APPENDIX E

AQUIFER TESTS AT THE BIG FORK FARM SITE

OVERVIEW

Location

The Bigfork Farm site is located approximately 1.5 mi north of Flathead Lake in the central Flathead Valley. This site is located on Farm Road (fig. E1).

Hydrogeologic Setting

The hydrostratigraphic units in the area of the BFF site have been the subject of several studies (Smith, 2004a,b,c; LaFave and others, 2004; Konizeski and others, 1968; Rose, 2018; Rose and others, 2022), including the current study documented in this report. The Flathead Valley is underlain by the Precambrian metasedimentary siltite, metacarbonates, and quartzite of the Belt Supergroup. Based on gravity data this bedrock is about 2,000 ft below ground surface at the BFF site (Smith, 2004a). The bedrock is overlain by the semi-lithified Tertiary sediments of the Kishenehn Formation (see main text). The Kishenehn Formation is composed of clayey gravel, mudstone, carbonaceous shale, sandstone, and conglomerate (Smith, 2004b). Glaciofluvial sands and gravels of the deep aquifer occur above the Kishenehn Formation. These materials were primarily deposited as outwash from the advancing Cordilleran ice sheet [~20 thousand years ago (ka); Smith, 2004c]. The deep aquifer is overlain by proglacial lacustrine sediments that were deposited as the ice sheet retreated. Lake levels dropped as the outlet near Polson downcut, which caused a shift from deep water sediments (silt and clay) to deltaic sediments (fine to medium sand) at the BFF site. These deltaic sand units form the shallow aquifer.

Well Completions

Five wells were installed at the BFF site (table E1, fig. E1). Wells BFF#1 to BFF#4 were installed in April 2011. Wells BFF#1 and BFF#2 were completed in the deep aquifer, well BFF#3 was completed in the confininglayer,andwellBFF#4wascompletedinthe shallow aquifer. Well BFF#5 was completed in the Tertiary aquifer in October 2021. An MBMG hydrogeologist observed well installation and described cuttings.

Aquifer Test Summary

Three aquifer tests were conducted at the BFF site:

1. An aquifer test pumping from the deep aquifer for 7 days.
2. A recovery test of the confining layer well following purging.
3. An analysis of drawdown and recovery data collected during sampling from the well in the Tertiary sediments.

The deep aquifer and confining unit tests were performed in 2011 after wells BFF#1 to BFF#4 were installed. The test of BFF#5 occurred in April 2022. Detailed aquifer test data (633 forms) are available by clicking on the “View scanned aquifer test” link on each well’s GWIC page.

1. DEEP AQUIFER TEST

1.1 Background

<u>*1.1.1 Purpose of Test*</u>

The purpose of this aquifer test was to estimate the transmissivity (T) and storativity (S) of the deep aquifer, and to evaluate the data for recharge or no-flow boundaries. The deep aquifer is a primary source of groundwater in the Flathead Valley.

<u>*1.1.2 Test Type*</u>

A constant-rate aquifer test was conducted for approximately 7 d by pumping from the deep aquifer (well BFF#1; table E1) from June 7 to June 14, 2011.

1.2 Field Procedures

The total pumping period was 168 h 40 min (~7 d). The well was pumped continuously with an average rate of 485 gpm.

Three onsite wells were installed at the site (BFF#2-4; table E1) and one shallow aquifer well was already present at the site. The three installed observation wells were in the deep aquifer (BFF#2), the overlying confining layer (BFF#3), and in the shallow aquifer (BFF#4). Eight off-sitewellswerealsomonitored, with five in the deep aquifer and three in the shallow aquifer (fig. E1, table E1). The existing deep aquifer wells were between 1,381- and 11,400-feet from the pumping well (fig. E1). The existing shallow wells were between 278- and 8,467-feet from the pumping well. The stage of Flathead Lake was also monitored during the test period (table E1).

<u>*1.2.1 Data Collection*</u>

Water-level transducers recording hourly water-

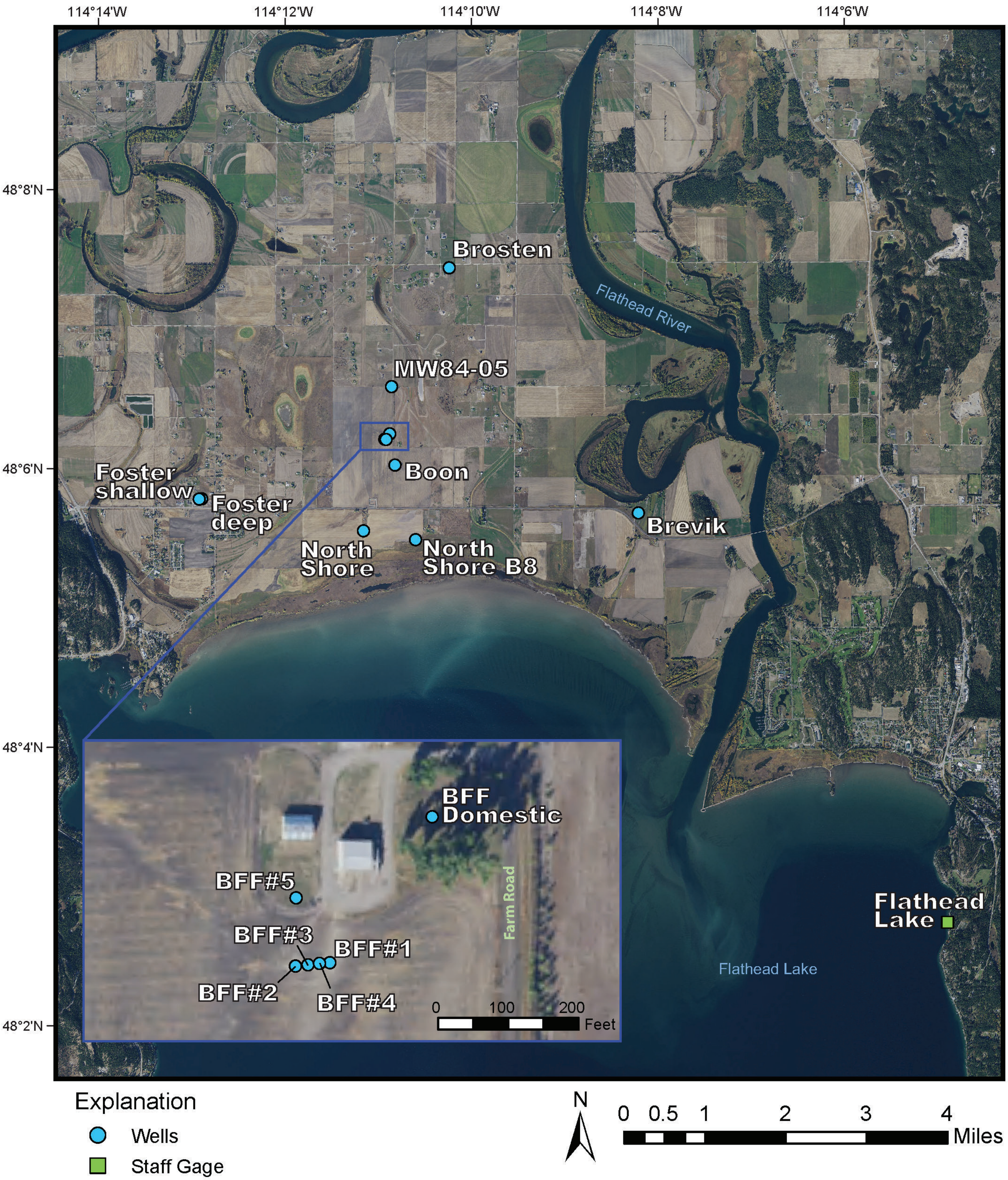


Figure E1. Five wells were installed at the BFF site (BFF#1-BFF#5, and one domestic wells was preexisting. Offsite locations were monitored during the 7-day test. Site details, including GWIC ID numbers, are included in table E1.

Table E1. Well designations, locations, and completion information.

GWIC ID	Name	Latitude* (DD - N)	Longitude* (DD - W)	Measuring Point Elevation (ft-amsl)*	Total Depth (ft)	Screen Interval (ft-bgs)	Comments
BFF Wells							
260892	BFF#1	48.103515	114.182153	2909.10	717	640-670 & 713-717	deep aquifer
260888	BFF#2	48.103515	114.182153	2908.76	672	642-672	deep aquifer
260889	BFF#3	48.103523	114.182073	2909.36	365	355-365	aquitard
260891	BFF#4	48.103532	114.182000	2909.64	80	75-80	shallow aquifer
317644	BFF#5	48.103806	114.182218	2909.59	1600	1540-1560	Tertiary aquifer
168764	BFF Domestic	48.104158	114.181276	2906.23	76	51-71	shallow aquifer
Off-Site Observation Wells							
141562	Boon	48.100425	114.180335	2907.58	400	400	deep aquifer-open bottom
261263	Brosten	48.123998	114.170640	2904.78	~600	unknown	deep aquifer
152883	Foster deep	48.096390	114.218916	2913.98	360	360	deep aquifer-open bottom
256774	Foster shallow	48.096354	114.215004	2913.49	48	48	shallow aquifer-open bottom
80745	Brevik	48.094702	114.136812	2903.66	400	400	deep aquifer-open bottom
6386	MW84-05	48.109803	114.180950	2907.17	23	15-20	shallow aquifer
236497	North Shore	48.092561	114.185965	2899.93	760	721-739	deep aquifer
262421	North Shore B8	48.091502	114.176654	2897.45	31	unknown	shallow aquifer
257114	Flathead Lake	48.045735	114.081523	2896.40	---	---	staff gage

*All locations were surveyed and locations reported using NAD83 and NAVD88 datums.

Note. ft-amsl, feet above mean sea level; ft-bgs, feet below ground surface.

level measurements were set in wells BFF#1–4 for several months prior to the aquifer test for long-term monitoring. The data from these wells was used to evaluate pretest water-level trends (figs. E2, E3).

For the pumping test, transducers recorded wa-ter levels at 1-min intervals in wells BFF#1–4 (figs. E2, E3), in the preexisting domestic well at the BFF site, and the figs. E3–E6).

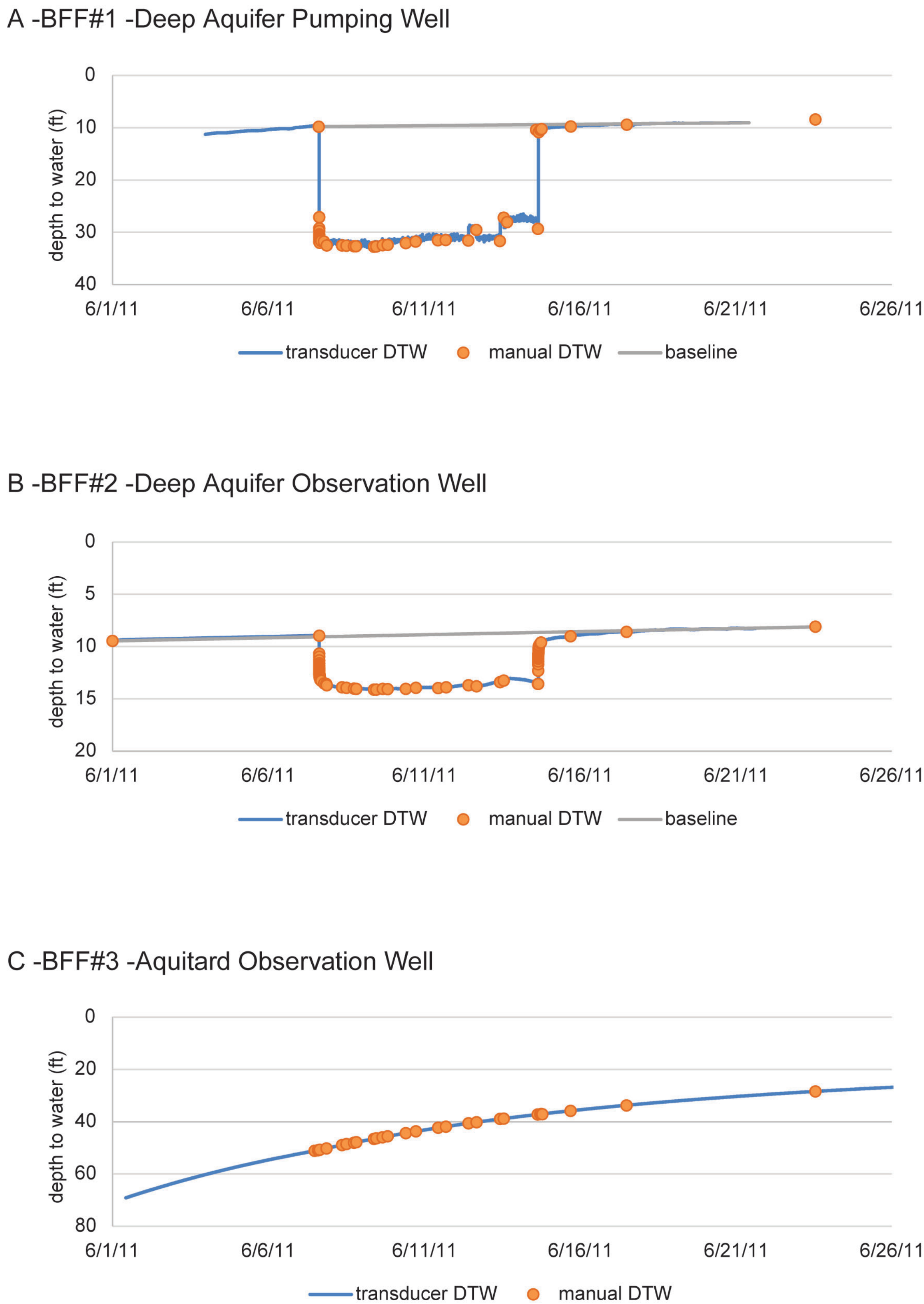
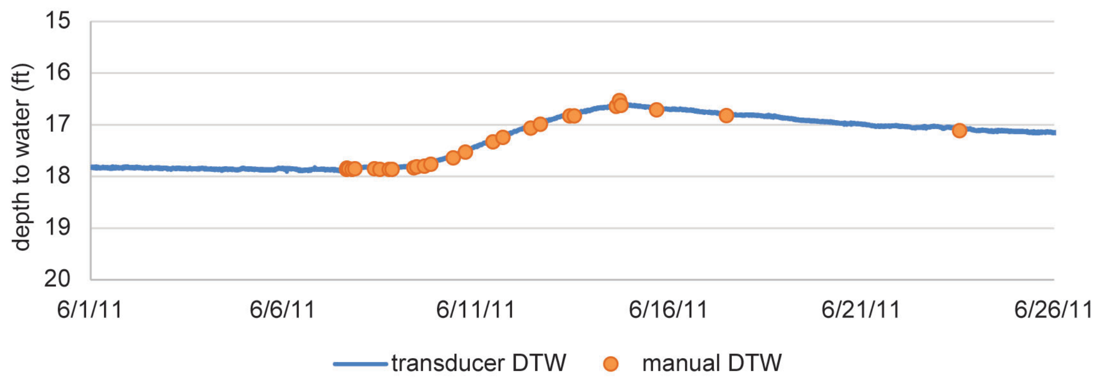
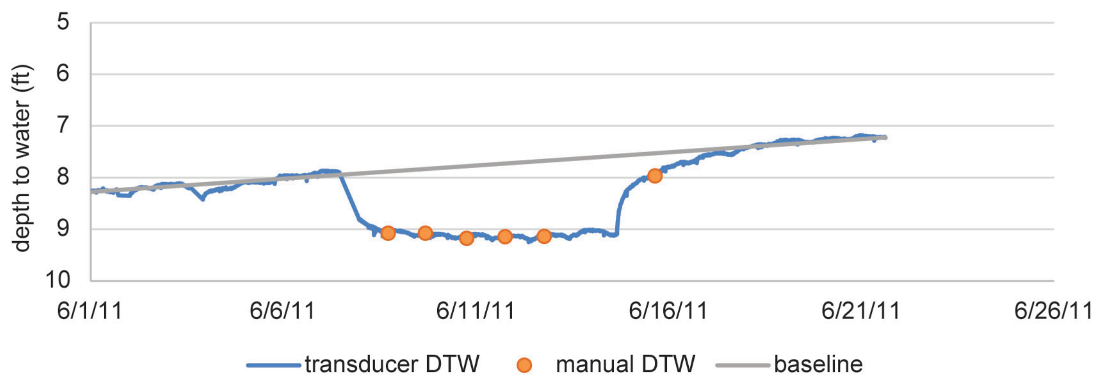


Figure E2. For on-site deep aquifer wells BFF#1 and BFF#2 drawdown was calculated as the diff erence between the observed and the baseline depth to water. Intermediate on-site well BFF#3 is completed in the aquitard and showed no response to the aquifer test. BFF#3 was recovering from previous well development through the test period.

A -BFF#4 -Shallow Aquifer Observation Well



B -Boon -Deep Aquifer Observation Well



C -North Shore Deep -Deep Aquifer Observation Well

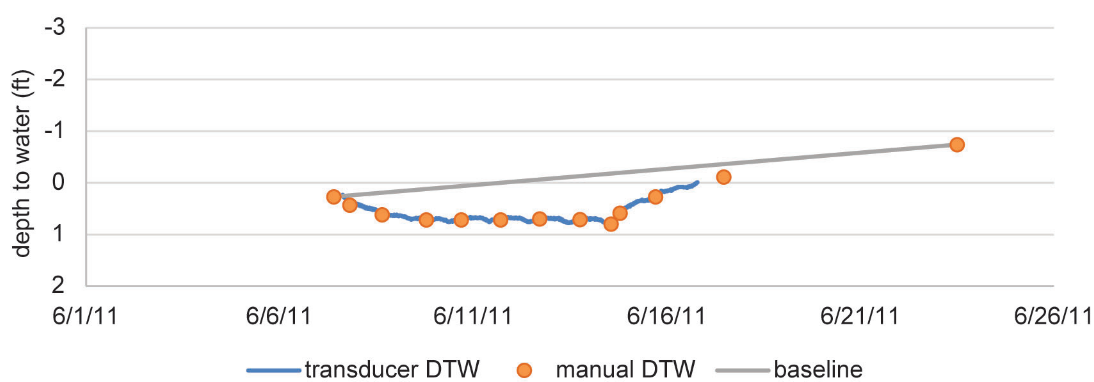
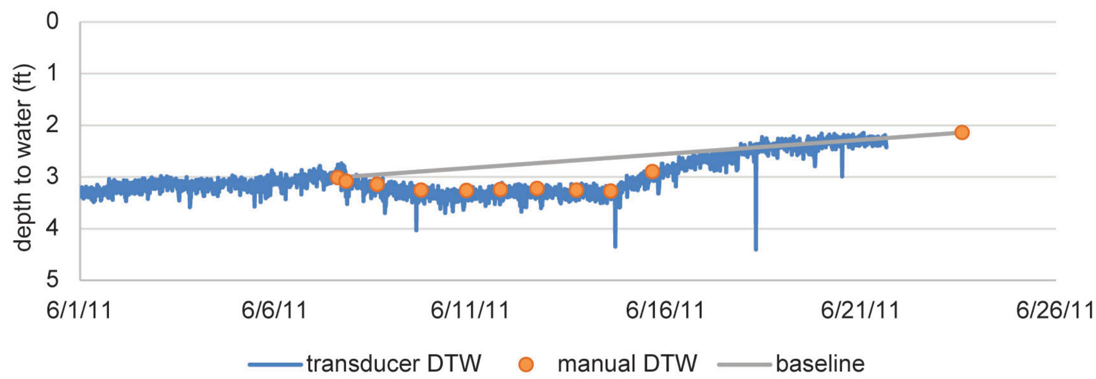
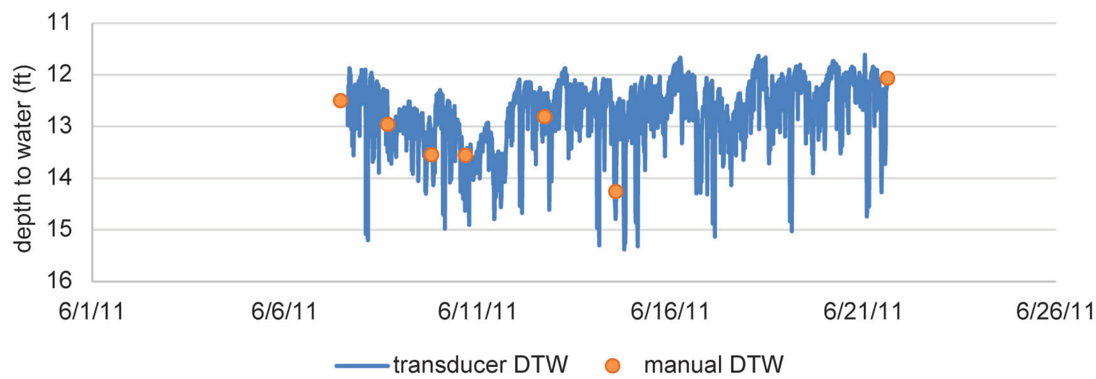


Figure E3. BFF#4 is completed in the shallow aquifer at the test site, and showed no response to pumping. The nearest offsite deep aquifer wells are Boon and North Shore (B and C). Drawdown in these wells was calculated as the difference between the observed and the baseline depth to water.

A -Brosten -Deep Aquifer Observation Well



B -Foster Deep -Deep Aquifer Observation Well



C -Brevik -Deep Aquifer Observation Well

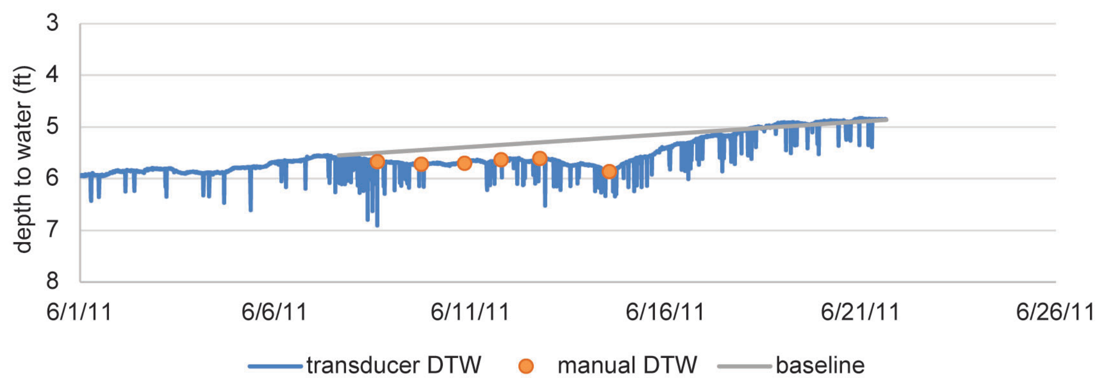
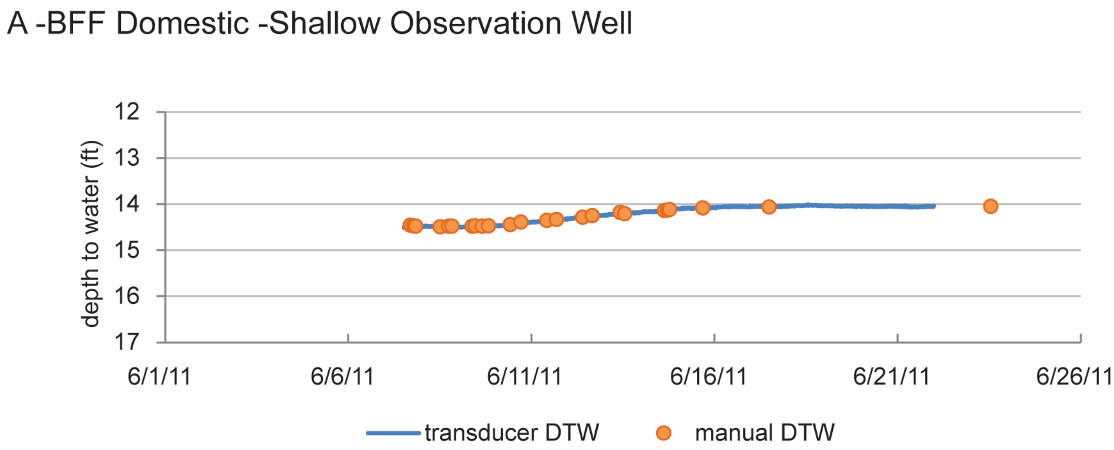
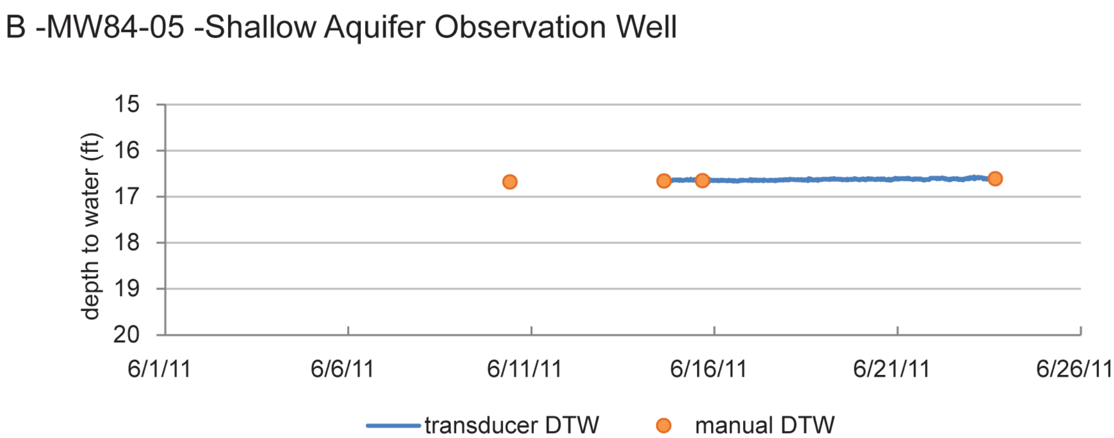


Figure E4. For monitored deep aquifer wells Brosten (A), Foster deep (B), and Brevik (C), drawdown was calculated as the difference between the observed and the baseline depth to water. Drawdown in Foster deep (B), was not quantified due to excessive pumping interference.





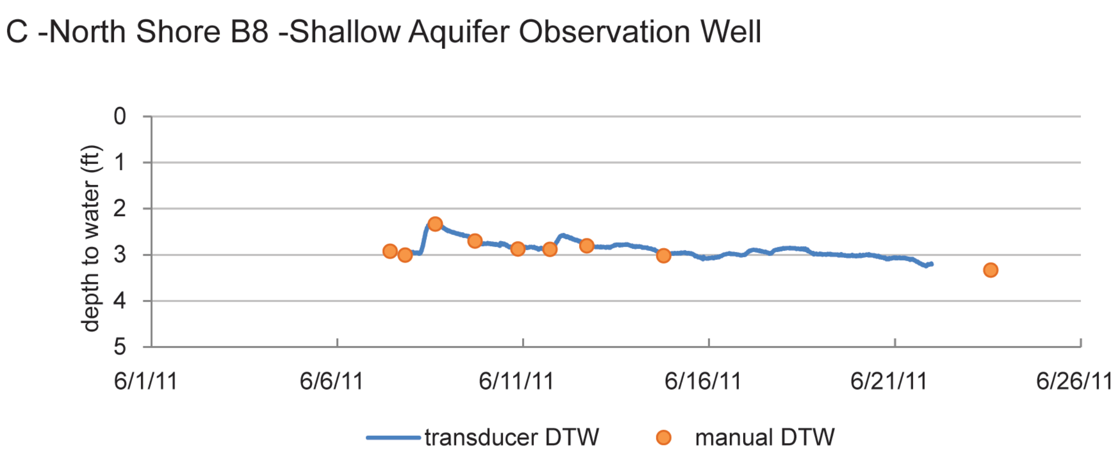
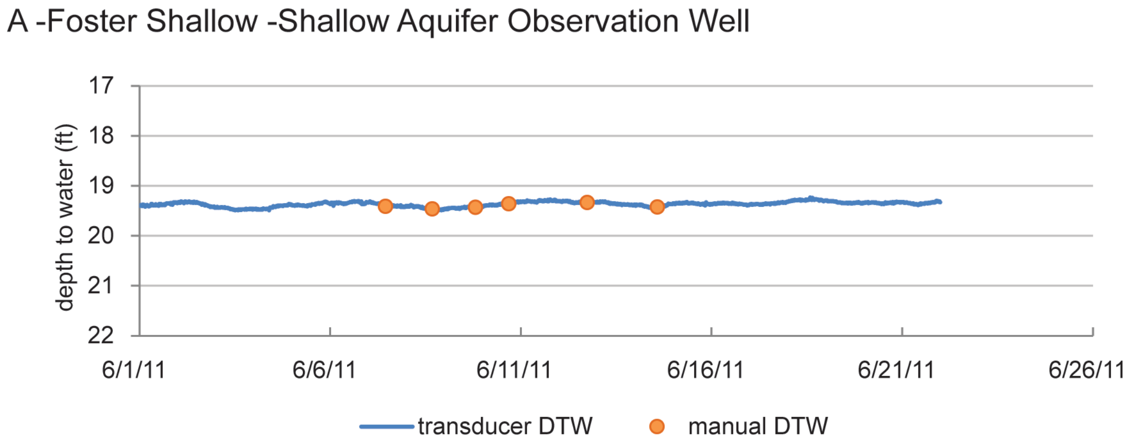


Figure E5. Shallow monitoring wells BFF Domestic (A), MW84-05 (B), and North Shore B8 (C) showed no response to pumping.



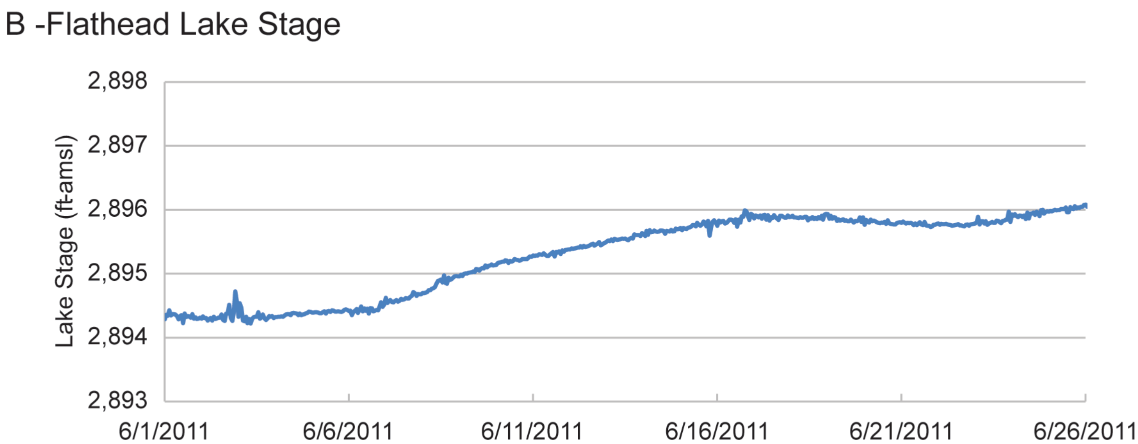


Figure E6. Foster shallow (A) is completed in the shallow aquifer and showed no response to pumping. The stage in Flathead Lake (B) rose throughout the test period.

Manual readings of water levels were made for all wells using an e-tape prior to placing transducers, and were made periodically during the test and recovery periods. These manual measurements were used to calibrate transducer response.

The pumping rate was monitored throughout the test using a totalizing flow meter. The objective for the constant-rate pumping test was to pump at 500 gpm; the discharge rate varied from 430 to 510 gpm (fig. E7). Average discharge for the test was 487 gpm. The pumped water was discharged through a perforated pipe approximately 100 ft to 600 ft downhill (south) from the pumping well.

1.3 Results

Discernible drawdown was observed in six wells in the deep aquifer (figs. E2–E4, table E2). Drawdown could not be quantified in the Foster deep well due to interference from pumping of that well (fig. E4B). None of the shallow or confininglayerwells showed a response to pumping.

1.3.1 Antecedent Trends

Water-level data collected before and after the aquifer test show a consistent rising trend. This trend was calculated based on background and recovered water levels at each well that showed a response to pumping (figs. E2–E4). Drawdown was calculated as the

water levels.

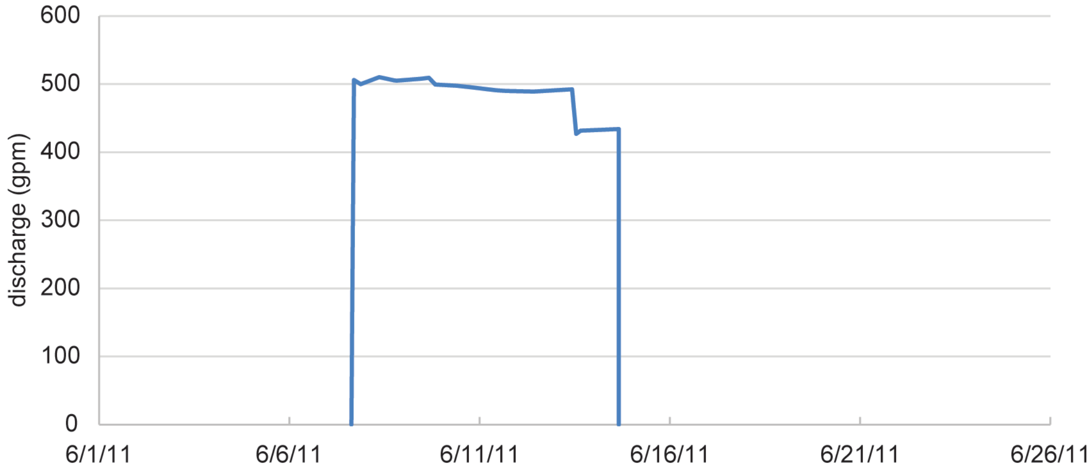


Figure E7. The aquifer test was conducted by pumping from BFF#1 from 6/7/11 at 15:00 to 6/14/11 at 15:40, for a total pumping time of 168 hr and 40 min (~7 d). The time-weighted-average flow rate was 485 gpm; however, a sharp decrease to 430 gpm average occurred on 6/13/11 at 10:12.

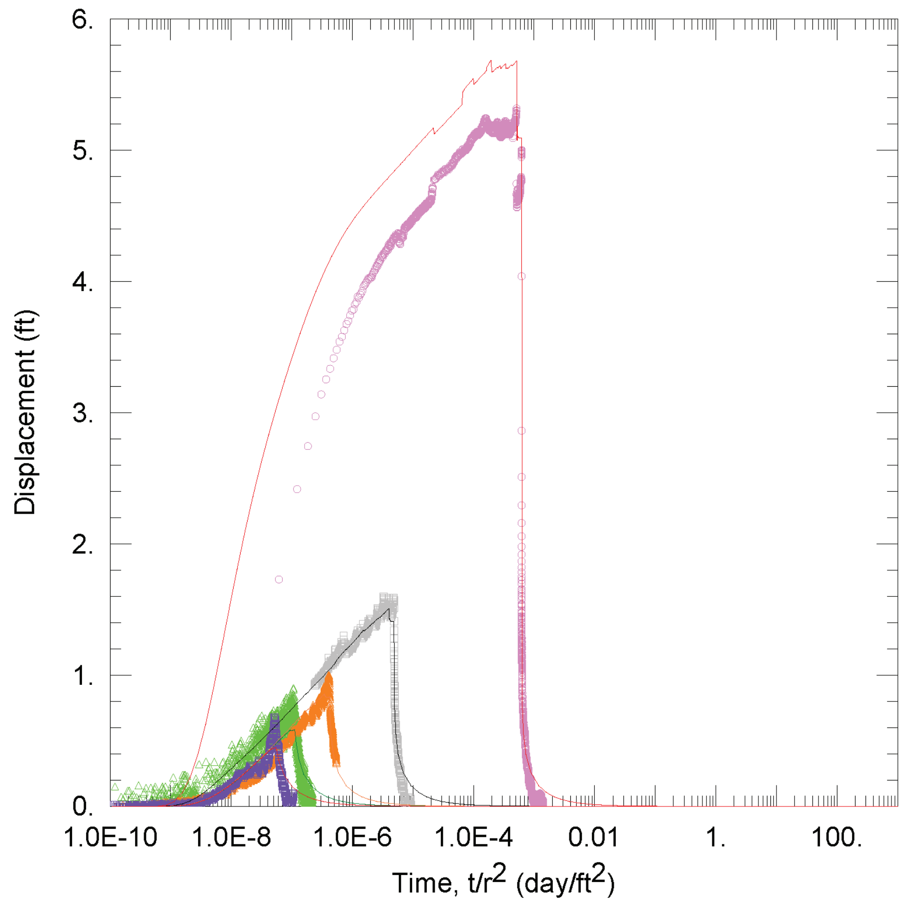
Table E2. Deep aquifer test well designations for responding wells, locations, completion information, and drawdown at 1,000 min.

GWIC ID	Name	Latitude* (DD - N)	Longitude* (DD - W)	Total Depth (ft)	Screen Interval	Radial Distance from Pumped Well (ft)	Drawdown at 1,000 min (ft)
260892	BFF#1	48.103515	114.182153	717	640-670 & 713-717	---	21.94
260888	BFF#2	48.103515	114.182153	672	642-672	106	4.95
141562	Boon	48.100425	114.180335	400	400	1,381	1.08
236497	North Shore	48.092561	114.185965	760	721-739	4,235	0.26
261263	Brosten	48.123998	114.170640	~600	unknown	7,690	0.18
80745	Brevik	48.094702	114.136812	400	400	11,400	0.04

1.3.2 Properties of the Deep Aquifer

Drawdown data for the deep aquifer wells were evaluated using Aqtesolv software (figs. E8, E9). We used the Theis (1935) method for confined aquifers. This method provided a good match with observations, which indicates that leakage through the confining layer is minimal, and boundaries were not encountered. Aquifer boundaries were evaluated based on drawdown observations and derivative plots (Renard and others, 2009). The pumping test showed a confined response from the deep aquifer that corresponds with the conceptual model for the site.

A good match can be obtained for all off-site deep aquifer observation wells using a transmissivity of 35,000 ft^2/d and a storativity of 5.2×10^{-4} (fig. E8). Drawdown data from the on-site deep aquifer observation well (BFF#2) fits best with the same transmissivity, but a storativity of 2.9×10^{-3}. This difference likely results from the fact that transmissivity is determined by the aquifer properties of the entire volume of the drawdown cone, while storativity is determined by the properties along the flowpath between the observation well and the pumping well. Since BFF#2 is much closer to the pumping well than the other observation wells, there is less aquifer heterogeneity encountered along the flowpath, resulting in a different value. A storativity of 2.9×10^{-3} is appropriate at the aquifer test site, but the bulk storativity of the aquifer is best represented by 5.2×10^{-4}. Pumping well BFF#1 is screened over 34 ft. When we apply an estimated 1.5 times the screened interval as the thickness of aquifer providing water to the well (Weight, 2008), the resulting hydraulic conductivity (K) is about 700 ft/day.



BIG FORK FARM AQUIFER TEST

Data Set: M:\...\4OWs_Theis.aqt
Date: 10/26/22 Time: 11:38:03

PROJECT INFORMATION

Company: MBMG
Client: BFF CR Test
Project: BWIPKL
Location: Flathead Valley
Test Well: BFF-01
Test Date: 6/7/2011

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
BFF#1	0	0

Observation Wells

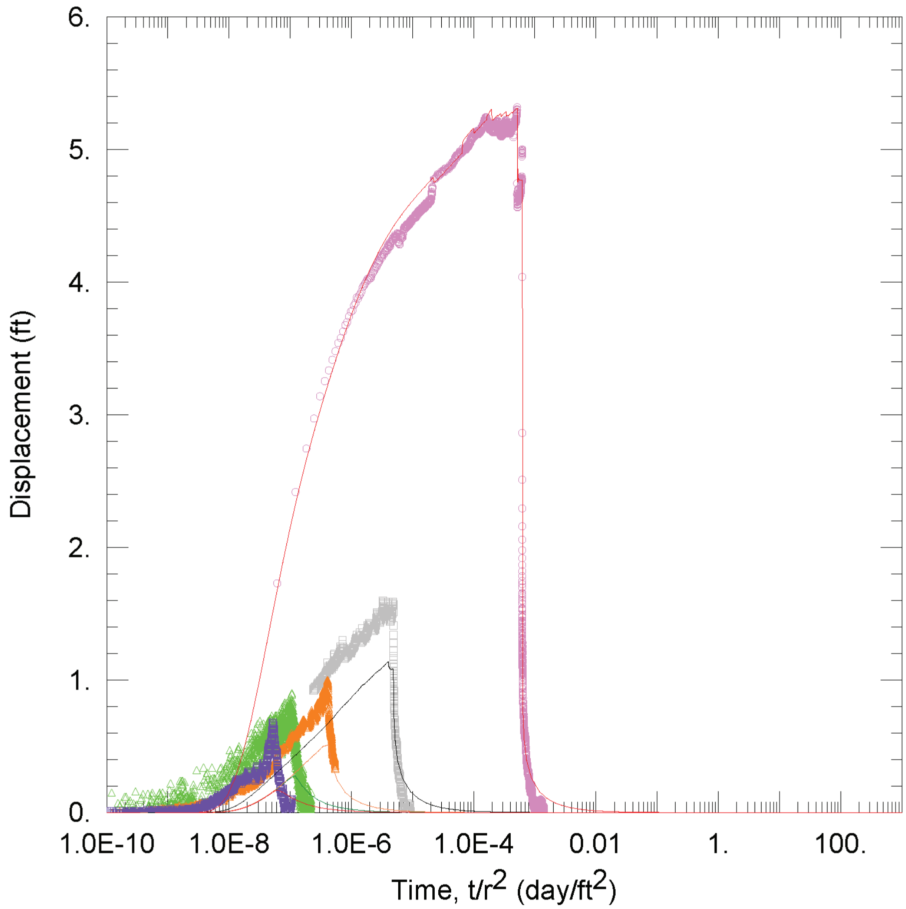
Well Name	X (ft)	Y (ft)
Broston	-3197	-7281
BFF#2	106	0
Boon	-322	1156
North Shore Deep	1188	3923
Brevick	-10808	3870

SOLUTION

Aquifer Model: Confined Solution Method: Theis

T = 3.5E+4 ft^2/day S = 0.00052
Kz/Kr = 1. b = 2125. ft

Figure E8. Aqtesolv plot of the Theis solution with a T of 35,000 ft^2/d and a S of 5.2 x 10^{-4}.



BIG FORK FARM AQUIFER TEST

Data Set: M:\...\4OWs_Theis.aqt
Date: 10/26/22 Time: 11:39:31

PROJECT INFORMATION

Company: MBMG
Client: BFF CR Test
Project: BWIPKL
Location: Flathead Valley
Test Well: BFF-01
Test Date: 6/7/2011

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
BFF#1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
Broston	-3197	-7281
BFF#2	106	0
Boon	-322	1156
North Shore Deep	1188	3923
Brevick	-10808	3870

SOLUTION

Aquifer Model: Confined Solution Method: Theis

T = 3.5E+4 ft^2/day S = 0.0029
Kz/Kr = 1. b = 2125. ft

Figure E9. Aqtesolv plot of the Theis solution with a T of 35,000 ft^2/d and a S of 2.9×10^{-3}.

This value is consistent with a sand and gravel aquifer (Heath, 1983).

1.4 Summary

The results of this aquifer test are replicated using the Theis method for confined aquifers, indicating that the aquifer is confined beneath an aquitard. The shallow wells did not respond to pumping, and no boundaries were encountered. The deep aquifer is productive, with a specific capacity of about 23 gpm/ft.

2. CONFINING LAYER TEST

2.1 Background

2.1.1 Purpose of Test

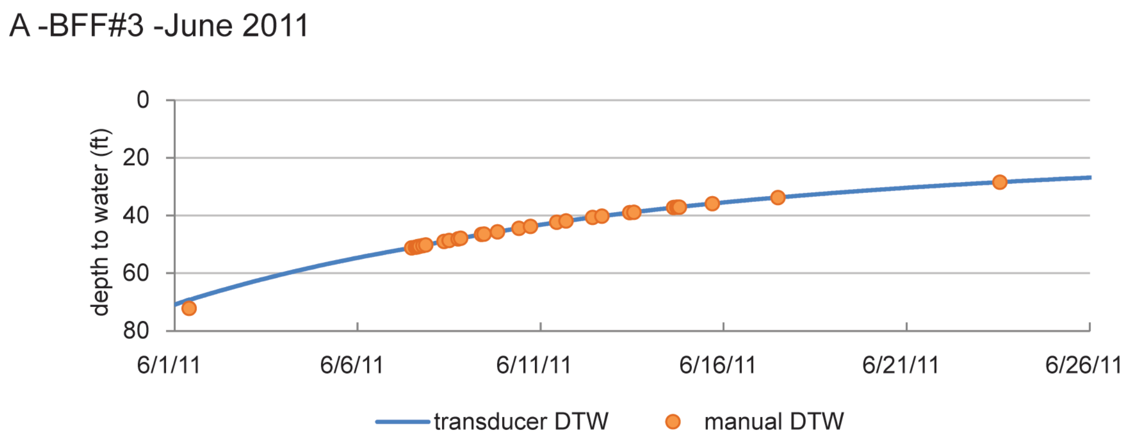
The tested well is completed in lacustrine sediments that compose the confining layer. This well was slow to recover from development. Analysis of the water levels recorded during recovery allowed estimation of the hydraulic conductivity (K) of the confining layer, and evaluation of whether there was a measurable connection to the deep or shallow aquifers.

2.1.2 Test Type

Water was pumped from well BFF#3 to aid in well development. The water level recovered slowly over several months. The recovery data were analyzed as a slug test.

2.2 Field Procedures

The well was pumped on May 17, 2011 to aid in well development. Pumping over 21 min withdrew 185 gal of water from the well before the water level was drawn down to the pump inlet. We installed a transducer and data logger in the well on May 27, 2011 and collected hourly water-level measurements. Water levels recorded between June 1 and June 26, 2011 were used for this analysis (fig. E10A). Water levels recovered by about 50 ft during this period and continued to recover after June 26 (fig. E10B). Manual



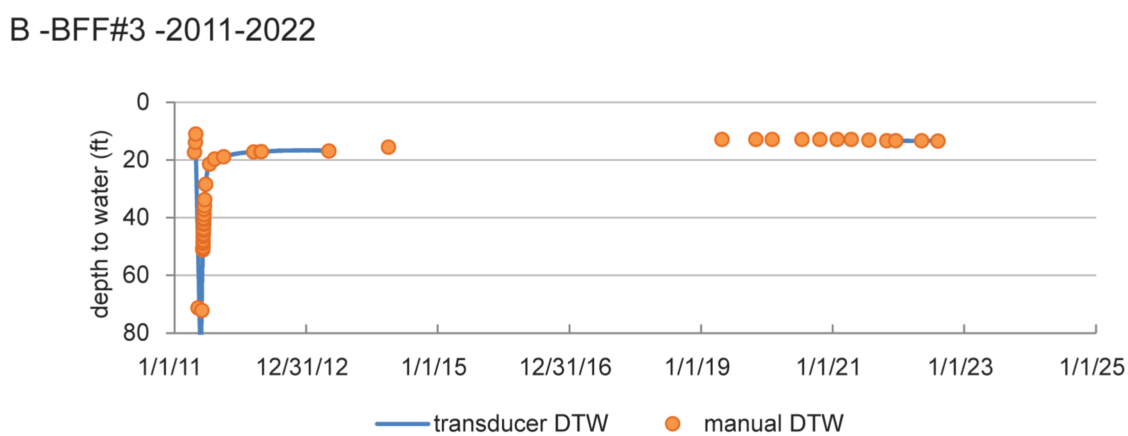


Figure E10. The recovery curve for well BFF#3 from June 1 to June 26, 2011 (A) was used to estimate hydraulic properties of the aquitard. Longer term monitoring (B) shows that several years were needed for water levels to fully stabilize.

water-level readings were made using an e-tape prior to installing the transducer and periodically during the recovery period. These manual measurements were used to correct for transducer drift.

2.3 Results

The 21 min of pumping can be treated as the instantaneous removal of a slug of water. The recovery data were analyzed using the Hvorslev (1951) method for a point piezometer, since the well is completed over a 10 ft interval within the 320-ft-thick confining layer. Since the actual screened interval is not a point, the calculated K value may overestimate high. The analysis yields a hydraulic conductivity (K) of approximately 0.0007 ft/d (fig. E11). This is in the expected range of K values for silt and clay (Heath, 1983).

No response to the pumping or slug recovery was detected in the nearby shallow aquifer well (260891) or deep aquifer well (260888). Pumping from the deep aquifer for the deep aquifer test (June 7 to June 14, 2011; see section 1 of this appendix) had no discernible effect on the recovery of BFF#3. Long-term monitoring shows the water level continued to recover and eventually to stabilize. The static water level measured on April 26, 2019 was 11.2 ft, a similar depth to the water level recorded during drilling.

2.4 Summary

The aquitard has a K value of about 0.0007 ft/d. As expected, the aquitard is a poor conductor of groundwater. This confining unit is a barrier to the exchange of groundwater between the deep and shallow aquifers. The confining unit is about 6 orders of magnitude lower in K than the deep aquifer, creating a confining cover over the deep aquifer in this area.

3. TERTIARY AQUIFER TEST

3.1 Background

3.1.1 Purpose of Test

This aquifer test was designed to estimate the transmissivity (T) of the Tertiary sediments in the Flathead Valley. This is the only well that we are aware of completed in the Tertiary sediments in the Flathead Valley, which we interpret as the Kishenehn Formation.

3.1.2 Test Type

BFF#5 was purged for water sampling in March–April 2022. During purging the water-level drawdown and pumping rates were measured to allow estimation of hydrologic parameters. This test was evaluated as a variable rate pumping test because the pumping rate was not steady nor continuous. This was a single well test since this is the only well completed in the silt-sand Tertiary sediments underlying the deep aquifer.

3.2 Field Procedures

We determined an appropriate pumping rate at the well on February 17, 2022. With the pump set at 100 ft-bgs and an average pumping rate of 3 gpm, manual depth to water measurements using an e-tape showed that the water level declined from a static level of 13.64 ft below measuring point to 90.47 ft in 45 min. This drawdown response suggested that a lower rate would be necessary to maintain a water level above the pump for the required purging time. A target rate of 0.5 gpm was selected for the longer test.

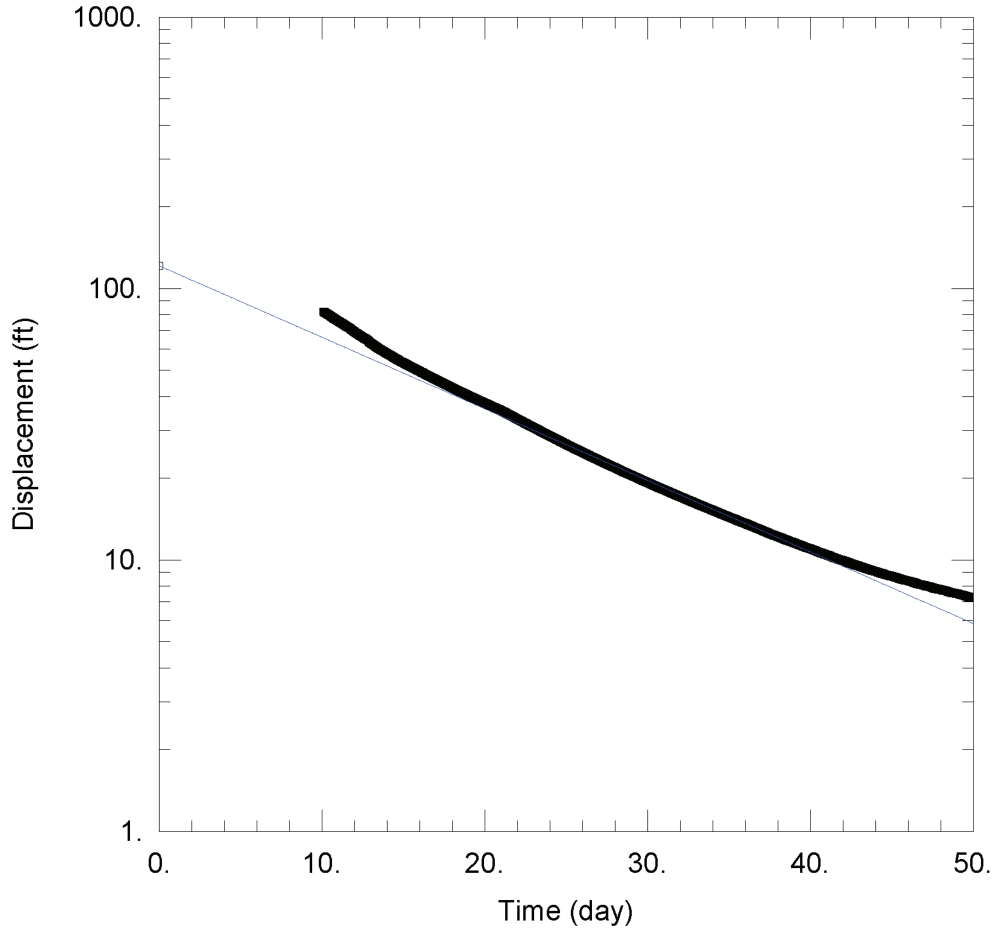
The well was pumped for a total of 125 h (5.2 d) over a 10-d period, March 29, 2022 through April 7, 2022. The time-weighted average pumping rate was 0.58 gpm during the pumping periods and purged about 1.6 well volumes. Pumping rates varied from 0.4 to 1.1 gpm, and there were intervals with no pumping (fig. E12). The pumped water was discharged through a hose onto the ground 50 ft west of the well.

3.2.1 Data Collection

A water-level transducer was set in BFF#5 for several months prior to the aquifer test to record hourly water levels and define antecedent trends. Water levels were recorded at 1-min intervals during purging. Manual measurements were taken to confirm transducer data. Transducers were also installed in BFF#1, BFF#3, and BFF#4. Recovery water levels were recorded by transducer hourly. Pumping rates were monitored throughout the test using a bucket and stopwatch.

3.3 Results

Due to variability in the well pumping rates, aquifer transmissivity was primarily estimated using data from BFF#5 during the first pumping interval from 0–500 min, and from the first 31 d of recovery. The other wells at the site showed no response to



RECOVERY FROM PUMPING CONFINING LAYER

Data Set: M:\...\BFF-03_recovery - y0=121pt45.aqt
Date: 10/26/22 Time: 12:32:10

PROJECT INFORMATION

Company: MBMG
Client: BWIPKL
Location: Big Fork Farm
Test Well: BFF-03
Test Date: 5/17/2011

AQUIFER DATA

Saturated Thickness: 300. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA (BFF#3)

Initial Displacement: 121.5 ft
Total Well Penetration Depth: 290. ft
Casing Radius: 0.25 ft
Static Water Column Height: 359.4 ft
Screen Length: 10. ft
Well Radius: 0.25 ft

SOLUTION

Aquifer Model: Confined Solution Method: Hvorslev

K = 0.0007 ft/day y0 = 121.5 ft

Figure E11. Aqtesolv plot of the Hvorslev slug test solution for the confining layer well.

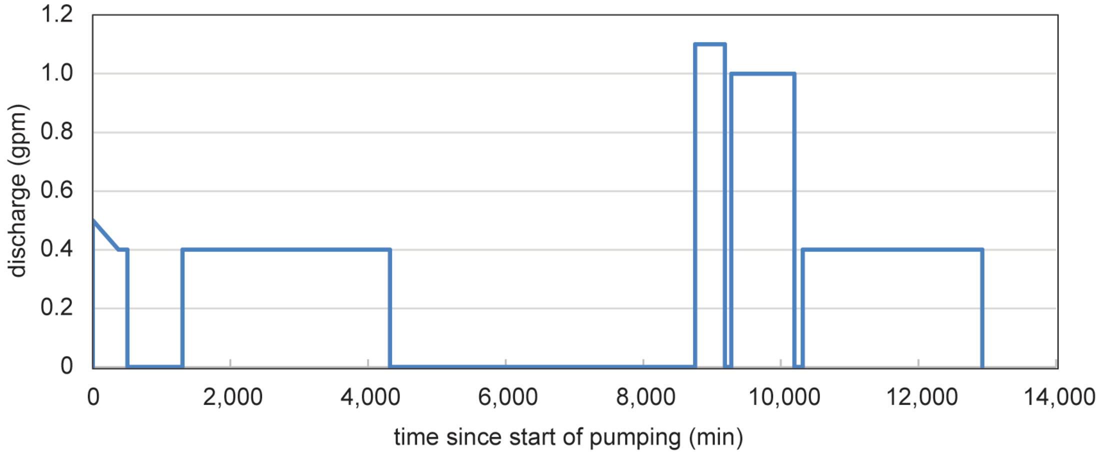


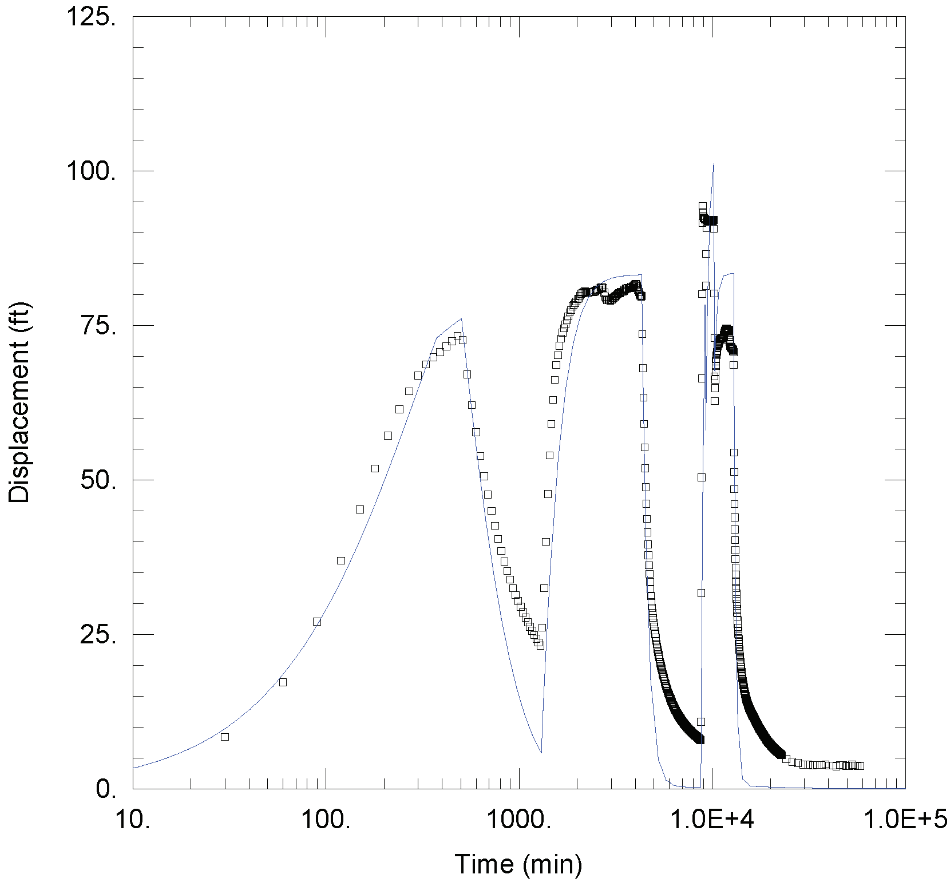
Figure E12. Pumping rates from BFF#5.

the pumping. The drawdown and recovery data from BFF#5 were analyzed using Aqtesolv software and the Dougherty–Babu (1984) method. This method was selected due to the variability in the pumping rates during this test and the importance of well bore storage. Analysis of data from the first 500 min of pumping results in a transmissivity estimate of about 15 ft^2/day (fig. E13). An analysis of the recovery data showed an estimated transmissivity of about 14 ft^2/day. These results also show that a non-leaky confined aquifer model matches observations reasonably well.

Using 1.5 times the well's screened interval to represent the thickness of aquifer supplying water to the well (Weight, 2008), hydraulic conductivity (K) is about 0.5 ft/d. This value is expected for fine-grained or silty sand (Heath, 1983).

3.4 Summary

Estimated T and K of the Tertiary sediments are about 15 ft^2/d and 0.5 ft/day, respectively. The Tertiary sediments showed a confined aquifer response to pumping.



WELL TEST ANALYSIS

Data Set: M:\...\All data Dougherty_2ALB.aqt
Date: 10/26/22 Time: 11:29:53

PROJECT INFORMATION

Company: MBMG
Project: BWIPDW
Location: Kalispell
Test Well: 317644
Test Date: 4/4/22

AQUIFER DATA

Saturated Thickness: 360. ft Anisotropy Ratio (Kz/Kr): 0.1

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
BFF#5	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ BFF#5	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Dougherty-Babu

T = 15.12 ft^2/day
Kz/Kr = 0.1
r(w) = 0.333 ft

S = 1.081E-6
Sw = 0.
r(c) = 0.25 ft

Figure E13. Aqtesolv plot of the Dougherty–Babu solution for pumping from BFF#5 completed in the Tertiary sediments.

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