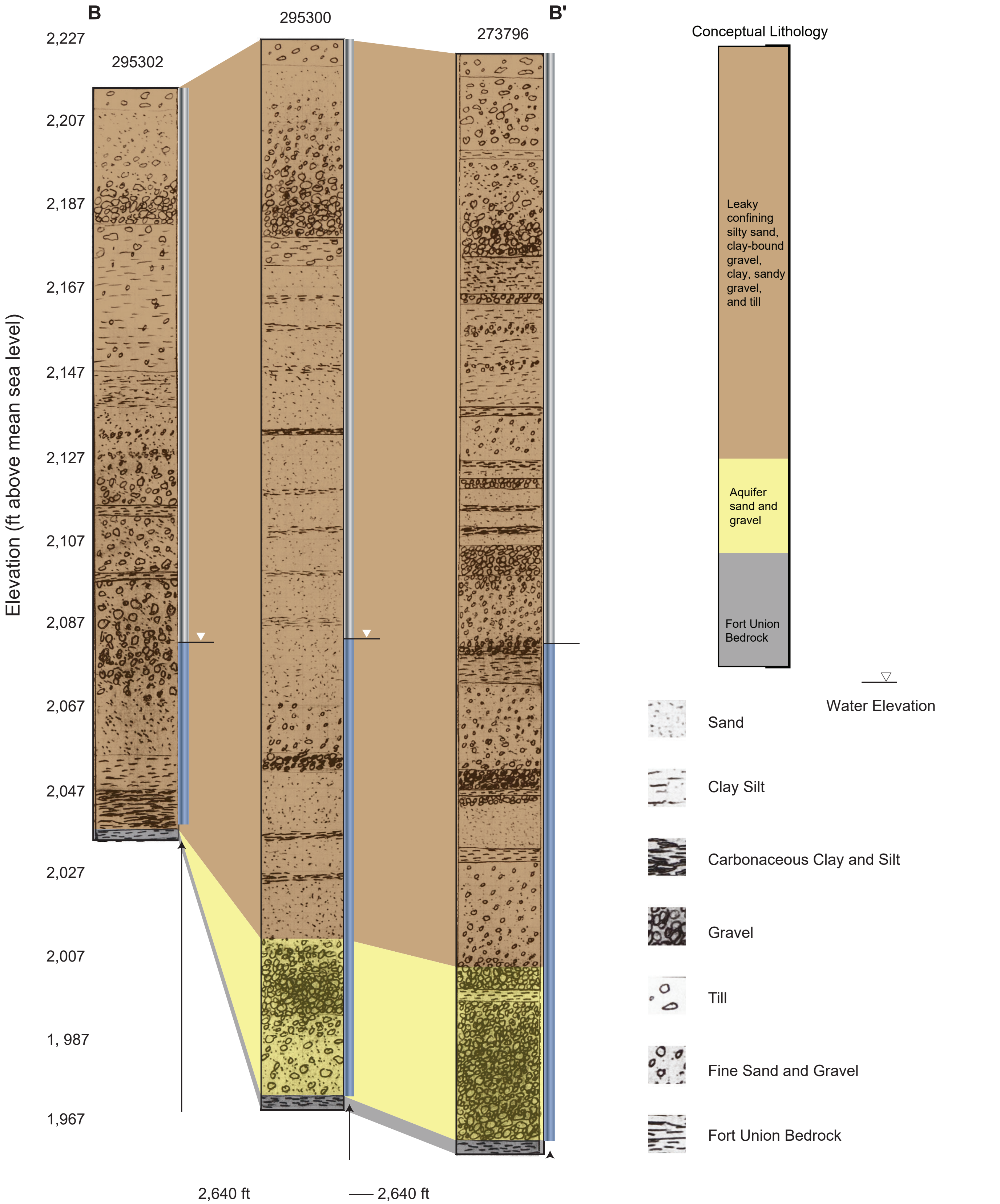


Figure 8. Sears–Crane upland schematic cross-section showing complex stratigraphy and lithology compared to simplified conceptual lithology. GWIC numbers are included above the wells. Distance between borings shown in feet.

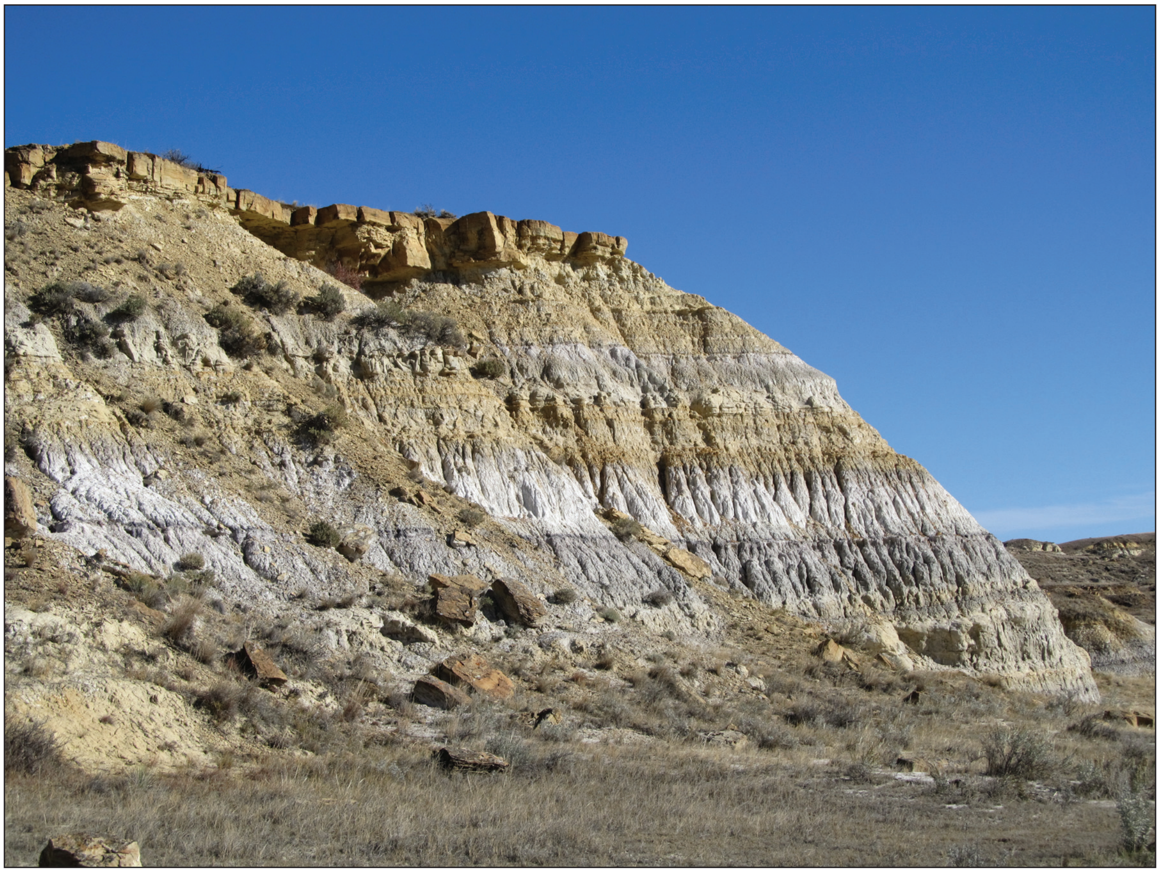


Figure 9. Fort Union Tongue River Member of the Fort Union Formation forms the basal confining unit underlying the aquifer.

Figure 10. Sandy silt leaky confined unit.

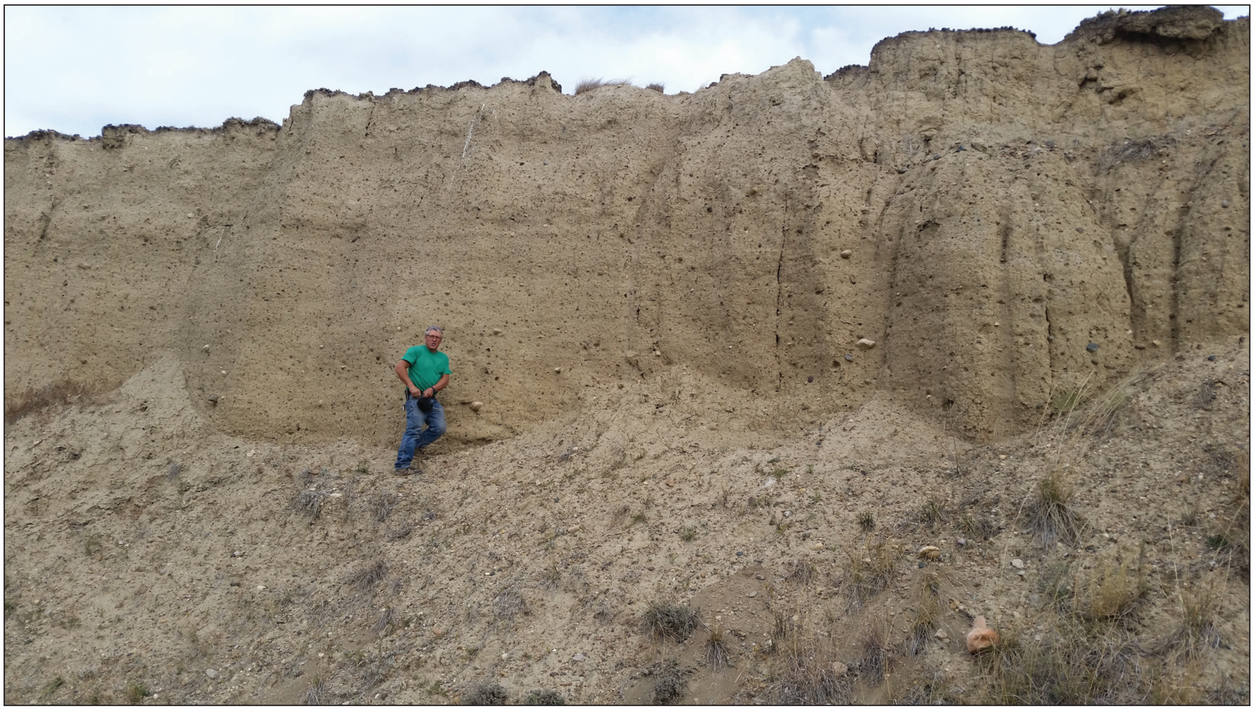


Figure 11. Glacial till is at the land surface over much of the aquifer. This outcrop is located east of the aquifer along Garden Coulee (latitude 47.443216°, longitude -104.419244°). Note vertical joints in the outcrop.

Figure 12. Gravel samples from the West Crane aquifer. Typically drill cuttings are multicolored as shown on the left. Drill cuttings from the deepest part of aquifer, shown on the right, are commonly made up of mostly dark-colored rock fragments.

Figure 13. West Crane aquifer gravels are cemented into a conglomerate on the valley slope above Burns Creek.

Aquifer Properties

We evaluated 14 aquifer tests conducted on irrigation wells completed in the West Crane aquifer. Details of these tests are discussed in Reiten and Chandler (2021b). The purposes of these tests were to estimate specific aquifer properties [such as transmissivity (T), hydraulic conductivity (K), storativity (S), and anisotropy], to estimate the degree to which this aquifer is confined, estimate aquifer boundaries (recharge and/or barrier), and evaluate groundwater/surface-water connection.

West Crane aquifer test results support the geologic interpretation indicating confined to leaky confined aquifer conditions. Box and whisker plots of the "best estimates" show the variability in aquifer parameter results (fig. 14). Aquifer transmissivities ranged from 4,310 ft^2/d to 34,240 ft^2/d. Nearby barrier boundaries appear to have affected the T values estimated at the Basta 1 (well 296537) and D. Jorgenson (well 290760) aquifer test sites. Our mapping places the aquifer edge near these sites. Overall, the best estimate of aquifer transmissivity is about 23,760 ft^2/d. Hydraulic conductivities (K) ranged from 360 ft/d to 1,300 ft/d, with a median value of 910 ft/d. Most K values ranged from 700 ft/d to 1,100 ft/d. Leaky confined storage values typically range from 0.001 (1×10^{-3}) to 0.03 (3×10^{-2}; Weight and Sonderegger, 2001). Best estimates of storage coefficients (S) ranged from 0.0001 (1×10^{-4}) to 0.03 (3×10^{-2}), with a median value of 0.0007 (7×10^{-4}). Barometric efficiencies determined from pre-test water-level data also indicate confining conditions.

Groundwater Flow

A potentiometric surface map of the West Crane aquifer is presented on plate 1. A groundwater divide near Garden Coulee separates flow into northerly and southerly groundwater-flow directions and is shown in cross-sectional view on plate 3. Both north and south of this divide, areas of relatively low hydraulic gradients are interrupted by short sections with high gradients. The horizontal hydraulic gradient of the West Crane aquifer is typically low (0.00028 to 0.0009) underlying the uplands. Higher hydraulic gradients (0.0026 to 0.0065) underlie the Burns Creek Valley slope near the southern extent of the aquifer and the Fox Creek Valley slope near the northern extent of the aquifer. Another area of high aquifer hydraulic

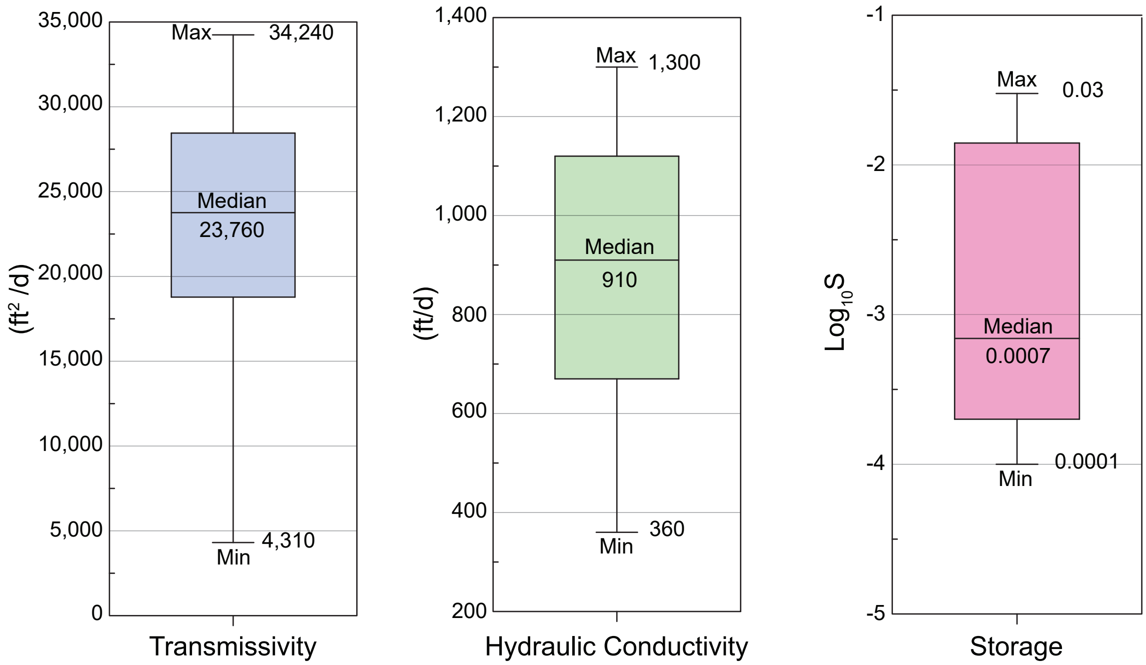


Figure 14. Best estimate box plots show the ranges in aquifer properties from the 14 aquifer tests (Chandler and Reiten, 2021).

gradient (0.0038) is located along a stretch of Crane Creek that aligns with the axis of the aquifer. Table 2 displays monitoring wells used to calculate horizontal hydraulic gradients and relates these gradients to the physiographic region overlying the aquifer.

Changes from low to high hydraulic gradients are related to the heterogeneity and anisotropy of the aquifer. Both heterogeneity and anisotropy are likely caused by stratigraphic offsets, lithologic changes, or thickness changes of the permeable aquifer materials. The high gradients north of Burns Creek coincide with areas of calcite cement, forming a low-permeability cemented gravel that restricts groundwater flow.

"Fill and Spill" Conceptual Model

Some portion of precipitation directly recharges the aquifer and is supplemented by infiltration of runoff from watersheds west of the buried valley (Fill). Groundwater discharges as seeps and springs along the east side and south end of the buried valley (Spill). Sears Creek and Dunlap Creek are intermittent streams west of and overlying the buried valley but form perennial streams near the east, downgradient boundary (fig. 15). Other tributary streams develop wetlands near the eastern edge of the buried valley where groundwater discharges from the aquifer. The flow volume from the tributary streams depends in part on the elevation of the notch eroded into bedrock

Table 2. Hydraulic gradients along the West Crane aquifer.

Monitoring Wells Used (GWIC ID)	Physiographic Region	Change in Head (ft)	Distance Apart (ft)	Hydraulic Gradient (ft/ft)
295197--298761	Burns Valley Slope	13	4,950	0.0026
298768--295226	Garden–Burns Upland	2.8	8,250	0.00034
295293--298768	Garden–Burns Upland	1.2	4,290	0.00028
295396--295293	Dunlap–Garden Upland	10.2	13,464	0.0008
273844--299153	Sears–Dunlap Upland	6.3	18,414	0.00034
273794--296818	Crane–Sears Upland	6.7	9,702	0.00069
297371--273794	Crane Creek Alignment	52.3	13,860	0.0038
239448--279891	Fox–Crane Upland	5.3	7,194	0.00074
239299--239702	Fox Valley Slope	56.4	8,712	0.0065

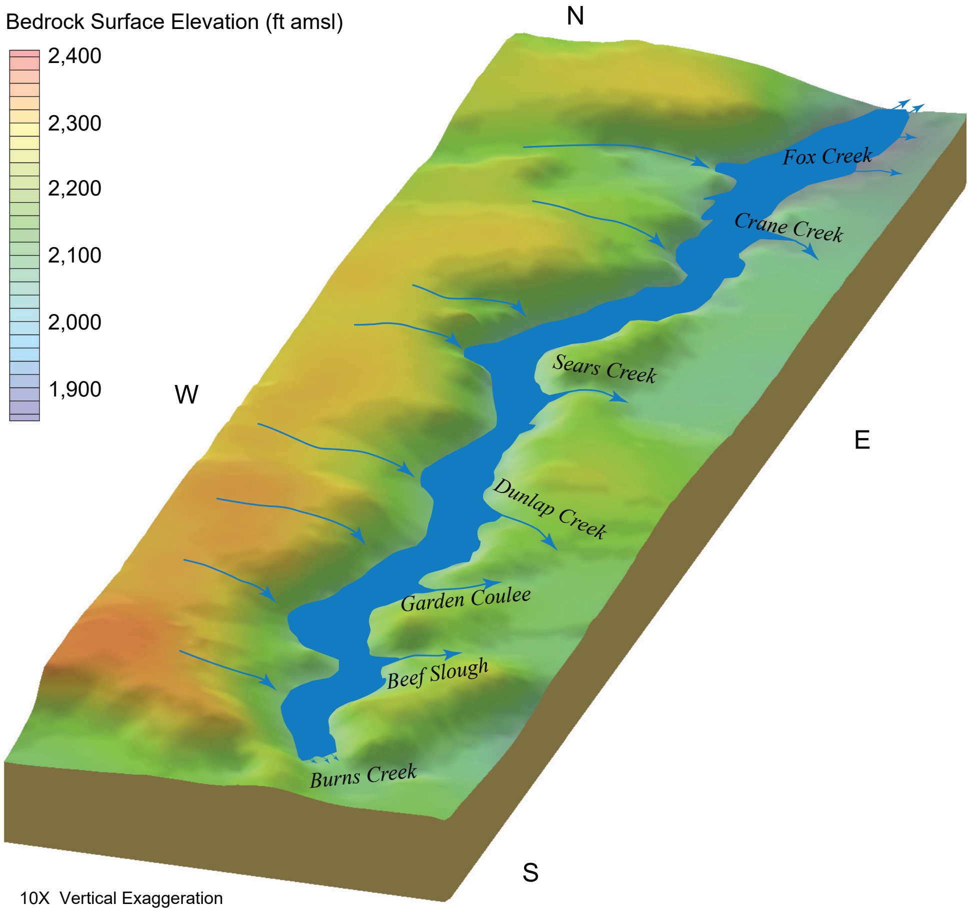


Figure 15. Schematic showing the fill and spill conceptual model. “Fill” is groundwater recharge into the aquifer and “Spill” is groundwater discharge from the aquifer.

along the east edge of the buried valley. Similar flow volumes observed at Sears and Dunlap Creeks are due to the similarity of the potentiometric surface in relation to the elevation of the bedrock notch. Groundwater flows north in the buried valley, where eventually the aquifer is referred to the Sidney aquifer. Groundwater also flows south towards Burns Creek, where it discharges to wetlands, seeps, and springs (plate 1). Groundwater also flows to the east towards the Yellowstone River through shallow alluvial aquifers underlying the tributaries.

Aquifer Storage

We generated a three-dimensional solid of the saturated thickness to estimate the potential volume of water stored in the West Crane aquifer. The aquifer-saturated thickness was generated by subtracting a model of the bedrock surface developed with a triangulated irregular network (TIN) from a TIN of the March 2019 potentiometric surface. The volume of the saturated solid was calculated to be 1,125,700 acre-ft for the model area (fig. 16). The aquifer storage volume was calculated for a range of effective porosities for the aquifer (table 3). Based on published estimates developed for sedimentary deposits, likely effective porosities for this aquifer and the overlying leaky confining unit range from 0.10 to 0.20 (Woessner and Poeter, 2020), resulting in aquifer storage volumes from 112,570 acre-ft to 225,150 acre-ft.

Much of the storage volume is in the leaky confined unit overlying the aquifer. The overlying leaky confined unit provides recharge to the West Crane aquifer. This recharge buffers the effect of pumping that causes aquifer drawdown.

Aquifer Response

Plate 3 displays hydrographs demonstrating multiple-year aquifer response at monitoring wells located along or slightly offset of the longitudinal cross-section (cross-section and well locations are shown on plate 1). Example hydrographs are referenced in this section by sites A through J as shown on plate 3. Fluctuations in these hydrographs reflect changes in aquifer storage. The storage changes include rising water

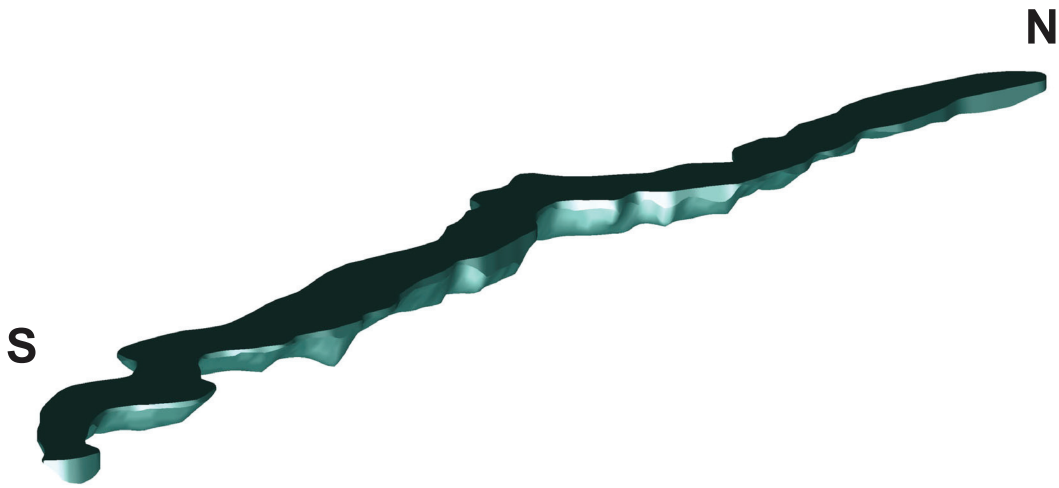


Figure 16. Schematic depiction of a solid generated by subtracting the buried valley bedrock surface elevations from the March 2019 water table. This solid was used to calculate a range of aquifer storage volumes (table 3).

levels caused by precipitation and snowmelt recharge events, or cessation of nearby pumping. Water-level declines indicate discharge events caused by pumping, surface-water and groundwater outflows, and evapotranspiration. Pumping causes immediate drawdown in nearby wells, but the water levels recover after pumping ceases. Wells with high barometric efficiencies respond to changes in atmospheric pressure, showing small, high-frequency water-level fluctuation. Such high-frequency changes in the water level are related to confining conditions in the aquifer and can obscure other factors that affect water levels.

The water-level response in wells along this profile is also influenced by position in the landscape. Upland wells (B, C, E, F, H, and I) generally have lower magnitude non-pumping fluctuations than wells in the creek bottoms (D and G). This likely relates to the depth of the aquifer, fewer confining layers, and more coarse-grained sediments underlying the creek bottoms. Transition areas (A and J, south and north ends of the cross-section, respectively) demonstrate a mixed response, with (J) responding to filling and draining of the Lower Yellowstone Irrigation Project canal. Limited data from paired wells indicate downward water-level gradients in upland areas (H) and upward gradients in creek bottoms (G). The magnitude of drawdown within the cone of depression of a pumping well decreases as the distance from the pumping well increases. One example of this is at site B, where an irrigation well pumping 250 gpm that is located very close to a barrier boundary causes over 8 ft of drawdown in a monitoring well located at a distance of 50 ft from it. At many other sites, distant from barrier boundaries, and at similar distances from irrigation wells, pumping at three to four times this rate produces much less drawdown, for example at sites C, E, F, and H.

Table 3. Estimated aquifer storage by upland areas.

Aquifer Area Name	Fox–Crane	Crane–Sears	Sears–Dunlap	Dunlap–Beef	Beef–Burns	Aquifer Total
Surface Area (acres)	4,180	2,980	3,130	4,680	2,570	17,540
Saturated Volume (acre-ft)	156,500	255,100	258,900	326,600	128,600	1,125,700
Effective Porosity	Groundwater Storage (acre-ft)					
0.1	15,650	25,510	25,890	32,660	12,860	112,570
0.15	23,480	38,270	38,840	48,990	19,290	168,870
0.2	31,300	51,020	51,780	65,320	25,730	225,150
0.25	39,130	63,780	64,730	81,650	32,160	281,450
0.3	46,960	76,530	77,680	97,990	38,560	337,720
0.35	54,780	89,290	90,620	114,320	45,020	394,030
0.4	62,610	102,040	103,560	130,650	51,450	450,310

Prior to 2020, water levels in parts of the aquifer underlying Garden–Burns (B), Dunlap–Garden (C), and Sears–Dunlap (E) uplands were rising. Water levels were dropping in parts of the aquifer underlying the Crane–Sears upland (F) from 2015 to 2019. Water-level trends in wells north of Sears Creek appear more responsive to climatic conditions and possibly irrigation development than wells south of Sears Creek. This is depicted in hydrographs from sites F, G, H, and I. Many factors can contribute to this response, including variability in precipitation over the landscape, spacing of irrigation wells, volume pumped, or a difference in the size of recharge areas. Aquifer heterogeneity, such as variation in storage, also affects the magnitude and timing of hydrograph response.

Recharge–Discharge Relationships

It is necessary to define the recharge–discharge relationships in the West Crane aquifer to understand the irrigation potential of the aquifer and to develop a water budget. We present many of the components of a water budget, but did not develop one for this report. The water budget will be refined in the groundwater model. Direct precipitation and runoff appear to recharge the West Crane aquifer. Most wells completed in the aquifer indicate high potential for irrigation with sufficient production rate and quality. Several irrigation wells have operated for 5–10 yr and water-level monitoring near these irrigation projects indicates recovery from irrigation withdrawals by the following growing season.

Aquifer Recharge

The primary source of recharge is snowmelt infiltrating directly into the land surface over the five drainage basins (fig. 1) or infiltration of snowmelt runoff as it floods drainages during late winter or early spring. Where the Yellowstone River tributary drainages cross the aquifer, they form braided gravel streambeds mapped as coarse-grained alluvium with poorly defined dry channels (plate 2B). During spring snowmelt, runoff can flood the dry stream channels for days or weeks. The result is infiltration of the snowmelt and aquifer recharge indicated by rapid groundwater-level increases (plate 3, sites D and G). The volume of groundwater flow into the aquifer's west side from the bedrock or shallow gravel deposits is unknown and difficult to measure because much comes from stream loss during flash flooding (fig. 17). The inflows are therefore estimated as a percentage of precipitation falling on the drainage basins.

Monitoring well 231902 is completed in a buried tributary valley to the West Crane aquifer (plate 1).

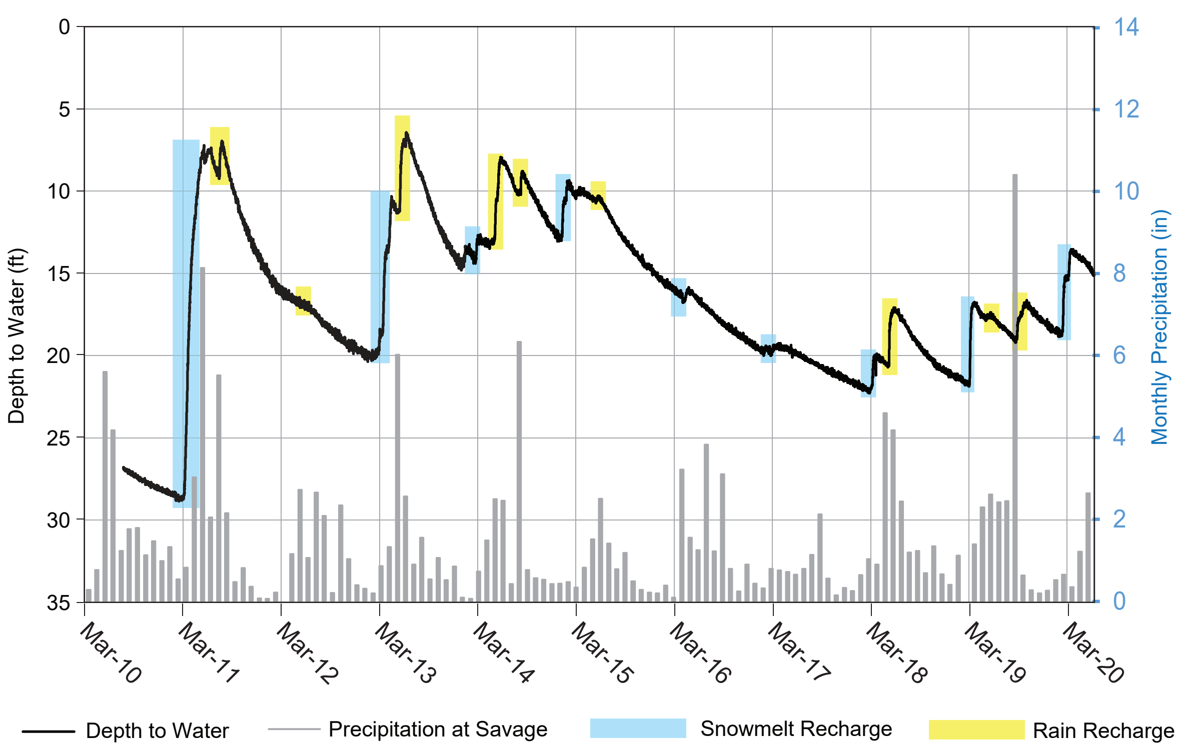


Figure 17. Water levels in well 231902 show greater recharge from snowmelt than rain events for the 10-yr period 2010–2020 (WRRC, 2021).

The well is located near the center of section 13 in T. 21 N., R. 57 E. The hydrograph for well 231902 shows large snowmelt recharge responses in 2011 and 2013, and little recharge in 2012 (fig. 17). The timing of the snowmelt events correlated with night temperatures above freezing (WRRC, 2021). Water levels throughout the aquifer were high in 2011–2013, and began to recede with little rain or snowmelt recharge in 2015–2017. Figure 18 demonstrates a rare summer recharge event. A 3.5-in rain event on June 28th, 2013 washed out a gravel pit access road in Crane Creek in an area where the stream channel is normally dry (fig. 18). All of this flow infiltrated into the aquifer in less than a mile. The creek flowed to the west of the aquifer for approximately 1 week following this rain event.

<u>*Aquifer Discharge*</u>

Evapotranspiration (ET)

Water levels in the West Crane aquifer are typically 20–200 ft below the surface and are not available to plants, with the exception of small areas where the groundwater discharges to the surface. Most of the aquifer is confined to semi-confined, and even though the potentiometric surface may be close to the land surface at some locations, riparian vegetation is absent since the groundwater is not available to plants due to the confining layers. Aerial imagery shows the limited locations where groundwater subirrigates surface vegetation, usually where the ephemeral channels become perennial streams along the east edge of the aquifer. These green riparian or wetland areas form fens at Burns Creek, Peabody Coulee, Dunlap Creek, Sears Creek, Crane Creek at Gartside Reservoir, and near Fox Creek. Fens typically form in areas of consistent upwelling groundwater. A maximum ET rate of 3.0 ft/yr was estimated at Gartside Reservoir fen through numerical modeling of the diurnal water-level fluctuations (Chandler, 2013). Diurnal water-level fluctuations from wetland wells show ET is at its maximum during sunny, warm summer days (fig. 19). Diurnal water-level fluctuations at shallow well 302852 in the Crane Creek riparian area show the greatest amplitude in July and August. Water levels recover on cool or rainy days with little ET. The maximum ET rate, seen here as fluctuations about 0.2 ft/d, only occurs for short periods in the summer months. The acreages of the visibly green areas were delineated using Google Earth Pro and found to be less than 5% of the land area over the aquifer. The total ET (acre-ft/yr) varies

Figure 18. Crane Creek washed out an access road following large thunderstorms in the watershed on June 28th, 2013.

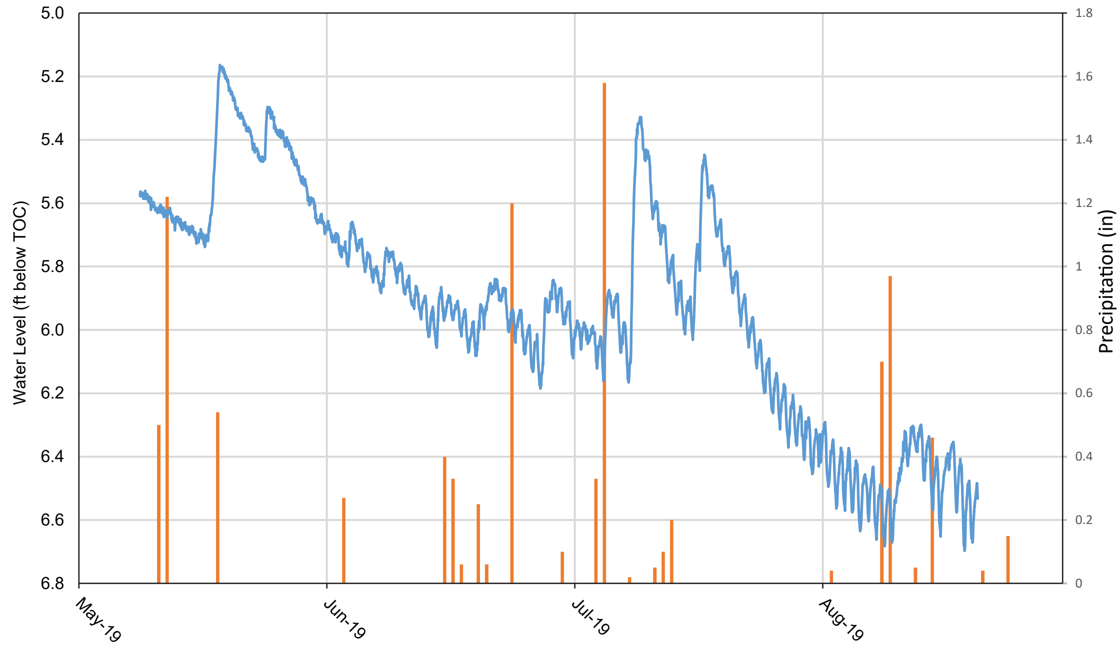


Figure 19. Evapotranspiration causes the diurnal water-level fluctuations shown at shallow well 302852. This well is located near wetlands of the Crane Creek riparian area (see plate 1 for location). Precipitation is also shown.

due to season, climatic conditions, and water availability. Rates of 0.5–3.0 ft/yr were used to calculate the range of ET values (table 4).

Groundwater Flux Out

Groundwater from the West Crane aquifer flows out at the north and south ends of the buried valley and under the wetlands along the east side of the aquifer as described in the ET section above. At Burns Creek the aquifer gravels are exposed and the base of the buried valley is above the current level of Burns Creek. The aquifer sands and gravels are tightly cemented, forming a hydraulic barrier at the south end of the aquifer. Groundwater seeps out through fractures and at the base of the cemented gravel. Several small springs emerge in this area and fens have formed on the hillside 50 ft above Burns Creek. At the aquifer north end, groundwater flow intersects or flows under the Fox Creek alluvium, and is influenced by the Lower Yellowstone Irrigation Project (LWIP) canal (plate 3, site J).

Table 4. ET estimates for riparian and wetland areas connected to the West Crane aquifer.

Site	Acres	ET Rate Applied 0.5 ft/yr	1 ft/yr	3 ft/yr
Fox Creek	288	144	288	864
Crane Creek	175	88	175	525
Wyman Ranch Wetland	35	18	35	105
Sears Creek	60	30	60	180
Dunlap Creek	102	51	102	306
Peabody Coulee	22	11	22	66
Garden Coulee	27	14	27	81
Burns Creek	69	35	69	207
Total ET (acre-ft/yr)	778	389	778	2,334

Darcy fluxes were calculated for the north and south margins of the aquifer within the study area and where the small streams cross the aquifer:

$$Q = KiA,$$

where Q is volumetric discharge rate (ft^3/d); i is hydraulic gradient (ft/ft); A is cross-sectional area of the alluvial aquifer perpendicular to flow; and K is hydraulic conductivity (ft/d).

Little is known about the saturated thicknesses of the alluvial gravels overlying the Fort Union bedrock where the small cross-cutting channels exit the east side of the aquifer. There are shallow wells in some of the drainages, but only a few wells document the bedrock contact. The flux ranges were calculated using estimated hydraulic conductivities, saturated thicknesses, and gradients (table 5).

Table 5. Estimated groundwater flow out of the West Crane aquifer.

Site	Hydraulic Gradient	Cross-Section Length (ft)	Aquifer Thickness (ft)	Cross-Section Area (ft^2)	Hydraulic Conductivity (ft/d)	Q flux (ft^3/day)	Q (cfs)	Q (gal/min)	Flux (acre-ft/yr)
Crane Creek (low)	0.008	1,400	10	14,000	150	15,960	0.18	110	180
Crane Creek (high)	0.008	1,400	25	35,000	150	39,900	0.46	210	330
Sears Creek (low)	0.01	500	10	5,000	150	7,200	0.08	40	60
Sears Creek (high)	0.01	500	20	10,000	150	14,400	0.17	80	120
Sears Creek 2 (low)	0.012	400	10	4,000	150	7,440	0.09	40	60
Sears Creek 2 (high)	0.012	400	20	8,000	150	14,880	0.17	80	130
Fox Creek (low)	0.006	4,405	18	79,290	300	136,860	1.58	710	1,150
Fox Creek (high)	0.008	4,405	18	79,290	300	197,750	2.29	1,030	1,660
Dunlap Creek (low)	0.008	1,400	10	14,000	150	17,400	0.2	90	150
Dunlap Creek (high)	0.008	1,400	20	28,000	150	34,800	0.4	180	300
Peabody Coulee (low)	0.017	450	10	4,500	150	11,760	0.14	60	100
Peabody Coulee (high)	0.017	450	20	9,000	150	23,520	0.27	120	200
Garden Coulee (low)	0.007	325	10	3,250	150	3,600	0.04	20	30
Garden Coulee (high)	0.007	325	20	6,500	150	7,210	0.08	40	60
Bums Ceek (low)	0.081	4,575	2	9,150	1	740	0.01	4	10
Bums Creek (high)	0.081	4,575	10	45,750	1	3,690	0.04	20	30

Note. Low and high discharge rates were developed from two estimates of the saturated aquifer thickness.

Stream Discharge

Perennial streams flow from the east side of the aquifer where Crane, Sears, and Dunlap Creeks cross above it; intermittent springs emerge from the southern end at Burns Creek. Seeps form wetlands at Peabody Coulee, Garden Coulee, Beef Slough, and at the northern end near Fox Creek. Hourly flume discharge measurements show consistent discharge at Sears and Crane Creeks with the exception of flash events during large precipitation events. Monitoring well 273787 where Dunlap Creek emerges shows a similar water-level pattern (plate 3, site D). For the stream discharges, average flow values were used from 2018 to 2019, and Dunlap Creek was assumed to flow with a volume similar to that of Sears Creek, based on field observations (table 6). The drainage basin areas are delineated on surface topography (fig. 1). Based on surface area extent, Sears Creek basin is less than half the size of Dunlap Creek basin. We speculate that the shallow groundwater flow doesn't necessarily follow surface gradients in the extensive plains between Dunlap and Sears Creeks. Rather than a drainage basin area, the

Table 6. Groundwater discharging from the West Crane aquifer into surface water.

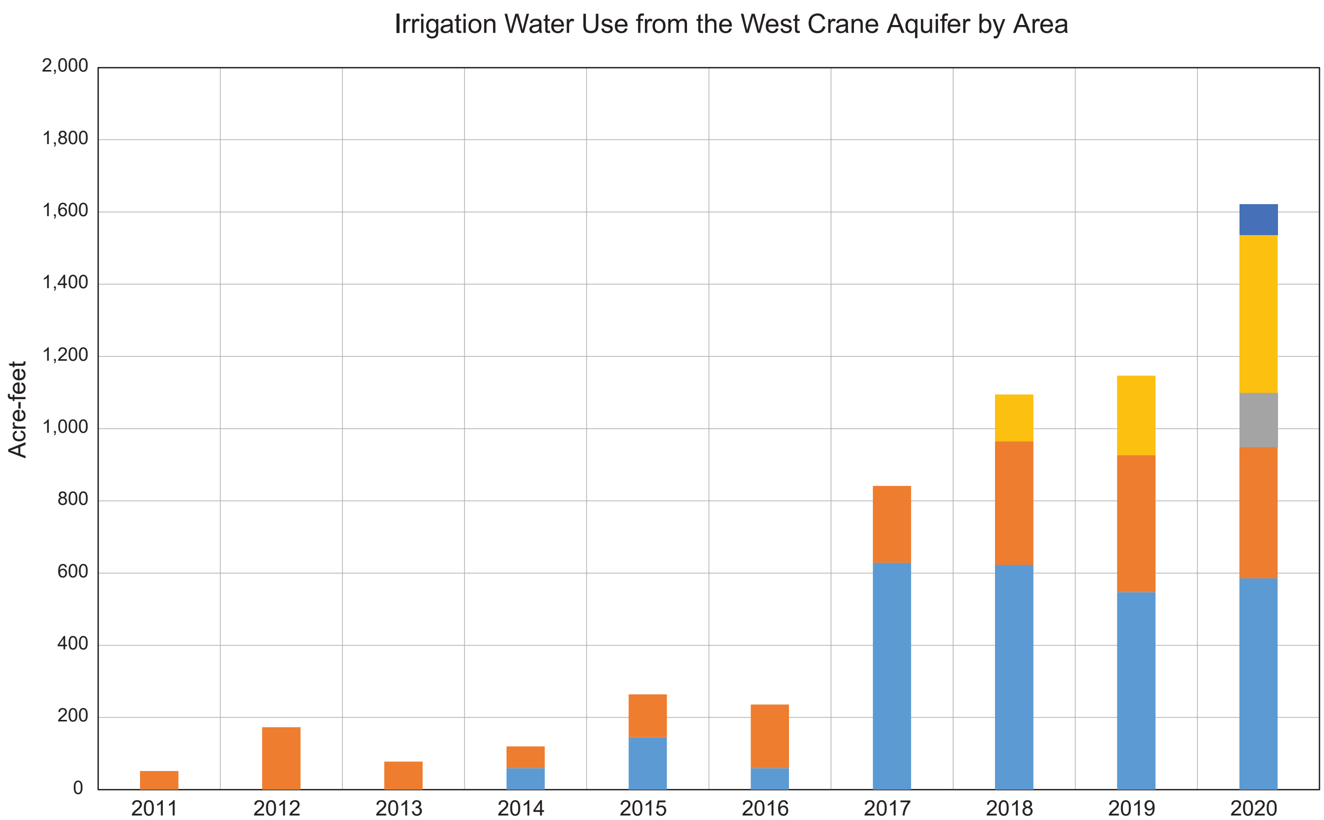
Site	GWIC ID	(ft^3/s)	(gal/min)	(acre-ft/yr)
Crane Creek Flume 2018	305918	0.224	100	160
Crane Creek Flume 2019	305918	0.369	170	270
Sears Creek Flume 2018	305915	0.651	290	470
Sears Creek Flume 2019	305915	1.141	510	830
Dunlap Creek (estimated) 2018	NA	0.651	290	470
Dunlap Creek (estimated) 2019	NA	1.141	510	830
Lange Spring Flume 2019	NA	0.028	13	20
Lange Spring1 Bucket Dam 2019	NA	0.009	4	6
		Total 2018	680	1,100
		Total 2019	1,210	1,950

volume of groundwater discharge to streams is likely caused by the relationship between the elevation of the potentiometric surface and the notch eroded into the Fort Union bedrock at the downstream (east) edge of the buried valley. This relationship is similar along Sears Creek and Dunlap Creek. The notch is probably higher at Garden Coulee and other streams with minimal discharges. While Burns Creek likely receives some discharge from the West Crane aquifer, we were unable to detect an increase in the Burns Creek flows when measured above and below the West Crane aquifer discharge.

Pumping

Irrigation water use is compiled for the five upland areas based on AGSENSE data plus on/off records where AGSENSE is not available. Irrigation withdrawals from the West Crane aquifer started in 2011 following approval of the first irrigation water right (fig. 20). Initially, 51.8 acre-ft of water was pumped in the Crane–Sears area. Irrigation water use increased relatively slowly until 2017, when withdrawals increased to 926.9 acre-ft as the result of two large appropriations in the Fox–Crane area. As more areas developed, water use increased incrementally to about 1,725 acre-ft in 2020. All five areas now have at least some development. As of March 2021, irrigation appropriations total 5,041 acre-ft annually.

All but one irrigation system in the West Crane aquifer used AGSENSE in 2019. For the well 295397 system, pumping volumes were calculated using on–off times determined from monitoring well responses, and the system pumping rate (table 7). Since 2019, three additional irrigation systems operate in the area, with the capacity to irrigate approximately 450 acres each. In 2020 there were approximately 2,100 acres under pivot systems. To estimate a range for irrigation use, a low volume of 0.5 ft/acre and a high volume of 2.0 ft/acre were applied. The low-volume estimate is based on records from 35 yr of water-use records of irrigation from the Clear Lake buried valley aquifer in nearby Sheridan County (Reiten and Chandler, 2021a).



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Beef–Burns										85.3
Dunlap–Beef								129.5	220.5	436.8
Sears–Dunlap									0	149.9
Crane–Sears	51.8	173.2	78.1	59.9	118.4	175.9	212.5	342.4	379.1	363.2
Fox–Crane				60.0	145.5	60.0	628.7	622.6	547.3	585.6

Figure 20. Graph of water-use history since initial irrigation development of the West Crane aquifer. The underlying table shows volume of annual use in acre-ft for each management area.

Table 7. Irrigation water use, 2019.

Site Name	Well GWIC ID	Gallons	ft^3	acre-ft
Cjohnson 1	285659, 285476, 291010	49,047,867	6,557,201	151
Cjohnson 2	285659, 285476, 291010	44,910,708	6,004,105	138
Cjohnson 3	285659, 285476, 291010	39,461,411	5,275,590	121
Cjohnson 4	285659, 285476, 291010	36,281,227	4,850,431	111
Bradley 1	253448	32,069,661	4,287,388	98
Wyman 1	250211	53,971,500	7,215,441	166
Kjonsson 1	249505	31,292,175	4,183,446	96
Kjonsson 2	284325	43,566,256	5,824,366	134
Lange 1	296426	24,143,865	3,227,789	74
Ler 1	295397	4,692,00	627,273	14
Jorgenson 1	290760	45,349,899	6,062,821	139
	Total	**400,094,569**	**54,115,851**	**1,242**

Note. With the exception of the Ler well, water use was calculated from AGSENSE reports. Water use at the Ler well was calculated using on–off times based on water-level fluctuations recorded in a nearby monitoring well data logger.

Table 8. Domestic and stock water use, 2019.

Well Type	Number of Wells	Gallons/day	Use (days)	Use (gal/yr)	Use (acre-ft/yr)
Domestic	10	600	365	2,190,000	6.7
Stock	21	10,000	90	18,900,000	58
Total				**21,090,000**	**64.7**

The high-volume estimate is based on the typical volume permitted by DNRC of 2.0 ft/acre.

Groundwater is also pumped from the aquifer for domestic and stock use (table 8). Stock-water wells are used sporadically because animals are rotated between pastures during the summer months and the well water supplements surface-water sources used by stock. The pumping volumes for domestic wells and stock wells are based on estimates used by DNRC (2008). The domestic and stock water used in 2019 is minimal compared to that extracted for irrigation.

Water Quality

The West Crane aquifer provides good quality water to all currently developed irrigation systems. The SAR and SC are useful measures when considering irrigation water quality. Water-quality samples showing major constituents are summarized in table 9. Water analyses are shown from 7 surface water sites, 67 West Crane aquifer wells, and 10 Fort Union aquifer wells.

Based on median values, the West Crane aquifer is sodium/calcium–bicarbonate type water and the Fort Union aquifer is sodium–bicarbonate type water. The similar water chemistry from the West Crane and Fort Union aquifers in this area makes it difficult to use water type as a means of discerning the source.

Poor water quality in parts of the West Crane aquifer can affect its suitability for irrigation. The usability of groundwater for irrigation is often characterized by comparing the SC and SAR of the water. The SAR is the ratio of calcium plus magnesium to sodium and is calculated using the formula shown below with concentrations measured in milliequivalents per liter:

$$\mathrm{SAR} = [\mathrm{Na}] / \sqrt{\frac{[\mathrm{Ca}]+[\mathrm{Mg}]}{2}} .$$

A plot of the SC versus the SAR (fig. 21) describes irrigation hazard potential (USDA, 1954). The SC increases with dissolved solids in the water and the SAR increases with increasing sodium relative to the

Table 9. Summary of water-quality analyses in the West Crane area.

	Field pH	Field SC (µS/cm)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Fe (mg/L)	Mn (mg/L)	SiO_2 (mg/L)	HCO_3 (mg/L)	CO_3 (mg/L)	SO_4 (mg/L)	Cl (mg/L)	NO_3-N (mg/L)	F (mg/L)	Total Dissolved Solids (mg/L)	SAR
Surface Water																	
Minimum	7.4	556	59.2	26.7	23.5	3.3	0.0	0.01	11.8	333.9	0.0	63.7	1.7	0.1	0.2	400	0.5
Maximum	8.5	1,892	98.2	107.0	239.5	9.6	1.5	0.35	22.3	574.6	16.8	700.0	18.0	0.1	0.6	1,458	4.2
Median	7.7	753	84.6	45.7	47.3	5.2	0.2	0.16	16.5	431.9	0.0	125.5	7.7	0.1	0.3	523	1.6
Mean	7.8	900	79.3	57.4	88.5	6.3	0.6	0.16	16.6	447.5	2.4	260.6	7.2	0.1	0.3	739	1.7
Count	7	7	7	7	7	7	3	5	7	7	7	7	7	1	6	7	7
West Crane Aquifer																	
Minimum	6.8	425	9.4	4.7	4.5	1.9	0.0	0.01	8.6	270.9	0.0	11.0	1.6	0.0	0.1	251	0.1
Maximum	8.9	2,910	163.1	121.7	723.6	7.5	3.5	2.53	33.3	982.9	38.9	799.8	33.9	19.5	5.2	2,014	48.1
Median	7.5	1,045	85.9	42.5	92.4	4.8	0.5	0.14	21.7	554.4	0.0	154.5	5.8	0.1	0.5	695	2.1
Mean	7.5	1,137	84.1	45.8	126.8	4.9	1.0	0.21	22.3	570.8	3.0	207.0	7.5	2.3	0.7	783	3.5
Count	60	65	67	67	67	67	37	54	64	67	67	67	67	15	64	67	67
Fort Union Aquifer																	
Minimum	6.7	454	2.1	1.3	24.4	1.9	0.1	0.01	8.8	287.4	0.0	25.4	1.4	0.1	0.2	290	0.7
Maximum	7.9	3,250	148.7	121.7	524.0	7.1	2.4	0.14	27.0	995.5	21.1	354.5	10.5	0.4	3.2	1,355	70.0
Median	7.2	1,272	63.1	38.4	166.1	4.5	0.2	0.04	14.6	669.2	0.0	248.4	3.9	0.1	0.4	890	3.4
Mean	7.2	1,362	69.2	46.2	175.9	4.6	0.9	0.06	16.3	644.5	2.1	230.4	5.4	0.2	0.7	869	10.4
Count	5	10	10	10	10	10	9	10	10	10	10	10	10	5	10	10	10

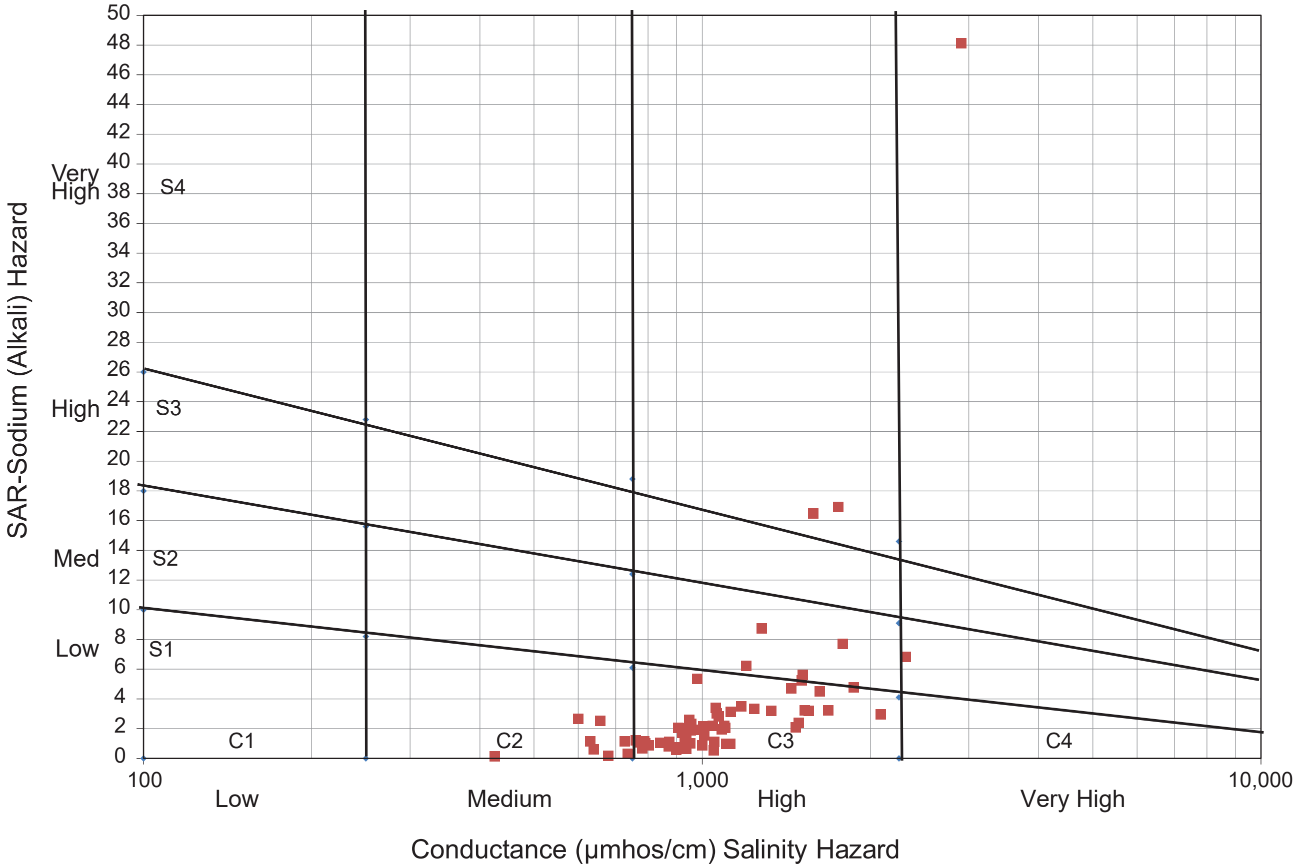


Figure 21. West Crane aquifer water-quality data plotted on a USDA water classification chart.

alkaline earth cations (calcium and magnesium). The groundwater SC commonly encountered in this area ranges from 750 to 2,250 micro-Siemens/cm (µS/cm). In this SC range, water poses a high sodium (alkali) hazard at SAR greater than about 10–13; medium hazard at SAR ranging from 4 to 10; and low hazard below SAR of 4. In northeastern Montana, high salinity hazards with SAR greater than 13 have resulted in soil damage and abandonment of irrigation systems. As a result, irrigation development is strongly discouraged if the water supply SAR exceeds 13.

The USDA water classification chart shown on figure 21 combines the SAR with SC, classifying the water with respect to the sodium hazard and the salinity hazard. This classification is simplified into four groups: low sodium–medium salinity (S1-C2) is very good quality, low sodium–high salinity (S1-C3) is good quality, medium sodium–high salinity (S2-C3) is marginal quality, and combined very high sodium–high salinity (S4-C3) and very high sodium–very high salinity (S4-C4) is poor quality. A map showing the water quality based on the USDA Irrigation Classification (fig. 22) can be used to identify areas where water quality may be marginal or unusable for irrigation. Elevated SAR values are the main concern with the compatibility of water quality to the soils being irrigated. At the very least, producers need to be aware of the location of potential water-quality problems. The areas are commonly located near the boundary of the buried valley aquifer and Fort Union bedrock. Similar water-quality problems have been identified in the Clear Lake aquifer (Reiten and Chandler, 2021a).

Groundwater Response to Climate and Pumping

There are numerous examples showing the fluctuations on hydrographs responding to either pumping or changes in climatic conditions. Figure 23 is a long-term record from well 234024 that shows responses to both. This well was constructed in 2007 about 600 ft northeast of the first irrigation well completed in the West Crane aquifer, located in the Crane–Sears upland area (for location see plate 1). Irrigation withdrawals typically cause drawdown during the growing season followed by recovery of water levels until the following growing season, when the cycle repeats. Rapid recovery occurs immediately following the irrigation

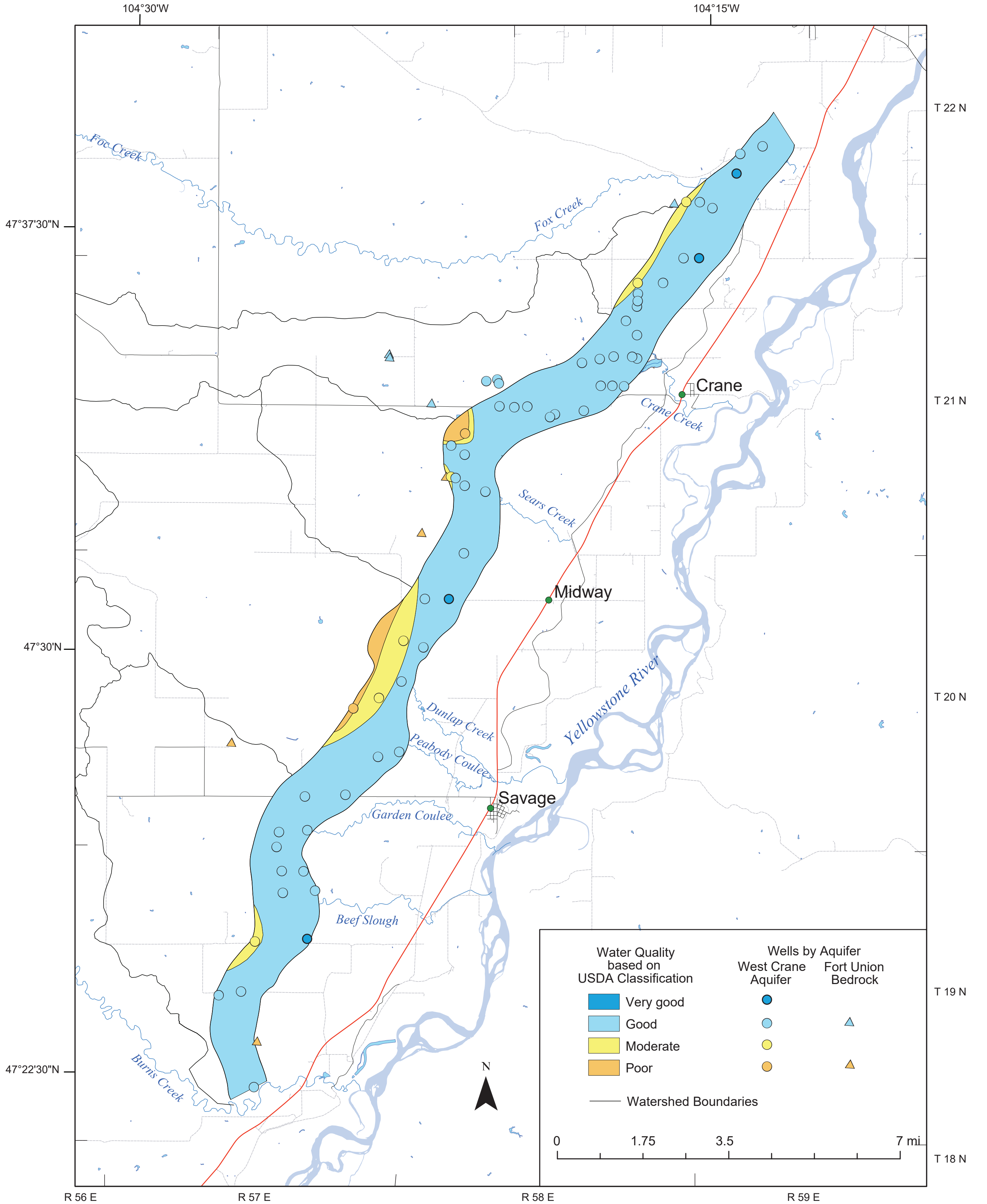


Figure 22. Map showing potential water quality of the West Crane aquifer based on the USDA water-quality classification. The quality of the water from individual wells is denoted by the color within the well symbol based on the USDA classification.

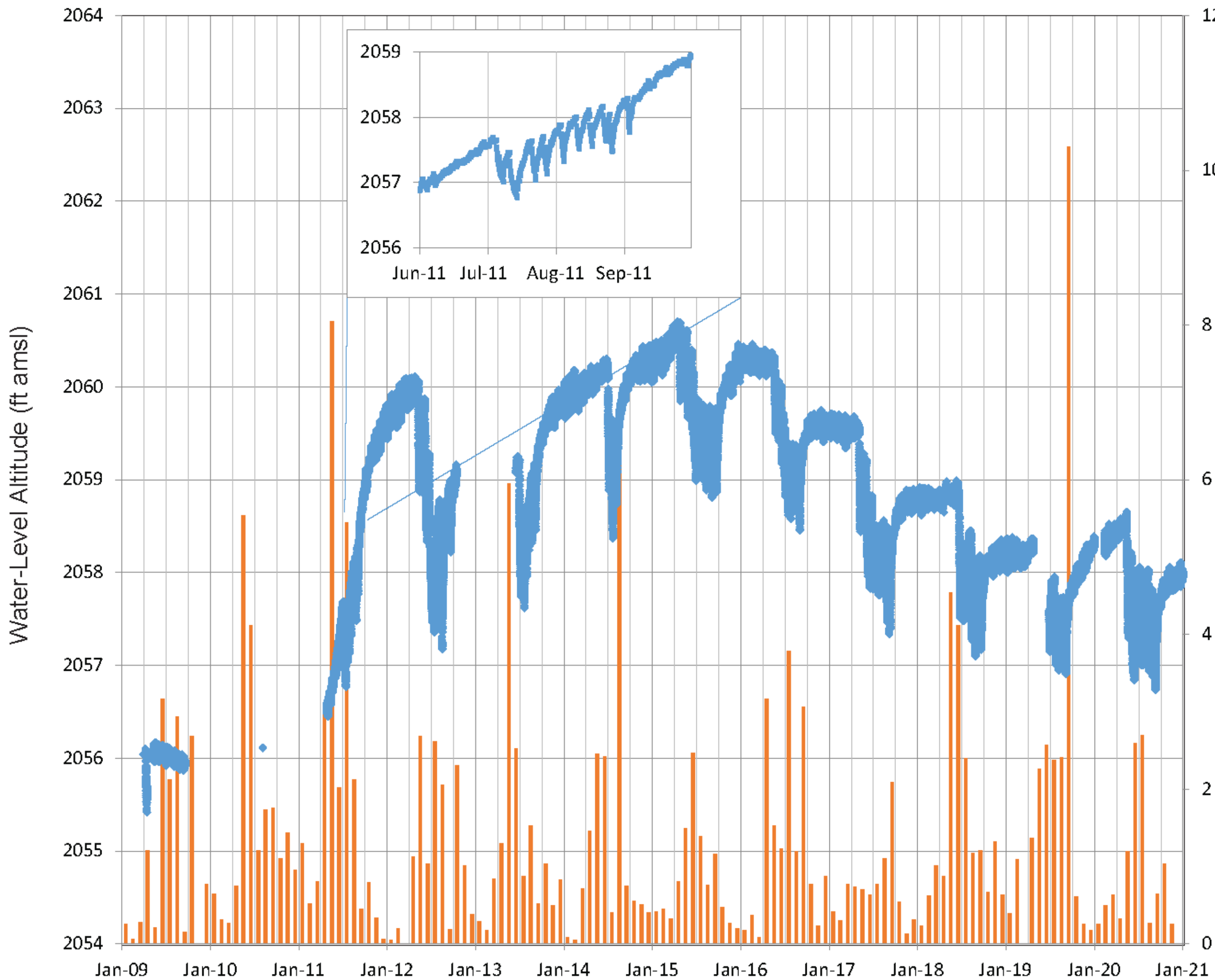


Figure 23. Long-term hydrograph from well 234024 with an inset from June to October 2011 showing an increase in head following individual pumping cycles.

season, but in most years recovery either flattens or declines during the winter. As previously discussed, late winter to spring snowmelt is the primary time and source of recharge.

Winters with little or no snow accumulation result in little or no recharge. Low-volume recharge years include 2016, 2017, 2018, and 2019 (WRRC, 2021). Relatively high-volume recharge years include 2011, 2012, 2014, 2015, and 2020. Refer to figure 17 for precipitation and snowmelt events. The inset in figure 23 shows the water-level response from June to October 2011. Snow accumulated as a 3- to 4-ft snowpack across the prairie and was followed by a rainy spring. Water levels recovered during the entire year and did not show the typical irrigation-season drawdown. Of particular interest, the water levels following most individual pumping cycles recovered to a level above the static water level from the previous cycle. At well 234024, recharge in 2011 caused about a 4-ft increase in water levels. Similar increasing water-level responses are noted in other parts of the aquifer as well as in other aquifers in eastern Montana, implying a single year of excessive recharge is capable of increasing water levels over large areas and replenishing storage in the aquifer. Because snowmelt is the dominant source of recharge to the aquifer, monthly or daily precipitation totals are poor measures of recharge. Except for rare thunderstorm events, during the growing season, precipitation is generally used by vegetation rather than contributing to recharge.

Water-level fluctuations from the 2020 growing season (May through October) are shown on figure 24. Well 297371 (80 ft deep) and well 302852 (8.5 ft deep) are located about 5 ft apart on the edge of a wetland west of Gartside Reservoir. The vertical gradients are upward from the deeper zone to the

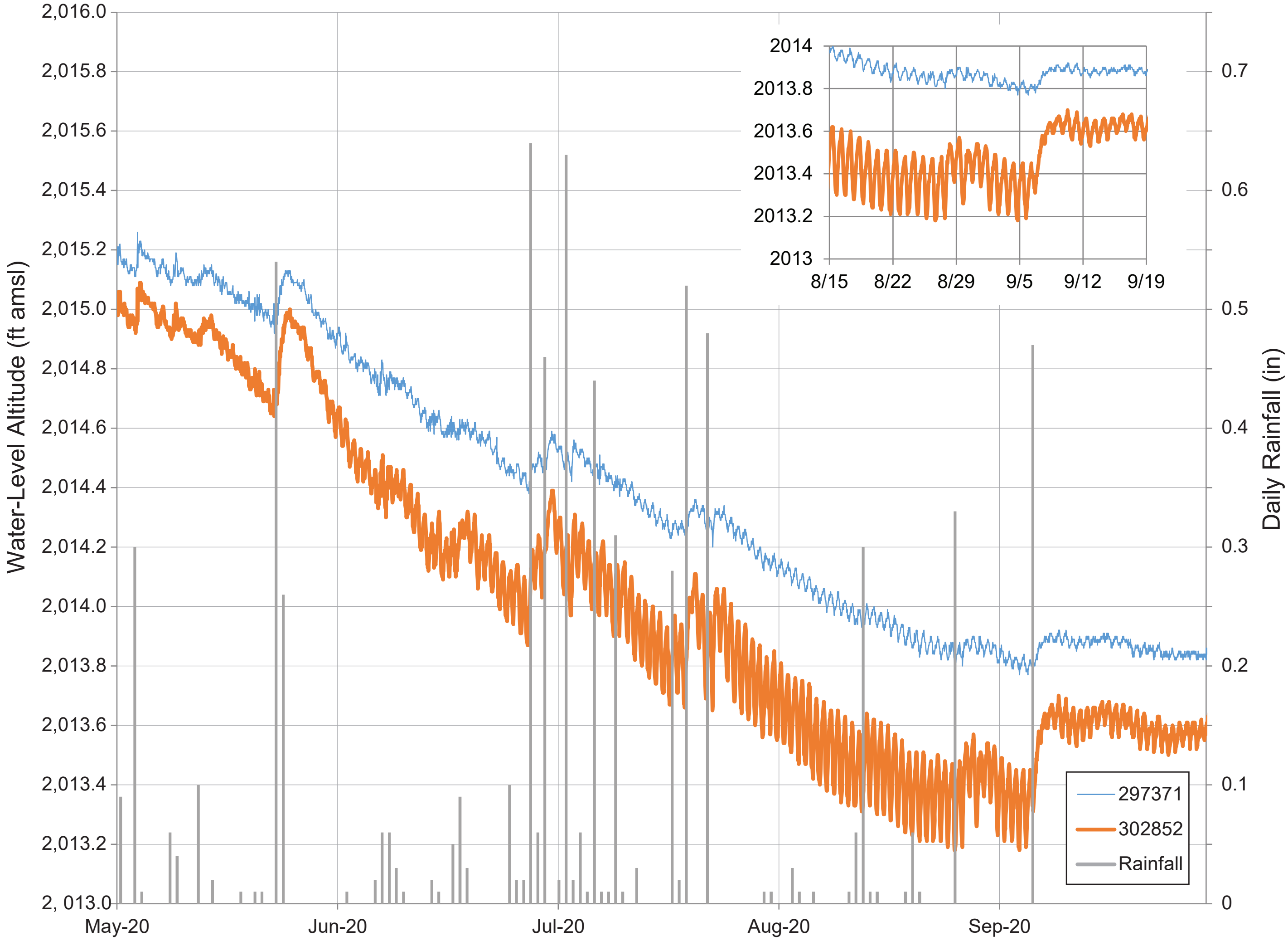


Figure 24. Hydrograph from paired wells 29731 and 302852 (total depth 80 and 8.5 ft, respectively) showing diurnal fluctuations and effects of climatic factors. Inset shows water-level fluctuations from August 15 to September 19 (WRRC, 2021).

shallow zone. Following rainfall events, the vertical gradients decrease because recharge reaches the water table, decreasing the difference in pressure between the shallow and deep wells. Although not shown here, the gradients reverse at times during 2019. The water-level fluctuations demonstrate responses caused by evapotranspiration, rainfall, and seasonal temperature changes. Diurnal fluctuations from transpiration are expressed as water-level declines during the day when plants extract water through photosynthesis. Water levels recover during the night. The magnitude of the daily fluctuations typically increases during the growing season from less than 0.01 ft to 0.3 ft as plants grow and water demand increases. The diurnal responses are much lower at the deep well, completed near the base of the leaky confined aquifer, due to little to no direct evaporation. In early September, the abrupt rise in water levels was caused by a rain event and two below-freezing mornings reducing the water demand by plants.

CONCLUSIONS

The West Crane aquifer has proven to be a resource capable of providing irrigation from groundwater. As of 2020, the DNRC has approved 14 water rights, and several more applications are in process.

Wells completed in the transmissive zone of the aquifer yield 250 to 1,300 gpm. At the lower range of yields, 2–3 wells may be manifolded together to supply a typical center pivot. The leaky confining layer overlying the aquifer stores a large volume of water that recharges the transmissive zone. Conservative estimates of the total aquifer storage range from 112,500 to 225,000 acre-ft of water. The volume of irrigation water used annually from initial development in 2011 to 2020 compared to the total volume appropriated is shown on figure 25. Water use peaked at 1,621 acre-ft in 2020, at approximately 34% of the total appropriation (table 10). In recent years, water use has been about 1/3 of the volume appropriated. High energy

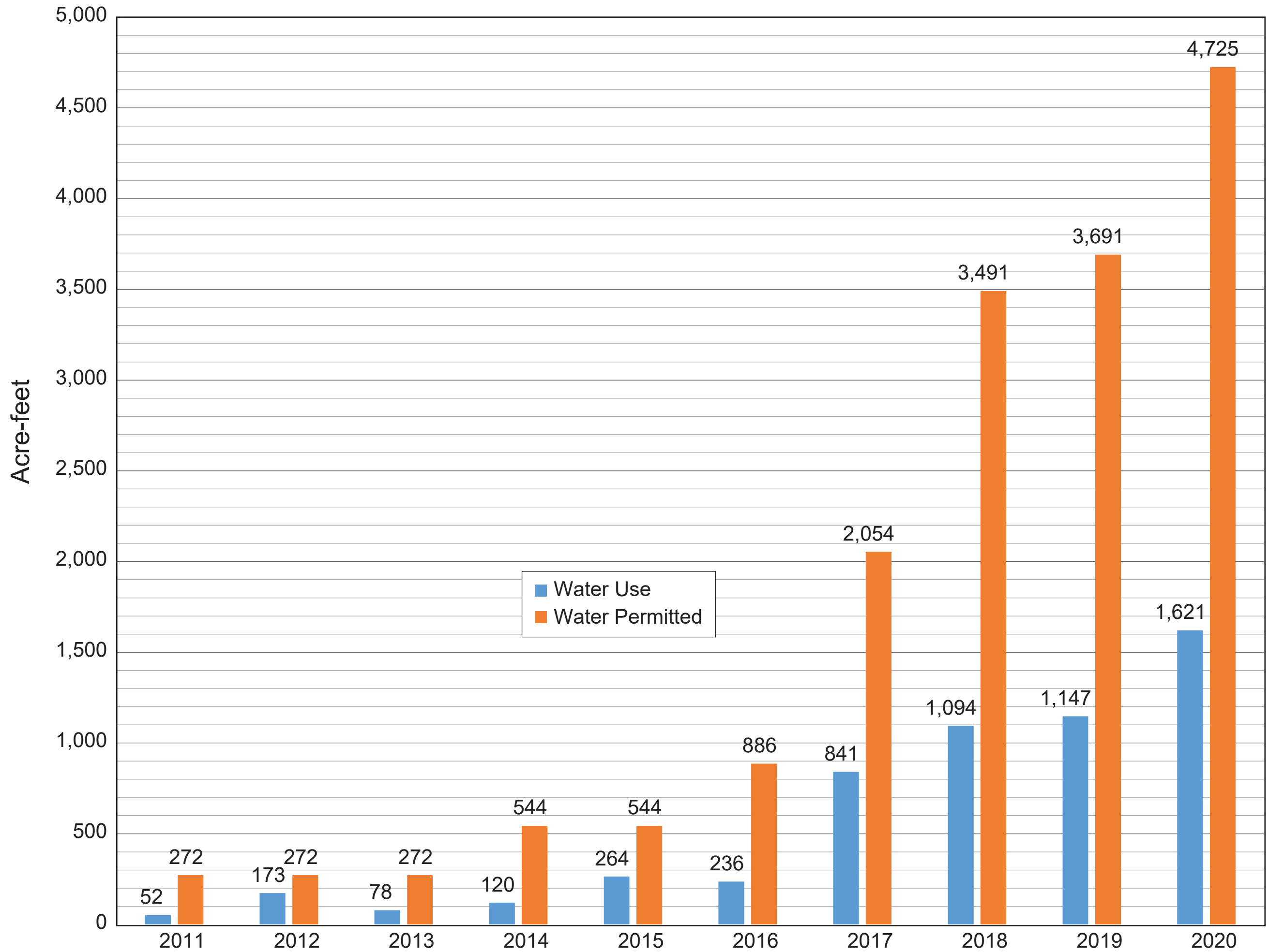


Figure 25. Chart comparing permitted and actual water use. Most years producers use about 1/3 of the permitted volume.

cost of pumping may encourage producers to limit irrigation to crop demand. In most years, irrigation supplements rainfall to meet crop needs.

Based on the 2020 appropriation, the volume of water permitted ranges from 2% to 4% of the volume in storage. This large storage volume effectively serves as a reservoir of groundwater until snowmelt recharges the aquifer. Extended periods of drought could lead to an increase in groundwater pumping during periods of little to no recharge. These conditions can lead to large drawdowns in confined groundwater systems. The consequences of drawdown include decreased discharge to surface-water features (fens and wetlands). The groundwater flow model being constructed for this area will provide a useful approach to investigating effects related to pumping during extended droughts.

Annual groundwater recharge is highly variable depending on local climatic and seasonal conditions. The timing and relative magnitude of recharge can be

Table 10. Comparison of actual water use to volume appropriated by permits.

Year	Acre-ft Used	Acre-ft Appropriated	Percent of Total Appropriation Used
2011	52	272	19%
2012	173	272	64%
2013	78	272	29%
2014	120	544	22%
2015	264	544	49%
2016	236	886	27%
2017	841	2,054	41%
2018	1,094	3,491	31%
2019	1,147	3,691	31%
2020	1,621	4,725	34%

tracked by viewing hydrographs of water-level fluctuations. Water levels in wells located close to tributary valleys typically correlate closely with recharge. It appears that there are two general responses to recharge across the aquifer based on water-level fluctuations: relatively constant, slower recharge in the uplands and flashy, faster recharge along the tributaries.

The few monitoring wells with water-level records prior to the spring of 2011 show the significance of that recharge event. Heads in 2020 for parts of the aquifer south of the Sears–Dunlap upland are above those prior to the fall of 2013 (plate 3, site E). Reduced recharge from 2015 to 2018 reflects dry climatic conditions. From Sears Creek to the north, water levels in most wells are approaching pre-2011 levels, dropping from the peak in the spring of 2011 and 2013. These declines are closely related to the reduced recharge from several years with limited snowpack (fig. 17). Some of the water-level declines may be related to irrigation withdrawals, but will require several more years of monitoring to clearly document. The groundwater model being developed will hopefully allow us to verify water-level fluctuations in various parts of the aquifer. Thirty-six years of monitoring climate, water levels, and water use in the Clear Lake aquifer of nearby Sheridan County have demonstrated the recovery potential of a similar buried valley aquifer (Chandler and Reiten, 2019a; Reiten and Chandler, 2021a). Increased irrigation development from the Clear Lake aquifer coincided with climate conditions fluctuating between extreme drought and abundant recharge. No long-term water-level declines were observed and aquifers did recover from 10 to 15 years of drought with a few years of normal to slightly above normal snowmelt.

High evapotranspiration rates are associated with wetlands along riparian areas within tributaries. Most wetlands form near the eastern boundary of the buried valley along these tributaries. Hydrographs from wells in these settings indicate climate-driven water-level declines in the West Crane aquifer and minimal impacts to date from irrigation withdrawals.

Actual water levels measured near points of surface-water discharge show a dampened response to recharge, and no response to pumping. Recharge spikes were recorded only during flash flooding events at these sites. It is possible that the actual aquifer and/or the leaky confined zone is larger than the area mapped. The aquifer boundaries were established by limited drilling and focused mainly on the productive zone. The aquifer likely feathers out laterally and intermeshes with shallow outwash gravel zones not included in the aquifer volume calculations.

The water quality from all irrigation wells in the West Crane aquifer is compatible with soils and crops. However, water samples from a few monitoring wells show areas of marginal to poor water quality, with high SAR and specific conductance. These areas are identified on figure 22. Any development close to these locations should include a careful evaluation of the water quality.

RECOMMENDATIONS

Sustainable development of groundwater from the West Crane aquifer will require continued monitoring at a subset of wells and flumes currently in the monitoring network. Water use and precipitation records could be compiled annually, in addition to updating hydrographs. A hydrogeologist can help compile, review, interpret technical data, and present assessments to the local management group and DNRC water resource managers. The five upland areas form discrete segments of the aquifer based on physiography, geology, and development potential. Since these uplands are hydrogeologically isolated from each other, the uplands form subareas appropriate for aquifer monitoring.

As new irrigation wells are constructed, water-quality samples and aquifer test results should be added to data currently stored in the MBMG GWIC database. New monitoring wells should be added to the monitoring network and sampled for water quality to expand the understanding of water-level fluctuations and potential changes in water quality associated with increased water development. Establishing continuous monitoring at the outlet of Gartside Reservoir should be considered in order to replace a problematic flume installed on Crane Creek above the reservoir.

Airborne geophysical surveys are shown to be valuable tools for mapping buried valleys in other areas (Legault and others, 2019). Preliminary on-ground geophysical testing indicates the geophysical properties of the bedrock and buried fill in the West Crane buried valley are similar and it may be difficult to clearly define the buried valley aquifer in this area using these tools. Additional geophysical testing may verify if geophysical tools will work in this area.

Hydrologic data collection, review, and interpretation support informed use of groundwater resources. Ideally, a rigorous numeric groundwater model will be a part of evaluating aquifer response to pumping and weather conditions. The groundwater model (in preparation) can be used to simulate proposed wells and changes in climatic conditions. Collaborative management of the aquifer involving farmers, irrigation specialists, RCCD, and the DNRC water resources division could be considered. Avoiding areas of concern such as locations close to known poor water quality will likely require greater monitoring and further study.

The large volume of water stored in the aquifer provides a buffer to drought conditions. It has been demonstrated that 1 yr of exceptional recharge (such as 2011) can increase aquifer storage and maintain elevated heads for several years. Balancing recharge, aquifer storage, and aquifer discharge can be accomplished by reviewing and interpreting causes of water-level fluctuations on hydrographs from representative wells across the aquifer. Climatic conditions will need to be compared to water-level fluctuations, in some cases requiring daily, monthly, and annual precipitation totals. A current weakness in climatic monitoring is determining the areal distribution of snowfall. Since snowmelt is the primary source of aquifer recharge, developing methods to map snow moisture over the landscape will improve recharge estimates.

Based on the drilling results, the lateral boundaries of the aquifer appear to be accurate to within a quarter of a mile. Additional test drilling would allow a better definition of the aquifer boundaries and define tributaries to the aquifer. Evidence of tributary channels was documented by test holes near Sears Creek and Crane Creek and would be likely areas for exploration drilling. Additional well pairs or nested wells would improve our understanding of vertical flow gradients and vertical hydraulic conductivity. Most of the wells have been completed near the base of the aquifer. Constructing shallow monitoring wells near these sites would be an efficient method of developing well pairs to evaluate the vertical connection between the overlying leaky confined part of the aquifer and the West Crane aquifer.

Managed Aquifer Recharge (MAR) projects in this area have the potential to offset increased groundwater use and should be investigated. MAR could be a possible means of increasing recharge by slowing down or storing snowmelt along tributaries of the Yellowstone River where they cross the aquifer. This idea was inspired by our observation of flows in Crane Creek caused by runoff generated by a thunderstorm. Less than a mile downstream, all surface-water flow infiltrated as recharge to the aquifer. Possible methods include taking advantage of gravel mining in areas overlying the aquifer by using gravel pits as storage basins rather than reclaiming them. Another option would be establishing a series of low berms along the creek bottoms to slow surface-water flow, enhancing the recharge potential.

ACKNOWLEDGMENTS

Landowners and farmers along the entire aquifer from Fox Creek to Burns Creek have been very helpful and supportive of this groundwater research. They have allowed access for test drilling, monitor well installation, flume installation, and continuous monitoring. Without this collaboration, this project would have not been possible. Current and past Montana Bureau of Mines and Geology staff contributed to mapping and well inventories of this area through the State Map Program (Susan Vuke) and Ground-Water Characterization Program (Larry Smith and John LaFave). Simon Bierbach assisted with data analyses, figure development, and GIS mapping.

The Richland County Conservation District was the project sponsor. Their interest and support drove the project from the start. In particular they provided contact information of the producers, provided field technicians, and provided data loggers used to monitor aquifer water-level fluctuations.

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APPENDIX A

WEST CRANE AQUIFER MONITORING WELLS AND SURFACE-WATER SITES

Appendix A. West Crane aquifer monitoring wells and surface water sites.

GWIC ID	Lat	Lon	Site Name	Site Type	Total Depth (ft)	Aquifer
32723	47.44160	-104.42110	Bosshard Lazy 9	Stock Well	113	Fort Union Formation
32729	47.41410	-104.42580	Thiel Stock	Stock Well	196	Sand and Gravel
34178	47.48859	-104.40732	Alco Ranches	Stock Well	120	Fort Union Formation
34234	47.44939	-104.43433	Searer Stock	Stock Well	151	Sand and Gravel
35153	47.57993	-104.34381	Thiessen Stock	Stock Well	60	Sand and Gravel
35160	47.54580	-104.37330	Bergstedt Stock	Domestic/Stock	65	Tongue River Member
35171	47.53500	-104.37610	Bergstedt, Cliff	Stock Well	155	Tongue River Member
35172	47.52860	-104.35110	Struckman State-Stock	Stock Well	247	Sand and Gravel
35209	47.58305	-104.28566	Montana Dept Fish Wildlife & Parks Mw7	Monitoring Well	46	Fort Union Formation
35214	47.58672	-104.29297	MW6 Monitoring Well	Monitoring Well	31	Sand and Gravel
35750	47.65249	-104.22786	Newlon Cemetery Asso	Domestic Well	85	Fort Union Formation
137975	47.39750	-104.46410	Basta House	Domestic Well	200	Sand and Gravel
210186	47.65396	-104.21784	Scott Staffanson	Irrigation Well	110	Sand and Gravel
231902	47.57939	-104.34861	Thiessen 3 Test Well	Monitoring Well	110	Sand and Gravel
234006	47.57873	-104.34313	Thiessen, Dwight	Monitoring Well	80	Sand and Gravel
234024	47.56961	-104.31859	Jonsson (WC-1)	Monitoring Well	164	Sand and Gravel
234036	47.57811	-104.29350	Wyman (WC-2)	Monitoring/Stock	120	Sand and Gravel
234741	47.59308	-104.28278	Bradley West Crane 4	Monitoring Well	160	Sand and Gravel
239299	47.64897	-104.22786	LYBC 25	Monitoring Well	80	Sand and Gravel
239448	47.61586	-104.26244	LYBC 32	Monitoring Well	130	Sand and Gravel
239479	47.64669	-104.23770	LYBC 24	Monitoring Well	40	Sand and Gravel
239651	47.63336	-104.22511	DAVE1	Monitoring Well	44	Sand and Gravel
239652	47.64250	-104.20400	LYBC 26	Monitoring Well	56	Sand and Gravel
239697	47.52850	-104.30092	LYBC38	Monitoring Well	55	Sand and Gravel
239702	47.63067	-104.24983	LYBC 23	Monitoring Well	107	Sand and Gravel
242568	47.60838	-104.27257	Bakken Stock Well	Stock Well	139	Sand and Gravel
249505	47.56878	-104.32075	Jonsson, Kjeld	Irrigation Well	180	Sand and Gravel
250211	47.57808	-104.29858	Wyman, Larry	Irrigation Well	118	Sand and Gravel
253448	47.59731	-104.28762	Bradley	Irrigation Well	180	Sand and Gravel
253450	47.59759	-104.28773	Bradley	Monitoring Well	165	Sand and Gravel
263799	47.57795	-104.29884	Wyman, Larry	Monitoring Well	118	Sand and Gravel
273754	47.58674	-104.29288	WCS5	Monitoring Well	102	Sand and Gravel
273787	47.49044	-104.38554	WCS1	Monitoring Well	104	Sand and Gravel
273791	47.57790	-104.28840	WCS4	Monitoring Well	102	Sand and Gravel
273794	47.57151	-104.33639	Theissen * WCS-3 MW	Monitoring Well	242	Sand and Gravel
273796	47.51541	-104.36567	WCS2	Monitoring Well	267	Sand and Gravel
273806	47.45644	-104.42923	WCS6	Monitoring Well	220	Sand and Gravel
273844	47.54647	-104.34853	WCS8	Monitoring Well	124	Sand and Gravel
275604	47.63698	-104.23305	Castro Domestic/Stock	Stock Well	120	Sand and Gravel
279883	47.61654	-104.27162	C. Johnson MW/Stock	Monitoring Well	195	Sand and Gravel
279891	47.60186	-104.28246	C. Johnson Monitoring Well	Monitoring Well	175	Sand and Gravel
283134	47.57190	-104.33109	Jonsson, Kjeld MW 2A	Monitoring Well	220	Sand and Gravel
284325	47.57190	-104.33065	Kjonsson Irr Well 2	Irrigation Well	250	Sand and Gravel
285474	47.60871	-104.28300	C. Johnson Irr Well	Irrigation Well	168	Sand and Gravel
285476	47.60531	-104.28240	Cjohnson Irr Well 2	Irrigation Well	190	Sand and Gravel
285484	47.60850	-104.28248	C. Johnson MW/Stock	Monitoring Well	174	Sand and Gravel
285659	47.60151	-104.28281	4-J Cattle Inc.	Irrigation Well	170	Sand and Gravel
290760	47.45695	-104.40969	Jorgensen, D Irr Well	Irrigation Well	210	Sand and Gravel
290815	47.45700	-104.40936	Jorgenson, D Mw	Monitoring Well	232	Sand and Gravel
291009	47.60290	-104.28251	C. Johnson Mw (CJ3A)	Monitoring Well	170	Sand and Gravel
291010	47.60318	-104.28224	C.Johnson Irr Well 3	Irrigation Well	169	Sand and Gravel
295188	47.39856	-104.46088	17WC11	Monitoring Well	195	Sand and Gravel
295197	47.38150	-104.46096	17WC8	Monitoring Well	180	Sand and Gravel
295226	47.41341	-104.44722	17WC16	Monitoring Well	192	Sand and Gravel
295282	47.42786	-104.43712	17WC36	Monitoring Well	200	Sand and Gravel
295293	47.44581	-104.43858	17WC19	Monitoring Well	160	Sand and Gravel
295294	47.46966	-104.38628	17WC20	Monitoring Well	130	Sand and Gravel
295296	47.42790	-104.44647	17WC31	Monitoring Well	140	Sand and Gravel
295300	47.51496	-104.37533	17WC25	Monitoring Well	257	Sand and Gravel
295302	47.51491	-104.38395	17WC35B	Monitoring Well	180	Sand and Gravel
295310	47.52875	-104.35843	17WC33	Monitoring Well	255	Sand and Gravel
295396	47.46821	-104.39570	Matt Ler MW 1A	Monitoring Well	118	Sand and Gravel
295397	47.46821	-104.39541	Matt Ler Irr. 1	Irrigation Well	130	Sand and Gravel
296426	47.45640	-104.42750	K. Lange Irr. Well 1	Irrigation Well	223	Sand and Gravel
296536	47.38550	-104.45728	Bloesser2	Irrigation Well	181	Sand and Gravel

Appendix A. West Crane aquifer monitoring wells and surface water sites.

GWIC ID	Lat	Lon	Site Name	Site Type	Total Depth (ft)	Aquifer
296537	47.38030	-104.46367	Bloesser1	Irrigation Well	181	Sand and Gravel
296761	47.38653	-104.45708	Bloesser3	Irrigation Well	183	Sand and Gravel
296812	47.53153	-104.36770	Bergstedt2	Monitoring Well	100	Sand and Gravel
296815	47.54845	-104.35797	Bergstedt3	Monitoring Well	154	Sand and Gravel
296817	47.550707	-104.362013	Bergstedt4	Monitoring Well	127	Sand and Gravel
296818	47.5576	-104.35798	Larson-1	Monitoring Well	240	Sand and Gravel
296819	47.57195	-104.34288	Thiessen 4	Monitoring Well	255	Sand and Gravel
296851	47.57069	-104.30617	17WC6-Wyman	Monitoring Well	252	Sand and Gravel
296852	47.58487	-104.30688	17WC21-Wyman	Monitoring Well	120	Sand and Gravel
296853	47.58616	-104.29905	17WC22-Wyman	Monitoring Well	100	Sand and Gravel
297355	47.63240	-104.25549	17WC45	Monitoring Well	141	Sand and Gravel
297358	47.63240	-104.26060	17WC23	Monitoring Well	152	Sand and Gravel
297362	47.58610	-104.28274	17WC49	Monitoring Well	80	Sand and Gravel
297371	47.58660	-104.28490	17WC37	Monitoring Well	82	Sand and Gravel
297373	47.64000	-104.23930	17WC3-Bell Hill	Monitoring Well	131	Sand and Gravel
297379	47.61500	-104.25589	17WC46	Monitoring Well	120	Sand and Gravel
297386	47.56000	-104.36397	17WC41	Monitoring Well	193	Sand and Gravel
297388	47.56390	-104.35783	17WC42	Monitoring Well	244	Sand and Gravel
297830	47.52541	-104.36770	Pust Stock New GWIC ID	Stock Well	184	Sand and Gravel
298761	47.37000	-104.44915	Lange-18WC1	Monitoring Well	65	Sand and Gravel
298762	47.39800	-104.45866	Basta -18WC2	Monitoring Well	229	Sand and Gravel
298764	47.42800	-104.42210	Lazy 9-18WC3	Monitoring Well	126	Sand and Gravel
298767	47.43400	-104.42772	Lazy 9-18WC4	Monitoring Well	237	Sand and Gravel
298768	47.43400	-104.43735	Lazy 9 18WC5	Monitoring Well	210	Sand and Gravel
298809	47.48500	-104.39525	Ler-18WC9	Monitoring Well	176	Sand and Gravel
299151	47.48230	-104.40620	Ler -18WC10	Monitoring Well	209	Sand and Gravel
299153	47.50090	-104.38380	Dan Pust 18 WC12	Monitoring Well	177	Sand and Gravel
299168	47.55100	-104.36383	Bergstedt 5(18WC14)	Monitoring Well	98	Sand and Gravel
299171	47.55130	-104.36610	Bergstedt 6 (18WC15)	Monitoring Well	87	Fort Union Formation
299175	47.50050	-104.37570	Dan Pust 18 WC16	Monitoring Well	215	Sand and Gravel
300254	47.44064	-104.44219	Lange MW3	Monitoring Well	180	Sand and Gravel
300256	47.44776	-104.42080	Lange2A- MW1	Monitoring Well	160	Sand and Gravel
300586	47.44776	-104.42080	Lange Irr2	Irrigation Well	142	Sand and Gravel
301471	47.37205	-104.44581	Lange Farms Llc	Piezometer	8	Sand and Gravel
301472	47.37205	-104.44581	Lange Shallow 2	Piezometer	8.6	Sand and Gravel
301476	47.54613	-104.34389	Struckman Corp.	Piezometer	4.7	Sand and Gravel
302852	47.58668	-104.28490	Wyman, Charlie	Piezometer	8.4	Sand and Gravel
302856	47.59758	-104.28770	Bradley, Gordon And Margaret	Monitoring Well	90	Sand and Gravel
305427	47.39860	-104.45836	Basta Ranches	Irrigation Well	226	Sand and Gravel
305475	47.38404	-104.45552	Basta Ranches Inc.	Monitoring Well	174	Sand and Gravel
305912	47.37011	-104.43760	Burns Creek Flume * Flume	Stream		
305915	47.54352	-104.34001	Sears Creek Flume * Flume	Stream		
305916	47.54471	-104.34324	Struckman Corp	Piezometer	7.5	Sand and Gravel
305917	47.54470	-104.34324	Struckman Corp	Piezometer	7.5	Sand and Gravel
305918	47.58397	-104.28496	Crane Creek Flume * Flume	Stream		
700519	47.57261	-104.32089	Goss Brothers	Domestic Well	160	Sand and Gravel

APPENDIX B
WATER CHEMISTRY

Appendix B. Water chemistry.

Gwic ID	Latitude	Longitude	Site Type	Depth (ft)	Sample Date	Water Temp (C)	Lab pH	Lab SC (µS/cm)	Ca	Mg	Na	K	Fe	Mn	SiO2	HCO3	CO3	SO4	Cl	NO3-N	F	TDS	SAR
SURFACE WATER																							
144394	47.373674	-104.426866	STREAM		6/28/2013	9.5	7.29	962	93.7	45.7	47.3	5.2	1.46	0.21	22.3	454.0	0.0	169.4	7.7	0.13	0.3	615	1.0
236134	47.64481	-104.2375	STREAM		11/5/1994	3.6	8.34	1920	84.6	102.2	239.5	8.7	0.02	0.01	12.0	574.6	16.8	700.0	9.0	<.25 P[1]	0.6	1458	4.2
273788	47.577776	-104.341111	STREAM		6/24/2013	21.2	7.96	833	75.1	34.6	37.2	3.8	0.19	0.35	19.1	464.1	0.0	93.3	1.9	<0.010 U[2]	0.2	493	0.9
273789	47.489111	-104.385252	STREAM		6/27/2013	20	7.7	646	59.6	34.9	36.3	4.6	0.032 J[3]	0.038 J	14.7	333.9	0.0	83.1	1.7	<0.010 U	0.2	400	0.9
273808	47.45021111	-104.401475	STREAM		6/25/2013	21.7	8.02	825	84.9	50.7	23.5	9.0	0.023 J	0.028 J	16.5	409.8	0.0	125.5	9.5	<0.010 U	0.2	523	0.5
273809	47.54616	-104.343	STREAM		6/27/2013	14.8	7.58	723	59.2	26.7	59.5	3.3	0.030 J	0.16	19.6	398.0	0.0	63.7	2.3	<0.010 U	0.3	431	1.6
273811	47.58406111	-104.2846806	DRAIN		5/2/2007	23.3	7.63	1716	98.2	107.0	176.0	9.6	<0.005	0.07	11.8	498.2	0.0	589.0	18.0	<0.5	<0.5	1256	2.9
WEST CRANE AQUIFER																							
239479	47.646695	-104.237677	WELL	40	3/11/2008	9.9	7.49	1067	61.7	39.0	139.0	4.5	0.039	0.02	12.6	371.3	0.0	299.0	10.7	<0.5	0.6	750	3.4
35153	47.579883	-104.343805	WELL	60	8/23/2019	10.9	7.17	1047	125.8	61.2	29.1	3.9	0.02	0.01	16.2	657.6	0.0	118.3	4.2	0.31	0.2	682	0.5
35214	47.58672	-104.29298	WELL	31	6/25/2013	9.9	7.32	806	110.0	37.3	15.4	5.0	1.09	0.13	16.8	429.4	0.0	107.5	4.8	<0.010 U	0.1	510	0.3
137975	47.397542	-104.464615	WELL	200	6/16/1995	12.5	7.88	1073	85.9	46.3	102.2	4.2	3.106	0.177	30.2	657.6	0.0	100.0	4.0	<.25 P	0.5	700	2.2
231902	47.579388	-104.348616	WELL	110	12/20/2006	9.6	8.81		98.9	73.1	60.0	3.9	0.10			402.7	30.0	153.2	25.7	19.5		664	1.1
234006	47.578732	-104.343119	WELL	80	8/21/2019	11.8	7.82	931	100.5	52.2	50.2	3.6		0.11	16.9	523.5	0.0	154.0	3.7	0.07	0.3	639	1.0
234024	47.569606	-104.318582	WELL	164	2/27/2007		7.46	956	68.0	36.0	95.0	5.0	0.20			476.0	0.0	82.0	7.0	0		527	2.3
234036	47.5781	-104.293512	WELL	120	2/28/2007		8.01	948	52.0	41.0	103.0	4.0	0.20			476.0	0.0	85.0	6.0	0		525	2.6
239299	47.648959	-104.227917	WELL	80	3/12/2008	11.2	7.62	795	57.1	45.1	51.2	4.3	0.006	0.006	16.5	362.0	0.0	161.0	12.5	0.078	0.3	527	1.2
239448	47.615853	-104.262453	WELL	130	8/20/2019	10.4	8.02	1120	119.9	57.7	52.8	5.5	0.03	0.28	26.9	438.8	0.0	294.7	8.5	0.040 J	0.3	784	1.0
239702	47.630663	-104.249838	WELL	107	8/20/2019	11	8.1	922	102.7	46.4	36.1	5.7	0.18	0.27	29.3	416.2	0.0	195.7	12.4	<0.010 U	0.4	633	0.7
242568	47.608549	-104.271413	WELL	139	8/20/2019	10.9	7.59	996	109.7	51.3	44.0	4.7	2.86	0.29	25.4	441.9	0.0	220.7	7.8	<0.010 U	0.3	685	0.9
249505	47.568778	-104.320754	WELL	180	8/6/2019	10.4	7.45	932	83.6	42.3	68.9	4.1	3.07	0.13	28.0	540.3	0.0	112.1	4.0	<0.010 U	0.5	612	1.5
250211	47.57808333	-104.2985833	WELL	118	8/6/2019	10.5	7.64	1004	89.5	49.1	73.7	4.5	3.51	0.15	30.6	532.4	0.0	159.1	6.5	0.030 J	0.5	680	1.6
253448	47.597304	-104.287614	WELL	180	8/7/2019	10.1	7.68	2202	163.1	121.7	206.3	6.1	2.03	0.17	15.4	625.1	0.0	799.8	17.5	0.030 J	0.7	1641	3.0
273754	47.586734	-104.29296	WELL	102	6/24/2013	10.4	7.29	875	91.4	43.8	41.0	5.2	2.00	0.11	22.1	438.0	0.0	146.0	5.8	<0.010 U	0.2	573	0.9
273787	47.490493	-104.385363	WELL	104	6/26/2013	11	7.69	835	82.6	39.0	47.9	4.8	<0.015 U	0.003 J	15.7	427.5	0.0	134.4	3.4	1.03	0.2	539	1.1
273791	47.577918	-104.288401	WELL	102	6/25/2013	13.3	7.73	1006	76.8	42.5	82.8	5.3	<0.015 U	0.09	25.8	537.8	0.0	148.4	5.4	0.06	0.4	651	1.9
273794	47.571707	-104.336333	WELL	242	6/23/2013	12.2	7.64	1076	110.3	45.3	57.0	5.4	<0.015 U	0.08	14.3	464.4	0.0	224.6	10.1	0.14	0.2	695	1.2
273796	47.514929	-104.364754	WELL	267	6/24/2013	11.1	7.4	1054	77.8	35.5	113.3	5.3	0.33	0.28	28.4	554.4	0.0	153.8	3.7	<0.010 U	0.5	690	2.7
273806	47.456424	-104.427917	WELL	220	6/27/2013	14.4	7.75	1471	108.7	60.0	174.9	7.1	<0.038 U	0.165	23.9	674.3	0.0	338.8	11.1	0.07	0.4	1057	3.3
273844	47.546686	-104.348908	WELL	124	6/28/2013	11.4	7.96	1223	47.7	27.7	187.6	4.0	<0.015 U	0.10	19.5	640.2	0.0	162.6	4.1	<0.010 U	0.7	771	5.4
284325	47.571906	-104.33065	WELL	250	8/6/2019	10.5	7.76	934	113.0	48.7	28.8	4.4	0.98	0.15	18.0	469.4	0.0	167.5	9.9	<0.010 U	0.3	623	0.6
285476	47.605302	-104.282406	WELL	190	8/7/2019	10.2	7.75	1720	101.7	88.4	183.7	6.0	1.89	0.10	22.2	693.0	0.0	436.2	14.4	<0.010 U	0.6	1196	3.2
285484	47.608498	-104.28248	WELL	174	8/20/2019	12.1	8.03	2351	98.9	79.3	374.8	5.5	0.02	0.26	21.2	928.2	0.0	575.8	33.9	<0.010 U	1.3	1647	6.8
285659	47.60151	-104.282808	WELL	170	8/20/2019	11.5	7.9	1498	95.4	84.4	133.6	4.6	1.43	0.11	20.2	572.7	0.0	402.1	15.8	0.040 J	0.8	1041	2.4
290760	47.456936	-104.409676	WELL	210	8/7/2019	10.8	7.62	969	80.7	41.1	85.3	4.8	2.305	0.203	31.6	567.6	0.0	110.8	2.3	<0.010 U	0.6	640	1.9
291010	47.603155	-104.282474	WELL	169	8/7/2019	10.4	7.48	1482	105.4	85.6	118.7	5.0	3.31	0.14	21.2	561.5	0.0	406.4	14.4	0.030 J	0.7	1036	2.1
295226	47.41344	-104.448904	WELL	192	5/21/2019	10.5	8.25	2237	70.9	44.6	337.4	6.0	0.044 J	0.134	29.8	845.7	14.4	347.9	6.8	<0.010 U	1.3	1275	7.7
295282	47.427864	-104.436828	WELL	200	5/21/2019	11.3	8.21	1818	72.2	54.4	217.1	5.4	0.086 J	0.134	29.2	791.2	10.7	206.1	5.6	<0.010 U	0.8	991	4.7
295293	47.445841	-104.438584	WELL	160	5/21/2019	9.4	8.05	1935	123.3	62.2	174.8	5.6	<0.038 U	0.14	21.4	725.3	0.0	344.1	14.9	<0.010 U	0.4	1104	3.2
295294	47.469663	-104.386252	WELL	130	5/20/2019	9.3	8.05	1030	73.5	39.7	87.4	6.6	0.023 J	0.12	33.0	555.7	0.0	105.2	2.1	<0.010 U	0.5	621	2.0
295300	47.514939	-104.375242	WELL	257	5/22/2019	10	7.9	1191	90.2	46.0	95.6	4.6	<0.038 U	0.13	20.1	572.6	0.0	159.8	9.9	<0.010 U	0.4	709	2.1
295310	47.528463	-104.35825	WELL	255	5/22/2019	11.7	7.96	1186	86.5	47.7	92.4	5.2	0.046 J	0.18	27.8	636.2	0.0	120.9	4.6	<0.010 U	0.8	699	2.0
295396	47.468176	-104.395497	WELL	118	5/20/2019	9.9	8.03	1601	96.2	51.4	156.2	5.9	0.188	0.254	30.6	739.3	0.0	213.4	3.7	<0.010 U	0.5	922	3.2
296426	47.45639	-104.427329	WELL	223	5/21/2019	10	7.59	1888	111.1	59.5	170.5	5.7	2.67	0.17	26.2	738.0	0.0	306.1	10.1	<0.010 U	0.4	1055	3.2
296815	47.548447	-104.357936	WELL	154	5/23/2019	10	7.97	1012	80.5	38.8	75.2	4.1	0.029 J	0.10	18.4	518.9	0.0	119.9	5.2	<0.010 U	0.7	598	1.7
296817	47.55074	-104.36195	WELL	127	5/23/2019	9.1	8.03	804	74.4	27.3	45.6	3.7	<0.015 U	0.08	11.2	404.9	0.0	89.4	5.0	0.17	0.8	457	1.2
296818	47.557615	-104.357984	WELL	240	5/23/2019	10.6	8.13	1178	71.2	37.4	127.4	4.0	<0.038 U	0.096 J	16.5	584.2	1.5	144.1	5.6	<0.010 U	1.1	695	3.0
296819	47.571952	-104.342827	WELL	255	8/21/2019	12.6	7.99	851	94.1	47.5	38.4	4.1		0.16	13.5	439.9	0.0	158.6	8.0	<0.010 U	0.5	582	0.8
296851	47.570681	-104.305981	WELL	252	8/21/2019	12.8	8.16	1122	74.4	41.4	135.8	4.3	0.09	0.18	29.7	642.4	4.0	154.5	3.9	<0.010 U	0.7	766	3.1
296852	47.584841	-104.306822	WELL	120	8/21/2019	10.1	7.9	930	94.4	42.4	60.2	4.5	0.03	0.12	18.4	389.1	0.0	232.4	7.3	<0.010 U	0.3	650	1.3
296853	47.585983	-104.299054	WELL	100	8/21/2019	10.3	7.98	814	80.7	42.4	45.2	4.5	0.18	0.10	22.0	481.5	0.0	105.5	4.1	<0.010 U	0.3	542	1.0
297355	47.632447	-104.255374	WELL	141	8/20/2019	10.9	8.07	1155	111.5	69.2	53.0	5.2	0.035	0.467	30.4	472.0	0.0	284.4	12.3	<0.010 U	0.4	797	1.0
297358	47.632493	-104.261265	WELL	152	8/20/2019	10.9	8.19	1940	92.3	80.6	260.5	5.7	0.014	0.125	28.5	882.6	12.0	400.4	12.6	<0.010 U	1.2	1330	4.8
297362	47.586161	-104.282708	WELL	80	8/21/2019	9.1	7.9	826	84.7	41.5	47.2	4.2	0.83	0.11	25.4	443.0	0.0	134.7	6.6	<0.010 U	0.3	563	1.0
297371	47.586688	-104.284874	WELL	82	8/21/2019	8.7	7.66	852	84.9	40.7	50.0	4.2	2.54	0.11	25.4	450.8	0.0	133.2	6.3	<0.010 U	0.3	569	1.1
297373	47.640911	-104.239292	WELL	131	8/20/2019	14.7	8.12	660	36.8	20.2	76.9	4.0	0.029	0.059	13.1	283.9	0.0	125.0	6.9	0.07	0.6	424	2.5
297379	47.615874	-104.255669	WELL	120	8/20/2019	10.5	8.07	630	72.8	30.6	24.0	4.2	0.51	0.23	28.3	386.3	0.0	60.7	3.0	<0.010 U	0.4	415	0.6
297386	47.560338	-104.363884	WELL	193	5/23/2019	10.5	8.09	986	67.6	39.3	86.2	4.3	<0.015 U	0.12	18.8	515.9	0.0	114.6	3.6	<0.010 U	0.5	589	2.1
297388	47.56391	-104.357827	WELL	244	5/23/2019	11.6	8.67	1971	21.2	13.9	408.1	3.2	<0.038 U	0.020 J	8.7	878.0	38.9	235.6	8.8	<0.010 U	5.2	1177	16.9
298761	47.370389	-104.449141	WELL	65	5/22/2019	10.6	8.14	1293	84.6	37.8	123.7	6.8	<0.038 U	0.282	33.3	618.4	2.0	135.5	2.4	<0.010 U	0.6	732	2.8
298762	47.398636	-104.454886	WELL	229	5/22/2019	10.5	8.21	1434	81.9	40.6	155.1	6.3	0.077 J	0.174	33.1	661.1	8.9	153.1	4.2	<0.010 U	0.8	809	3.5
298764	47.428565	-104.422764	WELL	126	5/21/2019	11.5	8.17	889	89.0	37.7	30.1	6.2	0.666	0.296	20.1	374.9	2.7	130.1	2.8	<0.010 U	0.4	505	0.7
298767	47.434272	-104.427817	WELL	237	5/21/2019	10.7	8.11	1274	90.4	43.2	100.4	6.3	0.090 J	0.221	32.1	611.2	0.0	122.0	2.5	<0.010 U	0.5	698	2.2
298768	47.434321	-104.437324	WELL	210	5/21/2019	10.1	8.2	1889	78.0	45.1	236.1	6.0	0.100 J	0.115 J	28.5	805.5	8.8	220.5	5.8	<0.010 U	0.7	1028	5.3

Appendix B. Water chemistry.

Gwic ID	Latitude	Longitude	Site Type	Depth (ft	Sample Date	Water Temp (C)	Lab pH	Lab SC (µS/cm)	Ca	Mg	Na	K	Fe	Mn	SiO2	HCO3	CO3	SO4	Cl	NO3-N	F	TDS	SAR
298809	47.485629	-104.395164	WELL	176	5/20/2019	9.6	8.13	1423	47.3	28.9	219.6	4.2	<0.038 U	0.077 J	21.5	633.4	1.5	205.4	3.7	<0.010 U	1.2	844	6.2
299151	47.482481	-104.40633	WELL	209	5/20/2019	10.3	8.6	3258	9.4	4.7	723.6	3.6	<0.075 U	0.021 J	10.5	982.9	33.8	734.7	6.4	<0.010 U	3.1	2014	48.1
299153	47.502522	-104.384519	WELL	177	5/20/2019	10	8.09	1730	74.3	39.2	241.0	5.5	<0.038 U	0.122 J	25.2	720.1	0.0	312.9	4.4	<0.010 U	0.7	1057	5.6
299168	47.551089	-104.363926	WELL	98	5/23/2019	10.6	8.42	1496	37.9	18.1	261.1	3.5	<0.038 U	0.044 J	9.6	704.4	17.5	165.0	5.6	<0.010 U	2.8	868	8.7
299171	47.551288	-104.366094	WELL	87	5/23/2019	10.2	8.28	1776	17.4	11.8	363.2	7.5	<0.038 U	0.039 J	8.6	824.3	11.0	216.1	10.8	<0.010 U	2.2	1054	16.5
299175	47.500581	-104.375814	WELL	215	5/20/2019	19.6	8.05	1888	94.9	57.9	224.5	5.6	0.07	0.16	32.8	870.8	0.0	282.0	4.5	<0.010 U	1.3	1133	4.5
300254	47.441425	-104.439622	WELL	180	5/21/2019	9.5	8.13	1316	90.7	48.7	103.6	5.8	<0.038 U	0.178	21.3	627.2	2.1	137.4	3.2	<0.010 U	0.4	721	2.2
300256	47.446438	-104.426235	WELL	160	5/21/2019	8.9	8.11	897	89.3	29.1	49.2	5.0	<0.015 U	0.15	22.8	481.5	0.0	74.0	1.6	0.54	0.3	510	1.2
301472	47.372049	-104.445811	WELL	7	5/22/2019	7.4	7.38	646	90.4	24.5	6.7	1.9	<0.015 U	0.021 J	16.5	275.8	0.0	81.1	2.2	12.43	0.4	372	0.2
301476	47.54613	-104.34389	WELL	8	5/23/2019	8.4	7.42	421	56.1	18.4	4.5	5.1	0.72	0.49	17.0	270.9	0.0	11.0	4.3	0.06	0.2	251	0.1
302852	47.586682	-104.284901	WELL	7	8/21/2019	13.1	7.32	936	118.0	45.0	31.7	4.8	0.72	2.53	18.8	523.0	0.0	142.0	8.8	0.030 J	0.2	632	0.6
FORT UNION AQUIFER																							
2521	47.4725	-104.4594	WELL	392	9/16/1976		8.5	2126	2.1	1.3	524.0	1.9	0.16	0.01	8.8	995.5	21.1	297.7	3.8	0.25	3.2	1355	70.0
2636	47.587515	-104.391061	WELL	214	9/13/1976		7.5	1220	33.4	38.0	200.0	5.4	2.40	0.04	11.3	568.5	0.0	204.4	2.6	0.40	0.4	777	5.6
32723	47.4416	-104.4211	WELL	113	8/22/2019	9.9	7.33	1450	98.4	42.3	189.1	5.8	0.67	0.05	19.0	714.9	0.0	292.4	2.9	0.05	0.2	1003	4.0
32729	47.414294	-104.426169	WELL	196	8/22/2019	11.3	7.64	433	49.8	15.7	24.4	4.5	1.90	0.14	26.0	287.4	0.0	25.4	1.4	<0.010 U	0.3	290	0.8
35171	47.534707	-104.376641	WELL	155	8/22/2019	10.5	7.85	1331	49.6	36.6	216.5	3.1	0.17	0.04	13.0	759.5	0.0	155.8	9.6	0.040 J	1.4	859	5.7
35209	47.583049	-104.285655	WELL	46	8/21/2019	8.2	7.52	919	76.5	38.8	82.6	4.6	2.33	0.12	27.0	494.9	0.0	145.6	5.9	<0.010 U	0.5	629	1.9
142678	47.5866	-104.3908	WELL	210	6/15/1995	10.9	7.6	1334	79.3	67.5	143.2	6.0	0.09	0.07	14.8	623.4	0.0	300.0	4.0	<.25 P	0.3	922	2.9
297346	47.63225	-104.266479	WELL	62	8/20/2019	10.3	7.31	1590	148.7	121.7	44.9	7.1	<0.0150 U	0.02	15.4	766.5	0.0	354.5	10.3	0.11	0.3	1080	0.7
302855	47.384128	-104.447831	WELL	N/A[4]	8/22/2019	11.9	7.72	1386	26.5	14.3	295.5	3.8	0.06	0.03	14.3	786.8	0.0	178.6	2.8	0.06	0.6	925	11.5
700494	47.573	-104.3725	WELL	85	6/20/1995	10.7	7.4	1230	128.1	85.8	38.8	4.1	0.12	0.07	13.7	447.7	0.0	350.0	10.5	<.25 P	0.3	853	0.7

Note. Units in mg/L unless otherwise stated.

[1]P, Preserved sample.

[2]U, Undetected quantity below detection limit

[3]J, Estimated quantity above detection limit but below reporting limit

[4]N/A, not available.