THREE AQUIFER TESTS IN THE TOBACCO VALLEY, NEAR EUREKA, MONTANA

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Front photo: View of the Tobacco Valley, looking west. Photo by Andrew Bobst, MBMG.

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TABLE OF CONTENTS

FIGURES

TABLE

ABSTRACT

Interest in commercial and residential development in the Tobacco Valley in and around Eureka, Montana is increasing. A more detailed understanding of the hydrogeology of this area is needed to understand how increased groundwater development will affect groundwater and surface-water availability. An important component of this is establishing reasonable ranges of aquifer properties for the major hydrogeologic units in the area.

The Montana Bureau of Mines and Geology performed aquifer tests at three locations in the Tobacco Valley, representative of the major hydrogeologic units that govern groundwater flow. These tests were conducted in: (A) confined glacial outwash sediments, (B) semi-confined Belt bedrock, and (C) unconfined deltaic gravels.

The tests showed a wide range of aquifer properties. The Belt bedrock was the least permeable (estimated hydraulic conductivity of 0.01 ft/d), the deltaic gravel was the most permeable (1,890 ft/d), and the sand and gravel of the glacial outwash was between these values (46 ft/d). The tested aquifers ranged from confined to unconfined.

PURPOSE OF THE AQUIFER TESTS

Aquifer tests were conducted in three of the major hydrogeologic units in the Tobacco Valley (fig. 1). These units are all used to supply water, but have different aquifer properties. Quantifying the aquifer properties for these units provides a reasonable range of those properties for the diverse aquifers in the valley. Aquitards, such as glacial basal till or fine-grained lacustrine deposits, are also present in the area, and will be less permeable than the tested aquifers. The hydrogeologic properties of the units (aquifers and aquitards) will be used in developing groundwater flow models for the area, which will help inform development decisions in the Tobacco Valley.

HYDROGEOLOGIC SETTING

Precambrian bedrock from the Belt Supergroup bounds the study area to the northeast, the southwest, and the west (Coffin and others, 1971; fig. 1). Bedrock is exposed at the surface along the Tobacco River, on the west side of Lake Koocanusa, and in the Whitefish Range (fig. 1). These bedrock units are believed to underlie the entire Tobacco Valley but are up to 3,000 ft below ground surface (bgs) due to the Rocky Mountain Trench transecting the area (Garland and others, 1961; Coffin and others, 1971; Harrison and others, 1992). The bedrock is overlain by valley-fill sediments, which include Tertiary sediments, glacial deposits, glacial lake deposits, and alluvium.

Most of the unconsolidated sediments were deposited during the Tertiary period (66 to 2 mya). There are no records of wells completed in the Tertiary sediments in the Tobacco Valley; however, these sediments are widely reported in nearby intermontane basins (LaFave and others, 2004). Tertiary sediments are also reported near Olney, about 33 mi southeast of the study area (Alden, 1953). Tertiary sediments exposed in the Canadian part of the Rocky Mountain Trench are lake deposits (Rice, 1937). Additionally, the Tertiary Kishenehn Formation near the Flathead Valley, south of the Tobacco Valley, is dominantly composed of fine sand and finer sediments (Smith, 2004). The Tertiary sediments are not generally productive aquifers, and instead function as a basal aquitard.

The Tobacco Valley has experienced at least three glaciations (Coffin and others, 1971). Deposits from the most recent of these, the Late Wisconsinian Pinedale Glaciation (with a maximum extent around 23.5 to 21 kya), formed the major aquifers and aquicludes in the area (Coffin and others, 1971). Older glacial deposits, such as those from the Bull Lake glaciation (Illinoian, from about 200 to 130 kya), have been largely obscured or eroded by the Pinedale Glaciation. However, remnants of these older glacial sediments may occur in the subsurface. During the Pinedale Glaciation, the Flathead lobe of the Cordilleran ice sheet flowed south through the Rocky Mountain Trench, reaching as far south as Polson, Montana. Proglacial outwash sand and gravel was deposited in some areas in front of the glacier (Smith, 2004). Basal till covers much of the area (fig. 1), in some cases forming southeast-trending drumlins. This till is typically an unsorted mixture of detrital material ranging in size from clay to boulders (i.e., diamicton). While the till functions as an aquitard in much of the area, it may include productive lenses of sand and gravel.

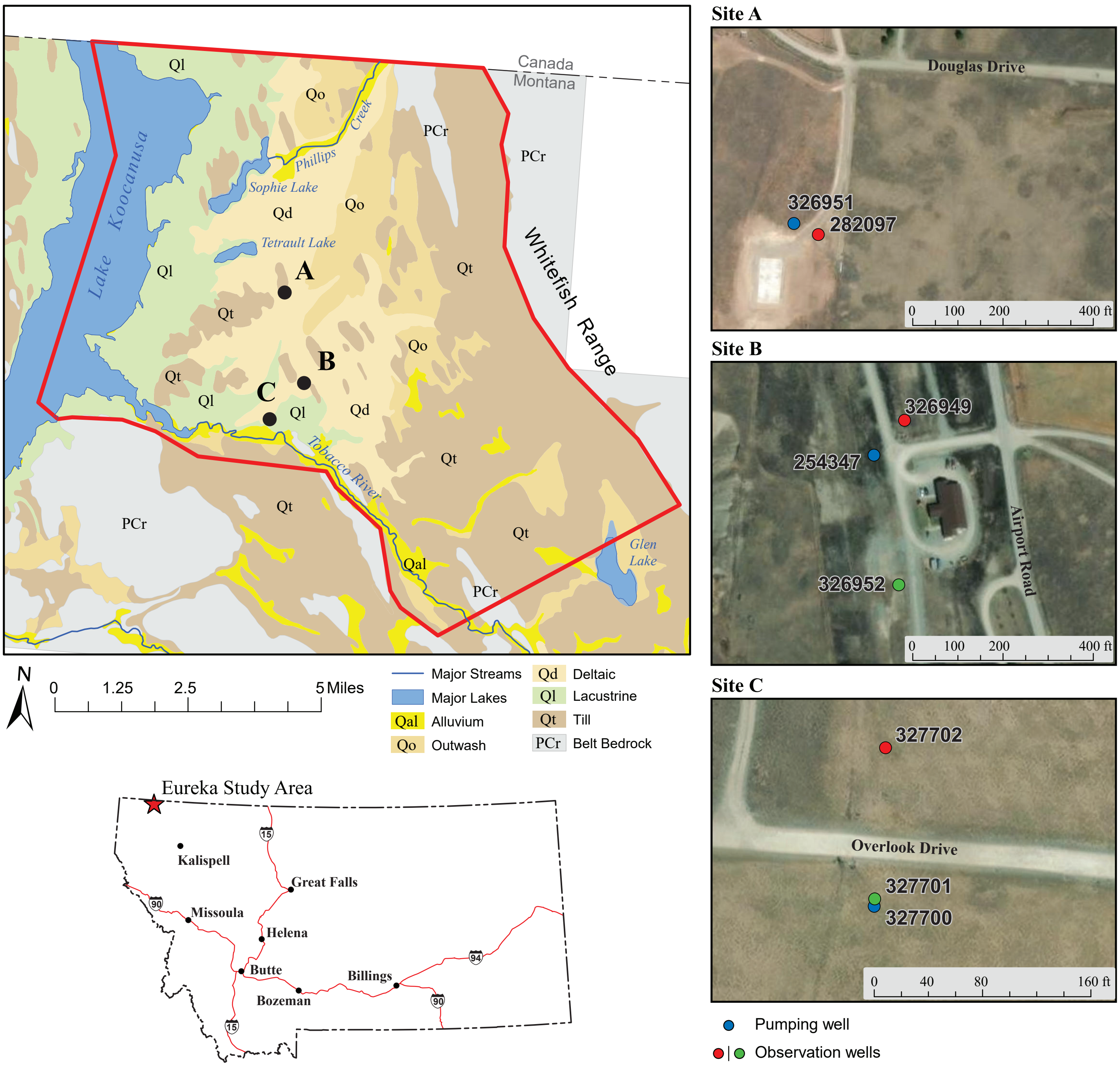

Figure 1. The Eureka study area (red outline) is in northwestern Montana. The three aquifer tests (A–C) are shown on the geologic map (modified from Coffin and others, 1971). Site layout maps are shown at the right. At each site there was a pumping well and at least one observation well. Observation well colors allow for correlation with subsequent figures. Additional well details are on table 1 and in GWIC (https://mbmggwic.mtech.edu).

As the Cordilleran ice sheet retreated, Glacial Lake Kootenai formed due to an ice dam on the Kootenai River to the south (Coffin and others, 1971). Similar to other ice-dammed glacial lakes in western Montana (e.g., Glacial Lake Missoula; Hanson and others, 2012), it is likely that this lake filled and drained many times, changing the location of the shoreline. Deep lake deposits are dominantly composed of silt and very fine sand. The deep lake deposits grade into near-shore, deltaic sand and gravel deposits formed by streams and rivers flowing into the lake (Coffin and others, 1971). Due to changing lake levels these sediment types are highly interfingered in the Tobacco Valley.

Holocene alluvium, deposited since about 9.7 kya, ranges from silt to gravel. The alluvium is present near the Tobacco River, Phillips Creek, and other modern streams and lakes (fig. 1). Alluvial materials from the Kootenai River also underlie Lake Koocanusa, which is a reservoir.

Previous aquifer tests have been conducted on at least 18 wells at 10 sites in the study area (DNRC, written commun., 2022); however, the reporting and analysis levels are inconsistent. At some sites several tests were performed but only average aquifer properties are reported. Additionally, there are anecdotal reports of aquifer tests that lack documentation. The test results are likely biased to more productive aquifers, since aquifer tests are only needed for more productive wells; reported pumping rates ranged from 43 to 481 gallons per minute (gpm). The available results from all tested aquifers (ranging in lithology from bedrock to gravel) show a wide range in transmissivity from 132 to 326,000 ft^2/d. The range in transmissivity values is likely due to a combination of differences in the screened intervals (which are not always reported), and differences in the aquifer materials. Estimated hydraulic conductivity values based on 1.5 times the screen length ranged from 14 to 8,000 ft/d, consistent with values for medium sand to coarse gravel (Heath, 1983). Reported storativity values ranged from 6.3 x 10^{-4} to 7.0 x 10^{-2} (unitless), indicative of semi-confined to unconfined aquifers.

GENERAL PROCEDURES

Field procedures were generally conducted in accordance with the Montana Bureau of Mines and Geology (MBMG) standard operating procedures (SOPs; Gotkowitz, 2023). Step-tests were conducted prior to the constant-rate tests to determine an adequate pumping rate for each test, but were not used for analysis and are not discussed in detail in this report. General field procedures for the aquifer tests are briefly described in this section, with additional details in the “Site-Specific Data Collection” sections for each test.

A near-constant pumping rate was used for each test. A check valve was installed directly above the pump to avoid flowback at the end of pumping. A totalizing flow meter was installed on the discharge line to track the amount of water pumped. Flow rates were calculated using manual readings of the totalizer at timed intervals throughout the test. Manual discharge measurements (e.g., bucket and stopwatch) were taken during the step-tests to validate totalizer-based measurements.

Each well was equipped with a vented transducer (InSitu LevelTroll 500) to measure water levels during the tests. Background water-level data were collected in some wells before and after the tests by installing vented or unvented transducers (InSitu LevelTroll 500 or InSitu RuggedTroll 100) to evaluate antecedent water-level trends. When unvented transducers were used the data were corrected for barometric variations using nearby barometric loggers (InSitu BaroTroll 500). Manual depth-to-water measurements were taken with an electric tape (sounder) to post-process transducer records and provide backup data in case of transducer failure. Following the MBMG SOPs, manual sounder readings were taken most frequently at the start of pumping, with intervals increasing with pumping time during the test but not exceeding 4 h (Gotkowitz, 2023).

All aquifer tests were analyzed using Aqtesolv software (Duffield, 2007). The solutions used are discussed for each test in the “Analysis Methods” sections.

The aquifer test data are available in 633 forms on the MBMG Ground Water Information Center (GWIC) online database (http://mbmggwic.mtech.edu) using the pumping well GWIC ID number (table 1). Wells in this report are referred to by their GWIC ID (e.g., pumping well 326951).

Table 1. Summary of Eureka area aquifer test results.

Site	Aquifer Type	GWIC IDs	Well Type	Total Depth (ft-bgs)	Measuring Point Elevation (ft-amsl)	Well Stickup Height (ft)	Distance From PW (ft)	Static Water Level (ft-bMP)	Maximum Drawdown (ft)	Average Pumping Rate (gpm)	Estimated Transmissivity (ft^2/d)	Estimated Hydraulic Conductivity (ft/d)	Estimated Storativity (unitless)	Solution Type
A	Proglacial Outwash	326951	PW	494	2645.03	2.53	—	142.10	24.80	84.0	1,380	46	$6.4x10^{-7}$	Confined
		282097	OW	486	2640.93	2.30	57.2	137.08	14.29					
B	Belt Bedrock	254347	PW	580	2658.96	2.50	—	105.88	154.51					
		326949	OW	602	2664.60	2.60	101.3	106.85	86.14	4.01	2.0	0.01	$4.0x10^{-5}$	Leaky Confined
		326952	OW	599	2661.40	2.40	291.9	105.65	1.92					
C	Deltaic Gravel	327700	PW	168	2591.25	3.25	—	83.57	4.87					
		327701	OW	127	2590.96	2.96	5.2	82.57	0.05	89.4	189,000	1,890	$3x10^{-3}$	Unconfined (S_y = 0.01)
		327702	OW	162	2593.13	3.13	119	85.76	0.24					

Note. See GWIC for additional details (https://mbmggwic.mtech.edu). PW, pumping well; OW, observation well; gpm, gallons per minute; ft-bgs, feet below ground surface; ft-amsl, feet above mean sea level; ft-bMP, feet below measuring point.

SITE A

Background

There are two wells at Site A (table 1, fig. 1), which are both completed in a sand and gravel unit interpreted to be proglacial outwash.

The 72-h constant-rate test ran from 9:30 AM on 10/24/2023 to 9:30 AM on 10/27/2023. The time-weighted average pumping rate was 84.0 gpm, with values ranging from 81.8 to 87.6 gpm. A variable-frequency drive (VFD) was used for the test and adjusted to maintain a steady pumping rate.

Well and Lithologic Descriptions

The MBMG completed pumping well 326951 in 2023 to a total depth (TD) of 494 ft below ground surface (ft-bgs; fig. 2A). A 10-ft screen was installed from 484 to 494 ft-bgs in a zone composed of gravel, cobble, and coarse sand (fig. 2A). This productive zone was overlain by clay-rich sediments from 305 to 434 ft-bgs (fig. 2A).

Observation well 282097 was installed into a sand and gravel zone in 2015 at a TD of 486 ft-bgs (fig. 2B). The lithologic description for this well indicates that the sand and gravel zone is overlain by clay-rich sediments from 180 to 470 ft-bgs (fig. 2B). This well is 57 ft southeast of the pumping well (fig. 1), and has an open-bottom completion.

Site-Specific Data Collection

Background water levels were collected hourly using unvented transducers in both wells. The transducer for observation well 282097 recorded from 4/21/2023 to 10/9/2023 and the transducer for pumping well 326951 recorded from 8/15/2023 to 10/9/2023 (fig. 3A). These data show that groundwater levels rose in the spring, reached a peak near the end of July, and then declined.

A vented transducer was installed in pumping well 326951 for the constant-rate test from 10/23/2023 to 10/30/2023 (fig. 2A). This transducer recorded water-level data at 1-min intervals from 8:10 AM on 10/24/2023 to 11:46 AM on 10/27/2023 (mainly during the pumping period). It was set to record at 15-min intervals before and after this time period.

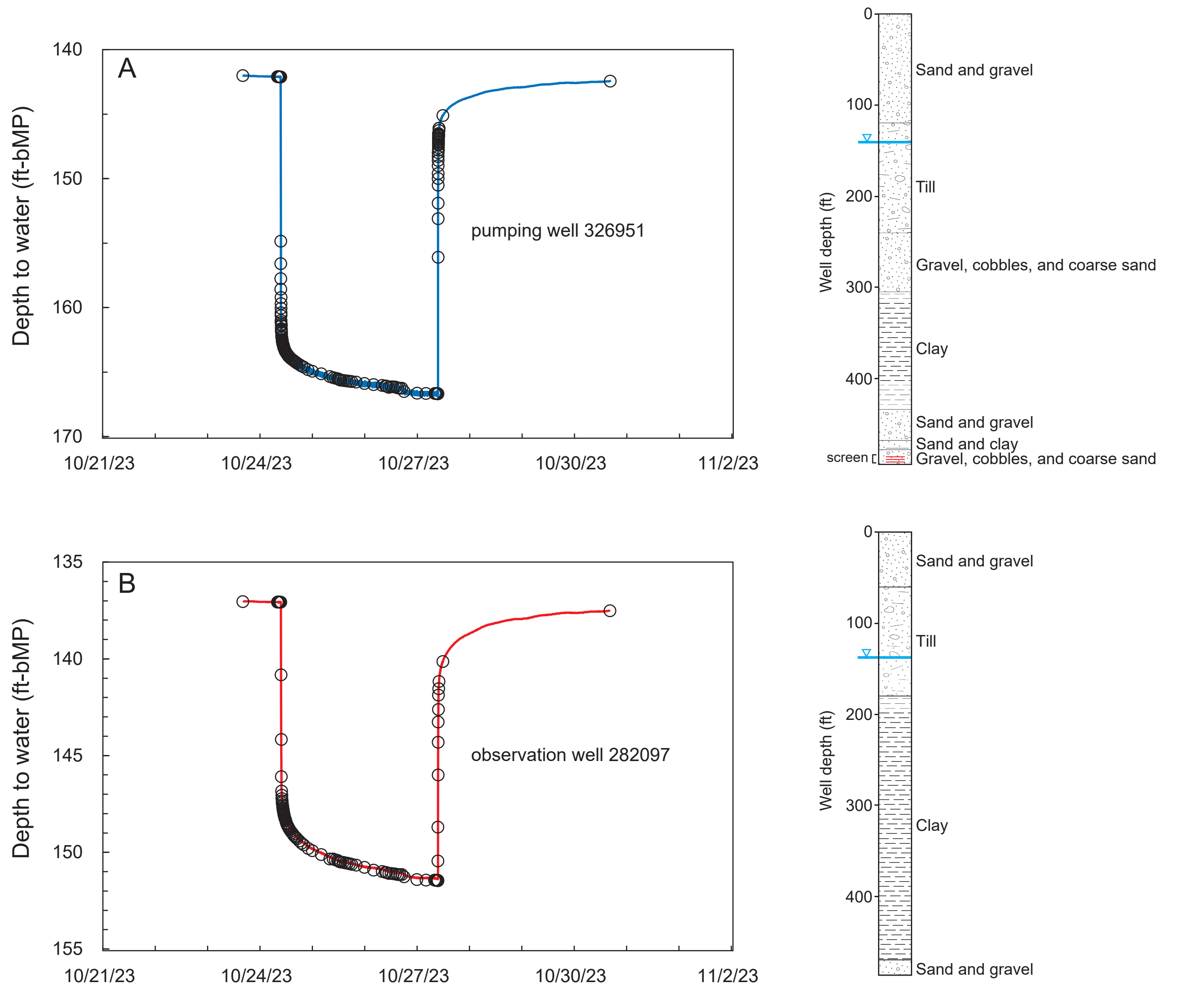

Figure 2. Site A hydrographs and well lithologies. Depth to water is not corrected for trend. Hydrographs include the measured pre-pumping, pumping, and recovery periods from transducers (lines) and manual sounder readings (circles). Note the different y-axis. On the lithologic logs the blue line shows the pre-test static water level and red lines show the screened interval.

Similar to the pumping well, a vented transducer was installed in observation well 282097 for the constant-rate test from 10/23/2023 to 10/30/2023 (fig. 2B). This transducer recorded water-level data at 1-min intervals from 8:12 AM on 10/24/2023 to 11:49 AM on 10/27/2023 (mainly during the pumping period). It recorded at 15-min intervals before and after this time period.

Background data and values after recovery show that water levels in pumping well 326951 during the constant-rate test experienced a downward antecedent trend of about 0.007 ft/d (fig. 3B). This antecedent trend was removed from both wells' data prior to analysis.

Analysis Methods

The data collected during this test were analyzed using the Theis step-test solution (fig. 4A; Theis, 1935), consistent with the aquifer being overlain by a thick clay-rich layer. This solution is for a confined aquifer and includes a linear well bore skin factor (S_w) to account for alteration of the aquifer near the well bore due to drilling and development. The solution was fit to the portion of the drawdown curves while the derivative plots were generally flat (fig. 4A), indicating that the aquifer was acting similar to a confined aquifer with infinite acting radial flow (IARF; a key assumption to many aquifer test solutions; Renard and others, 2009). The Theis recovery solution (Theis, 1935) was used to analyze residual drawdown (fig. 4B).

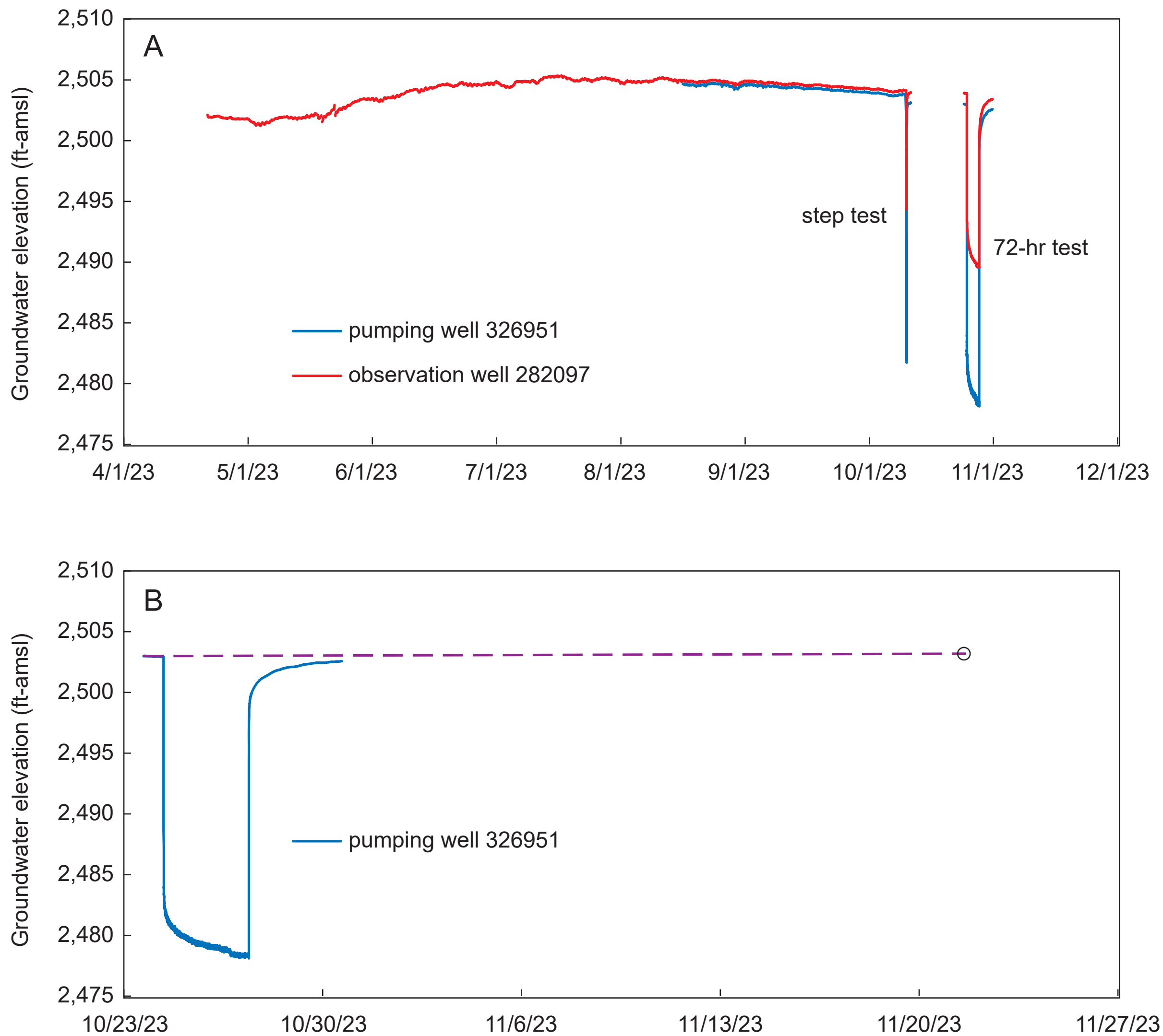

Figure 3. Monitoring at Site A from 4/21 to 11/21/23 (A) shows a rise in the spring, and then a drop starting in late July. During the 72-hr test (B) there was a downward antecedent trend (purple dashed line) of about 0.007 ft/d.

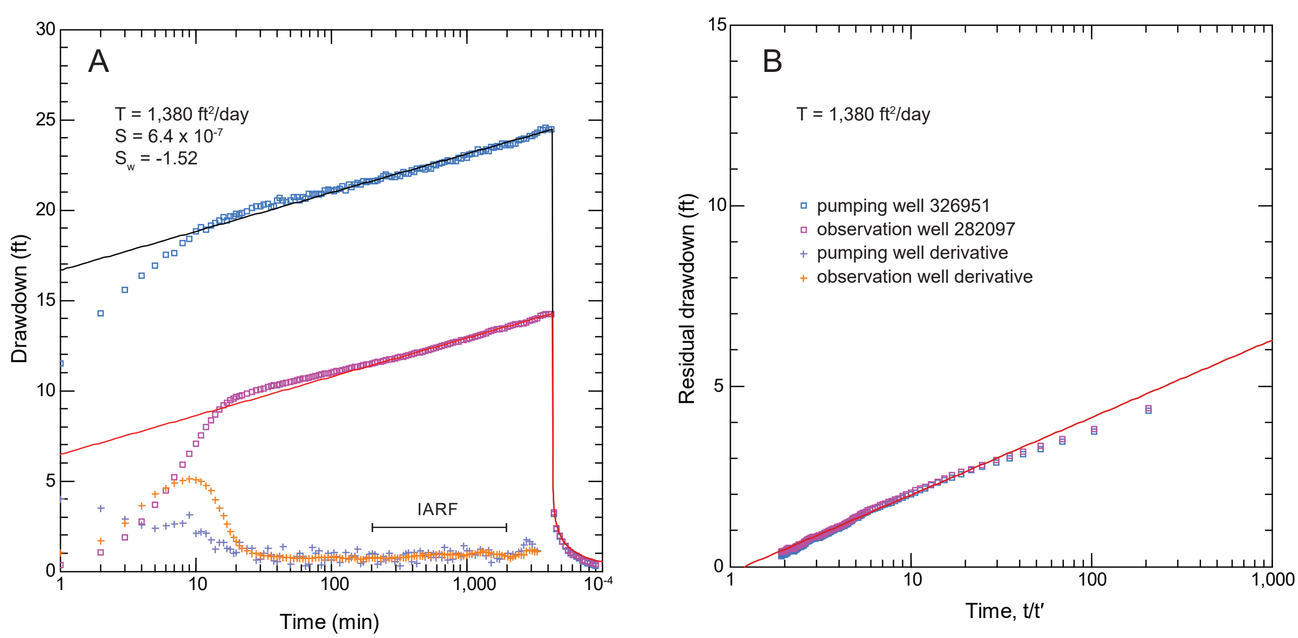

Figure 4. Analysis of trend-corrected data for the constant-rate aquifer test at Site A. (A) Theis step-test fits, while derivative plots indicate infinite-acting radial flow (IARF). (B) Analysis of recovery data is also consistent with a T of 1,380 ft²/d.

Results

Water-Level Response

Groundwater levels in pumping well 326951 were drawn down by a maximum of 24.80 ft during the test (fig. 2A, table 1). Water levels rapidly dropped at the start of pumping and then leveled off, but did not completely flatten as pumping continued. At the end of the test the water levels rose fairly rapidly, but 20 h was needed to reach 95% recovery.

Observation well 282097 responded similarly to the pumping well (fig. 2B), but the maximum drawdown was 14.29 ft (fig. 2, table 1), and 45 h was needed to reach 95% recovery.

Aquifer Properties

The Theis step-test solution fit to the drawdown data from the pumping well and the observation well provides an estimated transmissivity (T) of 1,380 ft^2/d, a storativity (S) of 6.4 x 10^{-7}, and an S_w of -1.52 (fig. 4A). This negative S_w suggests that well development removed fines near the well, making the aquifer near the pumping well more permeable than the aquifer as a whole. Analysis of recovery data using the Theis residual drawdown solution is also consistent with a T of about 1,380 ft^2/d (fig. 4B). Using an aquifer thickness of 30 ft, based on the thickness of sand and gravel encountered during drilling, results in an estimated hydraulic conductivity of 46 ft/d, which is consistent with literature-reported values for sand and gravel (Heath, 1983).

SITE B

Background

Three wells were monitored at Site B (table 1, fig. 1). These wells are all completed in Belt bedrock (fig. 5).

The 72-h constant-rate test ran from 10:45 AM on 10/24/2023 to 10:45 AM on 10/27/2023. The time-weighted average pumping rate was 4.01 gpm. During the first 5 min of the test the average pumping rate was at 7.6 gpm, but for the rest of the test values ranged from 3.78 to 4.30 gpm. A VFD was used for the test and adjusted to maintain a steady pumping rate.

Well and Lithologic Descriptions

Preexisting well 254347 was used as the pumping well. This well was drilled to a TD of 580 ft-bgs in 2010, it is screened from 520 to 580 ft-bgs, and the top of bedrock was encountered at 450 ft-bgs (fig. 5A). This well has been part of MBMG's statewide long-term groundwater monitoring network (Ground-Water Assessment Act Monitoring Network, GWAAMON) since 2017, so it has a detailed record of water levels (fig. 6A; https://www.mbmg.mtech.edu/WaterEnvironment/GWAP/).

The MBMG installed two observation wells in 2023. These wells are at different bearings from the pumping wells (fig. 1) to allow for evaluation of potential anisotropy that often results from fracture patterns in bedrock aquifer. Observation well 326949 has a TD of 602 ft-bgs and it is screened from 522 to 602 ft-bgs. The top of bedrock in observation well 326949 was encountered at 480 ft-bgs (fig. 5B), and it is 101 ft northeast of the pumping well. Observation well 326952 has a TD of 599 ft-bgs and it is screened from 519 to 599 ft-bgs. The top of bedrock in observation well 326952 was encountered at 372 ft-bgs (fig. 5C), and it is 292 ft south of the pumping well.

Site-Specific Data Collection

GWAAMON long-term monitoring data from pumping well 254347 show peak water levels in midwinter and the lowest groundwater levels in midsummer (fig. 6A). This suggests a response to the summertime pumping from nearby wells, likely for lawn watering. During this aquifer test groundwater levels were rising.

A vented transducer was installed in pumping well 254347 for the 72-h test and ran from 10/23/2023 to 10/30/2023 (fig. 5A). The vented transducer recorded at 15-min intervals, except that it recorded at 1-min intervals from 8:48 AM on 10/24/2023 to 12:29 PM on 10/27/2023 (mainly during the pumping period).

Antecedent water levels were measured hourly in observation well 326949 from 8/14/2023 to 11/21/2023 (fig. 6B) by an unvented pressure transducer. These data were collected throughout aquifer testing. During the 72-h test there was an antecedent trend of groundwater levels rising at about 0.022 ft/d. It was assumed that this same trend applied to all wells and it was removed from the data for all three wells prior to analysis.

A vented transducer was installed in observation well 326949 (along with the unvented transducer) for the 72-h test, which ran from 10/23/2023

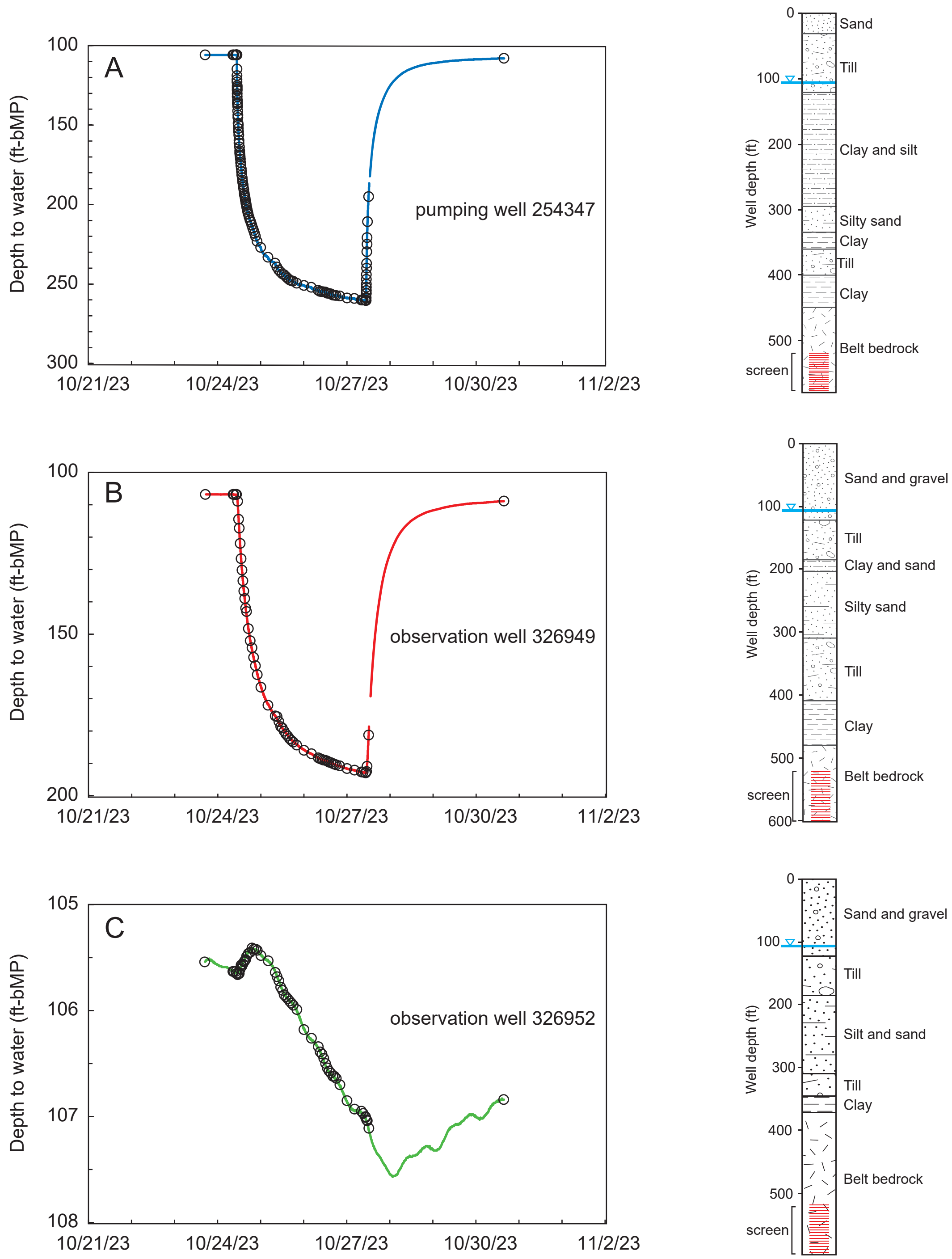

Figure 5. Site B hydrographs and well lithologies. Hydrographs include the measured pre-pumping, pumping, and recovery periods from transducers (lines) and manual sounder readings (circles). Note the different y-axis. On the lithologic logs the blue lines show the pre-test static water levels and red lines show the screened interval.

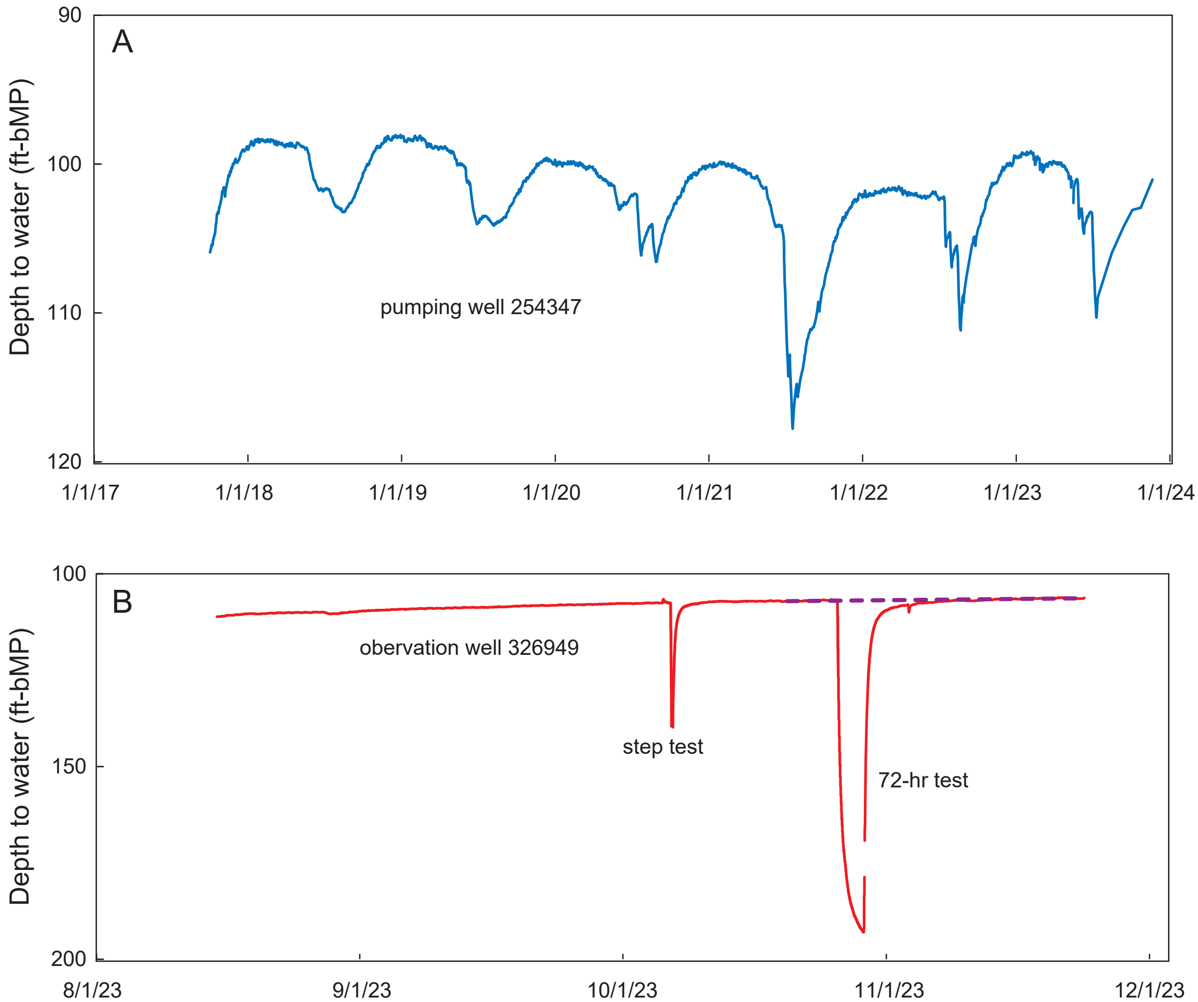

Figure 6. (A) Long-term monitoring of Site B pumping well 254347 shows that water levels peak in the winter, and then drop off with higher summer time pumping in the area. (B) During the testing period observation well 326949 shows an overall rise in groundwater levels, with an upward antecedent trend (purple dashed line) of about 0.022 ft/d.

to 10/30/2023 (fig. 5B). This transducer recorded at 15-min intervals, except that it recorded at 1-min intervals from 8:52 AM on 10/24/2023 to 12:23 PM on 10/27/2023 (mainly during the pumping period).

A vented transducer was installed in observation well 326952 for the 72-h test and recorded water levels from 10/23/2023 to 10/30/2023 (fig. 5C). This transducer recorded at 15-min intervals, except that it recorded at 5-min intervals from 8:50 AM on 10/24/2023 to 12:15 PM on 10/27/2023 (mainly during the pumping period).

Analysis Method

Monitoring results from the aquifer test were first evaluated on a composite plot (fig. 7A). This showed that the drawdown curves for pumping well 254347 and observation well 326949 were approximately parallel, suggesting that they are directly hydrologically connected through the bedrock fracture network. The drawdown curve for observation well 326952 falls well below the other wells' curves. It is much flatter (fig. 7A), which suggests that this observation well is not directly connected to the fracture network that the pumping well is withdrawing from. As such, data from well 326952 were not used for subsequent analyses.

The Theis step test, Hantush–Jacob, and Theis residual drawdown solution methods were used for analysis of this test (figs. 7B, 7C, 7D, respectively). The drawdown curves for pumping well 254347 and observation well 326949 were first fit using the Theis step-test solution (Theis, 1935), fitting to the periods where the derivative plots suggest IARF applies. While this approach fit the IARF portions of both drawdown curves well, it overestimated drawdown later in the test (fig. 7B). The shape of the derivative plots suggest that recharge is likely occurring due to leakage from the overlying bedrock and sediments (Renard and others, 2009; fig. 7B).

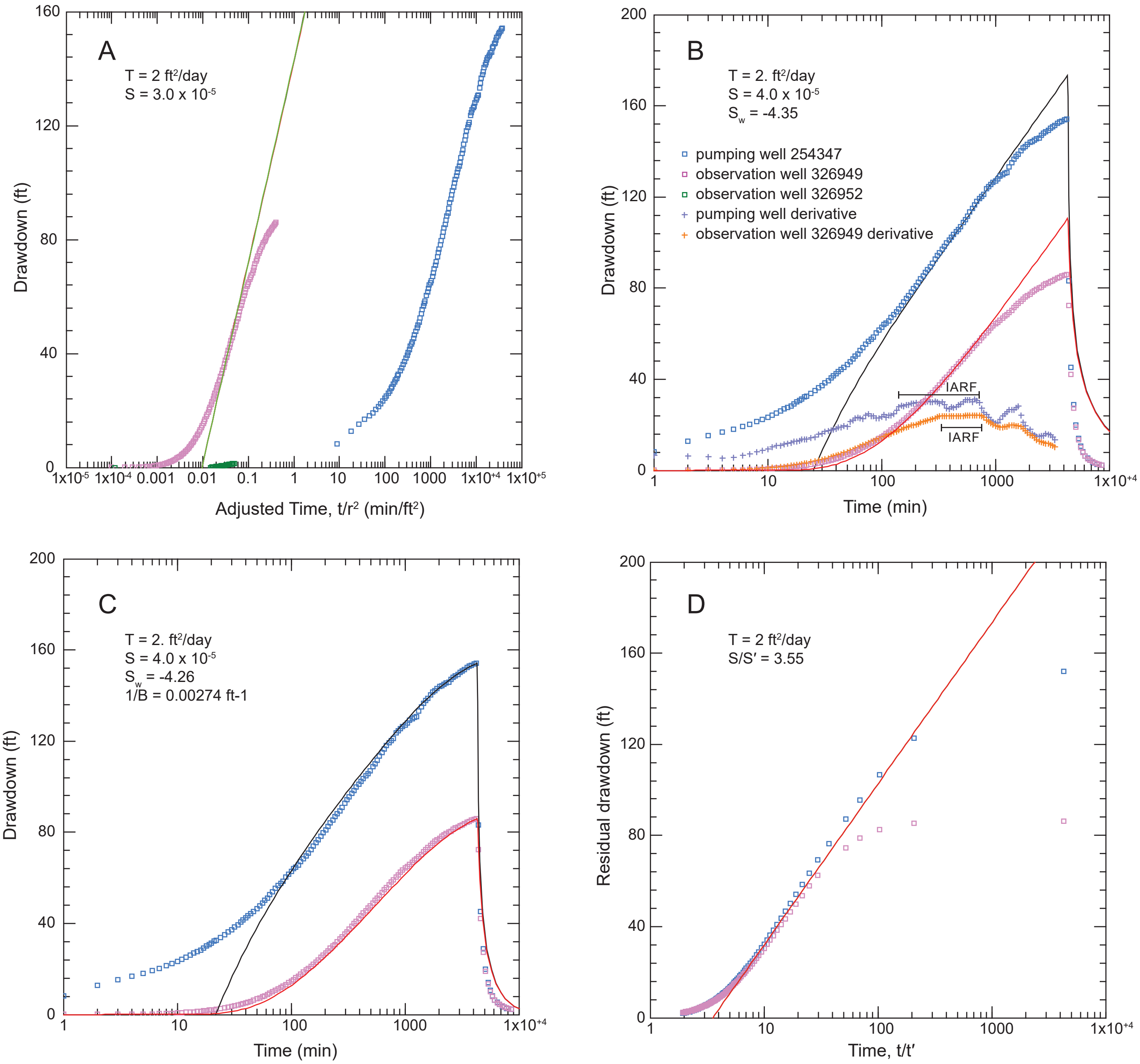

Figure 7. Analysis of constant-rate aquifer test at Site B. (A) Composite plot using a T of 2 ft²/d and a Cooper–Jacob solution. (B) Theis step-test solution, which incorporates a well bore skin factor (S_w) for the pumping well, and fit to the IARF periods. (C) Leaky-confined solution (Hantush–Jacob,1955) shows a good fit using the same T and S values as during the IARF period of B. (D) Analysis of recovery data is also consistent with a T of 2 ft²/d.

A good fit to the drawdown curves was achieved using the same T and S values determined using the Theis step-test solution during the IARF periods with the Hantush–Jacob solution for a leaky-confined aquifer (fig. 7C; Hantush and Jacob, 1955; Hantush, 1964). This solution adds leakage from the overlying materials.

The residual drawdown was also analyzed using the Theis recovery solution (fig. 7D; Theis, 1935). This resulted in a good fit to the recovery data using the same T as determined using the Theis step test and Hantush–Jacob methods.

Results

Water-Level Response

Groundwater levels in pumping well 254347 reached a maximum drawdown of 154.51 ft during the pumping portion of the test (fig. 5A, table 1). Water levels declined rapidly at the start of pumping, and then leveled off but did not completely flatten. At the end of the test the water levels rose somewhat slowly, with 27 h needed to reach 95% recovery.

Observation well 326949 responded similarly to the pumping well, but maximum drawdown was 86.14 ft (fig. 5B, table 1), and 42 h was needed to reach 95% recovery.

Observation well 326952 was indirectly affected by the pumping. It had a delayed response, with groundwater levels rising during the first 8.6 h of the test, and then generally but irregularly dropping (fig. 5C). The maximum drawdown was 1.92 ft, which occurred 14.8 h after the end of pumping. Recovery of this well was slow and not completely recorded, with it being only 38% recovered when transducers were removed on 10/30/2023 (fig. 5C). Water levels were 0.43 ft above the pretest levels at 3:12 PM on 11/21/2023.

Aquifer Properties

The composite plot shows that wells can be poorly connected even over short distances due to the complexities of the bedrock fracture network. The Theis step test and Hantush–Jacob solutions (Theis, 1935; Hantush and Jacob, 1955; Hantush, 1964) indicate a T of about 2 ft^2/d, an S of 4×10^{-5}, and an S_w of -4.26 (figs. 7B, 7C). The negative S_w value found in this bedrock aquifer, similar to Site A's sand and gravel aquifer, suggests enhanced aquifer permeability near the pumping well due to drilling and development. The Theis residual drawdown analysis of the recovery data is also consistent with a T of 2 ft^2/d (fig. 7D). For the Hantush–Jacob solution a leakage factor (1/B) of 0.00274 was estimated (fig. 7C). Using a saturated bedrock thickness of 150 ft, which is the thickness of bedrock encountered in the pumping well (fig. 5), the estimated K is 0.01 ft/d, which is consistent with reported values for fractured bedrock (Heath, 1983).

SITE C

Background

At Site C, three wells were monitored (table 1, fig. 1). These wells are all completed in what is interpreted as deltaic sediments deposited by the ancestral Tobacco River into Glacial Lake Kootenai.

The 72-h constant-rate test ran from 10:00 AM on 10/17/2023 to 10:00 AM on 10/20/2023. The time-weighted average pumping rate was 89.4 gpm, with measured discharge values ranging from 88.7 to 90.9 gpm. A VFD was used for the test and adjusted to maintain a steady pumping rate.

Well and Lithologic Descriptions

The MBMG installed the three wells at Site C (table 1) in July 2023.

Pumping well 327700 has a TD of 168 ft-bgs, and is screened from 158 to 168 ft-bgs (fig. 8A). Sand and gravel were encountered for the entire depth of this well, with the most fine-grained unit identified as a fine to medium sand layer from 119 to 150 ft-bgs (fig. 8A).

Observation well 327702 has a TD of 162 ft-bgs, and is screened from 152 to 162 ft-bgs (fig. 8B). It is completed in the same interval as the pumping well. This well is 119 ft north of the pumping well, on the north side of Overlook Road (fig. 1).

Observation well 327701 has a TD of 127 ft-bgs, and is screened from 122 to 127 ft-bgs (fig 8C). It was completed in the top of the fine to medium sand layer to evaluate vertical conductance. This well is 5.2 ft north of the pumping well (fig. 1).

Hydrogeologic Features

The Tobacco River and its associated alluvium are generally to the south of Site C (fig. 1). At its closest point, the Tobacco River is approximately 1,500 ft to the southeast.

Site-Specific Data Collection

A vented transducer in pumping well 327700 recorded from 10/10/2023 to 10/23/2023 (fig. 8A). This transducer recorded at 15-min intervals from 3:45 PM on 10/10/2023 to 2:15 PM on 10/16/2023. Subsequently, it recorded at 5-min intervals until 8:36 AM on 10/17/2023, followed by 1-min intervals until 11:36 AM on 10/20/2023 (mainly during the pumping portion of the test). Recovery was monitored at 15-min intervals until 3:15 PM on 10/23/2023.

A vented transducer in observation well 327702 recorded from 10/10/2023 to 10/23/2023 (fig. 8B). This transducer recorded at 15-min intervals from 4:15 PM on 10/10/2023 to 2:45 PM on 10/16/2023, then at 5-min intervals until 11:45 AM on 10/20/2023 (through the pumping portion of the test), and then at 15-min intervals until 3:00 PM on 10/23/2023.

Background water levels were collected throughout the testing period using an unvented transducer in observation well 327702, recording hourly from

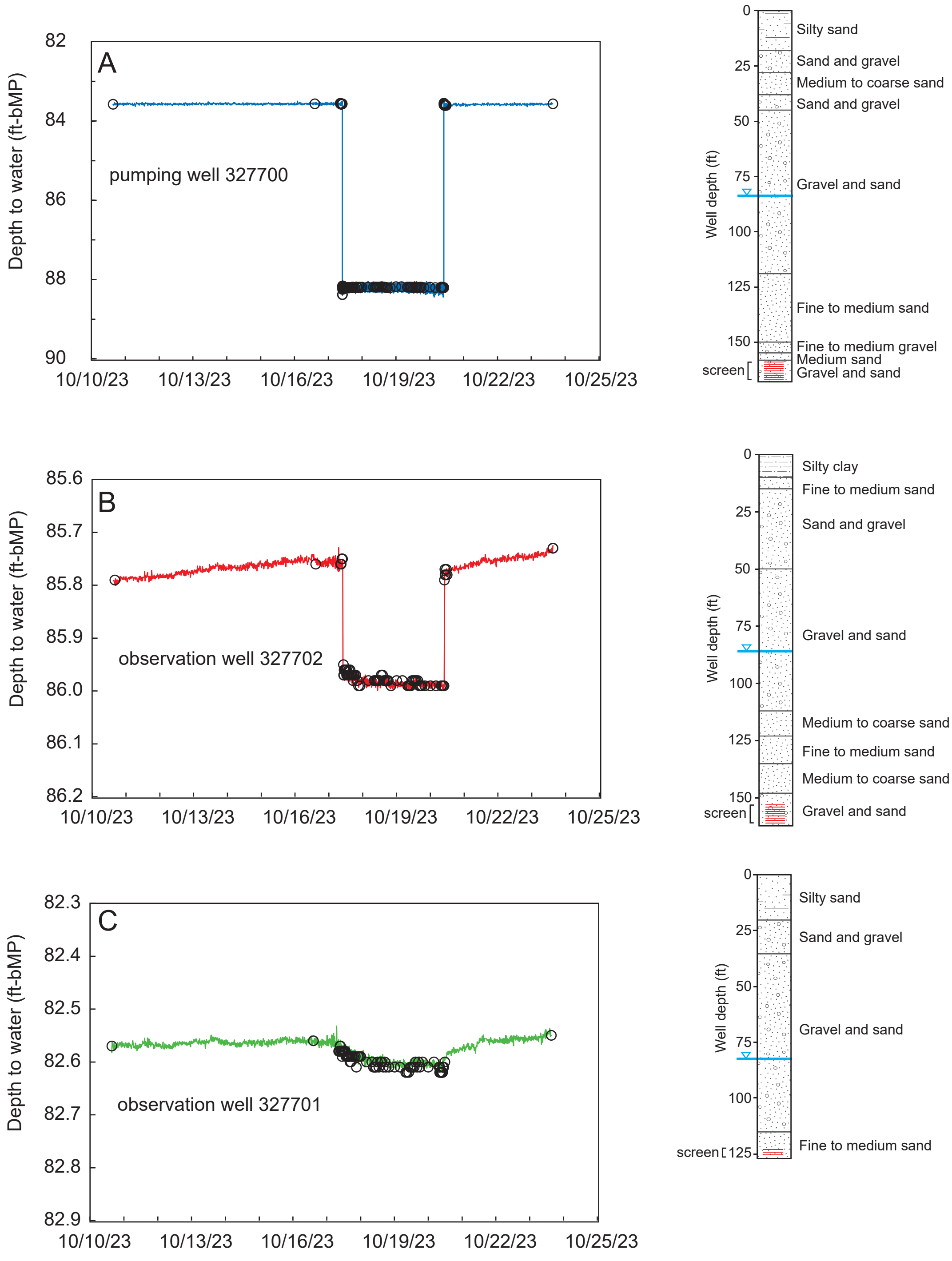

Figure 8. Site C hydrographs and well lithologies. The hydrographs include the measured pre-pumping, pumping, and recovery periods from transducers (lines) and manual sounder readings (circles). Note the different y-axis. On the lithologic logs the blue lines show the pre-test static water levels and red lines show the screened interval.

8/14/2023 to 11/21/2023 (fig. 9). These data indicate a trend of rising groundwater levels over this period. During the 72-h test, an antecedent trend of about 0.006 ft/d was removed from the test data for all wells prior to analysis.

A vented transducer in observation well 327701 recorded from 10/10/2023 to 10/23/2023 (fig. 8C). This transducer recorded at 15-min intervals from 3:45 PM on 10/10/2023 to 2:15 PM on 10/16/2023, at 5-min intervals until 11:35 AM on 10/20/2023 (covering the pumping portion of the test), and then at 15-min intervals until 3:15 PM on 10/23/2023.

Analysis Method

Aquifer test data were first evaluated on a composite plot, using a Cooper–Jacob straight-line solution (fig. 10A). This showed that the drawdown curves were approximately parallel, suggesting that they are directly hydrologically connected. Shallow observation well 327701 exhibited less drawdown than observation well 327702, reflecting vertical anisotropy in the aquifer.

The drawdown curves were then fit using the Moench solution for unconfined aquifers (Moench, 1997), resulting in a good fit (figs. 10B, 10C). Adding the Tobacco River as a constant-head boundary was tested; however, it did not cause changes in aquifer properties or change the curve fits, suggesting that the Tobacco River had little effect on the aquifer test. Analysis of the residual drawdown was conducted using the Theis recovery solution (fig. 10D; Theis, 1935).

Results

Water-Level Response

Groundwater levels in pumping well 327700 dropped rapidly when pumping began and then remained stable until the end of pumping (figs. 8A, 10B). The maximum drawdown was 4.87 ft (fig. 8A, table 1). When pumping ceased, groundwater levels quickly returned to pre-test levels, with 95% recovery occurring in less than 1 min.

Groundwater levels in observation wells 327702 and 327701 dropped more slowly than in the pumping well, and were slower to recover. Observation well 327702 had up to 0.24 ft of drawdown (fig. 8B, table 1), while observation well 327701 had up to 0.05 ft of drawdown (fig. 8C, table 1). About 1 day was needed to reach 95% recovery in both observation wells.

Aquifer Properties

The Moench solution (Moench, 1997) indicates a T of about 189,000 ft^2/d, an S of 3 x 10^{-3}, a specific yield (S_y) of 0.01, and an S_w of 29.5 (figs. 10B, 10C). This positive S_w value suggests reduced aquifer permeability near the pumping well due to drilling, partial penetration, and well screen limitations. The Theis residual drawdown analysis of the recovery data is also consistent with a T of 189,000 ft^2/d (fig. 10D). Using a saturated thickness of 100 ft based on the observed saturated thickness at this site (fig. 8), the estimated K is about 1,890 ft/d, which is consistent with reported values for gravel aquifers (Heath, 1983). The aquifer vertical anisotropy factor [vertical hydraulic conduc-

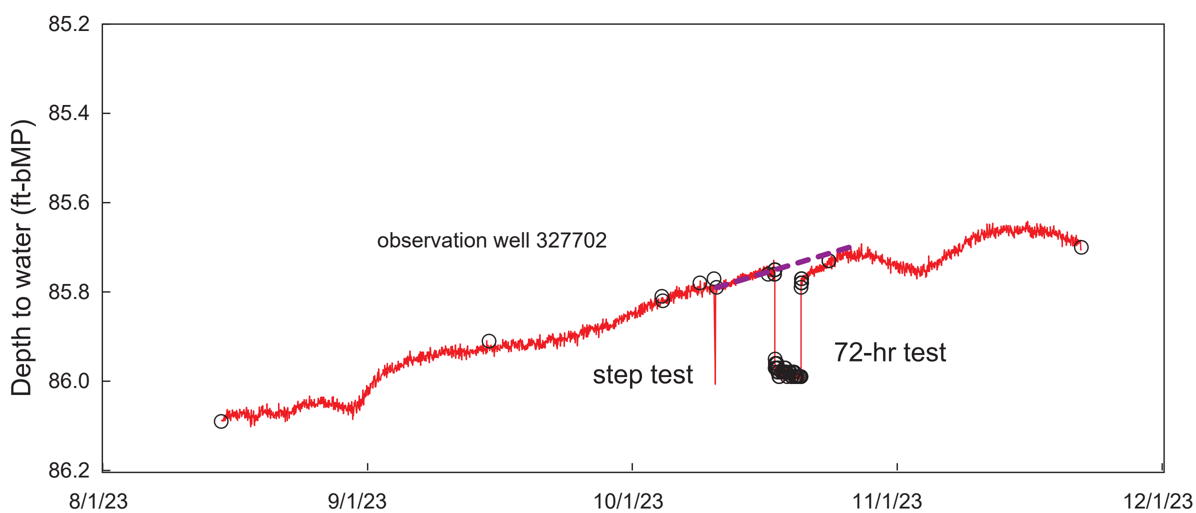

Figure 9. Groundwater levels rose overall at Site C as shown at observation well 327702. During the 72-hr test there was an upward antecedent trend (purple dashed line) of about 0.006 ft/d.

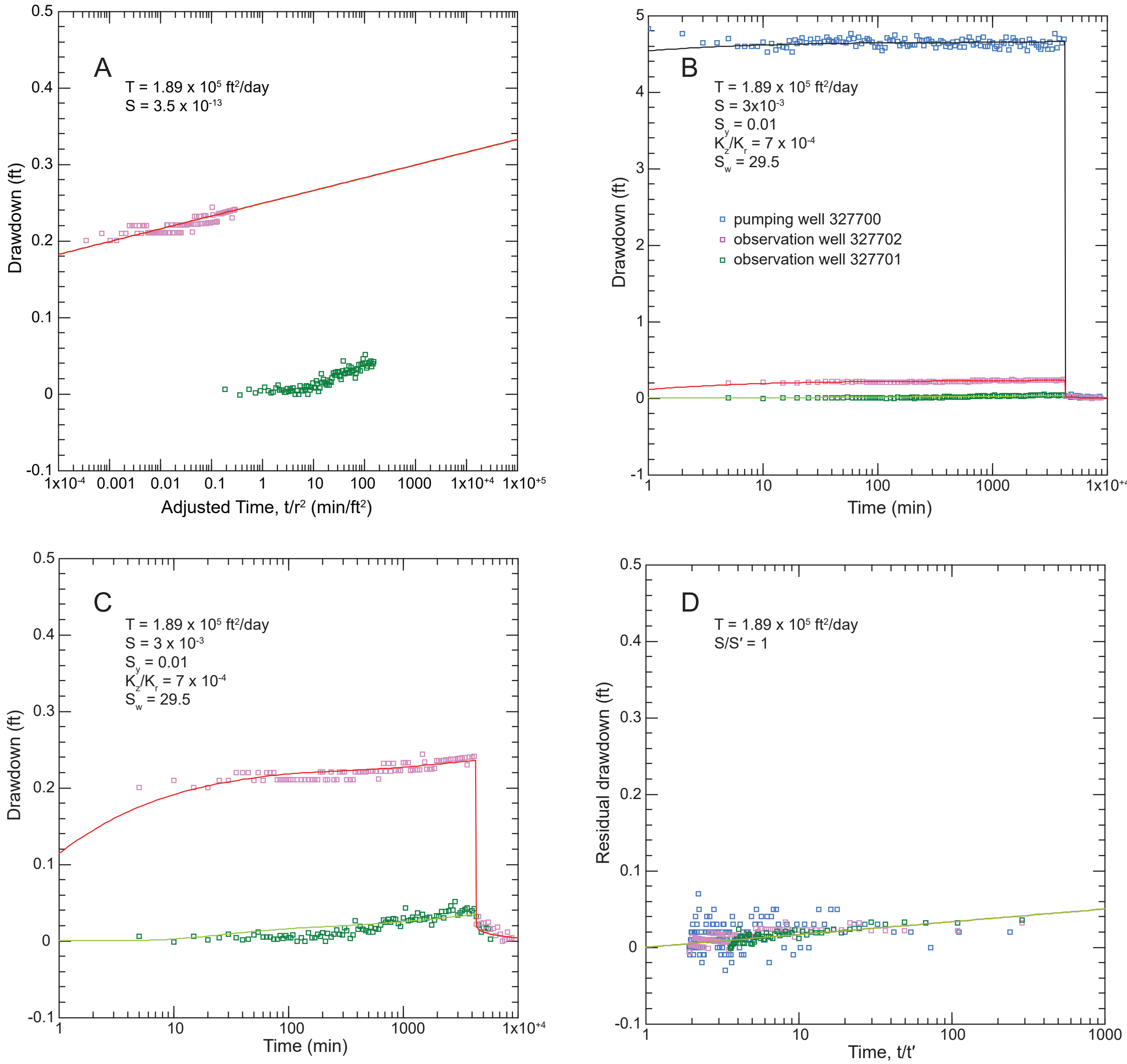

Figure 10. Analysis of constant-rate aquifer test at Site C. (A) Composite plot for the observation wells using a T of 189,000 ft^2/d. (B) Moench solution for unconfined aquifers. (C) Zoom in of B to show observation well fits. (D) Analysis of recovery data is also consistent with a T of 189,000 ft^2/d.

tivity (K_v)/radial hydraulic conductivity (K_r)] was 0.007, which indicates a K_v value of about 1.3 ft/d, which would be representative of the least permeable layer, and is consistent with reported values for fine sand (Heath, 1983).

SUMMARY

These aquifer tests reveal significant variations in hydraulic conductivity (K values) for aquifers in the Tobacco Valley, ranging by about five orders of magnitude (from 0.01 to 1,890 ft/d). This range reflects the highly variable aquifer materials, from bedrock to gravel. The solutions for the aquifer tests show that aquifers in the area range from well-confined (Site A) to unconfined (Site C).

The productivity of wells completed in the Tobacco Valley will vary depending on the type of materials they are completed in. The distribution of sediments is highly variable, as is common in glacial depositional systems (Menzies, 1997). The aquifer properties estimated from these tests will be used to guide the development of groundwater flow models for the area, which are intended to provide a more robust understanding of the groundwater flow system.

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REFERENCES

Alden, W.C., 1953, Physiography and glacial geology of western Montana and adjacent areas: U.S. Geological Survey Professional Paper 231, 200 p., https://doi.org/10.3133/pp231.

Coffin, D.L., Brietkrietz, A., and McMurtrey, R.G., 1971, Surficial geology and water resources of the Tobacco and upper Stillwater River valleys, northwestern Montana: Montana Bureau of Mines and Geology Bulletin 81, 52 p., 4 sheets.

Duffield, G.M., 2007, AQTESOLV for Windows Version 4.5 User's Guide, HydroSOLVE, Inc., Reston, VA.

Garland, G.D., Kanasewich, E.R., and Thompson, T.L., 1961, Gravity measurements over the southern Rocky Mountain Trench area of British Columbia: Journal of Geophysics Research, v. 66, no. 8, p. 2495–2505, https://doi.org/10.1029/JZ066i008p02495.

Gotkowitz, M.B. (ed.), 2023, Standard procedures and guidelines for field activities, Montana Bureau of Mines and Geology, Version 2: Montana Bureau of Mines and Geology Open-File Report 758, 99 p., https://doi.org/10.59691/UUYM4848

Hantush, M.S., 1964, Hydraulics of wells, *in* Advances in Hydroscience, Chow, V.T., ed., Academic Press, New York, p. 281–442.

Hantush, M.S., and C.E. Jacob, 1955, Non-steady radial flow in an infinite leaky aquifer: American. Geophysical Union Transactions, v. 36, p. 95–100, https://doi.org/10.1029/TR036i001p00095

Hanson, M.A., Lian, O.B., and Clague, J.J., 2012, The sequence and timing of large late Pleistocene floods from glacial Lake Missoula: Quaternary Science Reviews, v. 31, p. 67–81, https://doi.org/10.1016/j.quascirev.2011.11.009

Harrison, J.E., Cressman, E.R., and Whipple, J.W., 1992, Geologic and structure maps of the Kalispell 1° x 2° quadrangle, Montana, and Alberta and British Columbia: USGS Miscellaneous Investigations Series Map I-2267, 2 sheets, scale 1:250,000.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, https://doi.org/10.3133/wsp2220

LaFave, J.,I, Smith, L.N., and Patton, T.W., 2004, Ground-water resources of the Flathead Lake Area: Flathead, Lake, and parts of Missoula and Sanders counties: Part A—Descriptive overview: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-A, 144 p.

Menzies, J., 1997, Modern glacial environments: Processes, dynamics, and sediments: Butterworth-Heinemann, Oxford, UK.

Moench, A.F., 1997, Flow to a well of finite diameter in a homogeneous, anisotropic water-table aquifer: Water Resources Research, v. 33, no. 6, p. 1397–1407, https://doi.org/10.1029/97WR00651

Renard, P., Glenz, D., and Mejias, M., 2009, Understanding diagnostic plots for well-test interpretation: Hydrogeology Journal, v. 17, no. 3, p. 589–600, https://doi.org/10.1007/s10040-008-0392-0

Rice, H.M.A., 1937, Cranbrook map area, British Columbia: Canada Geological Survey Memoir, v. 207, 67 p.

Smith, L.N., 2004, Surficial geologic map of the upper Flathead River valley (Kalispell valley) area, Flathead County, northwestern Montana: Montana Bureau of Mines and Geology Montana Ground-Water Assessment Atlas 2-B-06, 1 sheet, scale 1:70,000.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union Transactions, v. 16, p. 519–524, https://doi.org/10.1029/TR016i002p00519