ANALYSES OF CONSTANT-RATE AQUIFER TESTS IN THE QUATERNARY–TERTIARY BASIN-FILL SEDIMENTS AND THE TERTIARY–ARCHEAN FRACTURED BEDROCK NEAR ENNIS, MONTANA

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Cover photo: Aquifer test site D overlooking subdivision growth near Ennis, Montana. Photo by Ann Hanson, MBMG.

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ABSTRACT

Groundwater from Quaternary–Tertiary basin-fill sediments and from Tertiary–Archean fractured bedrock units is used to support residential development in the Madison Valley, near Ennis, Montana. The Quaternary–Tertiary sediments are generally <340 ft deep and quickly pinch out to bedrock on the west side of the valley; therefore, fractured bedrock is the primary source of water for residents in growing subdivisions west of the valley bottom. Wells completed in the fractured bedrock produce a variable amount of water, with some wells being abandoned due to insufficient water for residential needs.

To assess the range of transmissivities for the different hydrogeologic units, the Montana Bureau of Mines and Geology Ground Water Investigation Program conducted five constant-rate aquifer tests in three areas of development. Transmissivities, hydraulic conductivities, and storativities (when possible) were calculated primarily using the Cooper–Jacob (1946) solution, but values were compared with other pumping and recovery solutions.

Transmissivity is highest in shallow Quaternary–Tertiary sediments at 1,400 ft^2/d (hydraulic conductivity of 20 ft/d) with a storativity of 5.5×10^{-4}. The deeper Tertiary sediments have a transmissivity of 75 ft^2/d (hydraulic conductivity of 0.5 ft/d). Highly fractured Cretaceous intrusive rocks have a transmissivity of 240 ft^2/d (hydraulic conductivity of 1 ft/d) and a storativity of 7.0×10^{-4}. Archean metamorphic bedrock has a transmissivity of 55–60 ft^2/d (hydraulic conductivity of 0.1 ft/d). Two wells completed in Archean bedrock had insufficient water production to conduct aquifer tests. Linear flow behavior, which is indicative of flow through fractures, was apparent in diagnostic plots for the Cretaceous bedrock aquifer test, the deep Tertiary sediments aquifer test, one of the two Archean bedrock aquifer tests, and both of the low-production Archean bedrock wells. Since locations of fractures can be highly variable, the transmissivities for the deep Tertiary sediments and Tertiary–Archean bedrock units should be considered local estimates, with transmissivities interpreted to be heterogenous throughout these units. Wells will need to be individually tested to predict the amount of groundwater they can provide.

PURPOSE OF AQUIFER TESTS

Variable well productivity from bedrock aquifers on the west side of the Madison Valley near Ennis results in an inconsistent water source for ongoing residential development. Development has been focused primarily in:

1. the Virginia City Ranches and Pronghorn Meadow subdivisions southwest of Ennis,
2. the neighborhoods within 1.5 mi of the town of Ennis (hereafter referred to as the Ennis area), and
3. the North Meadow Creek area northwest of McAllister.

Aquifer tests were conducted in these three areas to quantify transmissivities and storativities in the study area (figs. 1A–1E). The range of these aquifer properties can be used to better understand water availability and to help inform development decisions on the west side of the Madison Valley.

HYDROGEOLOGIC SETTING

The Madison Valley is a north–south-trending basin with Quaternary–Tertiary unconsolidated to semi-consolidated basin-fill sediments that overly Tertiary–Archean bedrock (Kellogg and others, 2007). The Quaternary–Tertiary sediments extend from north to south on the east side of the study area (fig. 1), but thin to the west where bedrock outcrops. The Quaternary–Tertiary sediments and the Tertiary–Archean fractured bedrock are water-bearing and can be hydrologically connected locally, forming an aquifer system. The hydrogeology of the three primary development areas discussed in this study is described in more detail below.

In the Virginia City Ranches and Pronghorn Meadows subdivisions, the Quaternary–Tertiary sediments are up to about 280 ft deep (MBMG, 2023) and overlie Archean metamorphic bedrock. Tertiary volcanics are interspersed between the Archean bedrock and Quaternary–Tertiary sediments. Where possible, wells are completed in the Quaternary–Tertiary sediments

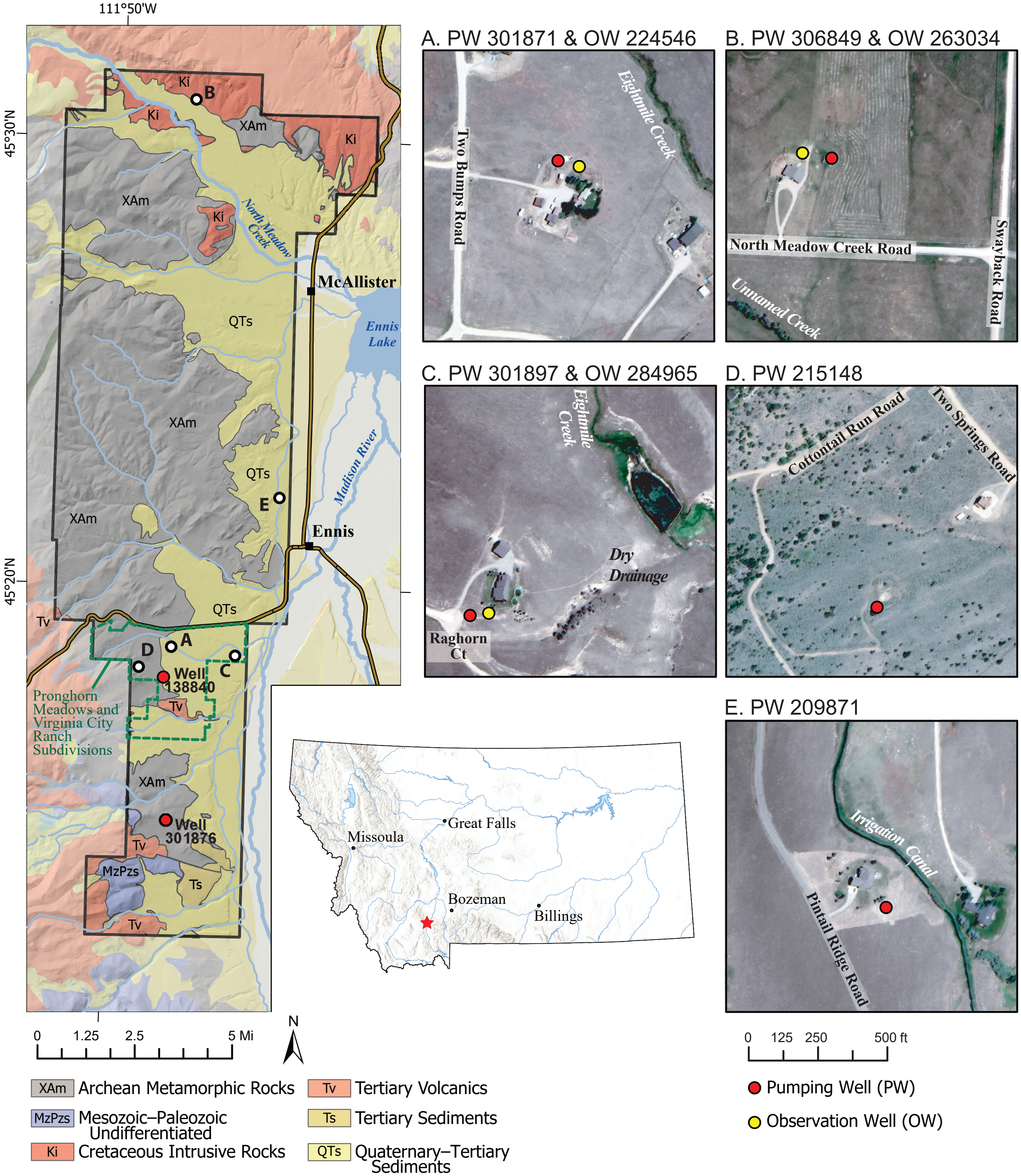

Figure 1. Geology of the study area simplified from Kellogg and Williams (2006). Locations of the five aquifer tests (sites A–E) are shown on the map with aerial photos of the sites to the right. Locations of the two low production wells (138840 and 301876) are also shown on the map.

(e.g., sites A and C; figs. 1A, 1C); however, the Archean metamorphic rocks are the primary bedrock water source in this area (e.g., site D; fig. 1D).

The Ennis area has Quaternary–Tertiary sediments up to 340 ft deep that pinch out to the west (MBMG, 2023). Thus, similar to the Virginia City Ranches and Pronghorn Meadow subdivisions, the underlying Archean metamorphic rocks (e.g., site E; fig. 1E) serve as the primary water source where the Quaternary–Tertiary sediments are too thin or absent.

Northwest of McAllister in the North Meadow Creek area, the Quaternary–Tertiary sediments overlie a Cretaceous batholith (the Tobacco Root Batholith) that intruded the Archean metamorphic bedrock. The Quaternary–Tertiary sediments are a reliable water source, though they are laterally limited and generally less than 160 ft deep. The intrusive batholith is composed primarily of fractured granite and diorite and is the primary water source in this area (e.g., site B; fig. 1B). At the time of this study, fewer than 20 wells had been completed in the Archean bedrock in the North Meadow Creek area (MBMG, 2023).

GENERAL FIELD PROCEDURES

All field procedures were conducted in accordance with the Montana Bureau of Mines and Geology (MBMG) standard operating procedures (Gotkowitz, 2023). Step-tests were conducted prior to the constant-rate tests to determine the appropriate pumping rate for each test, but were not used for analysis and are not discussed in this report. General aquifer-test procedures are described here with any pertinent additional information discussed in the “Site-Specific Data Collection” sections below.

All aquifer tests were conducted at residential dwellings where the primary water use is for household applications and lawn/garden irrigation, except for site D (fig. 1D; well 215148), which is currently unused. No water was pumped for domestic use during the aquifer tests and as little as possible during the recovery. At each site, the pumping wells and observation wells partially penetrated the aquifer unit being tested.

For each test, the wells were pumped at a constant rate, and a totalizing flow meter installed on the discharge line tracked the amount of water pumped. The flow rate was calculated using manual readings of the totalizer at timed intervals throughout the test. Manual discharge measurements were taken periodically to validate the recorded discharge.

Each well was equipped with a pressure transducer to continuously monitor water levels. Before and after the test, the transducers were programmed to record hourly measurements to detect any pre- or post-test water-level trends. During the test and the recovery period, the transducers recorded at least every minute. Manual depth-to-water measurements were taken with an electric tape to validate transducer records and provide a failsafe in case of transducer failure. Recovery was monitored at the same manual interval as the start of the test until water levels had reached greater than 95% of pre-pumping levels or until residential use of the groundwater resumed.

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 numbers.

METHODS OF ANALYSIS

Aquifer test drawdown and recovery data were analyzed using AQTESOLV software (Duffield, 2007). Early-time data were used to identify radial and linear flow, which can indicate borehole storage and fracture flow, respectively. Final transmissivity and storativity (when observation wells were monitored) for each of the aquifer tests were determined using a Cooper–Jacob (1946) solution. Where recovery data could be analyzed, the pumping and recovery results were compared to refine transmissivity estimates.

The Cooper–Jacob (1946) solution assumes the aquifer is confined, of infinite extent, homogeneous, and has horizontal flow, and that the pumping well fully penetrates the entire thickness of the aquifer. Additional assumptions can be found in Cooper and Jacob (1946). In all of the tests described below, more than one of these assumptions was not valid. However, based on the mid- to late-time drawdown data and the derivative data, the aquifer being tested responded as a confined aquifer with infinite-acting radial flow (IARF); thus, the Cooper–Jacob (1946) solution was appropriate for estimating aquifer properties. The derivatives of the drawdown data were used to interpret periods of IARF conditions and aquifer boundaries.

For the fractured-rock aquifer tests, the Barker (1988) curve-matching solution was attempted (sites B, D, and E). Barker (1988) provides a solution for flow in single-porosity fractured rock. However, the single-porosity solution has five unknowns, including hydraulic conductivity, specific storage, flow dimension, extent of flow regime, and wellbore skin—many of which are correlated in the equation. Since the aquifer tests conducted in this study were single-well or two-well tests, the number of unknown variables to known datasets resulted in nonunique solutions. For the late-time data, the Barker (1988) solution simplifies to the Cooper–Jacob (1946) solution when assuming two-dimensional flow. Therefore, without record of aquifer response from more wells or subsurface information on the location and orientation of fractures in the aquifer, the Cooper–Jacob (1946) solution was considered an appropriate solution technique.

Recovery measurements were matched to the Theis (1935) recovery solution and/or analyzed with the Cooper–Jacob (1946) straight-line solution after the data were transformed using the Agarwal (1980) method. The Agarwal (1980) method calculates recovery using an equation with max drawdown and residual drawdown; the reader is referred to Agarwal (1980) and/or Duffield (2007) for more details.

A summary of the site details and results are given in table 1.

SITE A: PUMPING WELL 301871 AND OBSERVATION WELL 224546

Background

Test Location

Site A is in the Virginia City Ranches subdivision located 4.5 mi southwest of Ennis along Two Bumps Road (fig. 1A). The pumping well (301871) was installed for this study; the observation well was residential well 224546.

Well Descriptions

The pumping well and the observation well are both 80 ft deep and 73 ft apart (fig. 1A). The lithology at the pumping well is unconsolidated silty clay with gravels to 25 ft below ground surface (bgs); below that is fine sand with semi-cemented fragments to 80 ft (fig. 2A). The well is screened from 60 to 80 ft bgs.

Table 1. Summary of the well details, including surveyed elevations and results for the analyzed aquifer tests near Ennis.

Site	Aquifer	GWIC ID number	Well type[a]	Depth (bgs, ft)[b]	Top of casing (measuring point) elevation (ft)	Well stick-up height (ft)	Static water level[c] (ft)	Maximum drawdown (ft)	Estimated transmissivity (ft^2/day)	Estimated hydraulic conductivity (ft/day)	Estimated storativity
A	Quaternary–Tertiary sediments	301871	PW	80	5,434.03	1.35	39.62	10.99	1,400	20	5.5×10^{-4}
		224546	OW	80	5,428.27	2.55	34.39	1.36			
B	Cretaceous intrusive rocks	306849	PW	186	5,558[d]	2.00	49.98	54.15	240	1	7.0×10^{-4}
		263034	OW	196	5,561.70	2.00	56.50	5.57			
C	Tertiary sediments	301897	PW	220	5,213.37	1.00	126.80	59.78	75	0.5	N/A
		284965	OW	218	5,213.31	1.55	128.04	2.14			
D	Archean metamorphic bedrock	215148	PW	508	5,810.04	2.43	72.24	103.81	60	0.1	N/A
E	Archean metamorphic bedrock	209871	PW	405	4,993.87	2.18	45.72	112.86	55	0.1	N/A

Notes:
[a] PW indicates pumping well, OW indicates observation well.
[b] bgs, below ground surface.
[c] Static measured below top of casing.
[d] Well was drilled after surveying was completed. Elevation estimated from DEM (USGS, 2023).

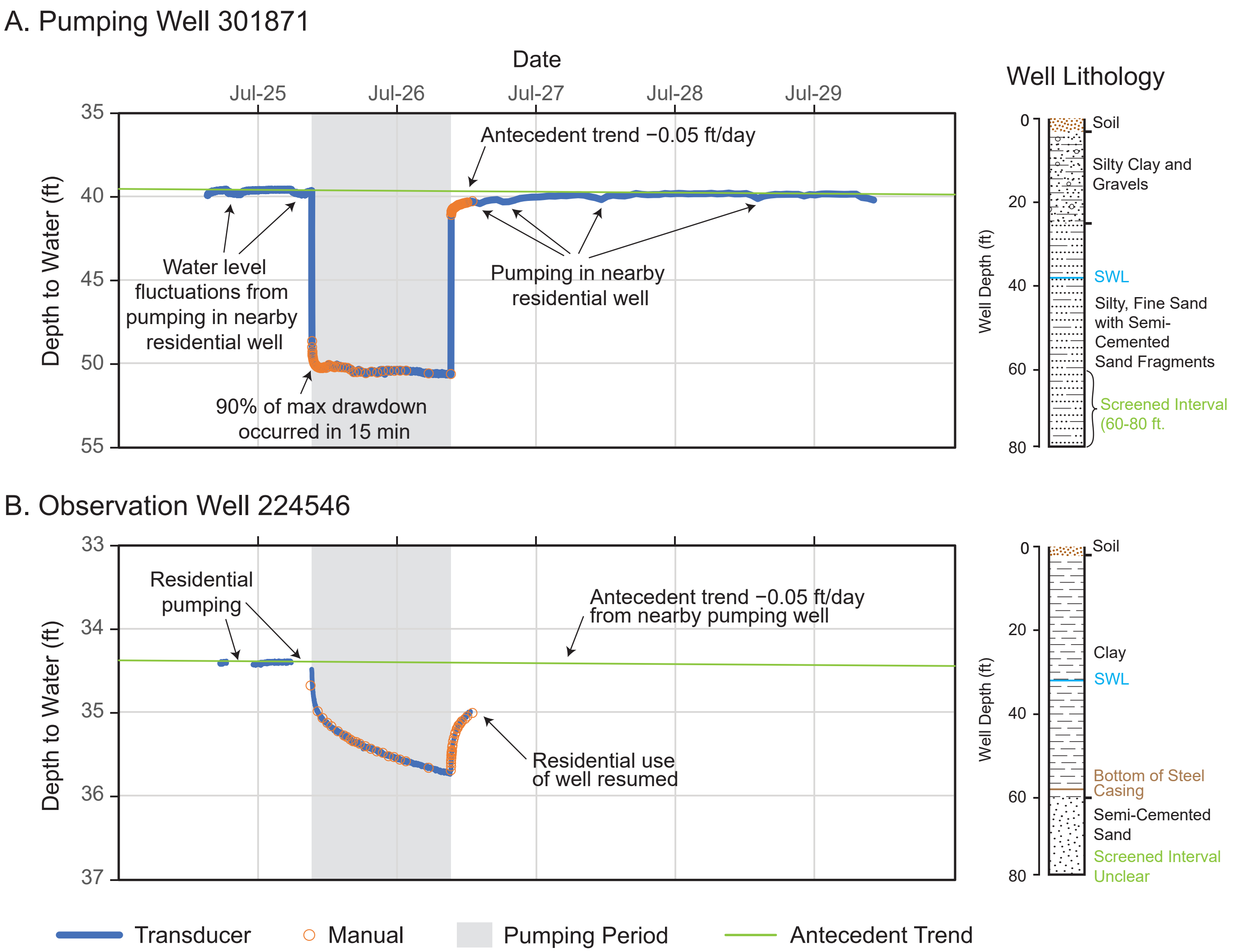

Figure 2. Site A hydrographs and well lithology of the pumping well 301871 (A) and observation well 224546 (B). Hydrographs include the measured background, pumping period, and recovery. Measurements in the observation well affected by domestic pumping before and after the aquifer test were not included. Note the different y-axis scales. SWL, static water level.

The well log for the observation well indicates clay down to 60 ft with sandstone (interpreted to be semi-cemented sand) between 60 and 80 ft bgs. There is no record of the well screen for the observation well; it is assumed to be screened below 60 ft. The pumping and observation well are interpreted to be completed in the Quaternary–Tertiary sediments (fig. 1).

Prior to the test, the pumping well had a static groundwater level of 39.62 ft below the top of the well casing (TOC) and the static level in the observation well was 34.39 ft below TOC (table 1).

Surface-Water Features

Eightmile Creek is approximately 400 ft from the pumping and observation wells (fig. 1A). A discharge of 0.10 and 0.25 cubic feet per second (cfs) was measured at two sites just upstream and downstream, respectively, of the aquifer test. These measurements were made following test recovery, but are assumed to be representative of streamflow during the aquifer test. The effect of the aquifer test on the stream was not monitored.

Site-Specific Data Collection

Well 301871 was pumped at about 13 gallons per minute (gpm) for 24 h starting July 25, 2019 at 9:15 a.m. (fig. 2A). It took 4 min for the pumping rate to reach 13 gpm and it remained nearly constant for the rest of the test, ranging between 12.4 and 13.4 gpm. Recovery was monitored for 73 h after pumping stopped. Residential use of the observation well 224546 occurred prior to the start of the aquifer test (fig. 2B), but was allowed to recover back to <0.10

ft of static before the aquifer test began. There were slight, <0.15 ft water-level fluctuations observed in the pumping well during the aquifer test, presumably from nearby residential pumping approximately 160 ft away (fig. 2A). Water from the pumping well during the aquifer test was discharged downslope into Eightmile Creek.

Results

Static water levels measured in the pumping well before and after the test decreased approximately 0.05 ft/d. There were not enough pre- and post-data for the observation well to determine changes in static water level. Therefore, a linear correction for the antecedent trend was applied to both the pumping and observation well data before analysis. A time-weighted average pumping rate of 13.2 gpm was used for test analyses.

Water-Level Response

The water level dropped 10 ft in the pumping well within the first 15 min of the test (90% of max drawdown). Over the remainder of the test, water levels decreased an additional 0.99 ft for a maximum drawdown of 10.99 ft (table 1; fig. 2A). After pumping stopped, the water level recovered to 1 ft pre-test static in about 20 min. The pumping well recovered 95% (10.44 ft) in approximately 6 h. However, the pumping-well recovery data were impacted by the resumption of residential pumping after 3.5 h; therefore, recovery data after this time were not used for the analysis.

In the observation well (224546), 73 ft away, drawdown was noted within the first minute of the test; the maximum drawdown reached 1.36 ft (table 1; fig. 2B). The observation well recovered 55% (0.75 ft) in 3.5 h before residential pumping resumed.

Aquifer Properties

The pumping- and observation-well drawdown data do not indicate radial or linear flow, suggesting that wellbore storage and fracture flow did not influence the results. The pumping well has irregular changes in the drawdown after 100 min (fig. 3A), possibly due to nearby residential pumping, that make aquifer boundaries difficult to interpret. However, the derivative of the observation well data shows that the aquifer reached IARF conditions (e.g., derivative curve is approximately flat applying the "smoothing" technique = 2) between 10 and 100 min (fig. 3B). The drawdown and the derivative data from the observation well show a deviation from the Theis (1935) curve after approximately 100 min. The late-time drawdown is greater than that expected by the matched solution, suggesting a no-flow boundary was reached (Renard and others, 2009). The no-flow boundary is interpreted to be the contact between the Quaternary–Tertiary sediments and less permeable bedrock.

Cooper–Jacob (1946) solutions for the mid-time data in the observation well and the mid- to late-time data in the pumping well yield an estimated transmissivity of 1,400 ft^2/d for the Quaternary–Tertiary sediments (fig. 3A; table 1). The slope of the Theis (1935) straight-line solution for the pumping data agreed with the observation-well data, giving an estimated transmissivity of 1,400 ft^2/d (fig. 3C). The Theis (1935) recovery solution also computes a value for S/S′ (storativity during pumping divided by storativity during recovery) of 0.083 (fig. 3C). A S/S′ <1 can indicate a no-flow boundary (AQTESOLV, 2023)—consistent with the derivative data interpretation from the observation well. Data from the observation well indicate a storativity of 5.5×10^{-4} (fig. 3A; table 1).

SITE B: PUMPING WELL 306849 AND OBSERVATION WELL 263034

Background

Test Location

Site B is in the Meadow Creek Ranch development on the corner of North Meadow Creek Road and Swayback Road (fig. 1B). Two wells were measured during the test: the pumping well (306849), which was installed for the study, and an observation well (263034), which is an existing residential well.

Well Descriptions

The pumping well (306849) is 186 ft deep. The lithology at the pumping-well site is dominantly fractured granite that is weathered to sands and gravels (fig. 4A) at the surface and at depth where the granite is highly fractured. Water was encountered between 150 and 180 ft bgs during drilling. The well was screened from 143 to 183 ft bgs; the static groundwater level was 49.98 ft below TOC prior to the start of the test (table 1).

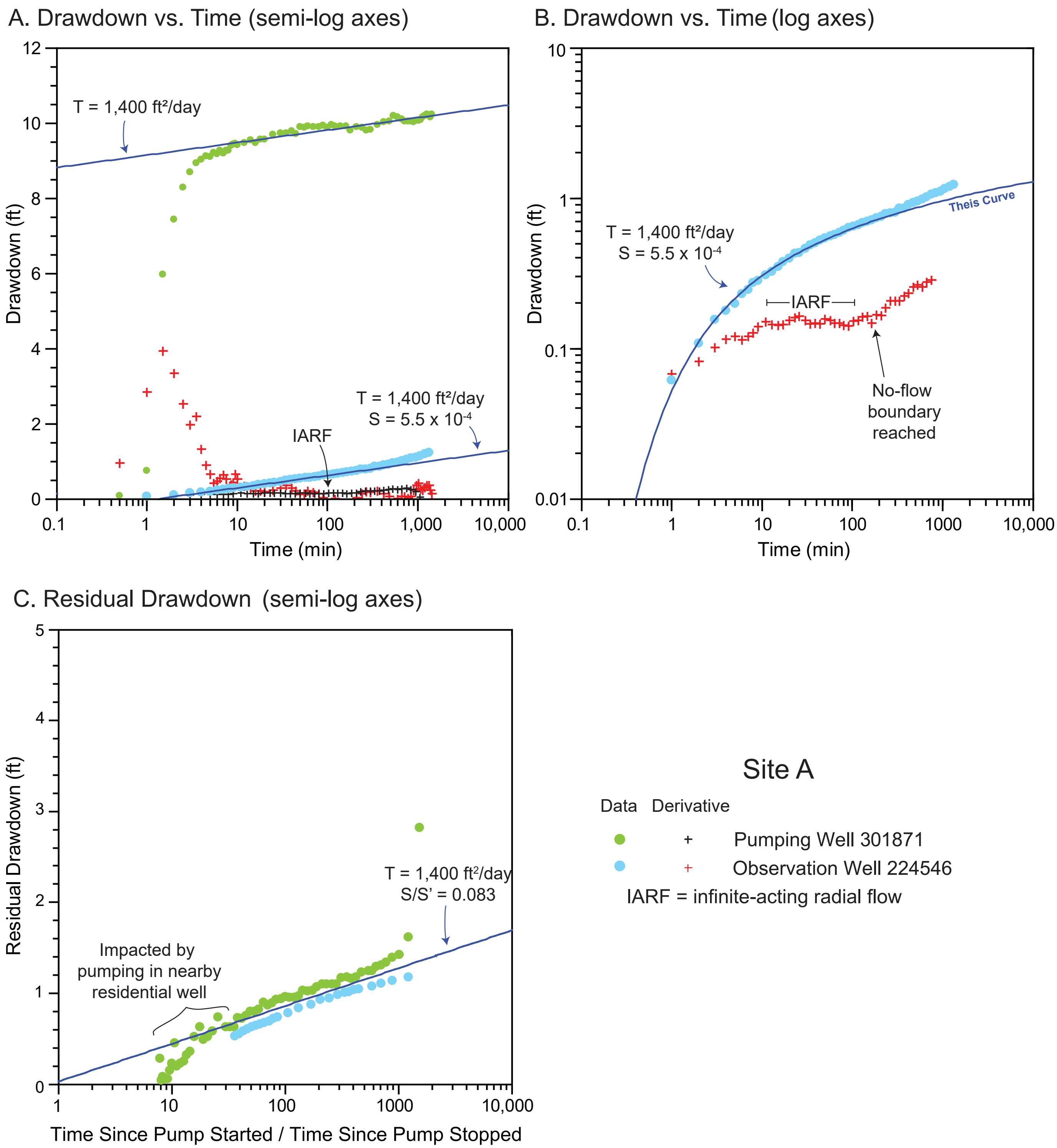

Figure 3. (A) Data from the pumping and observation well at site A show approximately parallel late-time slopes with a transmissivity of 1,400 ft²/d on a drawdown vs. time plot with semi-log axes. (B) Deviation from the Theis curve during the late-time data suggests a no-flow boundary. (C) The Theis (1935) recovery slope estimates a transmissivity of 1,400 ft²/d, consistent with the pumping period data.

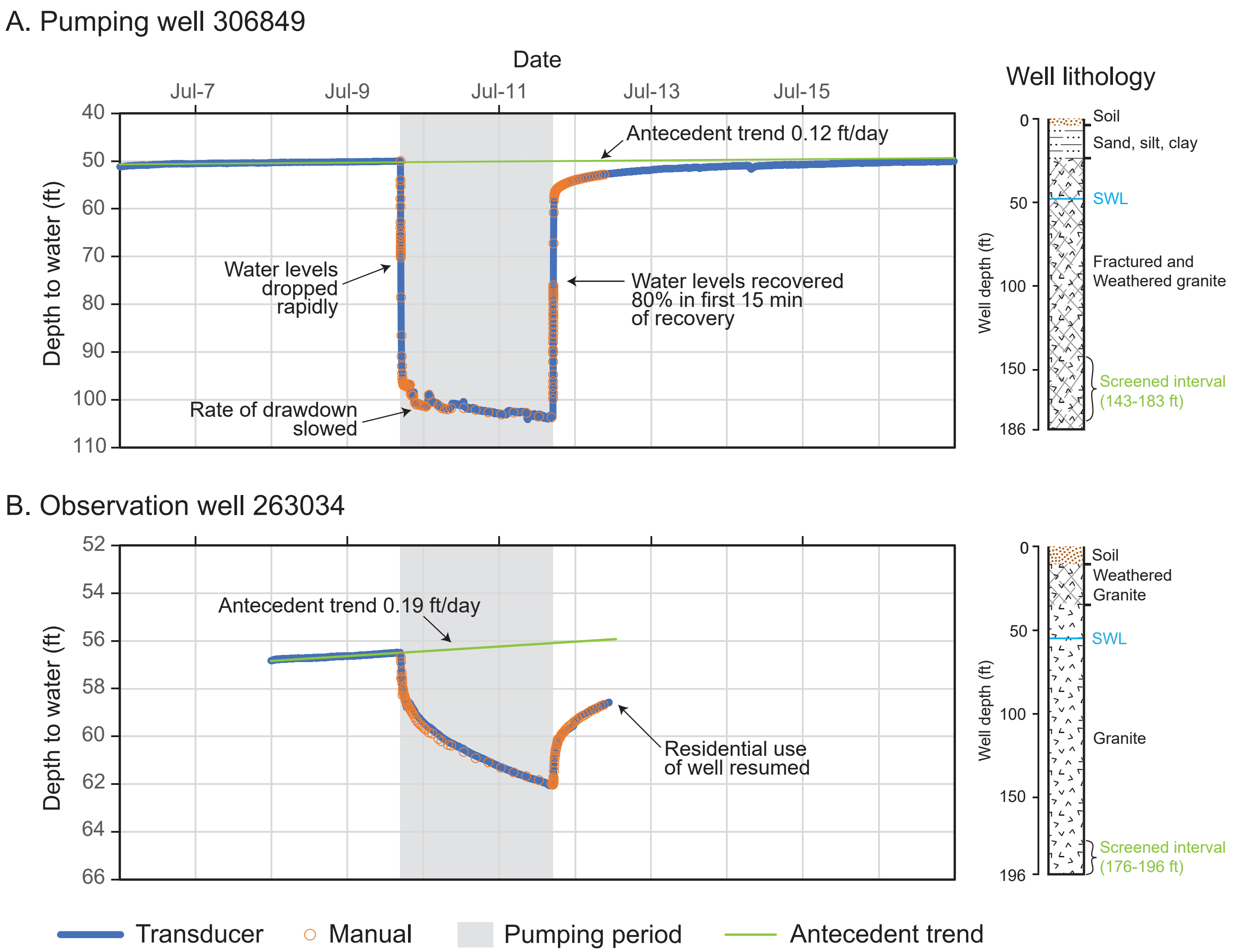

Figure 4. Site B hydrographs and well lithology of the pumping well 306849 (A) and observation well 263034 (B). Hydrographs include the measured background, pumping period, and recovery. Measurements in the observation well that were affected by domestic pumping before and after the aquifer test were not included. Note the different y-axis scales. SWL, static water level.

The observation well (263034) is 107 ft west of the pumping well (fig. 1) and is 196 ft deep. The well log indicates weathered to solid granite (fig. 4B). The well is screened from 176 to 196 ft bgs. The static groundwater level was 56.50 ft below TOC prior to the start of the test (table 1).

Both wells are interpreted to be completed in the granitic Cretaceous intrusive rocks (fig. 1).

Surface-Water Features

The site is 0.7 mi north of North Meadow Creek. A small unnamed tributary to North Meadow Creek is approximately 600 ft south of both the wells (fig. 1B); this tributary was dry during the test.

Site-Specific Data Collection

Well 306849 was pumped at 17 gpm for 48 h starting June 9, 2020 at 4:45 p.m. Recovery was monitored for more than 180 h after pumping stopped. Residential use of the observation well (263034) stopped 5 h before the test and resumed after 18 h of recovery; data with residential pumping fluctuations were excluded from the analysis. The pumping-well water levels were unaffected by the resumption of pumping at the observation well during recovery. The pumped water was discharged approximately 300 ft away in a ditch adjacent to North Meadow Creek Road.

Results

Water levels measured in the pumping well before and after the aquifer test increased by 0.12 ft/d. Similarly, pre-aquifer test water levels measured in the observation well showed an increase at a rate of 0.19 ft/d (fig. 4). A linear correction of these antecedent trends was applied to the data prior to analysis. A pumping rate of 17 gpm was used for test analysis.

Water-Level Response

Water levels in the pumping well 306849 dropped 40 ft during the first 4 h of the test and then declined at a slower rate over the rest of the pumping period. A maximum drawdown of 54.15 ft was measured in the pumping well (table 1). After pumping stopped, water levels recovered 80% (43.50 ft) in 15 min and were fully recovered after 141 h (fig. 4A).

Drawdown in the observation well (263034) was observed after 2 min of pumping. The maximum drawdown was 5.57 ft (table 1). The observation well was 63% (3.5 ft) recovered after approximately 18 h when residential use of the well resumed (fig. 4B).

Aquifer Properties

Early-time data from the pumping well indicate linear flow during the first 25 min of pumping, illustrated by the unit slope on a drawdown vs. time$^{1/2}$ plot (fig. 5A; Gringarten and Ramey, 1972; Duffield, 2007). This suggests early-time flow at the site is dominated by parallel flow toward the fracture(s) that intersect the well (Kruseman and de Ridder, 1990).

Derivatives of the late-time data for the pumping and observation wells have an approximately flat slope (applying the "smoothing" technique = 4), signifying the aquifer was acting with IARF conditions (fig. 5B). The observation well had a near-instantaneous 0.2 ft increase in water level around 135 min for an unknown reason; however, drawdown continued after this, following a similar slope. Therefore, the post-135-min data were used for curve-matching (fig. 5B).

The Cooper–Jacob (1946) solution for the late-time data from both wells are approximately parallel, giving a transmissivity of 240 ft^2/d for the Cretaceous intrusive bedrock at the site (fig. 5B; table 1). Similarly, the Theis (1935) straight-line solution of the residual drawdown for the mid- to late-time recovery data roughly approximates a transmissivity near 240 ft^2/d, consistent with the pumping-period data (fig. 5C). The storativity estimate for the observation well is 7.0 x 10^{-4} using the Cooper–Jacob (1946) solution (fig. 5B; table 1).

SITE C: PUMPING WELL 301897 AND OBSERVATION WELL 284965

Background

Test Location

Site C is located in the Pronghorn Meadows subdivision, 3.5 mi southwest of Ennis at the end of Raghorn Court Road (fig. 1C). Well 301897 was installed for the study and used as the pumping well. Residential well 284965 was used as an observation well.

Well Descriptions

The pumping well (301897) is 220 ft deep. The well-site lithology includes gravel, sand, and some silt from the surface to 40 ft; semi-consolidated shale between 40 and 120 ft bgs; semi-consolidated sandstone and conglomerate to 185 ft bgs; volcanic rock between 185 and 195 ft bgs; and semi-consolidated sandstone with mudstone clasts from 195 to 220 ft bgs (fig. 6A). The well is screened from 200 to 220 ft bgs. The pre-test static water level in the pumping well was 126.80 ft below TOC (table 1).

The observation well is 67 ft away from the pumping well and 218 ft deep. The lithology is similar to the pumping-well site, with gravel and sand that transitions to semi-consolidated sandstone and mudstone; the transition is at 23 ft bgs (fig. 6B). The observation well is screened from 198 to 218 ft. The pre-test static water level was 128.04 ft below TOC (table 1).

Both wells are interpreted to be completed in the Tertiary sediments (fig. 1).

Surface-Water Features

A small pond, formed by a dam on Eightmile Creek, is about 800 ft northeast of the aquifer test site and about 60 ft downslope (fig. 1C). Eightmile Creek was discharging approximately 0.35 cfs into the pond during September 2019, a week after the aquifer test. However, discharge measurements of Eightmile Creek were not monitored as part of the test.

Site-Specific Data Collection

Well 301897 was pumped for 24 h starting September 10, 2019 at 3:00 p.m. The pumping rate was adjusted to keep as constant as possible, but fluctuated between 8.2 and 12.2 gpm. There was no residential use of the observation well before, during, or

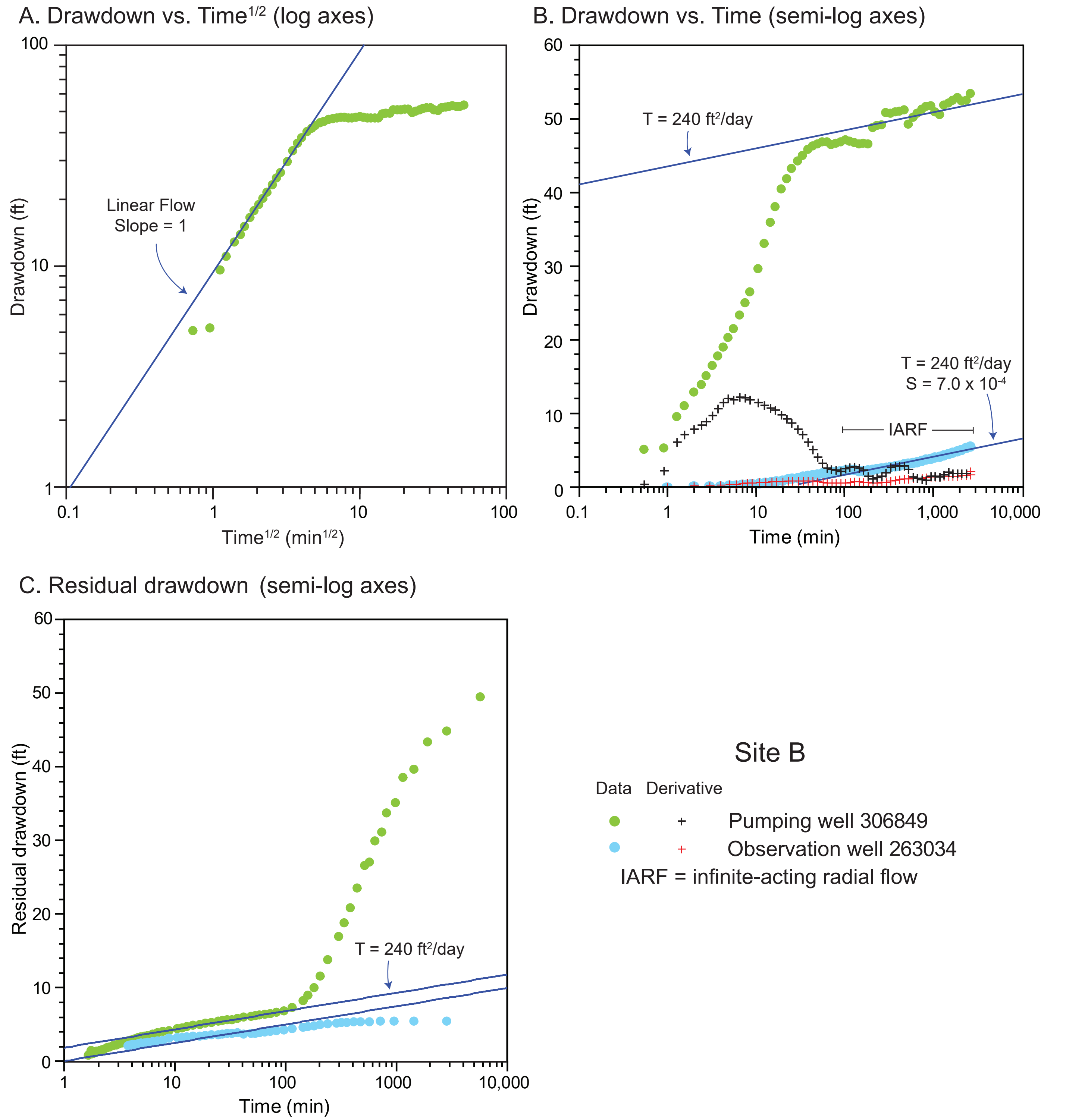

Figure 5. (A) The early-time data in the pumping well has a unit slope on a drawdown vs. time$^{1/2}$, which is indicative of linear fracture flow. (B) The pumping and observation wells have approximately parallel late-time slopes representing a transmissivity of 240 ft²/d. (C) The Theis (1935) recovery slope estimates a transmissivity of approximately 240 ft²/d, consistent with the pumping period data. The slope of the observation well recovery data is roughly parallel; the slightly shallower slope can be explained by heterogeneities in the aquifer. A transmissivity of 240 ft²/d is the most internally consistent value for site B.

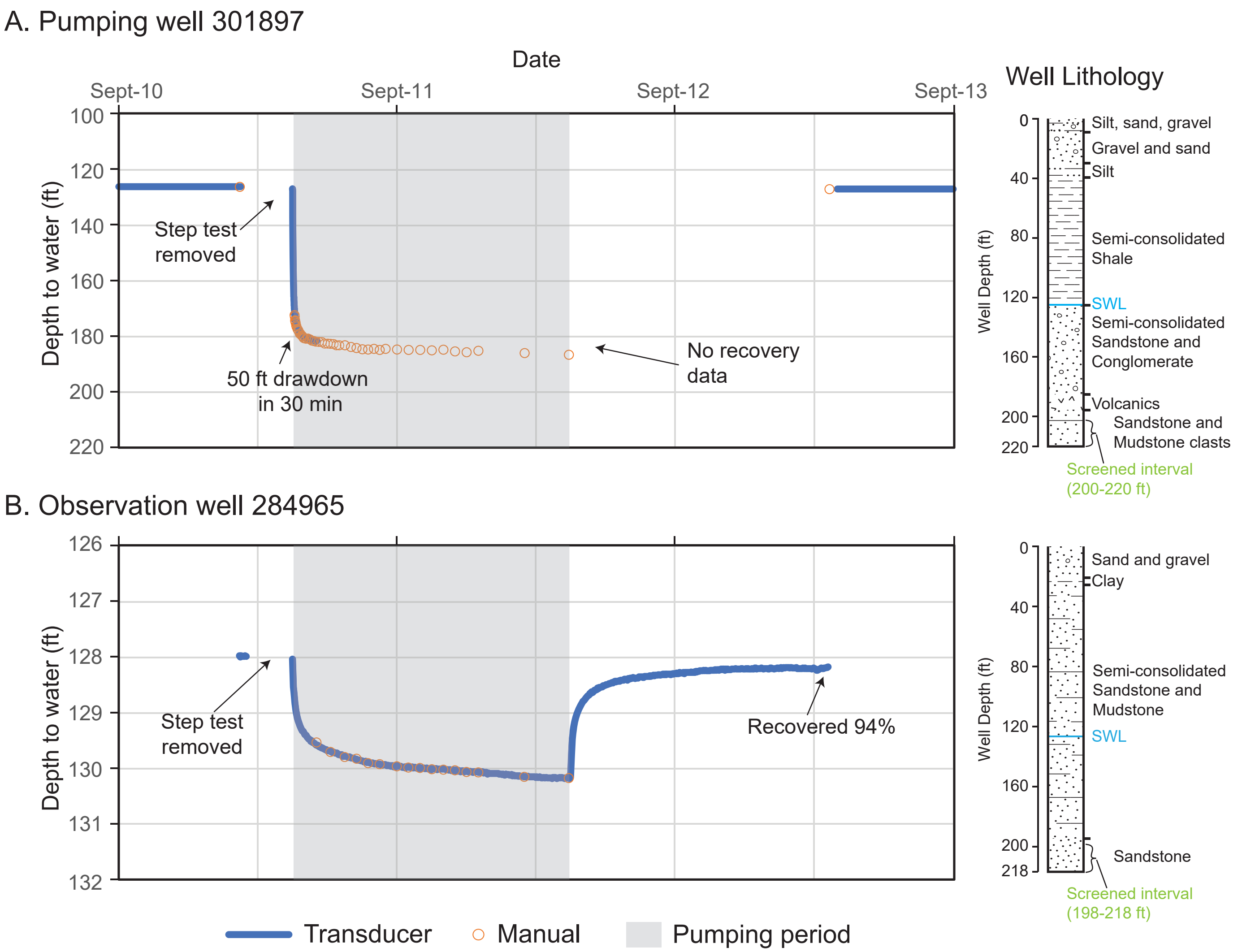

Figure 6. Site C hydrographs and well lithology of the pumping well 301897 (A) and observation well 284965 (B). Hydrographs include the measured background, pumping period, and recovery. Pumping well 301897 did not have any recorded recovery. Note the different y-axis scales. SWL, static water level.

after the aquifer test. Transducer measurements for the pumping well are only available for the first 3 h of the aquifer test due to instrument failure. Manual measurements are available for the subsequent 21 h. No recovery data are available for the pumping well. There were continuous (every 5 min) transducer readings and manual measurements from the observation well throughout the test. Recovery was monitored in the observation well for 22 h. The pumped water was discharged to the east into a dry drainage that sloped north away from the site.

Results

There were no measurable water-level trends in the pumping or observation well, so antecedent trend corrections did not need to be applied to the drawdown data. A time-weighted average pumping rate of 9.8 gpm was used for test analysis.

Water-Level Response

There was 50 ft of drawdown in the pumping well within the first 30 min of the test. Water levels reached a maximum drawdown of 59.78 by the end of 24 h (fig. 6A; table 1). Drawdown was noted in the observation well within 5 min. The observation well had a maximum drawdown of 2.14 ft (table 1). The observation well recovered 94% (2.01 ft) in 22 h (fig. 6B).

Aquifer Properties

The pumping well and the observation well demonstrated linear flow during the beginning of the aquifer test (fig. 7A), which is indicative of parallel flow to the fracture(s) that intersect the pumped well. The pumping well had linear flow for the first 5 min and the observation well had linear flow for up to 25 min.

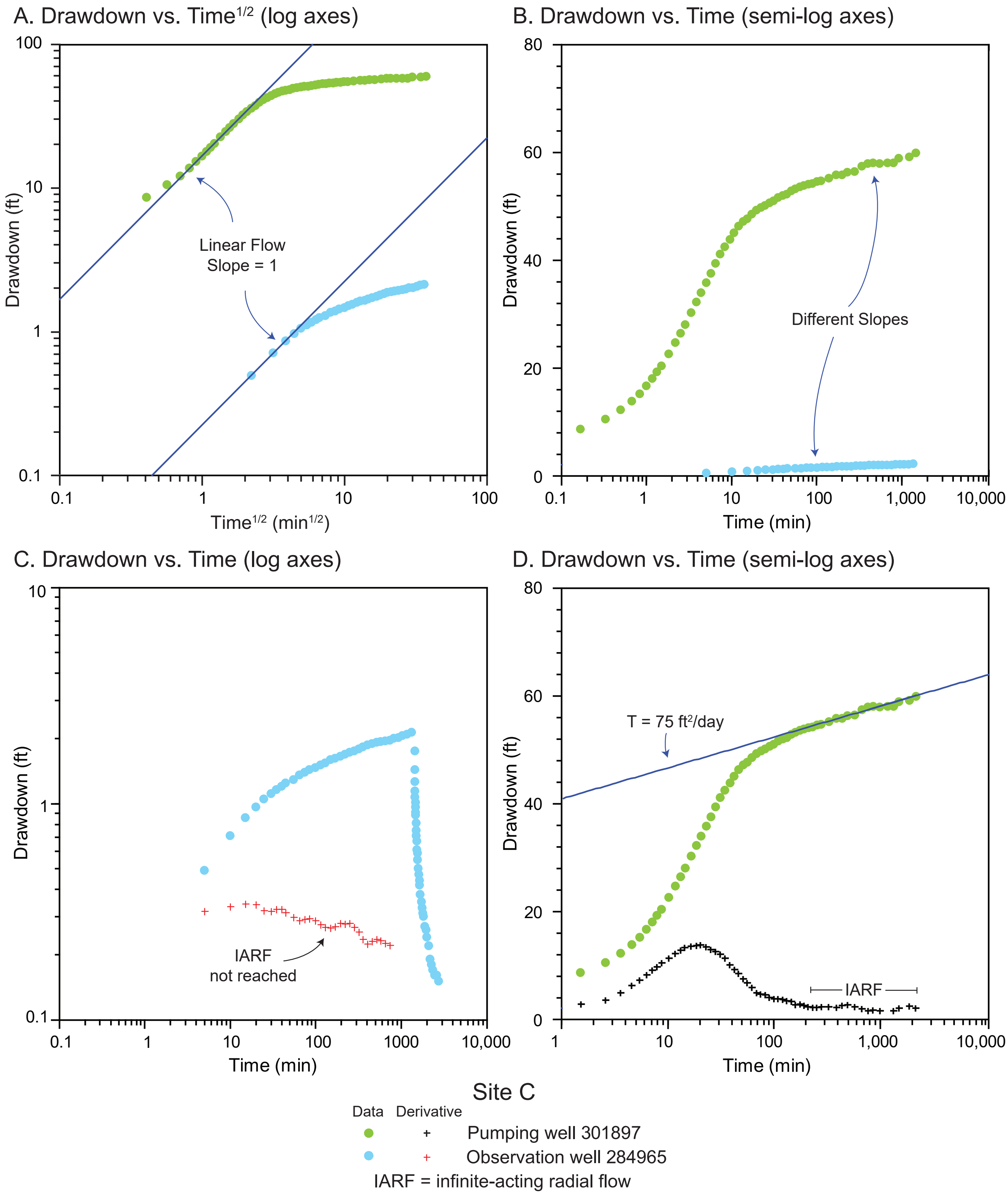

Figure 7. (A) The early-time data for the pumping and observation well are indicative of linear fracture flow as seen by the unit slope on a drawdown vs. time$^{1/2}$ plot. (B) The late-time slope of the pumping well and the observation well are different, suggesting inconsistent transmissivities between the wells. (C) The slope of the observation well derivative did not flatten out within the 24-h test; therefore, the IARF conditions necessary for the Theis (1935) and Cooper–Jacob (1946) solutions were not reached. (D) The late-time slope of the pumping well represents a transmissivity of 75 ft²/d for site C.

During analysis, it was determined that the observation well could not be used to estimate the transmissivity of site C for two reasons:

1. data for the pumping and observation well have different late-time slopes on the composite drawdown vs. time plot (fig. 7B), suggesting an inconsistent transmissivity estimate of the aquifer from the two wells, and

2. close examination of the observation well-data derivative shows pumping did not occur long enough to reach IARF conditions (e.g., the derivative did not flatten out when a "smoothing" technique = 1 was applied, fig. 7C).

The pumping-well data derivative does flatten out ("smoothing" technique = 2) during the late-time data, indicating IARF conditions occurred near the pumping well (fig. 7D). The Cooper–Jacob (1946) solution for the pumping-well data estimate a transmissivity of 75 ft^2/d (fig. 7D; table 1). A storativity could not be determined for this site since the observation well data could not be used.

SITE D: PUMPING WELL 215148

Background

Test Location

Site D is an undeveloped plot of land along Cottontail Run Road in the Virginia City Ranches subdivision (fig. 1D). The pumping well is located on a hillside within a sparsely developed section of the subdivision adjacent to a service road. It was a single-well test on an existing well (215148).

Well Description

The well is 508 ft deep; the well log describes decomposed granite from 1 to 15 ft bgs and granite from 15 to 508 ft bgs (fig. 8). Based on the mapped geology and the well log description, the well is interpreted to be completed in the Archean metamorphic (granitic- and tonalitic-gneiss) rocks (fig. 1). The well is assumed to be open-bottom. The pre-test static water level was at 72.24 ft below TOC (table 1).

Surface-Water Features

There are no surface-water features near the test site that would be likely to affect the aquifer test (fig. 1D).

Site-Specific Data Collection

Well 215148 was pumped at 12 gpm for 8 h and 17 min starting May 24, 2019 at 11:54 a.m. Recovery was monitored for 136 h. Since the surrounding land is undeveloped, there was no interference from pre- or post-residential pumping. The water was discharged down the adjacent hillslope at a distance sufficient to avoid recharge to the aquifer. Water levels were measured every second with a pressure transducer.

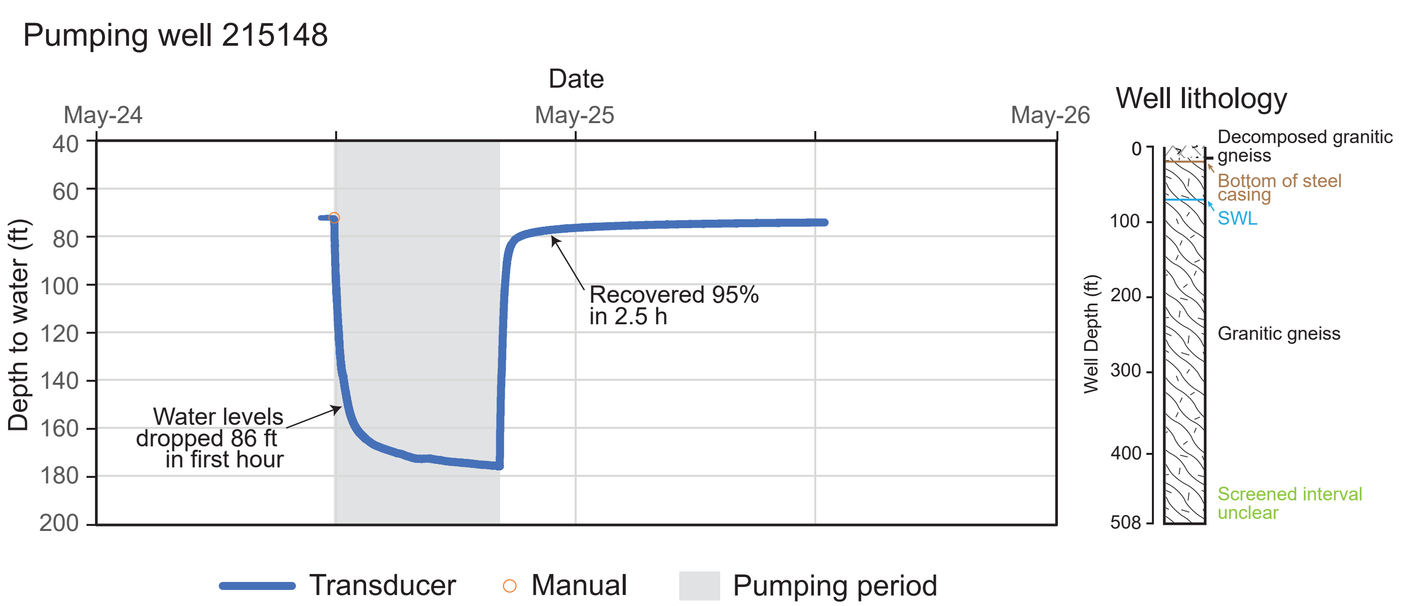

Figure 8. Site D hydrograph and well lithology for pumping well 215148. Hydrograph includes the measured available background, pumping period, and recovery. SWL, static water level.

Results

The pre- and post-aquifer test water-level measurements were insufficient to determine long-term antecedent trends. Therefore, no correction was applied before analysis. The pumping rate of 12 gpm was used for test analysis.

Water-Level Response

The water level declined 86 ft in the first hour of pumping (fig. 8). Drawdown slowed throughout the test and reached a maximum of 103.81 ft before pumping stopped after 8 h (table 1). Water levels recovered 95% (98.67 ft) within 2.5 h (fig. 8).

Aquifer Properties

Radial flow (unit slope on log-log plot of drawdown vs. time; Duffield, 2007) was observed during the first minute of the aquifer test when drawdown reached 10 ft. Radial flow is indicative of borehole storage; therefore, test data from the first minute were not used in the interpretation. Linear flow was not observed in the drawdown data, suggesting that flow to the well was not along a single fracture.

The pumping period of the aquifer test did not extend long enough for IARF conditions to be reached. The slope of the derivative in figure 9A is flattening out, suggesting that drawdown was close to a constant rate (fig. 9). However, it could not be determined with confidence that the aquifer was acting with IARF.

The recovery data were analyzed using the Agarwal (1980) method to extend the record. As seen in figure 9B, the derivative of the recovery data suggests IARF conditions occurred in the aquifer during recovery; the Cooper–Jacob (1946) straight-line solution through IARF-time data estimates a transmissivity of 60 ft^2/d at this site (fig. 9B; table 1). The Theis (1935) recovery solution indicates a similar transmissivity for the site. A reliable S could not be determined for this site without an observation well.

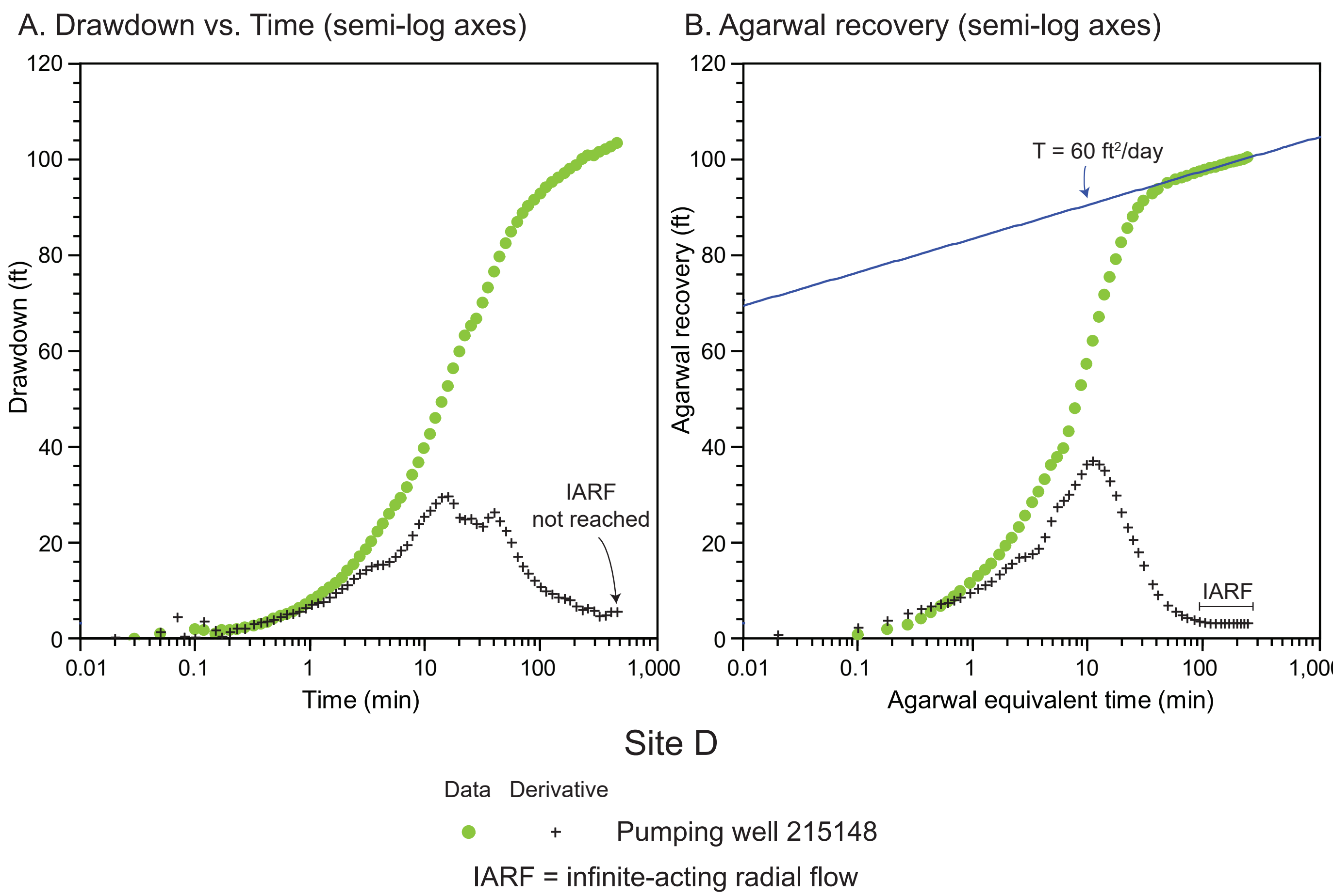

Figure 9. (A) The pumping well derivative did not flatten out; therefore, IARF conditions were not reached within the pumping time. (B) The recovery data transformed using the Agarwal (1980) method has a derivative that did flatten out; therefore, the IARF conditions are met and the Cooper–Jacob (1946) solution can be applied. An estimate of the transmissivity for site D is 60 ft^2/d.

SITE E: PUMPING WELL 209871

Background

Test Location

Site E is less than 1.5 mi from the Ennis town center on Pintail Ridge Road (fig. 1E). It was a single-well test using an existing well (209871) as the pumping well.

Well Description

The pumping well is 405 ft deep. The drillers' log indicates 60 ft of overlying, unconsolidated gravel before reaching bedrock (fig. 10). The well log describes the bedrock as black granite, but the lithology is interpreted to be Archean metamorphic rocks based on the geologic setting (fig. 1). The well is completed with an open hole at 405 ft bgs. The pre-test static water level was at 45.72 ft below TOC (table 1).

Surface-Water Features

An irrigation canal is approximately 150 ft east of the pumping well. The aquifer test was conducted when the canal was dry so it would not act as a recharge boundary. There are no other surface-water features nearby the test site.

Site-Specific Data Collection

Well 209871 was pumped for 8 h and 11 min starting July 10, 2019 at 9:09 a.m. The initial pumping rate was 6.2 gpm but decreased over the test to 5.9 gpm. Recovery was monitored for 39 h after the pumping stopped. The residential house well was not monitored; however, residential pumping was stopped for the pumping and recovery parts of the test. Water pumped during the test was discharged into the irrigation canal 150 ft away.

Results

Background water-level measurements show an increasing trend of 0.90 ft/d for the pumping well (fig. 10). A linear antecedent trend correction was used to adjust the water levels before data analysis. The time-weighted average pumping rate was 6.1 gpm.

Water-Level Response

Drawdown in well 209871 reached a maximum of 112.86 ft over the 8 h and 11 min of pumping (table 1). After pumping stopped, water levels recovered quickly—reaching 95% (107.47 ft) of pre-pumping levels within 36 min (fig. 10).

Aquifer Properties

Early-time drawdown in the pumping well follows a unit slope on the drawdown vs. time$^{1/2}$ plot in figure 11A. Drawdown slightly deviates from the 1:1 slope after 2 min, but curves back towards the line between 10 min and 8 h. Although there are these slight deviations, the overall drawdown suggests that linear flow

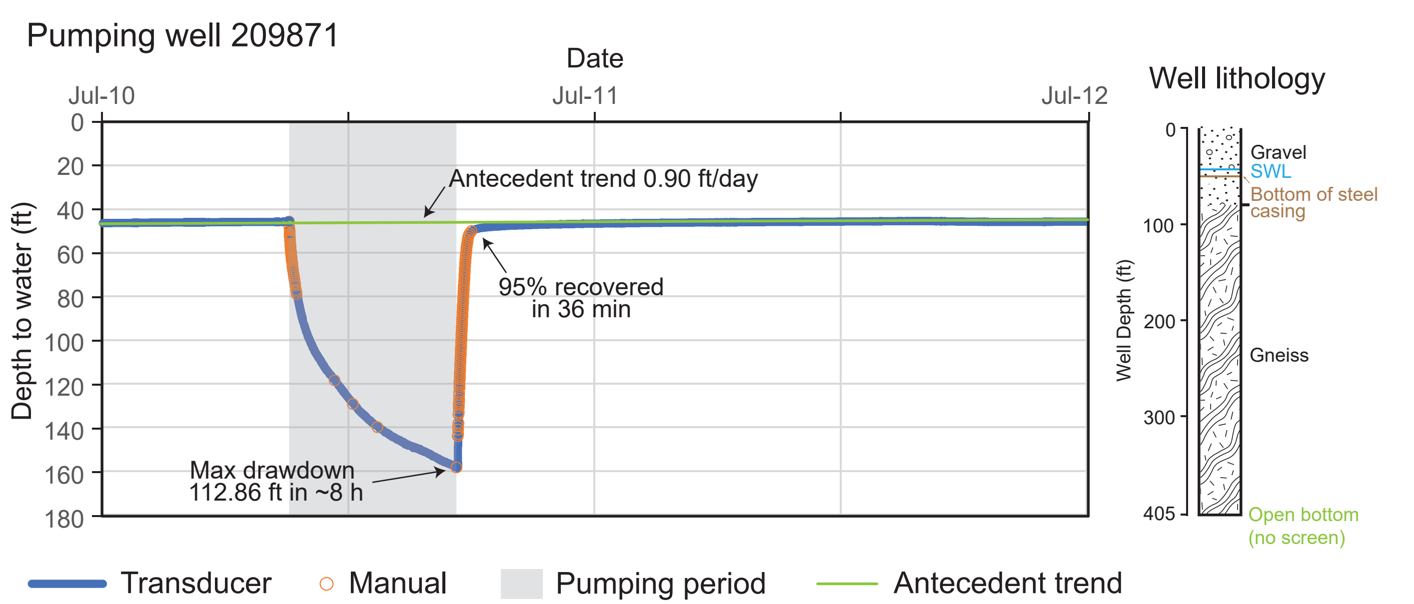

Figure 10. Site E hydrograph and well lithology for pumping well 209871. Hydrograph includes the measured available background, pumping period, and recovery. SWL, static water level.

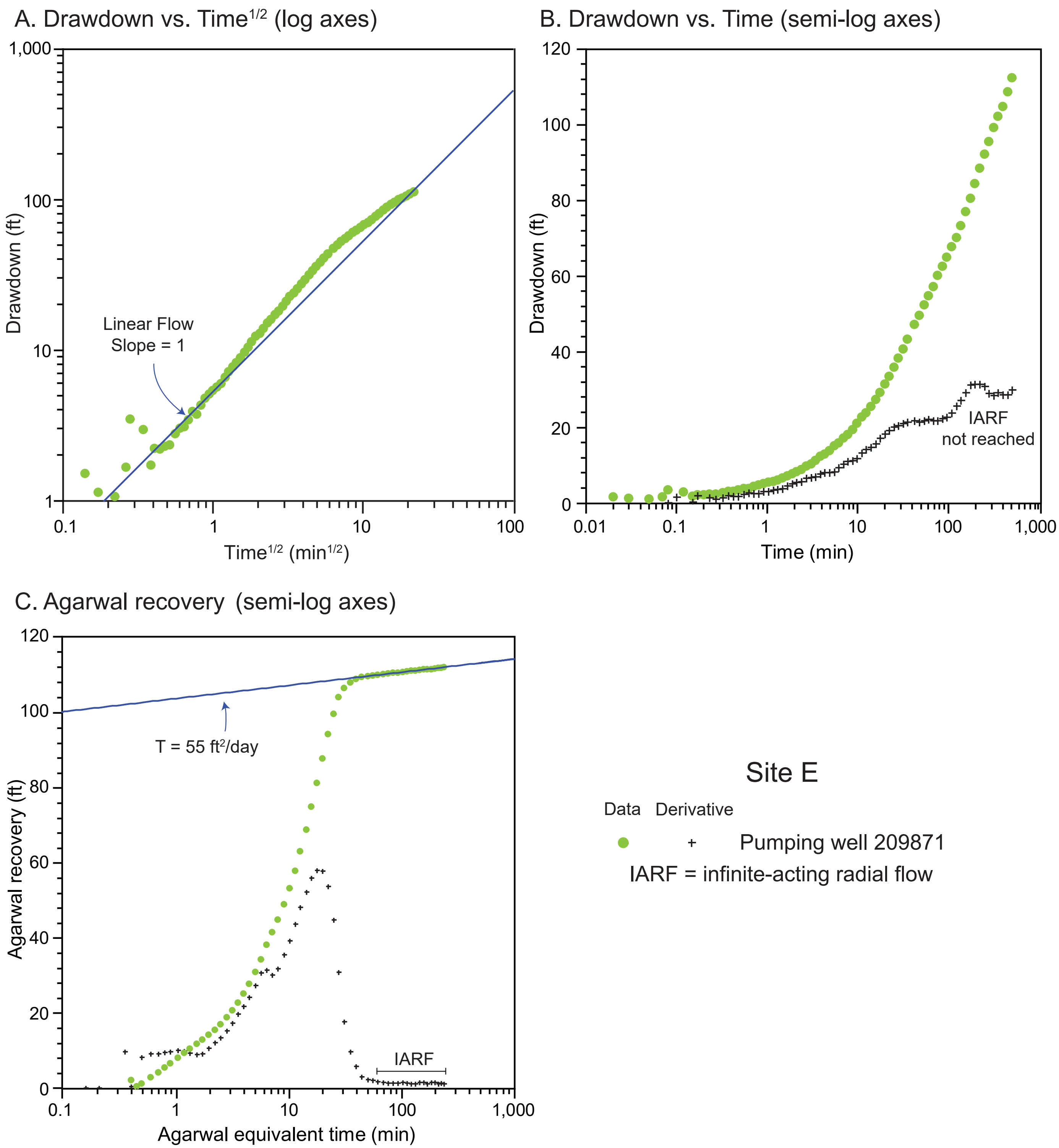

Figure 11. (A) The early-time data in the pumping well has a unit slope on a drawdown vs. time$^{1/2}$, which is indicative of linear fracture flow. (B) IARF conditions were not reached within the pumping time, as seen by the non-flat derivative slope. (C) The pumping-well recovery data using the Agarwal (1980) method did indicate IARF conditions. Site E has a transmissivity estimate of 55 ft²/d.

was dominant throughout the 8 h of pumping, suggesting fracture flow.

Since linear flow occurred throughout pumping, the drawdown did not stabilize (e.g., the derivative slope did not flatten; "smoothing" technique = 1 was applied to the derivative; fig. 11B), and IARF conditions were not achieved. The transformed late-time recovery data (Agarwal, 1980) suggest IARF conditions did occur in the aquifer during recovery. The Cooper–Jacob (1946) solution with the Agarwal (1980) transformation estimates a transmissivity of 55 ft^2/d for the Archean metamorphic rocks near site E (fig. 11C; table 1). This transmissivity estimate is also consistent with the Theis (1935) recovery solution. A reliable S could not be determined for this site without an observation well.

ADDITIONAL AQUIFER INFORMATION FOR THE ARCHEAN BEDROCK

Two aquifer tests were attempted in Archean bedrock wells, but were unsuccessful due to low well yields. One test at well 138840 (165 ft deep, static water level about 33 ft), located in the Virginia City Ranches subdivision, was pumped for only 8.5 min (at 10.5 to 3.3 gpm) before water levels reached 99 ft and the test was abandoned. Another test, well 301876 (400 ft deep, static water level approximately 90 ft), located in a subdivision south of Virginia City Ranches, was pumped at less than 1 gpm for 81 min before water levels approached the pump intake at 116 ft and the test was stopped. In both cases, the check-valve failed during recovery and the data were influenced by standing-pipe water reentering the well, making the analyses uncertain.

Although transmissivities could not be determined from these two wells, both wells show linear fracture flow during pumping (fig. 12). These wells likely intersect a small fracture network within relatively impermeable bedrock that limits the amount of water available.

DISCUSSION

The aquifer tests conducted for this study show the transmissivities range over three orders of magnitude in the geologic units on the west side of the Madison Valley, near Ennis. The shallow Quaternary–Tertiary sediments have the highest transmissivity in the study area (1,400 ft^2/d), but deeper Tertiary sediments have a much lower transmissivity (75 ft^2/d). The fractured Cretaceous intrusive rocks have the second-highest transmissivity (240 ft^2/d) of the five aquifer tests. The Archean metamorphic rocks have the lowest measurable transmissivities (55–60 ft^2/d; table 1). Finally, the two failed aquifer tests in Archean metamorphic rocks suggest even lower transmissivities—with one well unable to pump 1 gpm for more than 80 min.

Since the aquifer thickness is unknown at each of the sites, the corresponding hydraulic conductivities can be approximated using 1.5 times the minimum known thickness of the aquifer (e.g., distance from the bottom of the screen to the static water level) for tests greater than 24 h (Weight, 2008). To be conservative and not overestimate the hydraulic conductivity, we use the 1.5 times the minimum known thickness for the 8-h tests as well, since the fractures are likely to be greater than 1.5 times the screened interval.

Therefore, the hydraulic conductivity for the shallow Quaternary–Tertiary sediments is approximately 20 ft/d (table 1), which is consistent with the hydraulic conductivity of silty sands given by Heath (1983). The deeper Tertiary sediments had a hydraulic conductivity of 0.5 ft/d (table 1); this estimate is in the middle of the range for semi-consolidated sandstone (10^{-2} to 1 ft/d; Heath, 1983). The hydraulic conductivity estimate for the Cretaceous intrusive rocks is approximately 1 ft/d, while the hydraulic conductivity estimates for the Archean metamorphic rocks are approximately 0.1 ft/d (table 1). Hydraulic conductivities for igneous and metamorphic bedrock range from 10^{-7} to 10 ft/d depending on the extent of fractures (Heath, 1983). Thus, the Archean and Cretaceous rocks near sites B, D, and E are in the upper range of hydraulic conductivities for fractured bedrock. However, the two wells (138840 and 301876) that could not produce enough to run an aquifer test suggest hydraulic conductivities are locally variable and may not produce enough groundwater for domestic needs in some locations.

Storativity for the Quaternary–Tertiary sediments (5.5×10^{-4}) suggests confining conditions. There are flowing artesian wells to the west of site A, completed in the Quaternary–Tertiary sediments along Eightmile Creek. Flowing artesian conditions offer further evidence of confining conditions in the Quaternary–

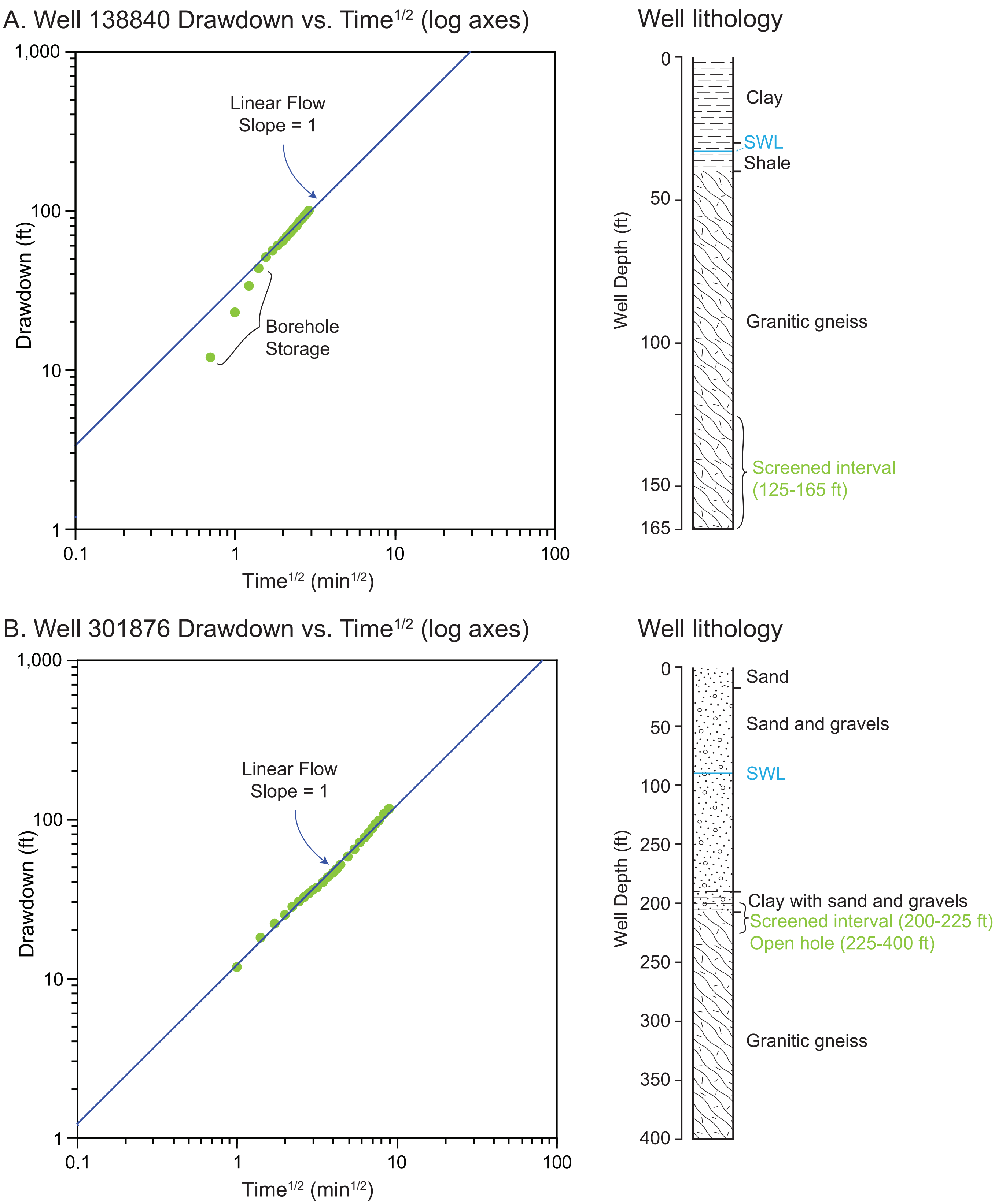

Figure 12. (A) Well 138840 demonstrated radial flow (borehole storage) and linear flow (fracture flow) during the 8.5 min of pumping. (B) Well 301876 demonstrated linear fracture flow during the 90 min pumping at <1 gpm. SWL, static water level.

Tertiary sediments. However, most wells completed in Quaternary–Tertiary sediments have unconfined conditions, suggesting a limited lateral extent to the confining layer. The storativity for the Cretaceous intrusive rocks (7 x 10^{-4}) suggests locally confining aquifer conditions in some of the bedrock aquifers, too, though flowing artesian conditions were not reported.

Finally, it is important to note that the deeper Tertiary sediments and four of the five bedrock wells (including the two unsuccessful aquifer tests) show linear flow during the early-time data. As mentioned previously, linear flow occurs when groundwater in the aquifer is moving towards the main fracture(s) the well intersects; the fracture is assumed to have a very high hydraulic conductivity that facilitates the movement of the groundwater from the fracture to the well (Kruseman and de Ridder, 1990). Thus, the Tertiary–Archean bedrock aquifers and the Tertiary semi-consolidated sediments did not act like porous equivalent media during early pumping; furthermore, site E and the two low-productivity wells did not act like porous equivalent media during any of the time they were pumped.

SUMMARY

A well drilled in bedrock or deeper Tertiary sediments near Ennis will be limited by the fracture network the well intersects—this can vary across and within different geologic units. Transmissivities of 75 to 1,400 ft²/d were determined for wells completed in the Quaternary–Tertiary basin-fill sediments, and transmissivities of 55 to 240 ft²/d were determined for wells completed in the Tertiary–Archean fractured bedrock. These transmissivities should be used with caution since they are local estimates; wells in the same unit or even right next to one of these sites may differ if they do not intersect the same fracture system. Thus, wells should be individually tested to predict the amount of groundwater they can provide.

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