MBMG Open-File Report 654

Hydrogeologic Investigation of the North Hills Study Area

Lewis and Clark County, Montana

Technical Report

2014

Andrew Bobst, Kirk Waren, James Swierc,[1] and Jane Madison

Montana Bureau of Mines and Geology

Ground Water Investigations Program

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[1] Lewis and Clark County Water Quality Protection District, Helena, Montana

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PREFACE

This report has been prepared by the Montana Bureau of Mines and Geology (MBMG) Ground Water Investigations Program (GWIP). The purpose of this program is to investigate specific areas where factors such as current and anticipated growth of agriculture, industry, housing, commercial activity, or other criteria have created an elevated level of concern over groundwater issues. The areas to be studied are prioritized by the Ground Water Assessment Steering Committee. Additional information on the program and the ranking process can be accessed at: http://www.mbmg.mtech.edu/gwip/gwip.asp. Project goals are accomplished by collecting and compiling groundwater and surface-water data for each study area and analyzing those data through mapping and modeling to understand changes that are happening and to project future changes.

The final products for this study include an Interpretive Report, a Groundwater Modeling Report, a Technical Report, and a comprehensive set of data. Collected data are permanently stored in the MBMG's Groundwater Information Center (GWIC) online database (http://mbmggwic.mtech.edu/) whenever possible. The purpose of each report is as follows:

Interpretive Report (Waren and others, 2012; MBMG 610): The interpretive report summarizes the project and presents interpretations of the data, evaluating them in the context of the overall area and activities within the study area. The Interpretive Report includes the results of all aspects of the project. This report is intended for use by the general public, interest groups, decision-makers, and hydrogeologists.

Groundwater Modeling Report (Waren and others, 2013; MBMG 628): The modeling report provides detailed documentation of the procedures and assumptions inherent in the models and communicates the findings of the models. That report is intended to allow the models to be evaluated and used by others. All files needed to operate the groundwater models are posted to the project website (www.mbmg.mtech.edu/gwip/). These files are intended to enable qualified individuals to use the overall models developed by GWIP to test specific scenarios of interest, or to provide a starting point for site-specific analysis.

Technical Data Report (this report): This report is a collection of relatively short technical reports that address specific aspects of the study. For example, details of aquifer testing and analysis are included. This report is intended to provide the technical data that will enable users of the Interpretive and Modeling reports to perform their own evaluations.

INTRODUCTION

The purpose of the North Hills Groundwater Investigation (Waren and others, 2012) was to scientifically assess the sustainability of current and potential future groundwater withdrawals, the potential for impacts to senior water-rights holders from groundwater withdrawals, and the potential for impacts to groundwater quality from septic effluent. Most of the data collected during this study are stored in the Ground Water Information Center database (http://mbmggwic.mtech.edu/).

Groundwater availability varies within the North Hills. Unconsolidated materials can produce significant volumes of water, but bedrock units do not always provide adequate water to wells. Current development has resulted in an observed area of reduced groundwater altitudes in and near relatively high-density subdivisions and where groundwater is extracted from bedrock or Tertiary aquifers.

Seventy-nine groundwater samples were collected at 28 sites. The nitrate concentration in one sample exceeded the primary drinking water standard. No other primary drinking water standards were exceeded. The most likely source of nitrate is septic effluent. Thin soils and fractured bedrock aquifers have limited ability to break down septic effluent due to low biological activity and rapid recharge.

Report Structure

This report supports the North Hills Interpretive Report (Waren and others, 2012), and contains a collection of technical information that has been prepared in support of the North Hills Groundwater Investigation. The sections of this report are as follows:

Site List: Includes all the sites used in this study, their purpose of use, their location, and their GWIC ID numbers. A site's GWIC ID number can be used at the GWIC website to access all data associated with that site.

Aquifer Tests Summary: Presents results from all known (at the time of publication) aquifer tests conducted in the North Hills. Included are tests conducted for DNRC water-rights applications, tests conducted in association with previous groundwater studies, and tests conducted as a part of this study.

Panoramic Meadows Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on private land in the Tertiary sediments just north of Lake Helena.

Helena Valley Fault Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on private land adjacent to the Helena Valley Fault. The Spokane Formation is to the south of the fault and the Greyson Formation is to the north.

Valley Excavating Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on private land in the Spokane Formation.

O'Reilly Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on private land in the Greyson Formation. For this test deep (260 ft) and shallow (45 ft) wells were completed, and the vertical communication between them was evaluated.

Purcell Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on private land in the Helena Formation, adjacent to a suspected fault.

State Lands East Aquifer Test Report
Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on State land in the Spokane Formation.

State Lands West Aquifer Test Report: Presents, describes, and evaluates data from an aquifer test conducted by the MBMG on State land in the Spokane Formation.

Hydrographs: Includes a series of hydrographs demonstrating long-term groundwater level changes.

Comparison of Hydrographs to Precipitation: Compares the trends observed in hydrographs to the 30-month Standardized Precipitation Index.

Potentiometric Surface Maps: Includes potentiometric surface maps developed to evaluate seasonal changes in the overall North Hills potentiometric surface, and comparisons of current surface to surfaces developed by previous studies.

Groundwater/Surface-Water Interactions: Includes surface-water and groundwater elevation and temperature graphs for three sites along Silver Creek.

Water Budget: A detailed evaluation of the groundwater budget for the North Hills.

Geophysical Investigations: Provides a summary of geophysical work conducted in the North Hills.

Water Chemistry: Provides supplemental details of water chemistry results.

Acknowledgments

We thank the many landowners and residents of the North Hills Study Area for their interest in the study, and for their permission to conduct various aspects of the investigation on their properties. Lewis and Clark County Local Water Quality Protection District provided significant assistance by contracting the services of Gary Burton for monthly measuring of water levels, and allowing hydrogeologist James Swierc to contribute to this project. Pat Faber assisted with the collection and collation of previous aquifer test data. Russell Levens and James Beck of the Montana Department of Natural Resources and Conservation (DNRC) contributed substantially by providing comments and direction regarding water rights, surface-water monitoring, Controlled Groundwater Areas, and groundwater modeling efforts.

Gary Icopini from the MBMG provided technical assistance for the sampling of Organic Waste-Water Chemicals. Allison Brown, a Montana Tech student, provided assistance in field and office aspects.

The Tenmile Creek and Lake Helena watershed groups provided opportunities for our program to discuss the study, and for improving our understanding of the local issues. The Montana Watershed Coordinating Council Groundwater Work Group provided a forum in which to share our plans and activities with hydrologists and geologists from other agencies. The Lewis and Clark County Conservation District provided permission for stream access for instrumentation used in the study. The Helena Valley Irrigation District (HVID) provided permission for access to the HVID canal and agricultural drains to measure flows and to instrument drains.

SITE LIST

The following table shows those sites that were used for the North Hills Study. Data from these sites are stored in GWIC. This includes sites that were periodically monitored, used for aquifer tests, or provided historical data. The table is organized by site type, then by GWIC ID number.

Site uses included:

> *Transducer*: Static groundwater level was measured, and a pressure transducer was installed for the remainder of the study. Data were recorded hourly, and the site was visited periodically (typically monthly) to download the transducer and obtain manual groundwater elevation measurements. These manual measurements were used to evaluate the transducer data, and correct for drift.
>
> *Monthly GWE*: Groundwater levels (depth to water from a designated measuring point) were collected from these sites monthly. The depths to water readings were converted to groundwater elevations based on the surveyed measuring point elevation.
>
> *Water Quality*: Sites sampled for water quality. Analytical results, depending on site, may have included major ions, metals, nutrients, oxygen isotopes of water, hydrogen isotopes of water, sulfur isotopes of sulfate, nitrogen isotopes of nitrate, oxygen isotopes of nitrate, or radon.
>
> *Surface Water*: Surface-water sites where the MBMG or others made discharge measurements, stage readings, continuous stage readings (digital logger), measured crest gauge water levels, or collected temperature readings.
>
> *Spring*: Monitoring typically included monthly measurements of flow, pH, temperature, and specific conductance (SC).
>
> *Aquifer Test*: A site that participated in at least one aquifer test. Transducers were installed before the start of the test to collect background data, and manual water-level measurements were done during and after the test to evaluate transducer data.
>
> *Precip*: Sites where the amount of precipitation was measured and/or where precipitation samples were collected for chemical analysis.
>
> *Historical*: Historical data such as lithologic descriptions or water levels were used from these sites.

Site types included:

> *Stream*: A surface-water site located on a naturally occurring moving body of water. A staff gauge and stilling well were typically installed.
>
> *Crest Gauge*: A surface-water site located on a naturally occurring ephemeral drainage. A crest gauge (indicates the highest stage experienced between visits) was installed.

Canal: A surface-water site located on a man-made channel used to conduct water to irrigated fields.

Drain: A surface-water site located on a man-made channel used to conduct water away from irrigated fields. In the Helena Valley the drains have been dug deep enough to intersect shallow groundwater and prevent water logging of fields. Water logging became a problem with increased irrigation in the valley due to the recharge of groundwater from canal leakage, and excess water applied to fields (variously called irrigation recharge, incidental recharge, or leaching fraction).

Precip: A site used to measure the amount of precipitation, or to analyze the chemistry of precipitation.

Spring: Developed springs where flow and water quality were measured at discharge pipes.

Well: Domestic or monitoring wells that are completed in various North Hills aquifers.

		Use													
GWIC ID	Site Name	Transducer	Monthly GWE	Water Quality	Surface Water	Spring	Aquifer Test	Precip	Historical	Installed for this Study	Lat	Lon	Geomethod	Altitude	Type
257663	VX CREST GAGE				X					X	46.75912	-112.06782	NAV-GPS	4250	CREST GAUGE
257664	UTICK CREST GAGE				X					X	46.73363	-111.96092	NAV-GPS	3925	CREST GAUGE
257665	DARGON CREST GAGE				X					X	46.73378	-111.94739	NAV-GPS	3915	CREST GAUGE
257666	FRASER CREST GAGE				X					X	46.75111	-112.08527	NAV-GPS	4180	CREST GAUGE
258104	WINSLOW CREST GAGE				X					X	46.73390	-112.05665	PHOTO-GM	3955	CREST GAUGE
255052	HVID D-2-2.3-1 (DA)			X	X					X	46.70377	-111.99996	SUR-GPS	3704.08	DRAIN
255069	HVID D-2-2.3-2L (DC)			X	X					X	46.68962	-112.00010	SUR-GPS	3686.18	DRAIN
255071	HVID D-2-0.7-1 (DD)			X	X					X	46.69319	-111.97897	SUR-GPS	3660.59	DRAIN
255072	HVID D-1_UPPER (DE)			X	X					X	46.70467	-111.97301	SUR-GPS	3664.49	DRAIN
255073	HVID D-1 (DF)			X	X					X	46.70417	-111.97306	NAV-GPS	3670	DRAIN
255074	HVID D-0 ARMSTRONG (DG)			X	X					X	46.70589	-111.95735	SUR-GPS	3665.10	DRAIN
257059	HVID D-2-2.3-2U (DB)				X					X	46.69050	-112.00010	PHOTO-GM	3690	DRAIN
257226	FWP BOATLAUNCH * DR-2			X	X					X	46.70277	-111.95752	PHOTO-GM	3655	DRAIN
256972	HVID-1 (MCHUGH LN)			X	X					X	46.63437	-112.03322	MAP	3790	IRRIGATION
256973	HVID-2 (JOHN G MINE RD)				X					X	46.68979	-112.04617	MAP	3787	IRRIGATION
259609	LLOYD, NEAL & DEBBIE				X					X	46.70935	-112.08212	MAP	3935	IRRIGATION
257227	SMITH RD. * S-1			X				X		X	46.70455	-111.95426	PHOTO-GM	3655	PRECIP
257228	STATE LAND * S-2			X				X		X	46.73349	-112.01984	PHOTO-GM	3930	PRECIP
257229	DIAMOND HILL * S-3			X				X		X	46.75927	-112.04002	PHOTO-GM	4330	PRECIP
257233	I-15 * S-4			X				X		X	46.76980	-112.03298	PHOTO-GM	4680	PRECIP
257235	VX * S-5			X				X		X	46.76222	-112.07293	PHOTO-GM	4355	PRECIP
257236	SILVER CREEK RD BRIDGE * S-6			X				X		X	46.69931	-112.10643	PHOTO-GM	4020	PRECIP
257237	MARYSVILLE RD * S-7			X				X		X	46.74924	-112.27049	PHOTO-GM	4900	PRECIP
257238	OTTAWA GULCH * S-8			X				X		X	46.74309	-112.30843	PHOTO-GM	5700	PRECIP
257240	SKI RESORT * S-9			X				X		X	46.75191	-112.31163	PHOTO-GM	5870	PRECIP
254993	SILVER CREEK_SC-SW3 * SC-SW3				X					X	46.70192	-112.09204	SUR-GPS	3954.58	STREAM
254994	SILVER CREEK; SW-SC1			X	X					X	46.70029	-112.10772	SUR-GPS	4022.42	STREAM
255000	SEVENMILE CREEK * 7M-SW1			X	X					X	46.64957	-112.12183	SUR-GPS	4080.97	STREAM
255001	SILVER CREEK; SC-2 * SC-SW2			X	X					X	46.70448	-112.07634	SUR-GPS	3888.94	STREAM
255059	TENMILE AT GREEN MEADOWS * 10M-SW1			X	X					X	46.63181	-112.04699	NAV-GPS	3815	STREAM
256969	LAKE HELENA CAUSEWAY			X	X					X	46.70210	-111.90108	SUR-GPS	3651.84	STREAM
257316	TENMILE CREEK AT MEHUGH LANE			X	X					X	46.63397	-112.03163	MAP	3790	STREAM
260287	SEVENMILE CREEK * 7M-SW2				X					X	46.63688	-112.08433	NAV-GPS	3925.71	STREAM
257239	DIAMOND HILL SPRING * SP-1			X		X					46.75915	-112.03962	SUR-GPS	4329.95	SPRING
5823	ROBBINS JANE * HELENA MT								X		46.72720	-112.03940	MAP	3882	WELL
5826	USGS RES WELL - HELENA VALLEY 23								X		46.70800	-111.97750	MAP	3690	WELL
5831	USGS RES WELL - HELENA VALLEY 24								X		46.70470	-111.96270	MAP	3670	WELL
5835	HILGER E * EAST HELENA MT								X		46.70470	-112.00020	MAP	3719	WELL
5836	JAKOVAC JOE * HELENA MT								X		46.71270	-112.02250	MAP	3783	WELL
5837									X		46.71330	-112.03970	MAP	3814	WELL
5838	ERWIN DAVID * HELENA MT								X		46.70500	-112.03020	MAP	3777	WELL
5839	JAKOVAC JOE * HELENA MT								X		46.74630	-112.02050	MAP	3757	WELL
5840	GOWEN RUSS * HELENA MT								X		46.70050	-112.04130	MAP	3795	WELL
5841	SCHNEIDER LEON G. * HELENA MT								X		46.69020	-112.04020	MAP	3767	WELL
5842	RADLEY P H * HELENA MT								X		46.69300	-112.02250	MAP	373.9	WELL
5843	USGS RES WELL * 5 MI SE VETERANS ADM CNTR								X		46.70440	-112.01970	MAP	3755	WELL
5846	USGS * LINCOLN RD EAST		X								46.70430	-111.99568	SUR-GPS	3706.45	WELL
5852	MASONIC HOME								X		46.69160	-111.98660	MAP	3680	WELL
5854	USGS * MASONIC WEST	X	X	X							46.69248	-111.97884	SUR-GPS	3666.52	WELL
5859	USGS * MASONIC EAST								X		46.69190	-111.97830	MAP	3665	WELL
5861	JOHNSON FLOWING WELL								X		46.70220	-111.97690	MAP	3672	WELL
5862	BRUNNER'S * HELENA MT								X		46.69550	-111.97750	MAP	3665	WELL
5911	BLAGG VIRGINIA * HELENA MT								X		46.70330	-112.06130	MAP	3910	WELL

		Use													
GWIC ID	Site Name	Transducer	Monthly GWE	Water Quality	Surface Water	Spring	Aquifer Test	Precip	Historical	Installed for this Study	Lat	Lon	Geomethod	Altitude	Type
5913	WAYLAND * HELENA MT								X		46.70470	-112.06250	MAP	3859	WELL
5917	UMFLEET CLARK * HELENA								X		46.69830	-112.04130	MAP	3790	WELL
5918									X		46.69610	-112.06050	MAP	3840	WELL
5919	SCHWINDT NANCY * HELENA MT								X		46.69080	-112.04800	MAP	3797	WELL
5920	WARDELL JOHN * HELENA MT								X		46.68880	-112.04470	MAP	3782	WELL
5921	WARDELL CALLIS * HELENA MT								X		46.68880	-112.04550	MAP	3784	WELL
5923	RIES * HELENA MT								X		46.67910	-112.05220	MAP	3808	WELL
5924	WAGNER ALVIN * HELENA MT								X		46.68020	-112.04970	MAP	3761	WELL
5925	USGS RES WELL * 6 MI NE VET ADM CENTER								X		46.67550	-112.04160	MAP	3734	WELL
64640	TRALLES, STEVE		X								46.73643	-112.01988	SUR-GPS	3960.93	WELL
64649	TRALLES, STEVE		X								46.73647	-112.01989	SUR-GPS	3961.37	WELL
64686	SING, JUE K.		X								46.74041	-112.02157	SUR-GPS	4003.13	WELL
64730	HEDDEN, BRETT AND KIRA		X	X							46.73197	-112.04097	SUR-GPS	3921.04	WELL
64737	STATE OF MONTANA * DEPT OF STATE LANDS		X								46.73175	-112.01927	SUR-GPS	3911.99	WELL
64740	SKILLMAN, DAN AND LOLA		X								46.72141	-112.00988	SUR-GPS	3812.49	WELL
64755	OFFICE OF STATE FORESTER	X	X								46.72330	-112.02014	SUR-GPS	3840.12	WELL
64771	PURCELL WILLIAM								X		46.72366	-111.99594	SUR-GPS	3830.50	WELL
64774	COLE CONNIE		X	X							46.72578	-111.96324	SUR-GPS	3841.57	WELL
64780	MOUNTAIN HERITAGE WATER SYSTEM - WELL B								X		46.71970	-111.93460	MAP	3770	WELL
64798	CHASE, ERIC		X	X							46.71862	-111.97417	SUR-GPS	3768.59	WELL
65088	HELM, SCOTT		X	X							46.66611	-112.01950	SUR-GPS	3714.33	WELL
65271	GARRICK GALEN		X								46.71936	-112.05326	SUR-GPS	3886.64	WELL
65294	WIGGINS DONALD								X		46.71770	-112.04130	MAP	3850	WELL
65315	SMELKO DANIEL B								X		46.70555	-112.07958	SUR-GPS	3905.10	WELL
65316	SMELKO, DANIEL B.	X	X	X							46.70460	-112.07717	SUR-GPS	3897.52	WELL
65422	MOOTS JOHN A AND LINDA M		X								46.70081	-112.04974	SUR-GPS	3815.41	WELL
65432	DRAKE RON AND VIVIAN	X	X								46.70294	-112.05922	SUR-GPS	3846.79	WELL
65536	SELVA ADOLFO	X	X	X							46.68542	-112.07122	SUR-GPS	4092.01	WELL
66319	WALTHER JAMES			X					X		46.75530	-112.02459	MAP	4260	WELL
121149	FENTON								X		46.67550	-112.04330	MAP	3735	WELL
122132	ADAMS HAROLD								X		46.69800	-112.02270	MAP	3733	WELL
123572	LEWIS AND CLARK CO								X		46.70220	-111.97690	MAP	3760	WELL
125628	ROSE CURT		X								46.71191	-112.03905	SUR-GPS	3813.94	WELL
128054	TUCKER LISA		X	X							46.73481	-111.95820	SUR-GPS	3944.59	WELL
138527	WALTHER JAMES		X	X							46.75536	-112.02436	SUR-GPS	4244.66	WELL
143645	SALISBURY JEFF AND JUDY		X	X							46.73866	-112.03077	SUR-GPS	3970.42	WELL
144725	STOLP, JUSTIN AND STACY		X	X							46.73462	-111.97720	SUR-GPS	3942.99	WELL
144726	CROWLEY PAT	X	X	X							46.71773	-111.99055	SUR-GPS	3782.58	WELL
145957	PURCELL WILLIAM S	X	X	X							46.72381	-111.99597	SUR-GPS	3832.24	WELL
147289	WALL JOHN		X	X							46.66366	-112.04917	SUR-GPS	3758.77	WELL
148259	JAFFE VAL		X								46.73297	-111.95544	SUR-GPS	3904.14	WELL
152551	HEDDEN ROGER		X	X							46.73570	-112.07425	SUR-GPS	4051.63	WELL
170202	JACOBS JOHN		X								46.71605	-111.91319	SUR-GPS	3818.68	WELL
176010	NYSTRAND ROBERT								X		46.72494	-111.97983	SUR-GPS	3825.22	WELL
176011	PURCELL WILLIAM S								X		46.72363	-111.99416	SUR-GPS	3831	WELL
176012	PURCELL WILLIAM S								X		46.72460	-111.99412	SUR-GPS	3839.95	WELL
178386	PETROSKY JEFF & ANGELE		X	X							46.74150	-111.98158	SUR-GPS	4037.80	WELL
180458	DRIVER, SHAWN AND EVELYN								X		46.73310	-112.03540	MAP	3922	WELL
180976	DONOHUE DAVE AND HANSEN CYNTHIA		X	X							46.73212	-112.08775	SUR-GPS	4185.94	WELL
187372	FLADLAND JASON AND JAMIE		X								46.71237	-112.04335	SUR-GPS	3823.69	WELL
187438	NJOS KAL		X	X							46.75403	-112.02092	SUR-GPS	4211.04	WELL
187850	WOEHL HERMAN		X								46.73399	-112.02423	SUR-GPS	3928.63	WELL
189417	MOOTS JOHN		X								46.70071	-112.04977	SUR-GPS	3815.51	WELL

		Use													
GWIC ID	Site Name	Transducer	Monthly GWE	Water Quality	Surface Water	Spring	Aquifer Test	Precip	Historical	Installed for this Study	Lat	Lon	Geomethod	Altitude	Type
191532	LCWQPD - NORTH HILLS WELL	X	X	X							46.72833	-112.03636	SUR-GPS	3882.78	WELL
191534	LCWQPD - GRAVEL PIT WELL		X	X							46.70537	-112.04146	SUR-GPS	3799.87	WELL
191537	LCWQPD - LINCOLN AND MONTANA WELL		X	X							46.70421	-112.02085	SUR-GPS	3756.81	WELL
191555	LCWQPD - APPLEGATE AND NORRIS NORTH WELL	X	X	X							46.67524	-112.04260	SUR-GPS	3736.68	WELL
194435	HEDDEN, MICHAEL AND CRISTIE		X	X							46.75470	-112.09208	SUR-GPS	4264.15	WELL
194850	DRAKE RON AND VIVIAN								X		46.70248	-112.05888	NAV-GPS	3845	WELL
195637	USGS RESEARCH WELL - COLLINS ROAD		X								46.71026	-111.97846	SUR-GPS	3702.24	WELL
196245	FORSYTHE REESE AND RITA		X								46.73983	-112.07264	SUR-GPS	4055.94	WELL
198749	RAND MICHAEL AND CYNTHIA		X	X							46.71912	-112.08243	SUR-GPS	4060.60	WELL
199992	CRAWFORD, LARRY		X								46.71444	-112.02706	SUR-GPS	3798.13	WELL
199993	TANGEN, AMBER AND LLOYD		X								46.71376	-112.02650	SUR-GPS	3794.50	WELL
199997	RATCLIFF RUSSELL AND KENDALL		X								46.74583	-112.07551	SUR-GPS	4107.59	WELL
202175	WINSLOW, LYNN AND TRUDY		X	X							46.73532	-112.05644	SUR-GPS	3965.21	WELL
204043	MEDEMA, WARREN		X								46.74469	-112.06299	PHOTO-GM	4073.47	WELL
206026	BRENSDAL KEN		X	X							46.72714	-112.05939	SUR-GPS	3947.65	WELL
206393	KREI ROBERT D.		X	X							46.74397	-112.03899	SUR-GPS	4040.62	WELL
206394	PARSLEY RICK AND TRACY		X								46.73672	-112.02723	SUR-GPS	3959.43	WELL
207290	SKILLMAN DAN AND LOLA		X								46.72140	-112.00984	SUR-GPS	3812.32	WELL
211387	FOLEY MICHEAL AND JANELL	X	X								46.74527	-112.02449	SUR-GPS	4073.85	WELL
216755	FOLEY MICHAEL & JANELL								X		46.73781	-112.02165	PHOTO-GM	3980	WELL
218593	NYSTRAND ROBERT	X	X	X							46.72503	-111.97898	SUR-GPS	3836.68	WELL
227906	STEVENS, JERRY		X	X							46.70158	-112.10926	SUR-GPS	4030.25	WELL
228212	PERLINSKI, JEREMY		X								46.68111	-112.05544	SUR-GPS	3823.66	WELL
237167	SMELKO, DAN	X	X								46.70466	-112.07654	SUR-GPS	3896.04	WELL
237331	VALLEY CONSTRUCTION	X	X				X				46.76009	-112.06802	SUR-GPS	4275.70	WELL
237990	BRELIN, STANTON E. II & REBECCA J.		X								46.73535	-112.02276	SUR-GPS	3948.72	WELL
238078	PANORAMIC MEADOWS LOT 62								X		46.71098	-111.91844	SUR-GPS	3732.88	WELL
238080	THE HARRIS FAMILY								X		46.71016	-111.92411	PHOTO-GM	3690	WELL
243352	WOEHL HERMAN		X	X							46.73396	-112.02424	SUR-GPS	3928.85	WELL
246101	SMELKO, DAN * EAST IRR WELL		X								46.70557	-112.07477	SUR-GPS	3896.46	WELL
246845	CURTIS LAURA								X		46.70921	-111.91684	PHOTO-GM	3700	WELL
250322	RUSSELL, SPENCER E. & DIANE L.								X		46.70953	-111.91568	PHOTO-GM	3725	WELL
250478	NOTTINGHAM, DAN								X		46.70962	-111.92236	PHOTO-GM	3690	WELL
251600	NELSON, KELSEY								X		46.71208	-111.91846	MAP	3738	WELL
251603	CHRISTIANSON & BURRELL CARL & KELSIE								X		46.70965	-111.92156	PHOTO-GM	3690	WELL
251605	SNOOK, KENT M. & GAYLE M.								X		46.71094	-111.92052	PHOTO-GM	3710	WELL
251637	HUSEBY LEONARD & RHONDA								X		46.71096	-111.91522	PHOTO-GM	3740	WELL
251595	PANORAMIC MEADOWS SUBDIVISION LOT 63						X				46.70966	-111.91970	SUR-GPS	3707.01	WELL
251596	PANORAMIC MEADOWS SUBDIVISION LOT 65						X				46.70974	-111.92040	SUR-GPS	3702.64	WELL
251597	PANORAMIC MEADOWS SUBDIVISION LOT 67						X				46.70977	-111.92110	SUR-GPS	3701.94	WELL
251598	PANORAMIC MEADOWS LOT 70						X				46.71121	-111.92199	SUR-GPS	3716.82	WELL
251599	PANORAMIC MEADOWS SUBDIVISION LOT 66	X	X				X				46.71095	-111.92038	SUR-GPS	3716.92	WELL
251602	PANORAMIC MEADOWS SUBDIVISION LOT 64						X				46.71083	-111.91958	SUR-GPS	3721.27	WELL
251605	PANORAMIC MEADOWS SUBDIVISION LOT 68						X				46.71109	-111.92119	SUR-GPS	3716.62	WELL
252818	PANORAMIC MEADOWS SUBDIVISION LOT 17								X		46.71037	-111.92110	SUR-GPS	3782.89	WELL
252835	PANORAMIC MEADOWS SUBDIVISION LOT 14						X				46.71621	-111.92125	SUR-GPS	3785.53	WELL
253818	DIAMOND HILLS - SHALLOW	X	X				X				46.75665	-112.04060	SUR-GPS	4265.07	WELL
254216	MBMG - UPPER SILVER CREEK (MW-SC1)	X	X							X	46.70029	-112.10768	SUR-GPS	4024.3	WELL
254227	MBMG - LOWER SILVER CREEK - SHALLOW (MW-SC2A)	X	X							X	46.70451	-112.07633	SUR-GPS	3895.44	WELL
254237	MBMG - LOWER SILVER CREEK - DEEP (MW-SC2B)	X	X							X	46.70451	-112.07632	SUR-GPS	3895.41	WELL
254242	MBMG - MIDDLE SILVER CREEK (MW-SC3)	X	X							X	46.70191	-112.09202	SUR-GPS	3958.23	WELL
254311	KEVIN DAMUTH								X		46.71022	-111.91562	MAP	3725	WELL
254325	PANORAMIC MEADOWS LOT 73								X		46.70992	-111.92324	MAP	3690	WELL

		Use													
GWIC ID	**Site Name**	**Transducer**	**Monthly GWE**	**Water Quality**	**Surface Water**	**Spring**	**Aquifer Test**	**Precip**	**Historical**	**Installed for this Study**	**Lat**	**Lon**	**Geomethod**	**Altitude**	**Type**
254327	PANORAMIC MEADOWS LOT 76								X		46.71147	-111.92399	MAP	3710	WELL
254356	MBMG VX-PW1						X			X	46.76191	-112.07342	SUR-GPS	4352.13	WELL
254357	MBMG VX-OW1						X			X	46.76185	-112.07338	SUR-GPS	4350.48	WELL
254359	MBMG VX-OW2						X			X	46.76165	-112.07329	SUR-GPS	4345.12	WELL
254360	MBMG VX-OW3						X			X	46.76193	-112.07332	SUR-GPS	4352.60	WELL
254361	MBMG VX-OW4						X			X	46.76200	-112.07304	SUR-GPS	4352.47	WELL
254459	NORTHSTAR DEVELOPMENT PHASE 6 WELL #1								X		46.72285	-112.02759	NAV-GPS	3840	WELL
254464	NORTH STAR PHASE 6 WELL#2								X		46.72313	-112.02762	NAV-GPS	3842	WELL
254485	NORTH STAR PHASE 6 WELL #6								X		46.72454	-112.02724	NAV-GPS	3853	WELL
254487	NORTH STAR PHASE 6 WELL#3								X		46.72386	-112.02723	NAV-GPS	3848	WELL
254574	SMELKO, DAN								X		46.70444	-112.07700	NAV-GPS	3896	WELL
254596	NJOS CAL AND TAMMY								X		46.75441	-112.02114	SUR-GPS	4202.45	WELL
257001	MBMG VX-OW5						X			X	46.76188	-112.07333	SUR-GPS	4351.40	WELL
257063	MBMG APPLEGATE & NORRIS	X	X	X						X	46.67530	-112.04259	SUR-GPS	3737.36	WELL
257064	MBMG COLLINS DRIVE		X	X						X	46.71027	-111.97864	SUR-GPS	3702.53	WELL
257065	MBMG PURCELL	X	X				X			X	46.72364	-111.99368	SUR-GPS	3826.95	WELL
257066	MBMG O'REILLY - DEEP	X	X				X			X	46.72948	-112.00751	SUR-GPS	3866.77	WELL
257067	MBMG O'REILLY - SHALLOW	X	X				X			X	46.72948	-112.00763	SUR-GPS	3867.33	WELL
258290	MBMG SLE-1	X	X				X			X	46.76801	-112.03574	SUR-GPS	4691.47	WELL
258294	MBMG SLE-2						X			X	46.76761	-112.03599	SUR-GPS	4693.67	WELL
258401	MBMG HVF-1						X			X	46.75869	-112.03866	SUR-GPS	4323.08	WELL
258402	MBMG HVF-2	X	X				X			X	46.75893	-112.03848	SUR-GPS	4336.71	WELL
258402	MBMG HVF-2						X			X	46.75893	-112.03848	SUR-GPS	4338.30	WELL
258454	MBMG SLW-1						X			X	46.77045	-112.10636	SUR-GPS	4673.32	WELL
258456	MBMG SLW-2	X	X				X			X	46.77076	-112.10608	SUR-GPS	4670.84	WELL
258597	MBMG HVF-3						X			X	46.75916	-112.03819	SUR-GPS	4365.36	WELL
268684	PANORAMIC MEADOWS SUBDIVISION LOT 60						X				46.71085	-111.91792	SUR-GPS	3729.47	WELL
706002	HARRIS JAMES								X		46.71940	-111.97720	PHOTO-GM	3765	WELL
890556	WILSON WAYNE								X		46.70470	-112.01860	MAP	3750	WELL
892105	HUNT DAVID								X		46.68720	-112.06220	MAP	3890	WELL
892106	HUNT DAVID								X		46.68750	-112.06270	MAP	3919	WELL
892125	LONGMIRE BOB								X		46.71750	-111.99880	MAP	3781.05	WELL
892126	BRAMBLETT TIM								X		46.70410	-111.97550	MAP	3675	WELL
892138	TAYLOR TREVOR								X		46.72940	-112.03470	MAP	3885	WELL
892182	SILVER CREEK								X		46.70500	-112.07130	MAP	3890	WELL

NA = Not Avalible

SUMMARY OF AQUIFER TESTS

Aquifer-test results were obtained from several area aquifers. From youngest to oldest, these aquifers are:

1) the Helena Valley Aquifer;

2) the Tertiary Aquifer;

3) the Granite Aquifer;

4) the Metagabbro Aquifer;

5) the Helena Formation (carbonate); and

6) the Argillite Aquifer (Greyson and Spokane Formations).

The Helena Valley Aquifer and the Tertiary Aquifer are in unconsolidated materials. The rest of the aquifers are in consolidated bedrock. For some aquifer tests, the aquifer being tested was not clearly defined. These tests are included in table AQ1; however, they are not included in the summary statistics (tables AQ2 and AQ3; fig. AQ1).

Table AQ1 includes results from DNRC groundwater rights applications (per DNRC, 2011), from previous hydrogeologic studies (Moreland and others, 1979; Moreland and Leonard, 1980; Briar and Madison, 1992; Thamke, 2000; Stahly, 2008), and from aquifer tests recently conducted by the MBMG in the Scratchgravel Hills (Bobst and others, 2013) and the North Hills Groundwater Investigation. These data were used to evaluate the likely range of aquifer properties in the North Hills. Where possible, the results of aquifer tests are included in table AQ1; however, in some cases there was not sufficient information to allow inclusion.

Five aquifer tests were completed by the USGS in the late 1970s (Moreland and others, 1979; Moreland and Leonard, 1980). Moreland and Leonard (1980) concluded that "because of lack of knowledge about the lithology and degree of penetration of the aquifer by the well casing, and the necessarily short duration of the tests, complete quantitative analysis of the data was not justified". However, Moreland and Leonard (1980) were able to show that confining layers in the Helena Valley Aquifer were not continuous over large distances and that a reasonable estimate of the transmissivity of the Helena Valley Aquifer was about 10,000 ft^2/d.

Seven additional aquifer tests were later completed by the USGS (Briar and Madison, 1992) in the Helena Valley; however, these tests "…were affected by many of the same problems experienced by previous investigators". Despite the problems, Briar and Madison (1992) concluded that the Helena Valley Aquifer transmissivity of about 10,000 ft^2/d developed by Moreland and Leonard (1980) appeared to be reasonable, and that the effective horizontal hydraulic conductivity was about 200 ft/d.

Thamke (2000, p. 54) evaluated aquifer properties in bedrock units near the Helena Valley, and concluded that their hydrologic conductivities would be in the range of 1×10^{-8} to 1 ft/d.

Individual aquifer test evaluations (tables AQ1, AQ2, and AQ3; fig. AQ1) provide further information on the variability of aquifer properties. In general, geometric mean hydraulic conductivity values are lower than mean values, and for any particular hydrogeologic unit values range over about three orders of magnitude. Granite values are more variable and range across four orders of magnitude. The range for gabbro is quite narrow; however, these values are from three closely spaced wells (table AQ1).

The aquifer test results provide an understanding of how aquifer properties vary in each hydrogeologic unit, and provide a first-order estimate of aquifer properties so that the values calculated through inverse modeling can be critically evaluated.

Table AQ1

Results of Aqufier Tests conducted near Helena, MT

GWIC ID	Site	Township/ Range	Section	Lat (DD N)	Long (DD W)	Test Date	Rate (gpm)	Duration (hrs)	Max dh (ft)	T (ft^2/d)	S (unitless)	Analysis Method	Sat Z (ft)	K (ft/d)	Source
Helena Valley Aquifer															
230734	GMCC	T10NR4W	SESE14	46.618221	112.066071	10/3/2006	80	24	12	13300	NC	CJ	91.5	145	DNRC
208453	Frontier	T11NR4W	SWSE13	46.704896	112.047500	10/31/2003	175	24	25	1630	0.01	CJ	114	14	DNRC
209187	Frontier	T11NR4W	SWSE13	46.707404	112.051703	5/19/2004	211	72	34	228	NC	N	108	2.1	DNRC
—	Frontier	T11NR4W	SWSE13	46.706570	112.050354	1/12/2004	40	24	53	108	NC	CJ	108	1.0	DNRC
228861	Lincoln Heights	T11NR4W	SWSE14	46.706185	112.072238	8/4/2006	11	24	22	2580	NC	TR	45	57	DNRC
211564	Bridge Cr	T11NR3W	NESW17	46.710075	112.019138	10/2/2003	33	24	4	1600	NC	TR	24	67	DNRC
204558	Bridge Cr	T11NR3W	NWSW17	46.709402	112.017404	3/21/2003	608	78	20	7870	NC	TR	261	30	DNRC
204557	Bridge Cr	T11NR3W	NWSW17	46.709597	112.017099	4/10/2003	560	24	39	7950	0.002	TR	200	40	DNRC
204558	Bridge Cr	T11NR3W	NWSW17	46.709402	112.017404	7/26/2004	505	72	25	10900	NC	HJ	261	42	DNRC
204554	VF	T11NR3W	NWSW17	46.709699	112.017405	4/14/2003	565	24	15	8590	NC	CJ	200	43	DNRC
207597	Bridge Cr	T11NR3W	SENW17	46.713746	112.013575	10/21/2003	50	24	5	4240	NC	TR	17	249	DNRC
207596	Bridge Cr	T11NR3W	SENW17	46.713746	112.013575	10/8/2003	38	24	9	3990	NC	TR	27	148	DNRC
180982	Fieldstone	T11NR3W	SWNE17	46.709000	112.011102	3/8/2000	900	24	21	15855	NC	TR	176	90	DNRC
180981	Fieldstone	T11NR3W	SWNE17	46.713797	112.003496	11/15/2002	894	72	16	15100	0.008	TR	176	86	DNRC
64824	Ranch View III	T11NR3W	SWNW17	46.714655	112.020518	5/13/1997	600	4	7	52300	0.0008	CJ	76	688	DNRC
204563	Silver Cr Commer	T11NR3W	SWSW17	46.706505	112.020097	4/5/2003	470	24	89	5790	NC	CJ	163	36	DNRC
204564	Silver Cr Commer	T11NR3W	SWSW17	46.706199	112.020109	4/8/2003	540	24	75	6030	NC	CJ	164	37	DNRC
64846	Lone Wolf	T11NR3W	NENE18	46.717379	112.024377	2/7/2000	75	8	1	26700	NC	TR	40	668	DNRC
216639	Polaris	T11NR3W	SENE18	46.714625	112.023069	12/8/2004	108	24	5	33100	NC	TR	63	525	DNRC
237114	Frontier Village	T11NR3W	NESW19	46.694400	112.035158	3/23/2007	953	24	14	19500	0.05	CJ	125	156	DNRC
248761	Libation Station	T11NR3W	NWNW19	46.702721	112.040446	1/13/2009	86	24	3	34800	NC	TR	38	916	DNRC
156462	Applegate	T11NR4W	NESE24	46.695257	112.045604	4/16/1997	175	9	4	75500	NC	TR	94	803	DNRC
—	Rosemary Acres	T11NR4W	SESW24	46.694992	112.056233	5/11/2002	20	24	13	3710	NC	TR	100	37	DNRC
Helena Valley Aquifer or Tertiary Aquifer															
163866	Big Valley 11B2A	T11NR3W	NWSE7	46.724645	112.029340	8/29/2005	29	72	65	1890	NC	TR	90	21	DNRC
223771	North 40	T11NR3W	SWNW7	46.727411	112.033308	6/8/2006	20	24	5	2420	NC	CJ	64	38	DNRC
206648	Big Valley Lot 17	T11NR3W	SWSW7	46.719897	112.037105	8/8/2003	12	24	110	25.5	NC	CJ	202	0.13	DNRC
65293	Lincoln Heights	T11NR4W	SESW14	46.705282	112.073557	8/18/2006	17	24	61	1630	NC	TR	53	31	DNRC
Tertiary Aquifer															
252821	Panoramic Meadows	T11NR3W	NE&SE13	46.709739	111.920398	11/18/2009	38	144	3	15000	0.006	CJ	94	160	MBMG
254311	Panoramic Meadows	T11NR3W	NESE13	46.710220	111.915614	5/23/2006	43	24	13	1410	NC	TR	62	23	DNRC
252835	Panoramic Meadows	T11NR3W	NWNE13	46.716206	111.912510	5/26/2006	12	24	166	17	NC	TR	173	0.10	DNRC
202172	Gable Est	T11NR3W	NWNW13	46.717003	111.933293	3/13/2003	20	24	2	4890	NC	TR	43	114	DNRC
254327	Panoramic Meadows	T11NR3W	NWSE13	46.711474	111.923984	5/30/2006	37	24	66	497	NC	TR	162	3.1	DNRC
195488	Gable Est	T11NR3W	SENE14	46.714375	111.939542	3/14/2003	17	24	2	7190	NC	TR	63	114	DNRC
187343	Gable Est	T11NR3W	SWNE14	46.714109	111.943964	2/13/2001	20	4	2	6920	NC	TR	53	131	DNRC
246771	North Star	T11NR3W	SWNW7	46.728336	112.039899	8/26/2008	30	24	174	34	NC	TR	240	0.14	DNRC
154877	Foothills	T11NR3W	SWSE9	46.720162	111.985067	5/19/2005	27	24	39	477	NC	TR	50	9.5	DNRC
176013	Foothills	T11NR3W	SWSW9	46.721997	111.998364	5/21/2005	30	24	44	413	NC	CJ	50	8.3	DNRC

T = Transmisivity
S = Storativity
Sat Z = Thickness of the saturated aquifer
K = Hydrolic Conductivity

DNRC = Montana Department of Natural Resources and Conservation
NC = Not Calculated
dh = drawdown

CJ = Cooper-Jacob (1946)
N = Neuman (1974)
TR = Theis Recovery (1935)
HJ = Hantush-Jacob (1955)

Table AQ1 (cont.)
Results of Aqufier Tests conducted near Helena, MT

GWIC ID	Site	Township/ Range	Section	Lat (DD N)	Long (DD W)	Test Date	Rate (gpm)	Duration (hrs)	Max dh (ft)	T (ft^2/d)	S (unitless)	Analysis Method	Sat Z (ft)	K (ft/d)	Source
Tertiary Aquifer or Argillite Bedrock Aquifer															
193701	Northern Lights	T11NR3W	NWNW7	46.732476	112.033952	10/9/2001	51	24	14	885	NC	T	135	6.6	DNRC
—	Northern Lights	T11NR3W	NWNW7	46.731876	112.039045	6/14/2004	56	72	12	2370	0.0005	T	135	18	DNRC
—	Hillview	T11NR3W	SWNW6	46.749390	112.037248	5/17/2006	20	24	2	2780	NC	TR	160	17	DNRC
150328	Bandy	T11NR4W	NENW13	46.716353	112.055034	12/3/1999	33	24	46	119	NC	CJ	153	0.78	DNRC
Argillite Bedrock Aquifer															
258597	Helena Valley Fault	T12NR3W	SWNW30	46.759165	112.038187	5/18/2010	100	8	18	1621	NC	D	70	23	MBMG
258401	Helena Valley Fault	T12NR3W	SWNW30	46.758694	112.038658	5/20/2010	23	8	48	121	NC	D	18	7	MBMG
258402	Helena Valley Fault	T12NR3W	SWNW30	46.758930	112.038479	5/24/2010	104	97	83	387	NC	D	20	19	MBMG
254356	Valley Excavating	T12NR4W	NWNE35	46.761912	112.073418	6/10/2010	14	144	71	350	0.02	CJ	120	3	MBMG
257065	Purcell	T11NR3W	NWSW9	46.723644	111.993675	3/24/2011	16	24	139	70	NC	CJ	280	0.25	MBMG
257066	O'Reilly	T11NR3W	SWNE8	46.729477	112.007506	3/22/2011	46	24	117	200	0.03	H	250	0.80	MBMG
258290	State Lands East	T12NR3W	NWSW30	46.768006	112.035738	4/7/2011	30	48	27	475	0.0011	CJ	150	3.2	MBMG
258454	State Lands West	T12NR4W	SENE28	46.770455	112.106357	4/18/2011	18	48	13	575	NC	CJ	75	7.5	MBMG
159011	Gruber	T10NR4W	SESE10	46.632765	112.087910	12/17/1996	100	1	82	326	NC	D	82	4	Stahley, 2008
137168	Schatz Ranch	T10NR4W	NWNE15	46.630162	112.093799	7/14/1993	135	4	63	573	NC	D	72	8	Stahley, 2008
62588	Hiltabrand	T10NR4W	NW14	46.627420	112.079775	2/16/1984	95	3	43	591	NC	D	66	9	Stahley, 2008
62589	Hiltabrand	T10NR4W	NW14	46.627420	112.079775	6/12/1980	98	1	170	157	NC	D	192	0.82	Stahley, 2008
237817	Cornerstone	T10NR4W	SWNW14	46.625580	112.082516	8/7/2007	520	24	106	1307	0.0006	CJ	110	11.9	Stahley, 2008
237817	Cornerstone	T10NR4W	SWNW14	46.625580	112.082516	11/5/2007	594	72	139	1264	0.0005	TR	110	11.5	Stahley, 2008
240376	Cornerstone	T10NR4W	SWSW14	46.6277	112.0792	10/27/2007	228.5	24	221	179	0.0004	TR	112	1.6	Stahley, 2008
222881	Overlook	T11NR3W	NESE6	46.740212	112.025016	11/25/2005	30	24	2	11100	NC	TR	68	163	DNRC
193704	North Star	T11NR3W	NWSE7	46.721882	112.028019	9/25/2001	110	25	20	1010	NC	CJ	102	9.9	DNRC
193705	North Star	T11NR3W	NWSE7	46.721882	112.028019	2/26/2004	98	72	15	1650	NC	CJ	102	16	DNRC
194427	North Star	T11NR3W	NWSE7	46.723863	112.027235	2/19/2002	65	24	6	1110	NC	T	101	11	DNRC
64642	Southern View	T11NR3W	SWNW5	46.742504	112.018298	9/30/2005	13	24	79	416	NC	TR	60	6.9	DNRC
252485	70North Star	T11NR3W	SWNW7	46.728336	112.039900	9/17/2009	91	24	226	52	NC	TR	470	0.11	DNRC
254487	North Star	T11NR3W	SWNW7	46.723863	112.027235	1/11/2008	56	72	11	1600	0.0006	CJ	431	3.7	DNRC
246772	North Star	T11NR3W	SWNW7	46.728336	112.039900	12/4/2009	84	24	235	43	0.0002	T	470	0.090	DNRC
65152	Welsh Estates	T11NR4W	NENE1	46.746298	112.041297	4/4/2006	12	24	2	875	NC	CJ	103	8.5	DNRC
227178	Welsh Estates	T11NR4W	NENE1	46.747838	112.046139	7/3/2006	27	24	7	1120	NC	CJ	60	19	DNRC
199996	MJM	T11NR4W	NESE1	46.739269	112.044751	9/19/2002	18	24	16	165	NC	CJ	170	0.97	DNRC
166421	Hoovestal	T11NR4W	NWSW14	46.709810	112.082780	4/21/1999	65	6	3	6410	NC	TR	386	17	DNRC
228176	Dee Minor	T11NR4W	SESW2	46.736413	112.078424	8/17/2006	30	24	36	823	NC	TR	130	6.3	DNRC
231833	Belmont View	T12NR5W	SESE36	46.750036	112.172043	1/11/2007	6	24	65	22.8	NC	TR	65	0.35	DNRC
231835	Belmont View	T12NR5W	SWSE36	46.750036	112.177416	6/20/2007	5	24	95	12	NC	TR	95	0.13	DNRC

T = Transmisivity
S = Storativity
Sat Z = Thickness of the saturated aquifer
K = Hydrolic Conductivity

DNRC = Montana Department of Natural Resources and Conservation
NC = Not Calculated
dh = drawdown

CJ = Cooper-Jacob (1946)
T = Theis (1935)
TR = Theis Recovery (1935)
D = Driscoll (1986)

Table AQ1 (cont.)
Results of Aqufier Tests conducted near Helena, MT

GWIC ID	Site	Township/ Range	Section	Lat (DD N)	Long (DD W)	Test Date	Rate (gpm)	Duration (hrs)	Max dh (ft)	T (ft^2/d)	S (unitless)	Analysis Method	Sat Z (ft)	K (ft/d)	Source
Mettagabbro															
193572	Fort Harrison	T10NR4W	SWNE9	46.639694	112.114069	10/19/2004	100	27	31.36	307	0.0011	CJ	114	2.7	DNRC
193573	Fort Harrison	T10NR4W	SWNE9	46.639694	112.114069	7/8/2005	75	73	46	322	0.00067	T	157	2.1	DNRC
193573	Fort Harrison	T10NR4W	SWNE9	46.639694	112.114069	12/21/2005	109	29	45	306	NC	TR	157	1.9	DNRC
Helena Formation															
217220	Ryan Gruber	T11NR4W	NWSW30	46.681445	112.167869	2/4/2006	12	24	2	2750	NC	CJ	139.6	20	DNRC
216659	Stallion Ridge	T11NR4W	NWSW30	46.679480	112.166718	11/8/2004	60	25	17	819	NC	T	385	2.1	DNRC
216661	Stallion Ridge	T11NR4W	NESE30	46.679480	112.151130	11/9/2004	20	25	101	33.2	NC	TR	288	0.12	DNRC
216662	Stallion Ridge	T11NR4W	NENE31	46.672353	112.151098	11/15/2004	15	25	212	8.3	NC	TR	334	0.025	DNRC
217193	Stallion Ridge	T11NR4W	SWNE31	46.679480	112.166718	11/29/2004	37	24	5	1640	NC	TR	139	12	DNRC
Granite Aquifer															
127089	Maykuth	T11NR4W	NENE23	46.701741	112.068439	6/7/2000	15	2	64	13.6	NC	CJ	98	0.14	DNRC
230903	LincolnH	T11NR4W	NENW23	46.702679	112.072398	10/4/2006	17	25	51	66.6	NC	TR	90	0.74	DNRC
158499	Green Meadow Vista	T11NR4W	SWNW24	46.695259	112.062022	7/12/2007	7	26	29	146	NC	TR	100	1.5	DNRC
198164	Lazy JC	T11NR4W	SWSW24	46.690629	112.060656	11/1/2002	25	25	113	71.9	NC	TR	187	0.38	DNRC
131305	Timber Acres II	T11NR4W	SWSW24	46.692481	112.060656	9/21/2005	20	4	7	598	NC	TR	42	14	DNRC
195225	4965 Garnet Rd	T11NR4W	NWSW32	46.665048	112.145872	4/4/2002	12.5	1	75	5.9	NC	CJ	100	0.059	DNRC
120469	Liberty Baptist	T11NR4W	SESE36	46.662085	112.046476	5/28/2007	7.5	24	54	21	NC	CJ	60	0.35	DNRC
224335	Cornerstone	T10NR4W	SWNE11	46.639267	112.083128	7/7/2005	200	24	134	113	NC	TR	282	0.4	Stahley, 2008
62470	Chase	T10NR4W	SE11	46.634729	112.068875	7/1/1978	12	1	198	16.2	NC	D	180	0.09	Stahley, 2008
62469	Voelkol	T10NR4W	SE11	46.634729	112.068875	9/13/1980	15	1	164	24.5	NC	D	65	0.38	Stahley, 2008
202046	Wiseman	T10NR4W	NWSE11	46.635640	112.073034	4/1/2003	18	1	176	27.3	NC	D	136	0.20	Stahley, 2008
184602	Chistison	T10NR4W	SESE11	46.632908	112.066103	6/8/2000	12	1	284	11.3	NC	D	283	0.04	Stahley, 2008
256999	Skinner	T10NR4W	SWSW2	46.646769	112.083496	6/25/2010	54.8	121	62	130	NC	TR	138	0.94	MBMG
256998	Skinner	T10NR4W	SWSW2	46.646813	112.082098	4/13/2011	1.4	0.417	41	0.15	NC	TR	178	9E-04	MBMG
239912	Skinner	T10NR4W	SWSW2	46.648704	112.083417	4/13/2011	1.7	2	3	185	NC	TR	130	1.1	MBMG
239913	Skinner	T10NR4W	SWSW2	46.648686	112.082122	4/13/2011	1.8	2	1	225	NC	TR	205	1.5	MBMG
257312	BLM Head Ln	T11NR4W	NENW34	46.673852	112.099745	8/17/2010	2	14	86	0.75	NC	TR	205	0.004	MBMG
257312	BLM Head Ln	T11NR4W	NENW34	46.673852	112.099745	3/30/2010	0.95	48	85	0.75	NC	TR	205	0.004	MBMG

T = Transmisivity
S = Storativity
Sat Z = Thickness of the saturated aquifer
K = Hydrolic Conductivity

DNRC = Montana Department of Natural Resources and Conservation
MBMG = Montana Bureau of Mines and Geology
NC = Not Calculated
dh = drawdown

CJ = Cooper-Jacob (1946)
T = Theis (1935)
TR = Theis Recovery (1935)
D = Driscoll (1986)

Table AQ2
Statistical Summary of Hydraulic Conductivity (K) values from Aquifer Tests by Hydrogeologic Unit

	maximum	minimum	mean	geometric mean	count (n)
Helena Valley	916	1.0	212	75	23
Tertiary	160	0.10	56	10.7	10
Argillite	163	0.09	12	3.7	30
Gabbro	2.7	1.9	2.2	2.2	3
Helena Fm	20	0.02	6.8	1.1	5
Granite	14	0.0009	1.2	0.18	18

K values are in ft/d.

Table AQ3
Statistical Summary of Storativity (S) values from Aquifer Tests by Hydrogeologic Unit

	maximum	minimum	mean	count (n)
Helena Valley	0.046	0.00082	0.013	5
Tertiary	0.006	0.00048	0.0032	2
Argillite	0.030	0.00020	0.0067	8
Gabbro	0.0011	0.00067	0.00089	2

S values are unitless.

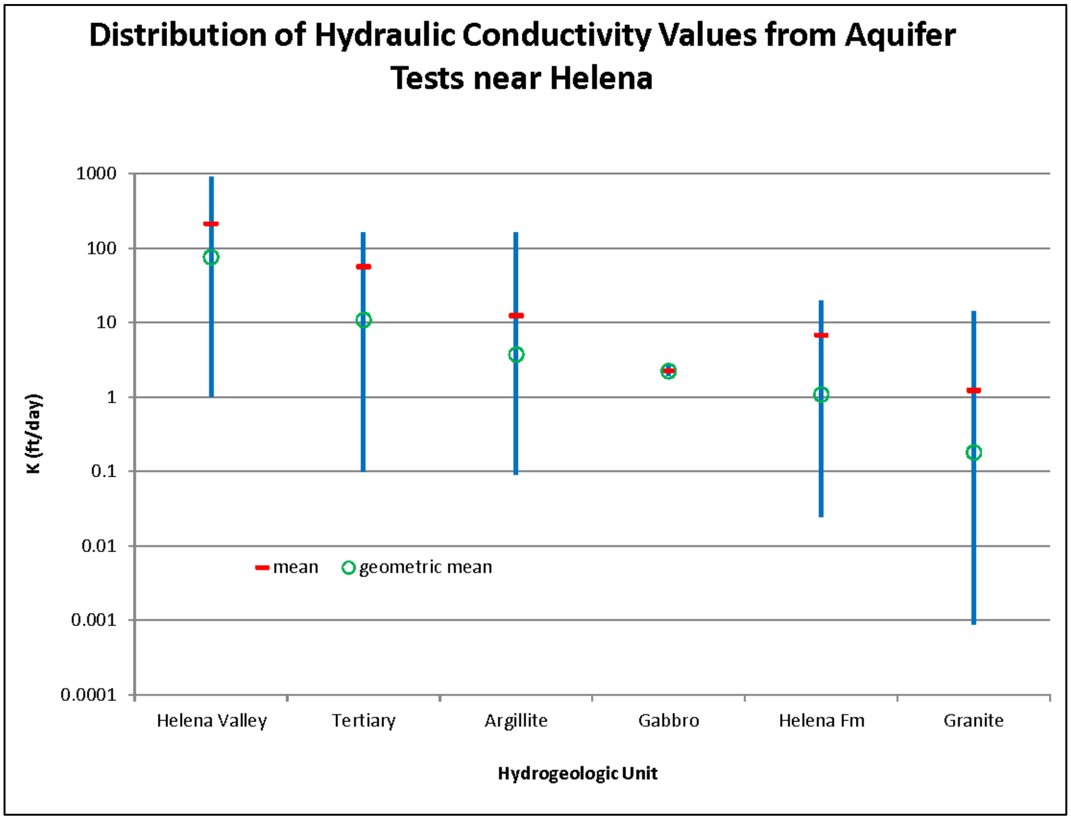

Figure AQ1. Hydraulic conductivity values within each hydrogeologic unit are variable, with the variation covering approximately three orders of magnitude. Values for the gabbro are very uniform; however, all values came from a single site. Values for granite are more variable, ranging more than four orders of magnitude.

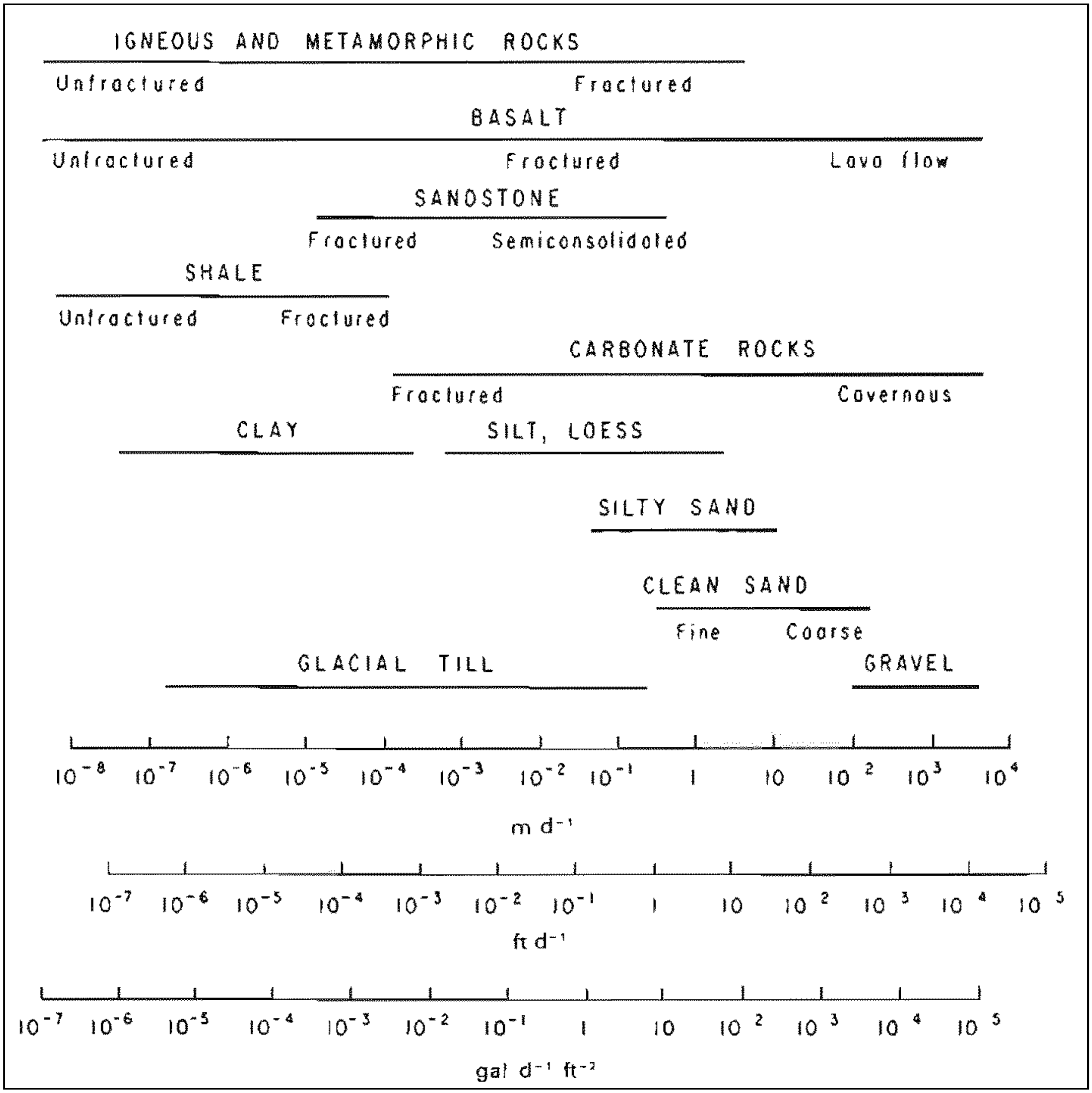

Figure AQ2. Heath (1983) presents the expected hydraulic conductivity for selected rock and sediment types.

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PANORAMIC MEADOWS AQUIFER TEST—
TERTIARY SEDIMENTS

PANORAMIC MEADOWS
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
November 2009

STEP TEST
AND
144-HOUR (6-DAY) CONSTANT-RATE TEST

Background

The following is an analysis of a step test and a 144-h (6-d) constant-rate pumping test performed in November 2009 using pre-existing wells within the Panoramic Meadows Subdivision. All but one of the wells used for this test were located in lots that had no construction, and with no pumps in the wells. The sole exception was Lot 68, where a house was being constructed and a pump had been installed; however, the owner indicated that no water was being used and that the plumbing had not been hooked up in the house. Houses were also under construction on Lots 69 and 71; however, the houses were not occupied at the time of the testing, thus any pumping from these homes is believed to be minimal and these wells were not used for the test.

The Panoramic Meadows test was designed to estimate the transmissivity (T), storativity (S), and anisotropy of the Tertiary sediments aquifer. Pressure transducers were deployed in nine wells within the Panoramic Meadows Subdivision. Measurable drawdown was recorded in all wells except for PM-14.

Location

The test area is located in the northern part of the Helena Valley, immediately to the north of Lincoln Road. Lake Helena is located approximately 1,100 ft south of the pumping well (PM-65). All wells are located in Township 11 N., Range 3 W., Section 13, E½, in Lewis and Clark County, Montana (fig. PM1).

Hydrogeology

The surficial geology at the aquifer test site is mapped as pediment gravels (Holocene[?] and Pleistocene) (fig. PM2; Reynolds and Brandt, 2005). Brier and Madison (1992) show this area as being covered by Quaternary-Tertiary pediment deposits. It is difficult to differentiate the Quaternary deposits from Tertiary deposits from drill cuttings due to their unconsolidated to weakly consolidated nature (Briar and Madison, 1992). Based on driller’s lithologic descriptions, it appears there is a surficial layer of unconsolidated sediments from 32 to 146 ft thick in the test area. This layer is underlain by a somewhat more indurated material (reported as “hard clay” and “shale”). The surficial unconsolidated material is interpreted to be Quaternary pediment materials, and the deeper, slightly more indurated material is interpreted to be Tertiary sediments. Both of these units are considered to be part of the valley-fill sequence. The wells used for this test were all completed in this deeper zone. These materials are composed of “poorly sorted, tan-to-brown, micaceous sandy siltstone with laterally discontinuous sandy-pebble and cobble-gravel interbeds and lenses” (Briar and Madison, 1992). The clasts reflect the composition of local bedrock.

There are no faults or other suspected no-flow boundaries. The Helena Valley Irrigation Ditch runs through Panoramic Meadows and canal leakage recharges the aquifer between April and October. Lake Helena forms a nearly constant-head feature to the south.

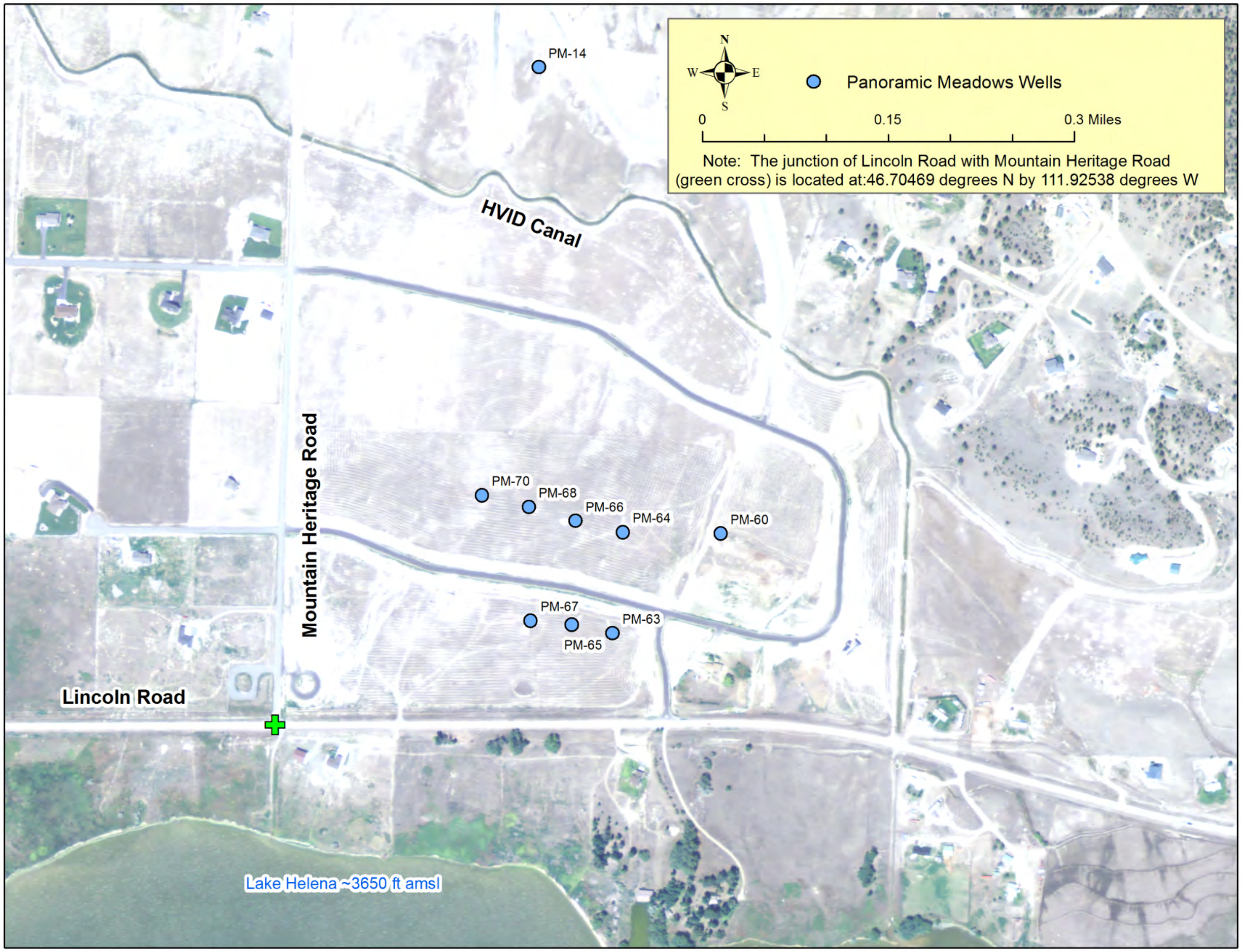

Figure PM1. Locations of wells used for the Panoramic Meadows Aquifer test, November 2009.

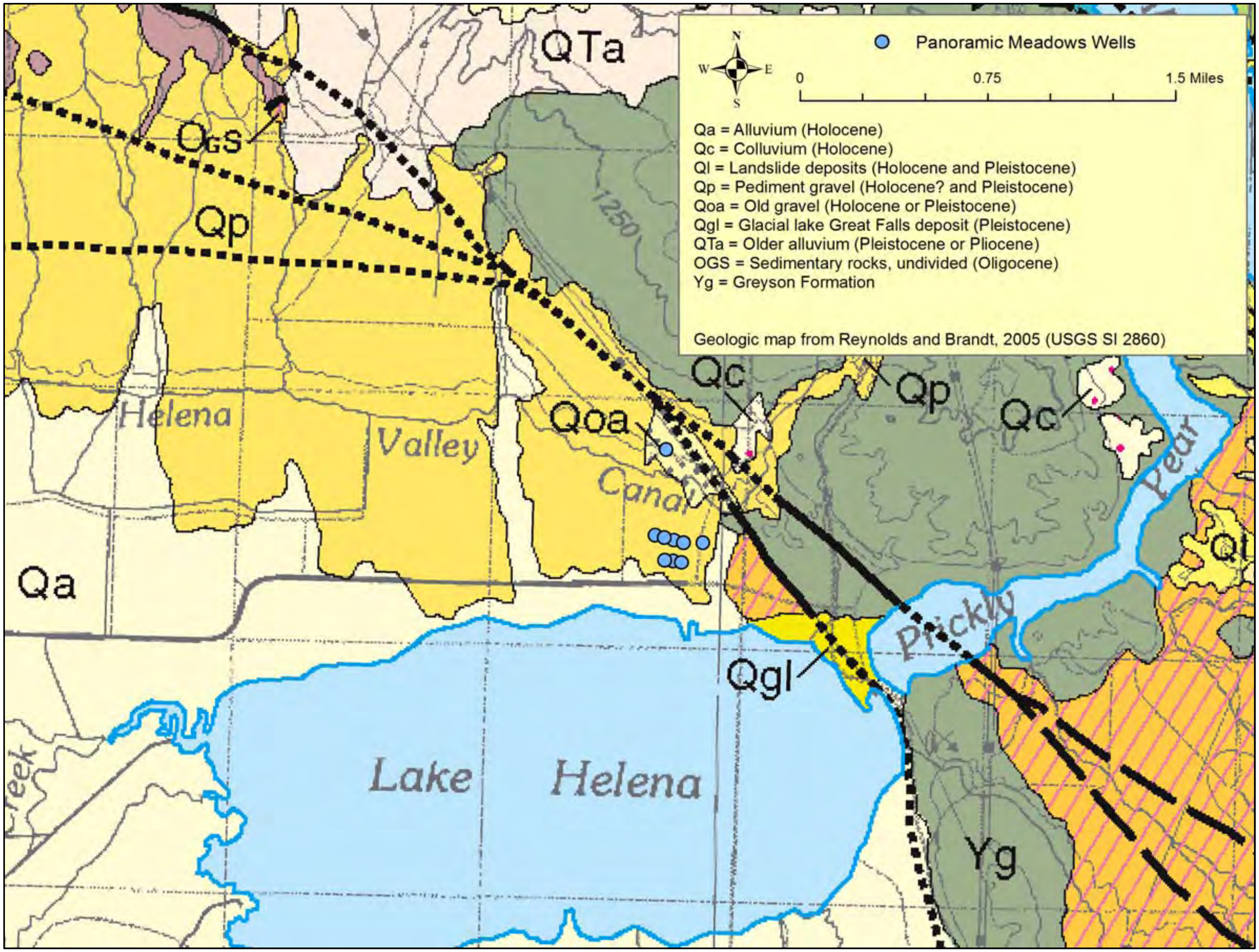

Figure PM2. Geologic map of the Panoramic Meadows Area (Reynolds and Brandt, 2005).

Well Details and Static Water Levels

Well depths are reported to range from 134 to 260 ft (table PM1). Pre-test depth to water (DTW) readings (11/17/2009) produced groundwater elevations between 3,663.10 and 3,710.85 ft above mean sea level (ft-amsl). These results and the overall North Hills potentiometric surface (Waren and others, 2012) indicate that groundwater generally flows south–southeast, toward Lake Helena and the ephemeral drainage east of PM-60 (fig. PM3). Note that the gradient was very flat for most of the test area. This may indicate relatively high permeability in this zone. Pre-test monitoring conducted from late October until November 17 shows that groundwater levels were dropping (figs. PM4–PM12) after the Helena Valley Irrigation Canal (HVID Canal) had been shut off in October. Because antecedent water levels were falling in wells located downgradient from the canal, the water-level data needed to be detrended prior to quantitative analysis (figs. PM4–PM12). Note that well designations used in this report are based on subdivision (PM) and lot number and may not match designations used by others.

Methodology

The MBMG conducted the Panoramic Meadows aquifer test. The pumping rate was monitored throughout the test using a calibrated 5-gallon bucket and stopwatch; each recorded value was the average of five measurements. Discharge was controlled using a gate valve and then routed from the pumping well (PM-65) to a ditch along Lincoln Road, approximately 400 ft distant and away from all monitored wells. The water infiltrated in the ditch, and extended a maximum of 100 ft below the outfall.

Pressure transducers were used to record water levels in the pumping well (PM-65) and observation wells (PM-14, PM-60, PM-63, PM-64, PM-66, PM-67, PM-68, and PM-70). Transducers rated at 30 ft (accuracy of ±0.03 ft) were used on all wells except for PM-68 and PM-65, where transducers rated at 100 ft (accuracy of ±0.10 ft) were installed. Monitoring at PM-68 began after the test had started, because owner permission had not been obtained prior to startup. All transducers were unvented, and because water levels from unvented instruments require barometric compensation, a barologger was placed in PM-66 to record barometric pressure. All transducer water levels were corrected for barometric pressure.

Manual water-level readings were recorded for all wells prior to placing transducers, and were recorded periodically during the test, during recovery, and prior to uninstalling the transducers. Manual measurements were used to verify transducer response. All water-level data are available from GWIC by using the GWIC ID (http://mbmggwic.mtech.edu/).

Transducers were placed in all observation wells except for PM-68 on November 6, 2009 to determine antecedent trends. The aquifer tests began on November 17, 2009. The transducer for PM-68 was installed during the afternoon of November 18 (after the constant-rate test

Table PM1
Well Designations, Locations, and Completion Information
Panoramic Meadows Aquifer Test—November 2009

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 11/17/2009 (ft below MP)	Groundwater Elevation 11/17/09 (ft-amsl)	Distance from PM-65 (ft)	Comments
251596	PM-65	46.7097393	-111.920398	3704.82	134	41.48	3663.34	---	Pumping Well
251595	PM-63	46.7096563	-111.919702	3708.80	134	45.41	3663.39	178	Primary Observation Well
251597	PM-67	46.7097729	-111.921096	3704.01	170	40.54	3663.47	176	Primary Observation Well
251599	PM-66	46.7109458	-111.920384	3721.03	147	57.19	3663.84	441	Primary Observation Well
268684	PM-60	46.7108528	-111.917917	3731.71	NA	68.61	3663.10	742	Secondary Observation Well
251602	PM-64	46.7108323	-111.919578	3723.11	168	59.83	3663.28	447	Secondary Observation Well
251605	PM-68	46.7110903	-111.921186	3718.03	162	NA	NA	530	Secondary Observation Well, Added after aquifer test had begun.
251598	PM-70	46.7112114	-111.921989	3718.73	181	51.30	3667.43	668	Secondary Observation Well
252835	PM-14	46.7162080	-111.921248	3787.57	260	76.72	3710.85	2368	Background Well

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

NA = Not Available

* = Horizontal Datum is NAD 83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined survey grade GPS.

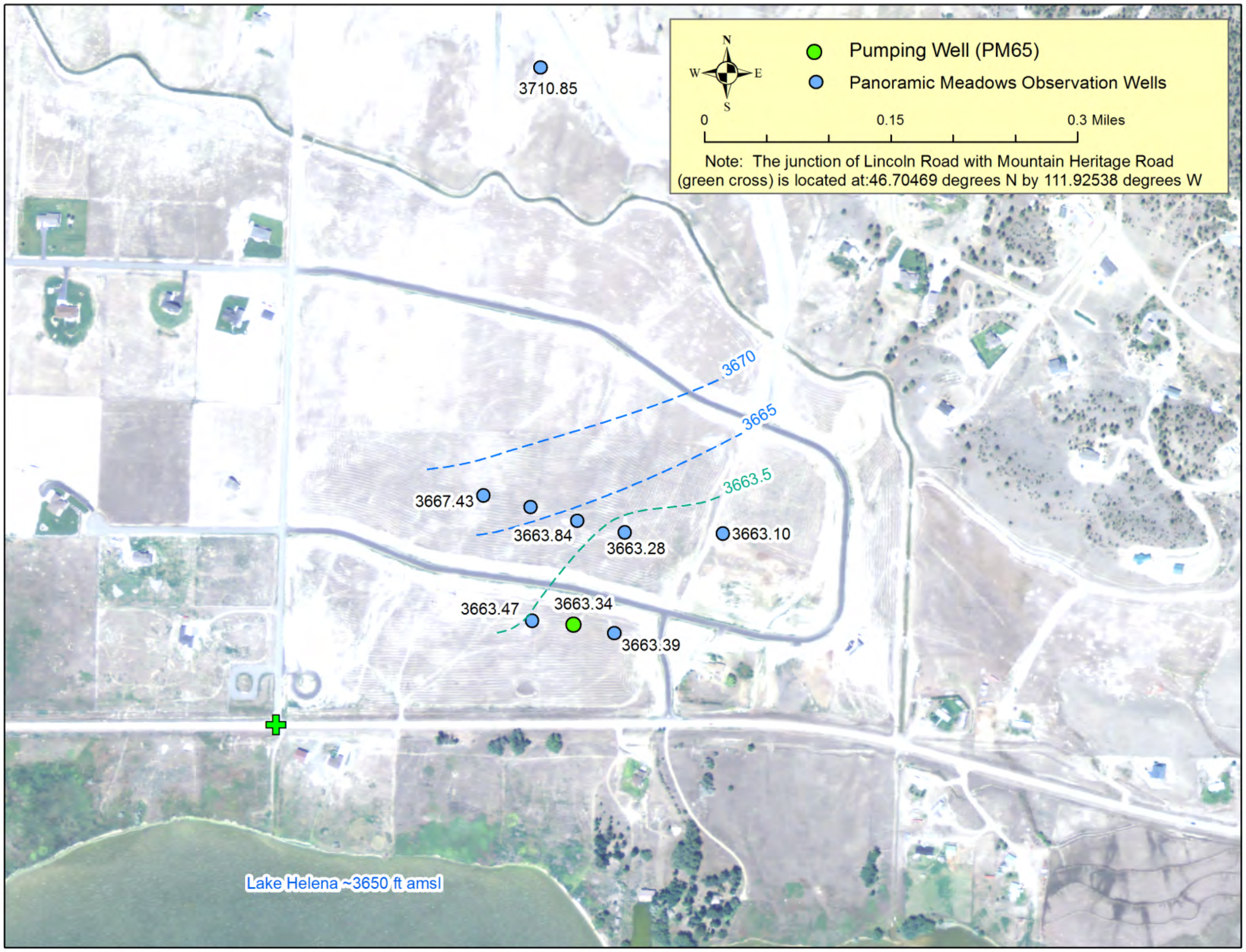

Figure PM3. Groundwater levels measured on November 17, 2009, prior to the start of the step test, show that groundwater flow is generally south–southeast, following the land surface contours towards the ephemeral draw to the east of well PM-60, and toward Lake Helena. Note that blue contours are 5 ft and the green contour is a single contour in the flat portion of the potentiometric surface.

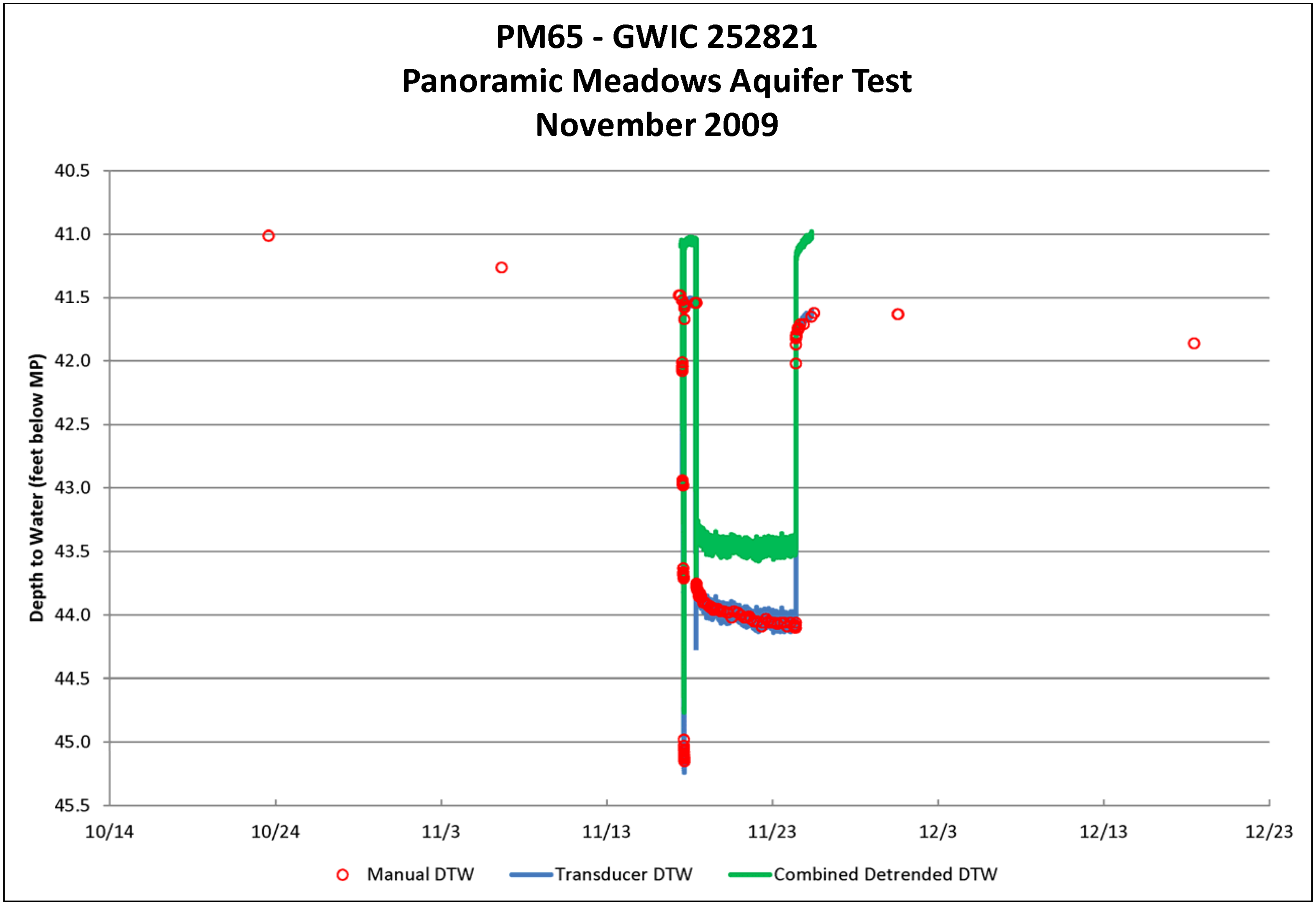

Figure PM4. Depth to water readings [ft below measuring point (MP)] in well PM-65 (pumping well) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

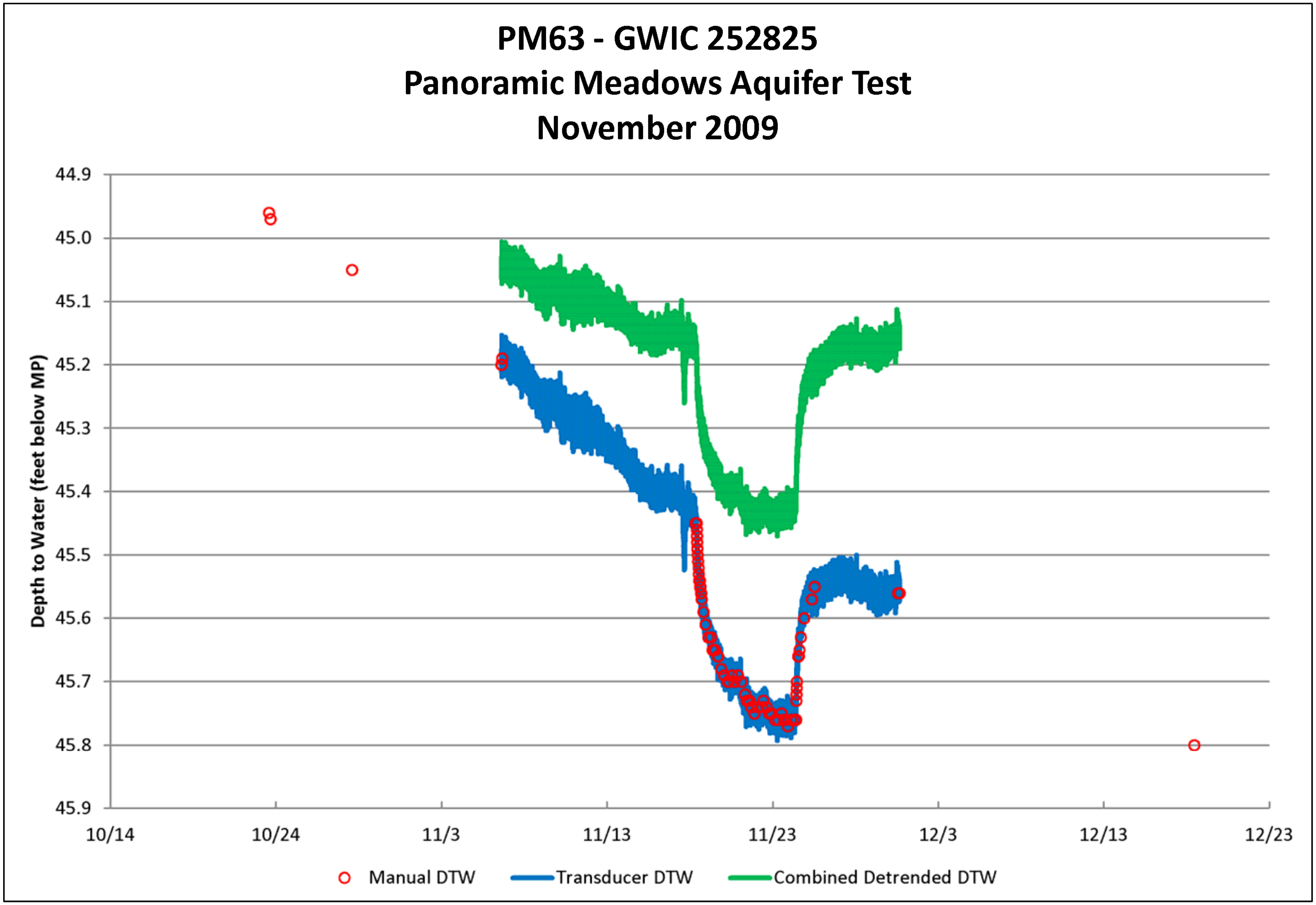

Figure PM5. Depth to water readings in well PM-63 (178 ft west of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test.

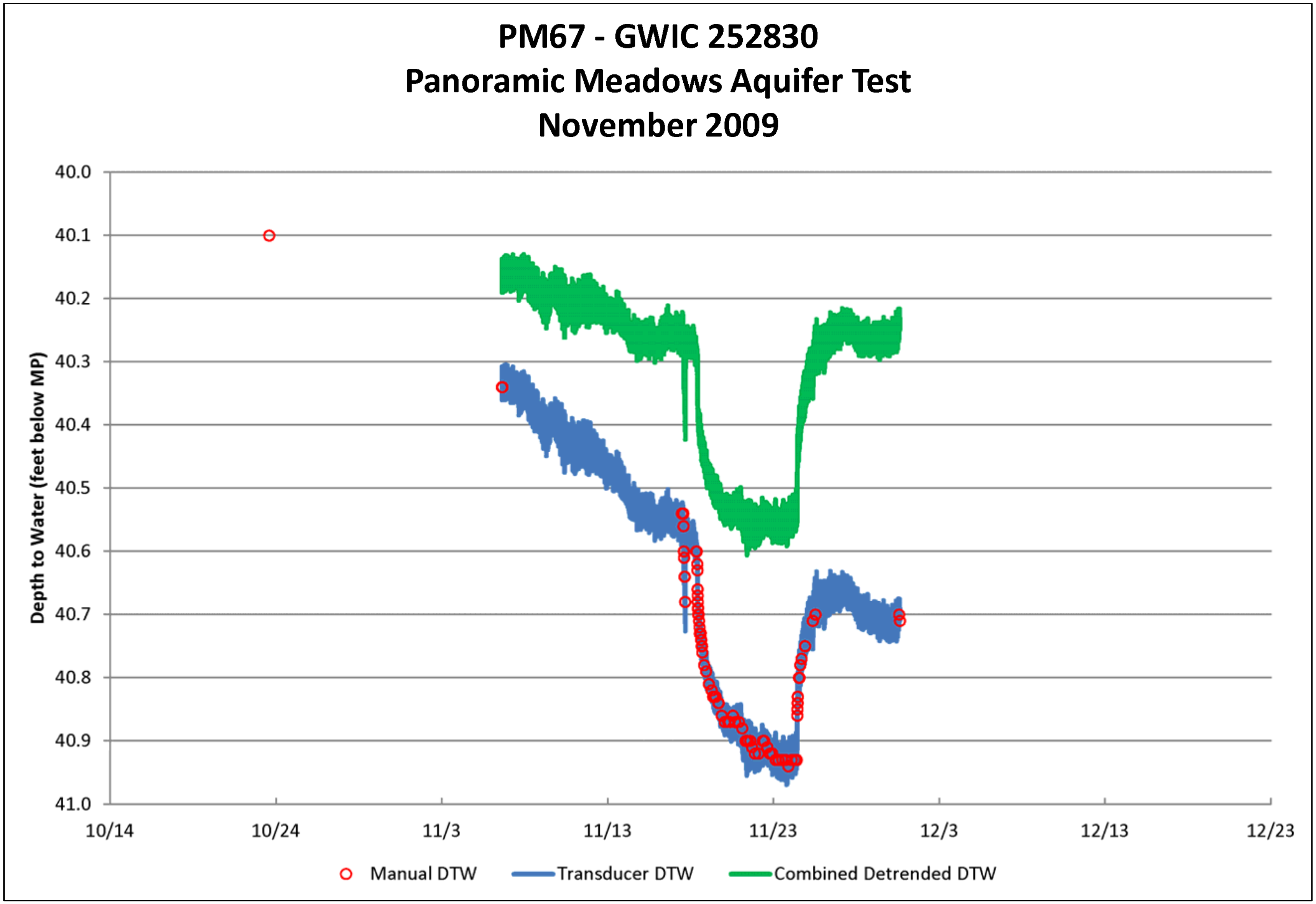

Figure PM6. Depth to water readings in well PM-67 (176 ft east of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

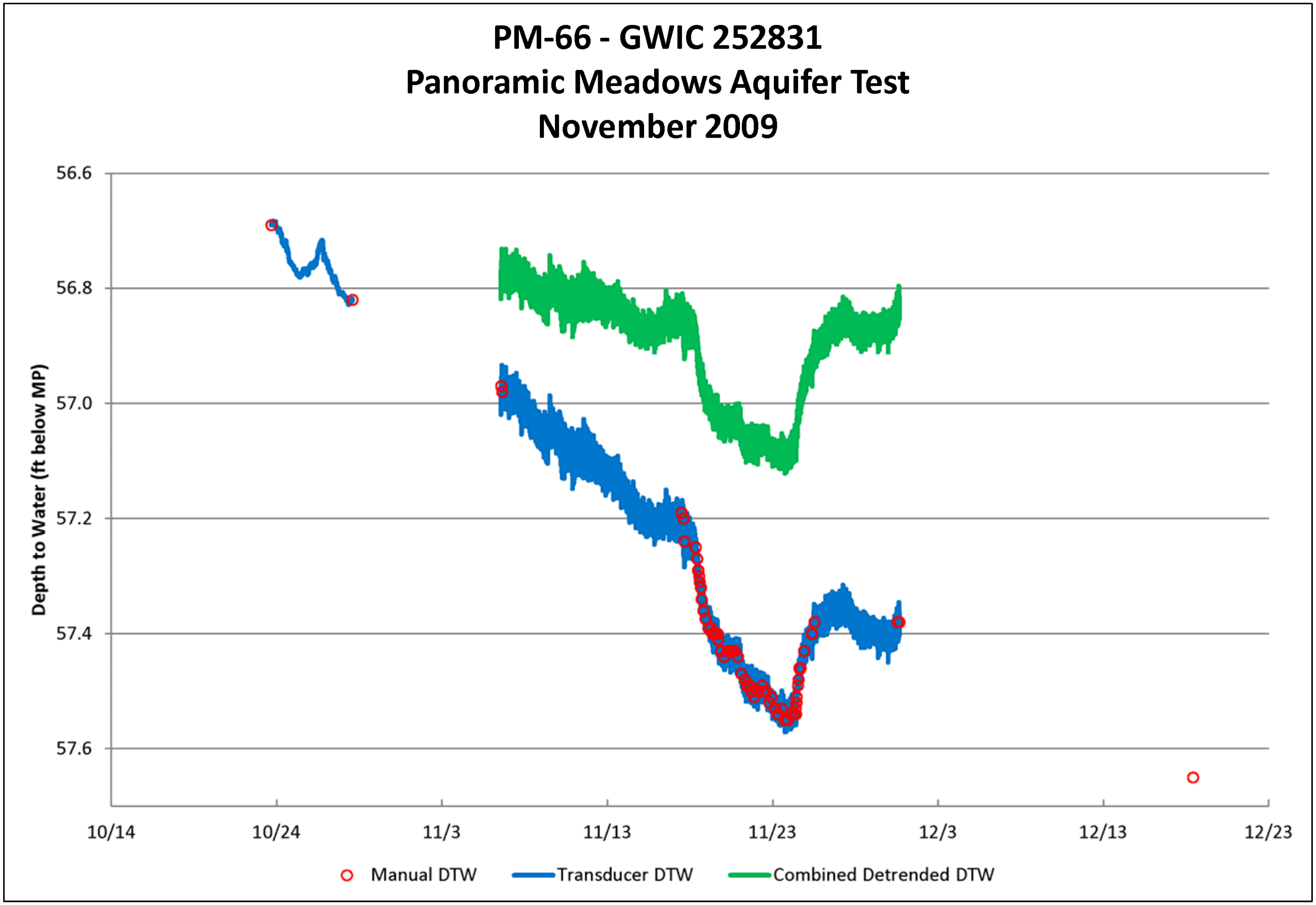

Figure PM7. Depth to water readings in well PM-66 (441 ft north of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

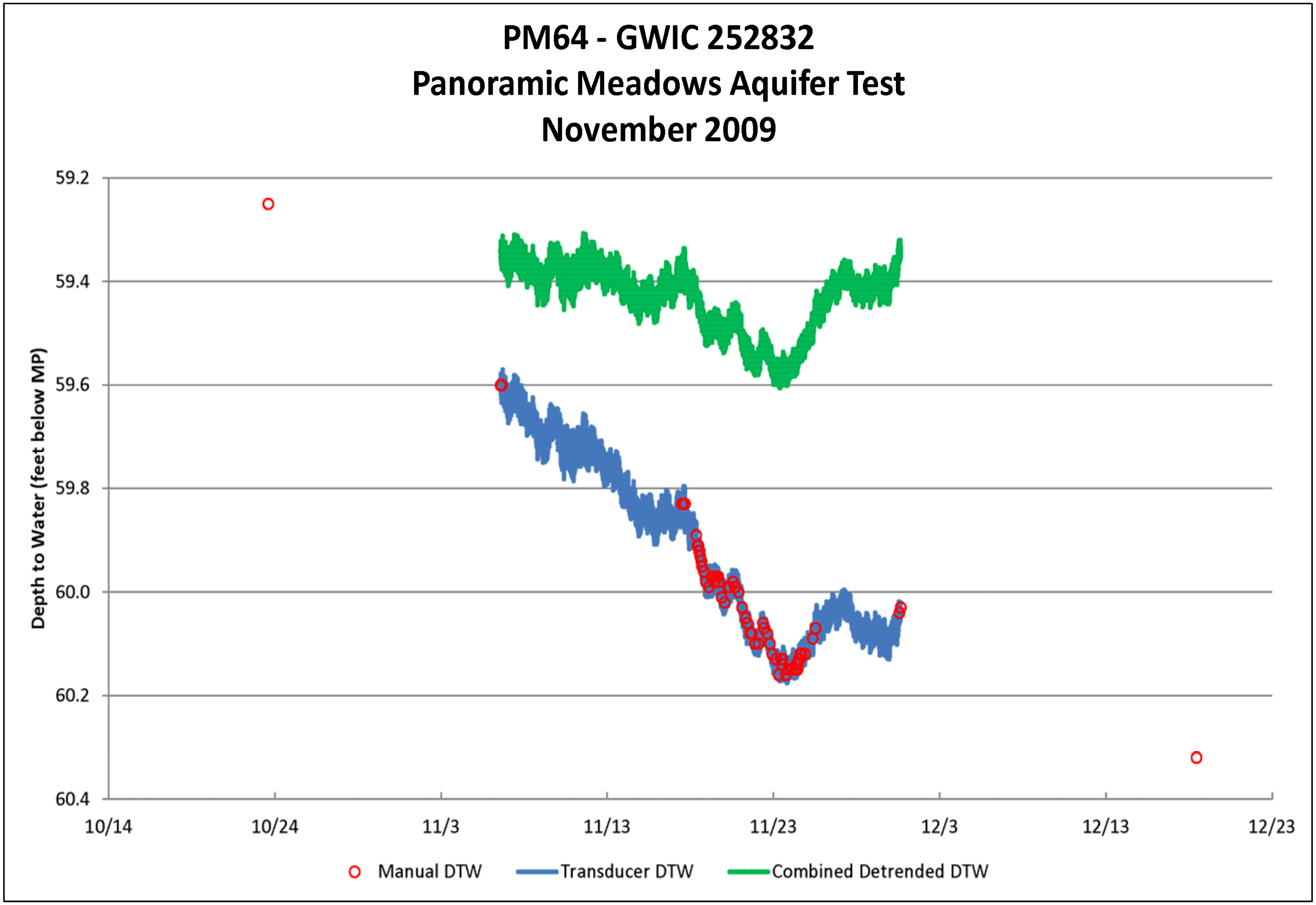

Figure PM8. Depth to water readings in well PM-64 (447 ft north northeast of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

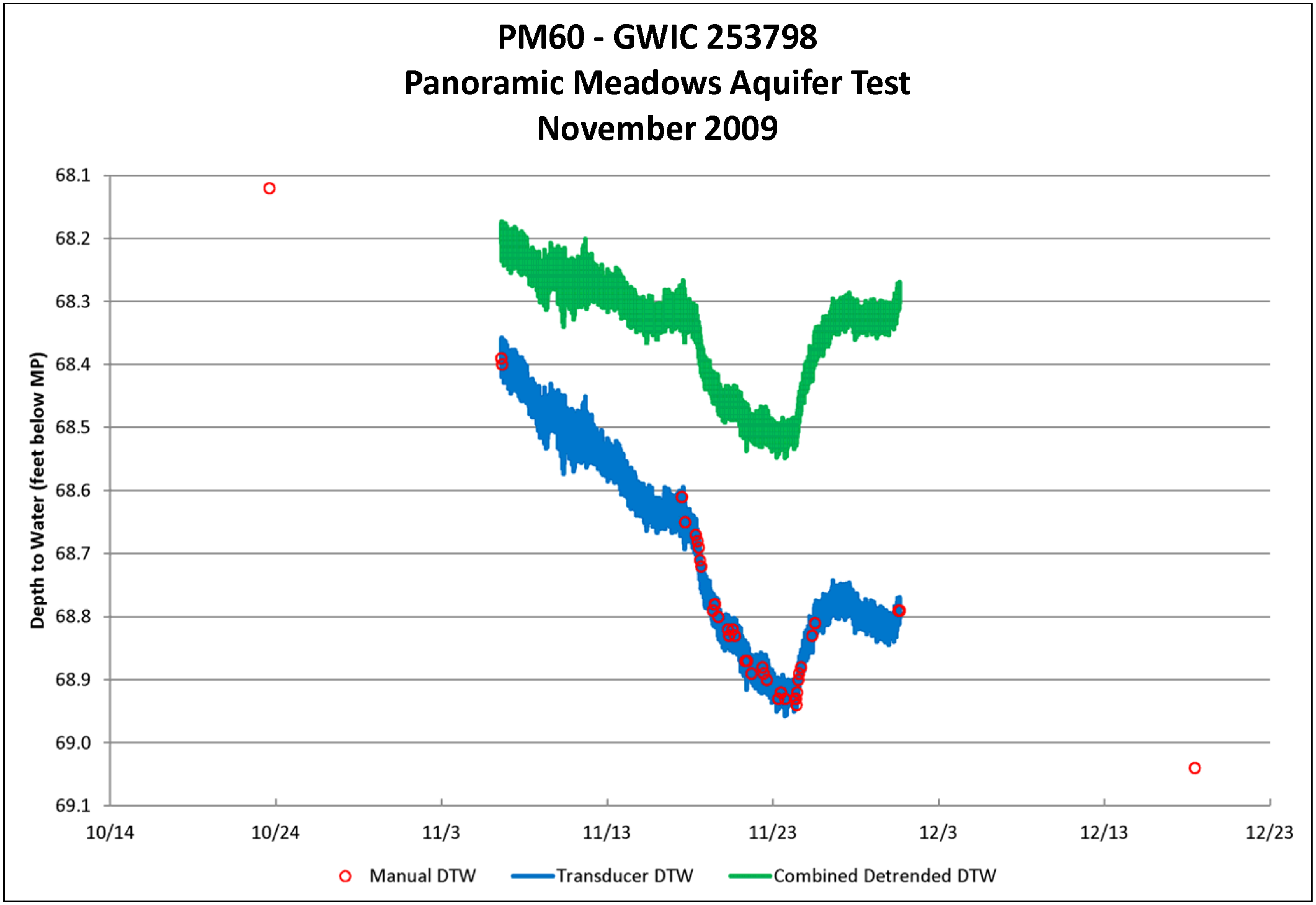

Figure PM9. Depth to water readings in well PM-60 (742 ft northeast of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

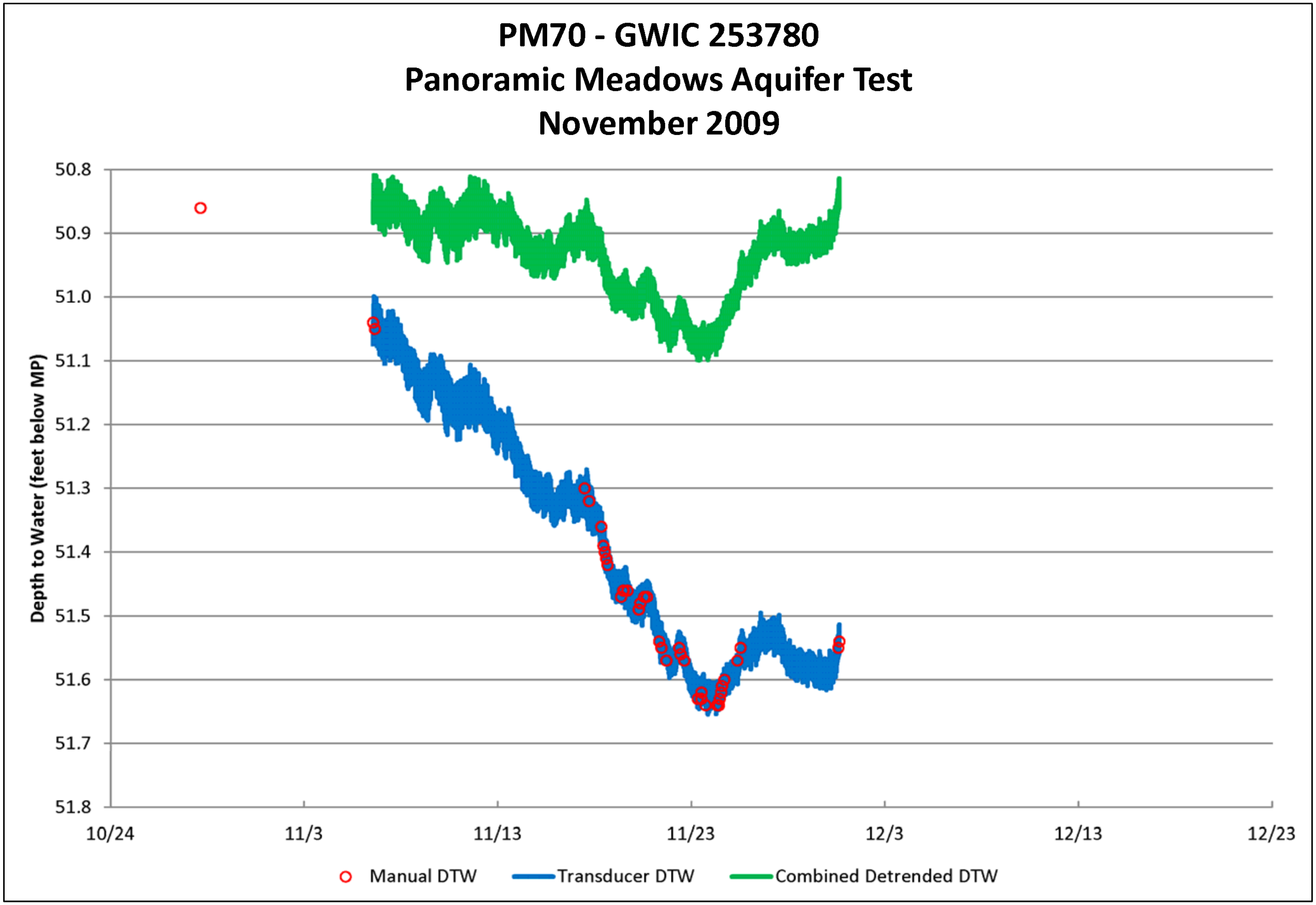

Figure PM10. Depth to water readings (ft below MP) in well PM-70 (668 ft northwest of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. Actual and detrended values are shown.

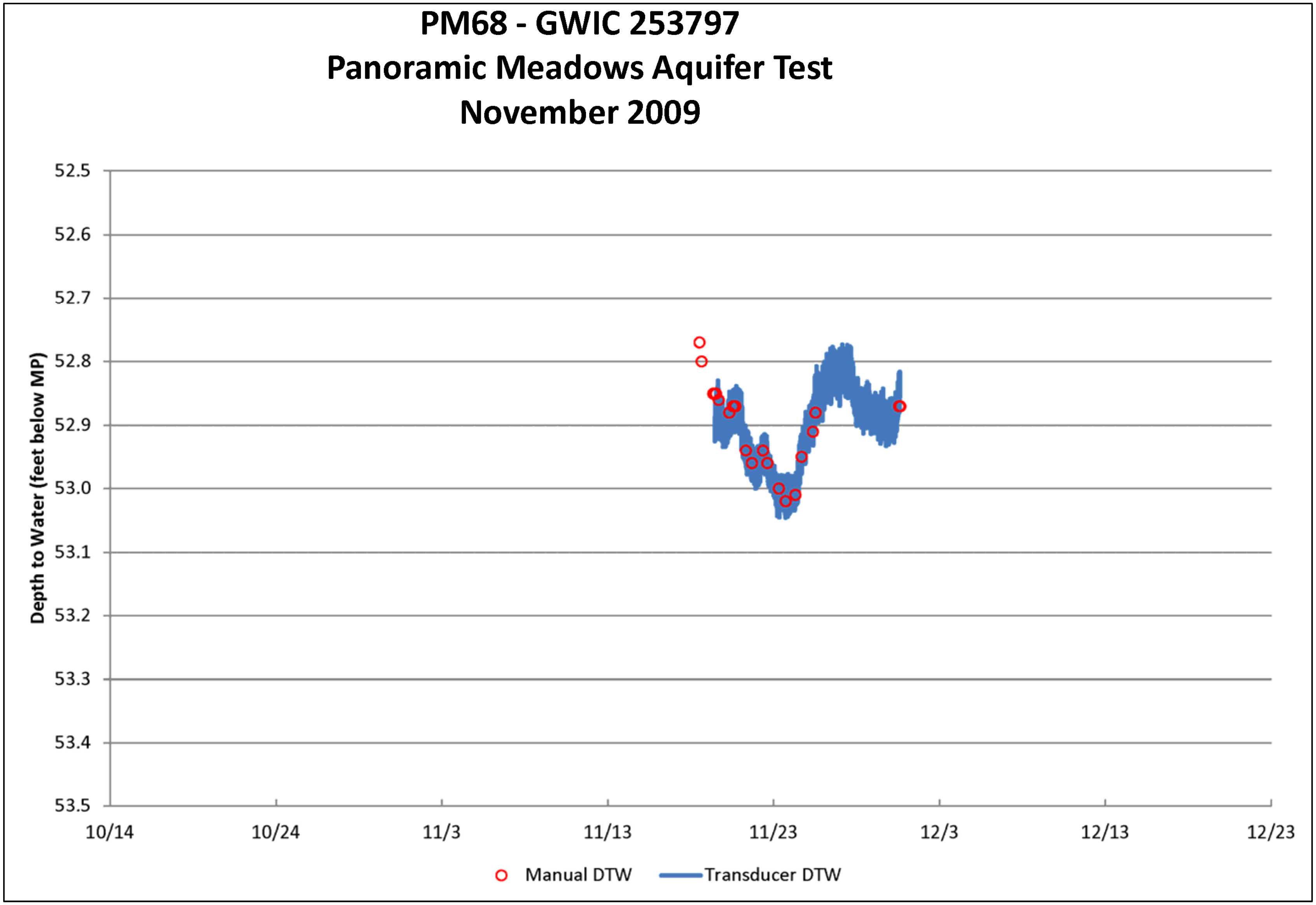

Figure PM11. Depth to water readings (ft below MP) in well PM-68 (530 ft north northwest of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test.

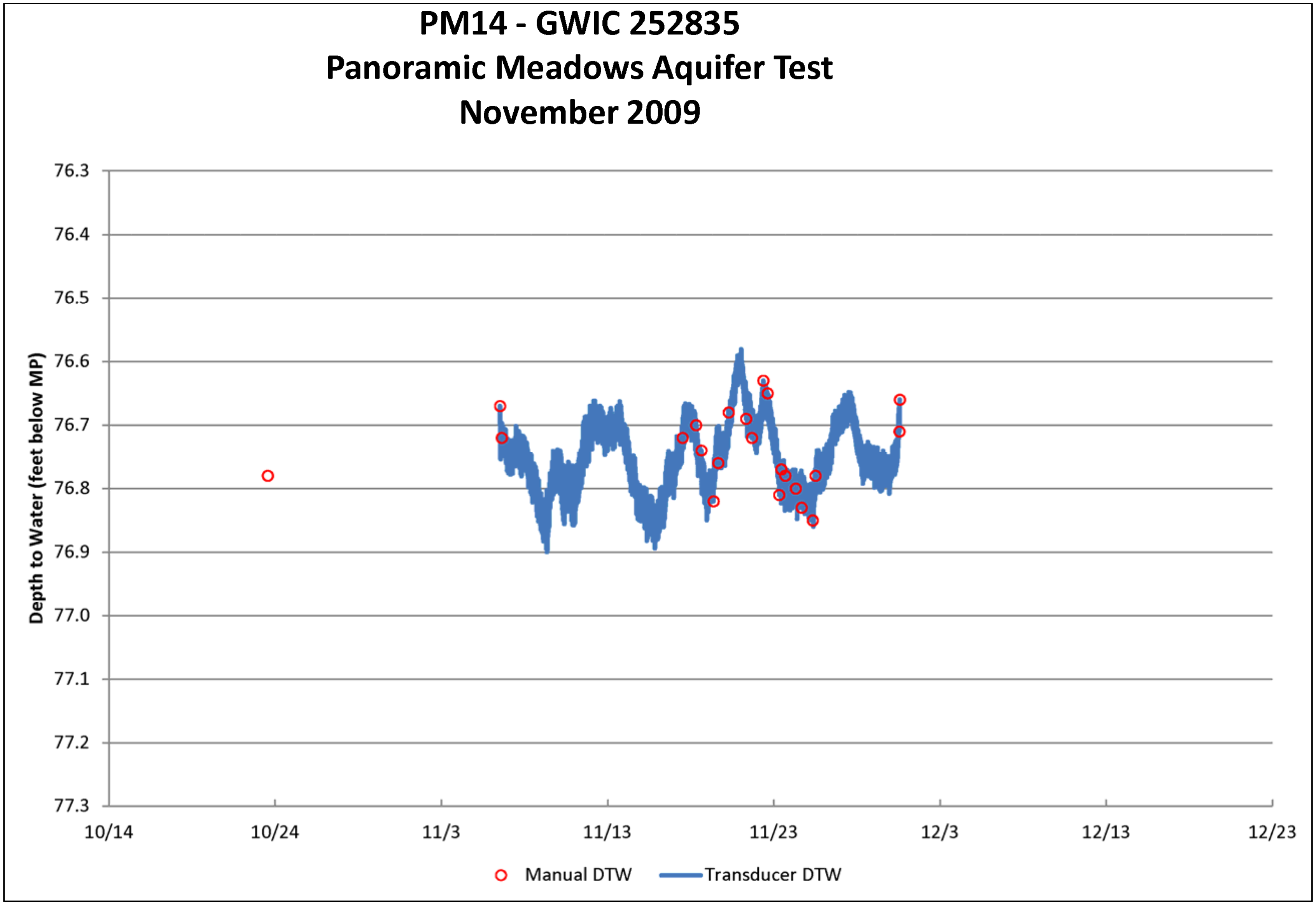

Figure PM12. Depth to water readings (ft below MP) in well PM-14 (2,368 ft north of PM-65) vs. time for the duration of the Panoramic Meadows Aquifer test. PM-14 is above the irrigation ditch.

was started). All transducers were left in place until at least November 30. The transducer in PM-66 was left in place until March 30, 2011.

Measurements of water quality were also obtained during the tests. Parameters measured were pH, SC, and temperature (table PM2; fig. PM13). Field pH and SC meters were calibrated each day prior to use.

Because the Helena Valley irrigation canal had been shut off about a month prior to the test, the test occurred during a period of general water-level decline. The water-level data were detrended using a straight-line extrapolation of data immediately before the step test, and after recovery (figs. 4 to 12, PM14).

Table PM2
Water-Quality Measurements (PM-65)
Panoramic Meadows Aquifer Test—November 2009

Date/Time	Flow Rate (gpm)	pH	SC (µS/cm)	Temperature (°C)
11/17/2009 14:09	26.79	7.68	602	12.6
11/18/2009 11:45	37.41	7.76	603	12.2
11/21/2009 10:00	39.09	8.12	630	11.0
11/22/2009 9:02	38.67	8.07	618	10.6
11/24/2009 8:55	37.91	8.12	625	10.6

gpm = gallons per minute
SC = Specific Conductance
µS/cm = microSiemens per centimeter
°C = degrees Celsius

Step Test

On the afternoon of November 17, a step test was conducted on well PM-65 to determine an appropriate pumping rate (table PM3; fig. PM15). Because it was desired that the long-term pumping rate not be significantly more than that used for well development, a rate of approximately 35 gpm was selected, and valves were set accordingly. As discussed below, the actual weighted average pumping rate for the constant discharge test was 38.25 gpm. PM-65 was constructed with a 4-in 20-slot screen 20 ft long. Thus, the entrance velocity at 38 gpm would be 0.01 ft/s, which is well below the 0.1 ft/s threshold recommended by Heath (1983) for laminar flow.

Table PM3
Step Test Summary
Panoramic Meadows Aquifer Test—November 17, 2009

Start Step	End Step	Rate (Q, gpm)	Final Drawdown (s, ft)	Q/s
13:16	13:44	13.1	0.50	26.2
13:44	14:43	26.9	1.47	18.3
14:43	15:36	35.1	2.17	16.2
15:36	16:19	48.9	3.63	13.5

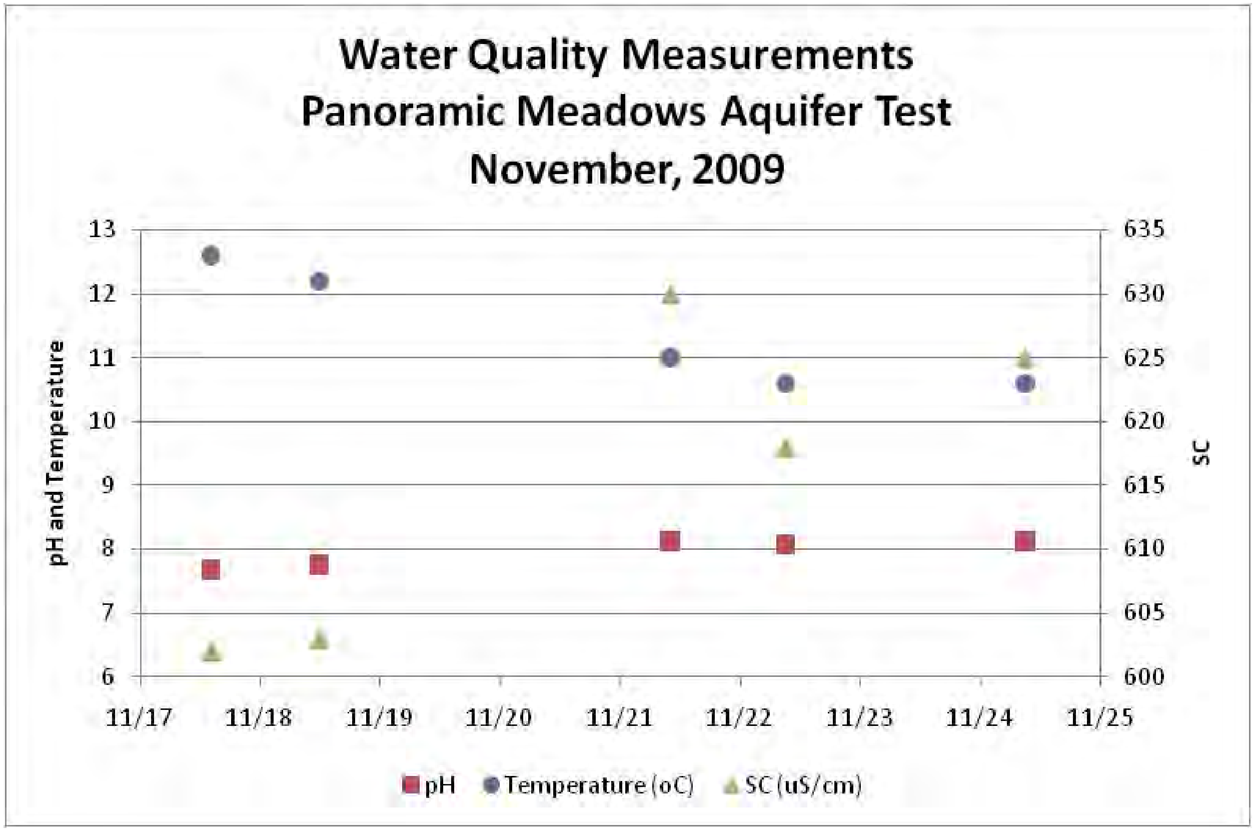

Figure PM13. Water-quality information obtained from the pumping well (PM-65) during the Panoramic Meadows Aquifer test.

Data obtained during the step test also allows the specific capacity (discharge per unit of drawdown, Q/s) of PM-65 to be determined at different pumping rates (fig. PM16). This information can then be used to determine the maximum rate that the well can be pumped, without exceeding a target drawdown. Given that the top of the screen in PM-65 is at 114 ft below ground surface (bgs), that the static water level is at 40 ft bgs, and that it is typically desired that the water level stay at least 10 ft above the top of the screen, the target drawdown in well PM-65 would be 64 ft. Using the calculated relationship from the step test data, it appears that PM-65 would need to be pumped at about 147 gpm to achieve this drawdown.

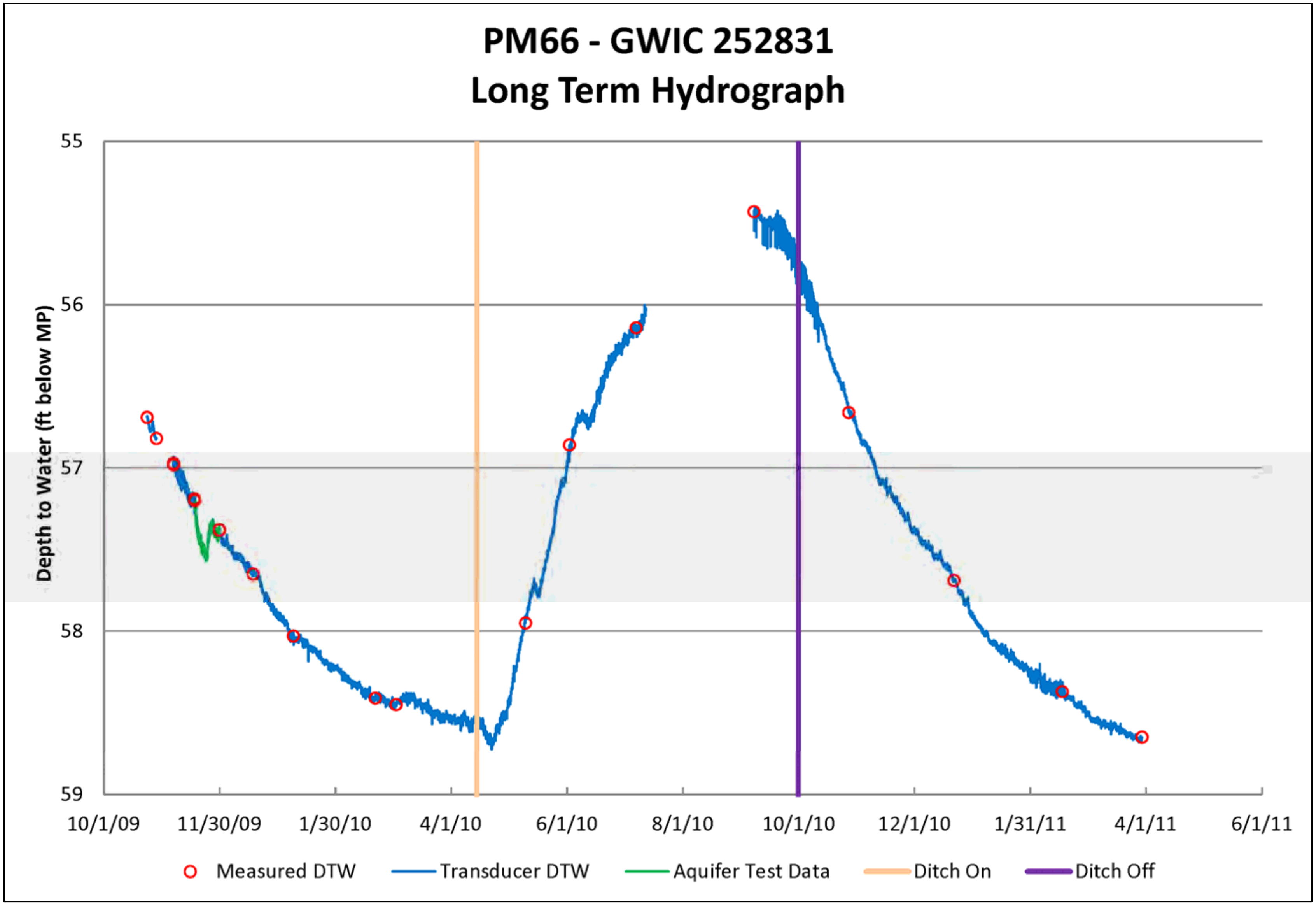

Figure PM14. Long-term hydrograph for PM-66, showing the effect of the irrigation ditch.

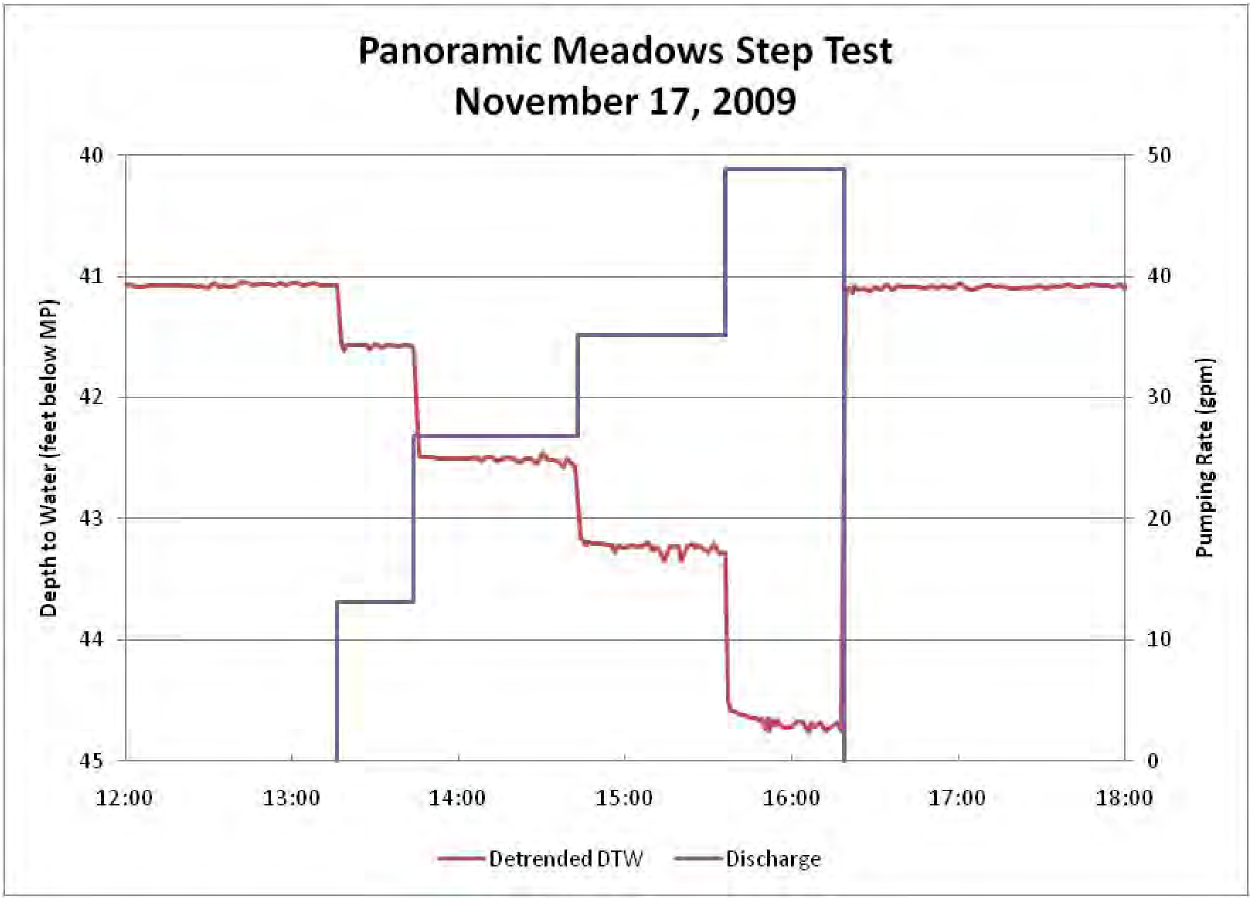

Figure PM15. Depths to water and pumping rates during step test.

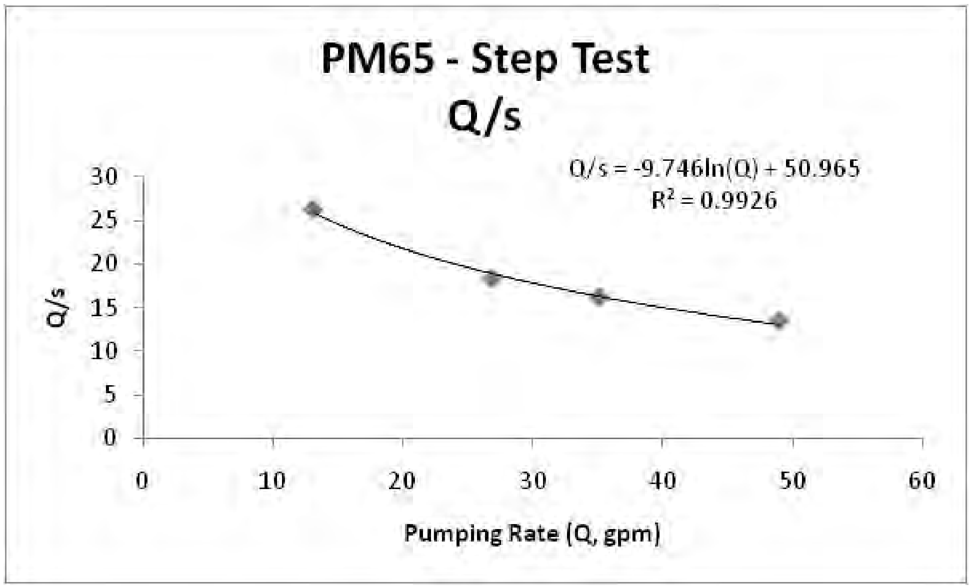

Figure PM16. Specific capacity (Q/s) vs. pumping rate (Q) for PM-65. This relation can be used to determine the maximum pumping rate for the well.

Constant-Rate Test Analysis

The constant discharge test started at 09:55 on November 18, 2009 and ended at 10:00 on November 24, 2009 at a total pumping time of 144 h, 5 min. The time-weighted average pumping rate was 38.28 gpm. The maximum recorded pumping rate was 39.09 gpm and the minimum recorded pumping rate was 36.59 gpm. Thus the maximum deviation from average was 4.4 percent. Total drawdown in well PM-65 at the end of the test was 2.52 ft. Drawdown in well PM-65 showed a rapid initial increase but the rate slowed as pumping continued. Drawdown was still increasing slightly at the end of the test. After pumping ceased, water levels in well PM-65 recovered rapidly and 90 percent of drawdown was gone after approximately 12 min (fig. PM17).

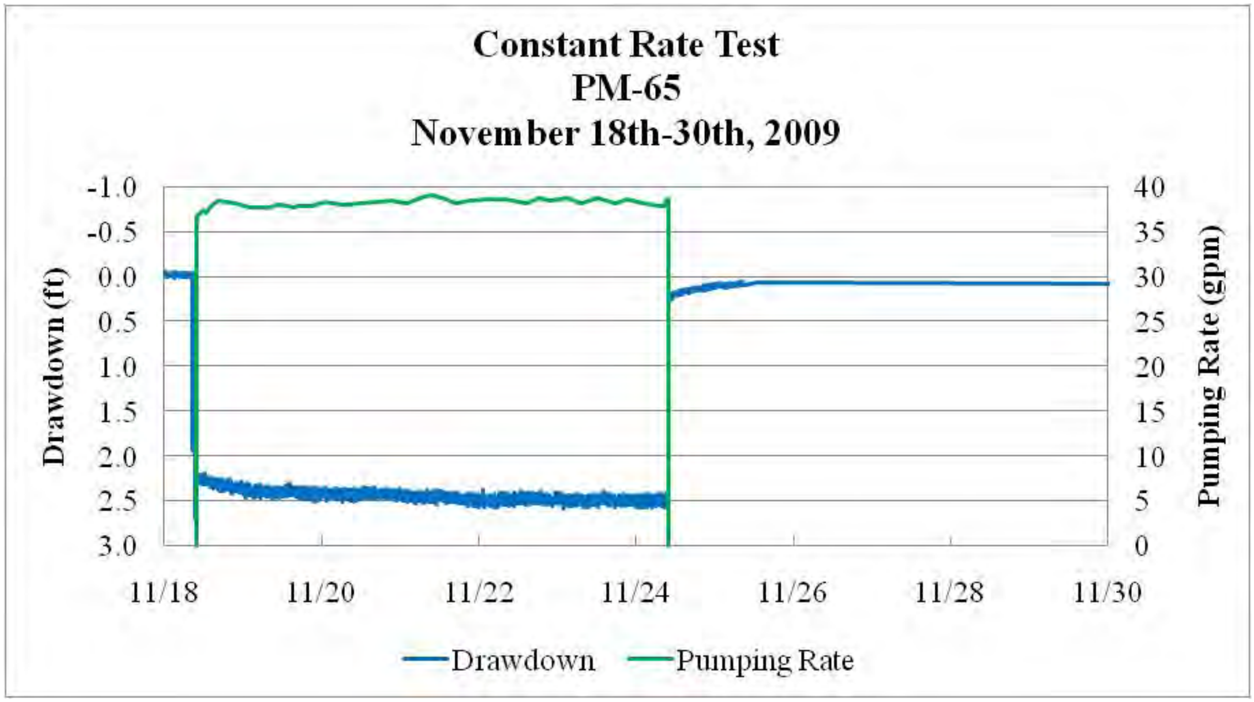

Figure PM17. Depth to water and pumping rates recorded during constant-rate test.

Drawdown in all observation wells mirrored the drawdown in the production well except that the magnitude was less, and more time was required for recovery. The maximum detrended drawdown values show that a relatively shallow but wide cone of depression developed, and there was no noticeable effect from anisotropy (figs. PM18, PM19; table PM4). Data from PM-68 were not used quantitatively since data from prior to the start of the test were not available.

Figure PM18. Maximum drawdown (ft) observed during the Panoramic Meadows Aquifer test.

Table PM4
Maximum Drawdown Values—Constant-Rate Test
Panoramic Meadows Aquifer Test—November 2009

Well	Maximum Drawdown (ft)	Distance from PM-65 (ft)
PM-65	2.54	0.00
PM-63	0.30	178
PM-67	0.32	176
PM-66	0.24	441
PM-64	0.21	447
PM-60	0.18	742
PM-70	0.17	668

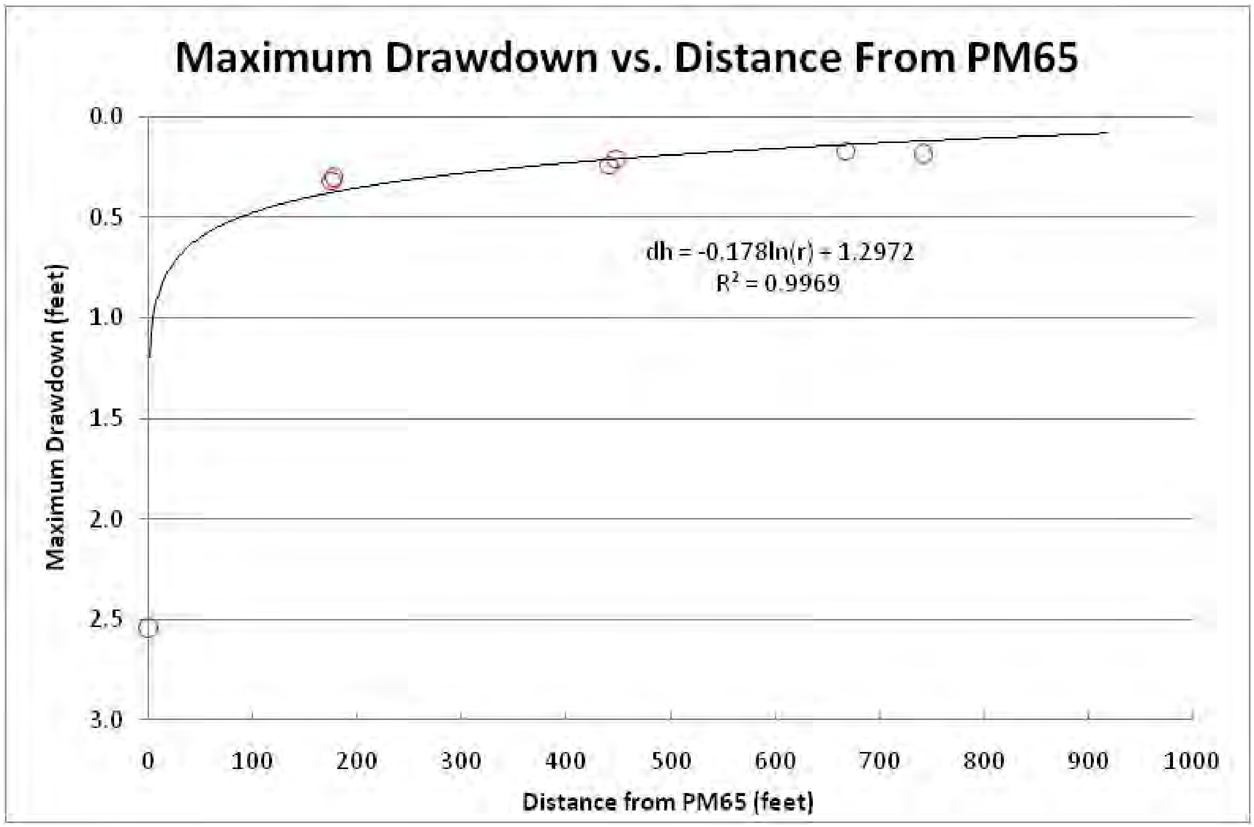

Figure PM19. Maximum drawdown (ft) observed during the Panoramic Meadows Aquifer test.

Data from the 144-h aquifer test were analyzed using multiple methods to determine aquifer parameters, including transmissivity (T) and storage coefficient (S). Detrended data from all wells except PM-68 were analyzed using the Cooper–Jacob straight-line method (Cooper and Jacob, 1946; Jacob, 1950; Fetter, 1994; and ASTM Standard D4105-96, 2008). Analyses of data from PM-63, PM-67, and PM-66 were also conducted using the software program AQTESOLV

(HydroSOLVE, 2007) for comparison to the Theis, Cooper–Jacob, and Hantush–Jacob methods. Analysis plots are included as appendix PM-A.

The geometric mean of transmissivity values (T) obtained using the Cooper–Jacob method is 15,600 ft^2/d but ranged from13,343 to 19,923 ft^2/d. Given that the saturated thickness in PM-65 is 93 ft, the geometric mean hydrologic conductivity (K) is about 170 ft/d (fig. PM20; table PM5).

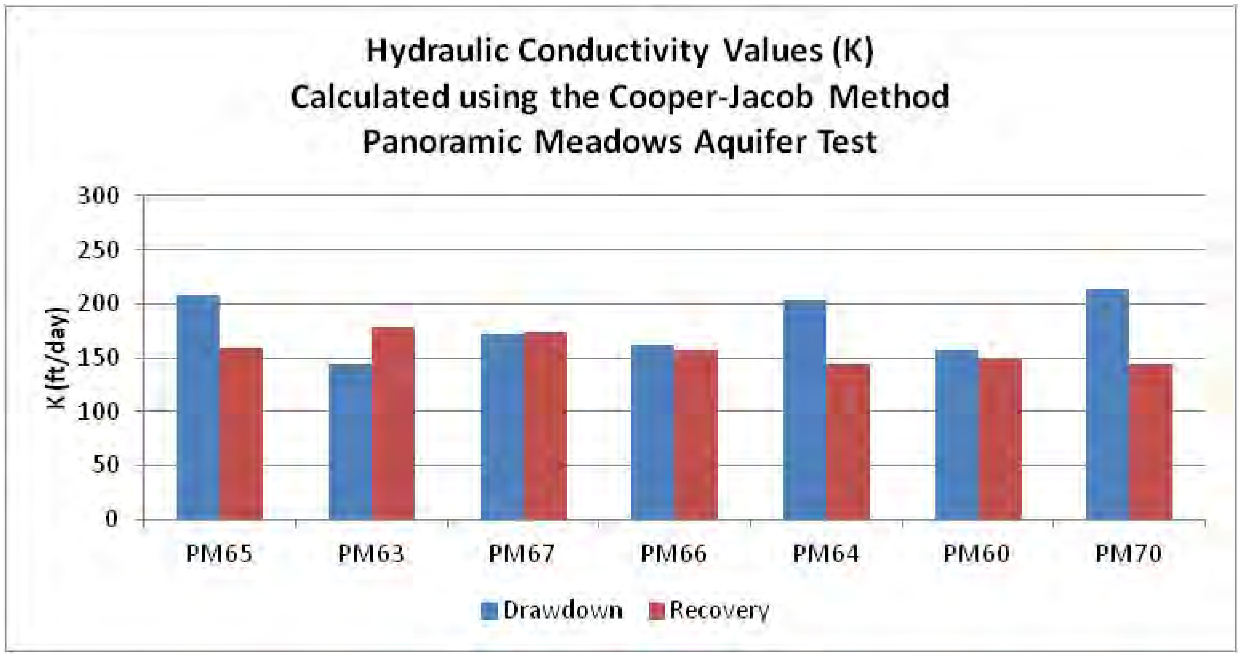

Figure PM20. Hydraulic conductivity values calculated by the Cooper–Jacob method, from Panoramic Meadows Aquifer test data.

Table PM5
Transmissivity and Hydraulic Conductivity Values
Calculated using the Cooper–Jacob Method
Panoramic Meadows Aquifer Test—November 2009

Well	**Transmissivity (T, ft^2/d)**		**Hydrologic Conductivity (K, ft/d)**	
	Drawdown	**Recovery**	**Drawdown**	**Recovery**
PM-65	19,395	14,754	209	159
PM-63	13,404	16,546	144	178
PM-67	16,004	16,181	172	174
PM-66	15,019	14,644	161	157
PM-64	18,895	13,343	203	143
PM-60	14,644	13,880	157	149
PM-70	19,923	13,373	214	144
Geometric Mean T		15,573	Geometric Mean K	167
Minimum T		13,343	Minimum K	143
Maximum T		19,923	Maximum K	214

K values are based on a saturated thickness of 93 ft, as seen in well PM-65.

The average of the storage coefficients (S) obtained using the Cooper–Jacob method is 0.008. Results from this method ranged from 0.0014 to 0.0186 (fig. PM21; table PM6).

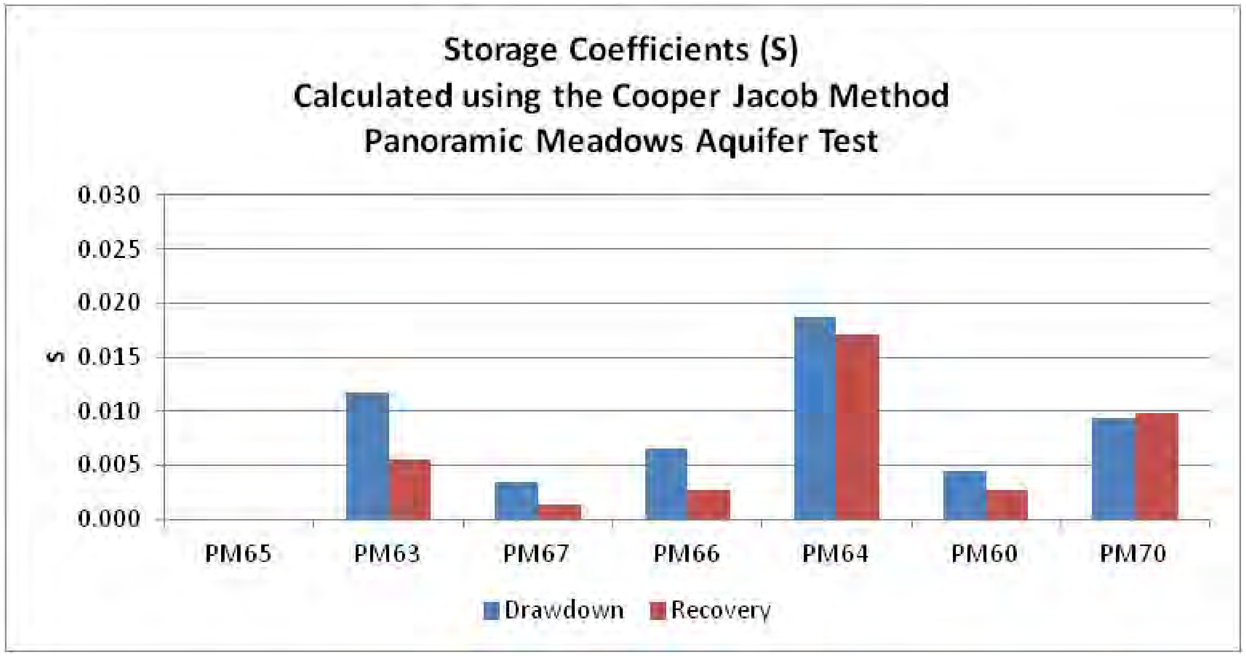

Figure PM21. Storage coefficients calculated from Panoramic Meadows Aquifer test data.

Table PM6
Storage Coefficients
Calculated using the Cooper–Jacob Method
Panoramic Meadows Aquifer Test—November 2009

Well	**Storage Coefficient (dimensionless)**	
	Drawdown	**Recovery**
PM-63	0.0118	0.0055
PM-67	0.0035	0.0014
PM-66	0.0066	0.0027
PM-64	0.0187	0.0171
PM-60	0.0044	0.0027
PM-70	0.0093	0.0098
Average Storage Coefficient		0.008

Log-log plots of drawdown vs. time indicate that the aquifer is semi-confined to confined (figs. PM-A1 to PM-A7 in appendix PM-A). Storativity values also support this assessment.

These data can also be evaluated using a Cooper–Jacob composite plot, where the data from several wells can be plotted on one semi-log plot, using time over radius squared (t/r^2) on the logarithmic axis and drawdown on the arithmetic axis. Using this approach, a best-fit line for all the data can be determined. This analysis was done using drawdown and recovery data from wells PM-63, PM-67, and PM-66. There is considerable noise due to the small magnitude of drawdown in these wells; however, a reasonable trend line can be drawn (fig. PM22). The composite plot analysis results in T = 14,200 ft^2/d, K = 150 ft/d, and S = 0.006.

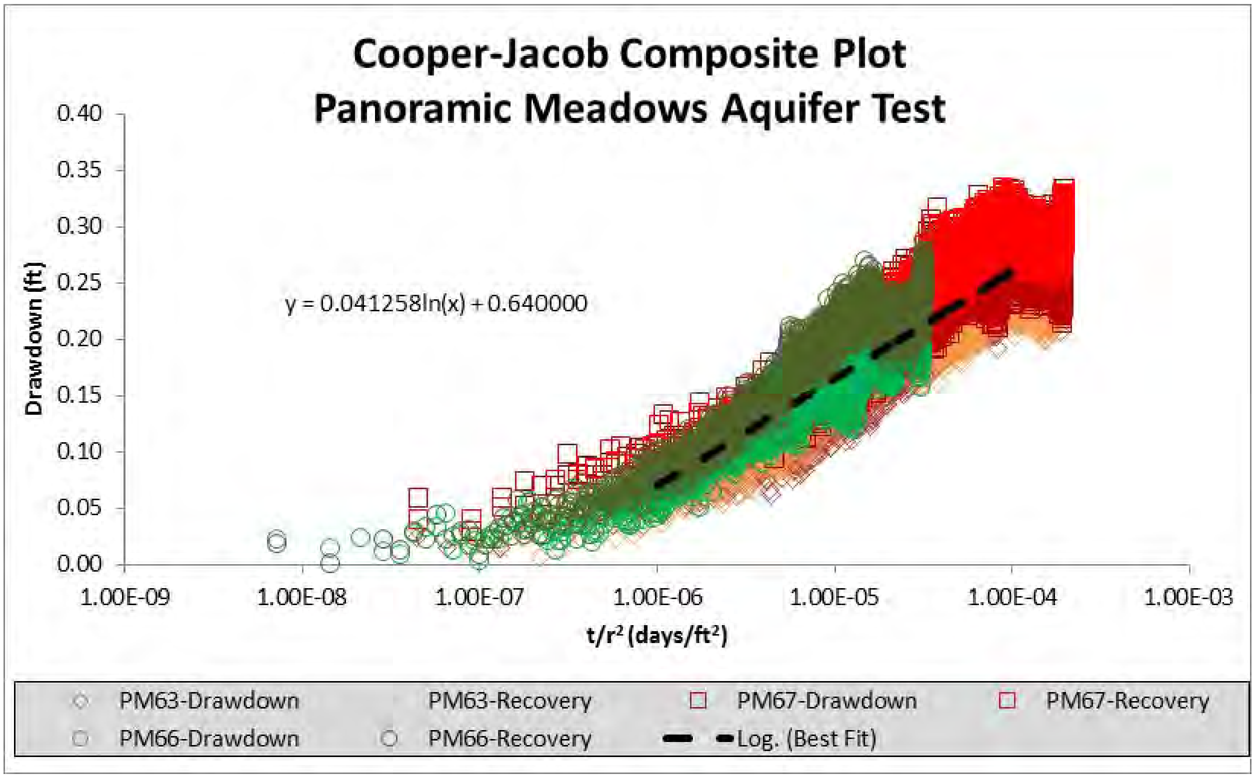

Figure PM22. Cooper–Jacob composite plot of drawdown and recovery data from PM-63, PM-67, and PM-66.

The recovery data were also assessed using the Cooper–Jacob (1946) straight line analysis method (fig. PM23). A line was fit to the data, using the best straight line portion of the curves, and with the x-intercept at 1 (x=1, y=0), to avoid the effects of boundaries (drawdown should approach zero as time approaches infinity). This analysis results in a T = 17,613 ft^2/d, which corresponds to a K = 189 ft/d.

Analysis using AQTESOLV and the Theis, Cooper–Jacob, and Hantush–Jacob methods results in a geometric mean T = 17,800 ft^2/d (K = 191 ft/d), and a mean S = 0.006 (table PM7). These results are consistent with those discussed above.

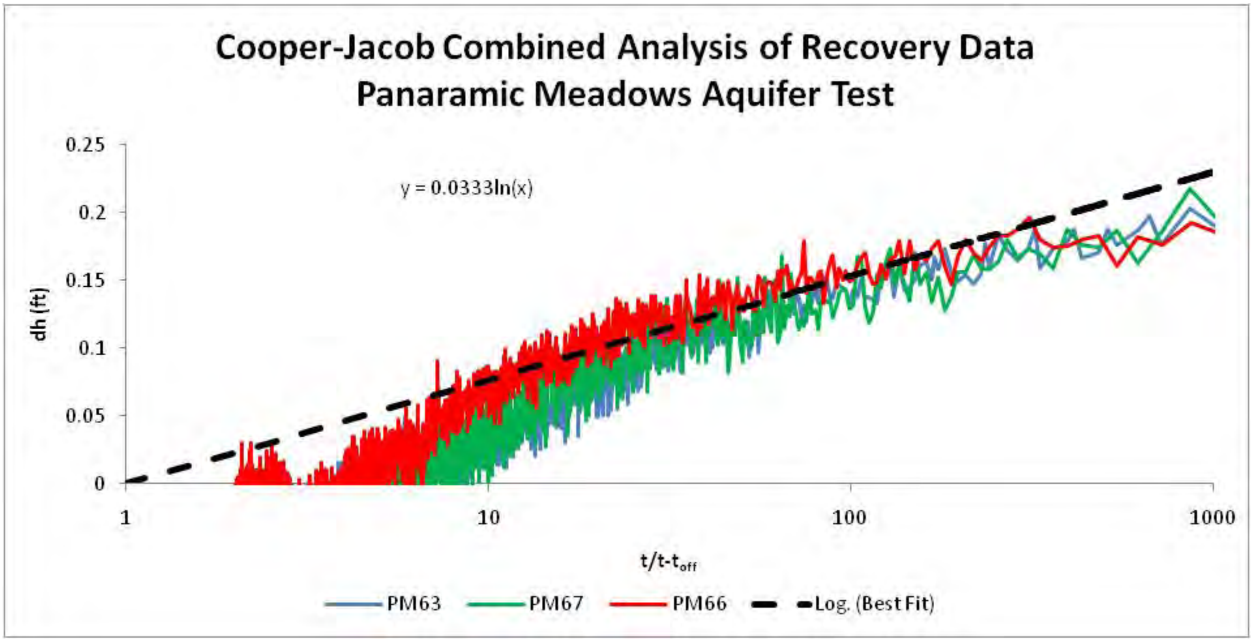

Figure PM23. Cooper–Jacob analysis of recovery data.

Table PM7
AQTESOLV Results Summary
Panoramic Meadows Aquifer Test—November 2009

Pumping Well	Observation Well	Method	T (ft^2/d)	S
PM-65	PM-63	Theis	22,740	0.0029
	PM-63	Cooper–Jacob	22,830	0.0029
	PM-63	Hantush–Jacob	8,741	0.0284
	Geometric Mean for PM-63		**16,556**	**0.0062**
	PM-66	Theis	17,940	0.0049
	PM-66	Cooper–Jacob	19,000	0.0039
	PM-66	Hantush–Jacob	15,480	0.0065
	Geometric Mean for PM-66		**17,409**	**0.0050**
	PM-67	Theis	25,650	0.0003
	PM-67	Cooper–Jacob	25,650	0.0003
	PM-67	Hantush–Jacob	11,480	0.0084
	Geometric Mean for PM-67		**19,620**	**0.00091**
	Geometric Mean T for all Wells		**17,800**	
	Mean S for all Wells			**0.006**

In summary, the most reasonable bulk T is about 15,000 ft^2/d, bulk K is about 160 ft/d, and bulk S is about 0.006. Given the uncertainty of the results, primarily due to the high signal to noise ratio and the need to correct for antecedent trends, a reasonable range of T values from this test would be from 14,000 to 18,000 ft^2/d (K from 150 to 195 ft/d). A reasonable range of S values would be from 0.004 to 0.01.

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ASTM, 2008, Standard test method (analytical procedure) for determining transmissivity and storage coefficient of nonleaky confined aquifer by the modified theis nonequilibrium method, D4105-96 (Reapproved 2008).

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APPENDIX PM-A
LOG-LOG AND SEMI-LOG PLOTS OF DRAWDOWN VS. TIME

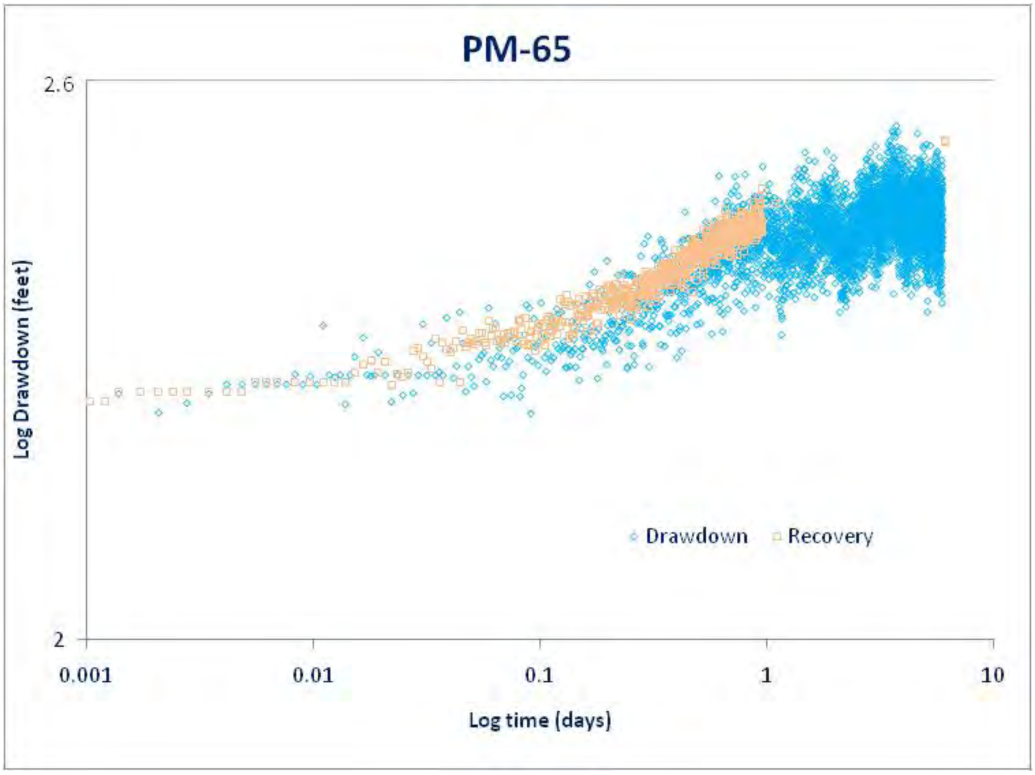

Figure PM-A1. Log-log plot of drawdown and recovery data from PM-65 (pumping well).

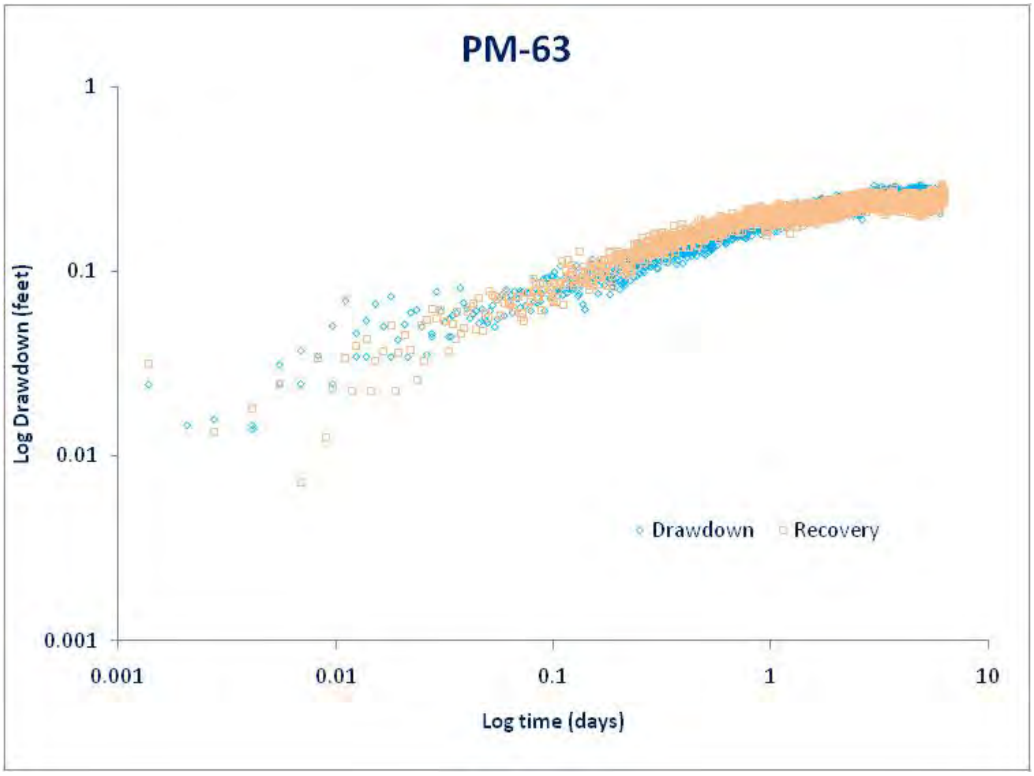

Figure PM-A2. Log-log plot of drawdown and recovery data from PM-63 (178 ft from PM-65).

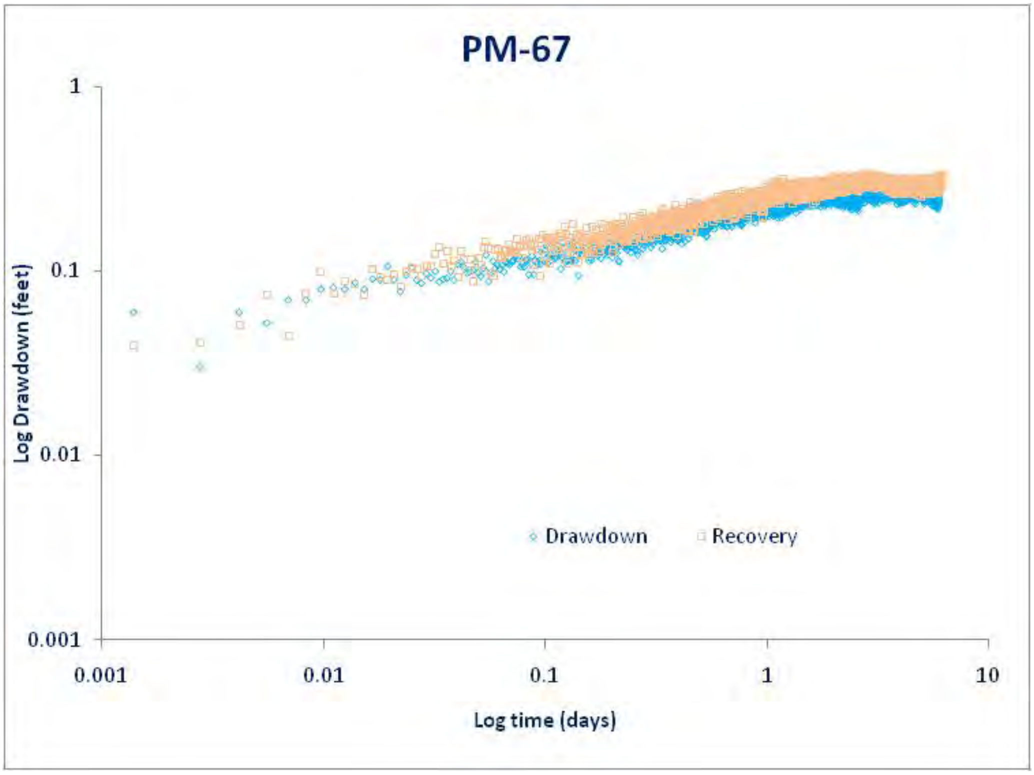

Figure PM-A3. Log-log plot of drawdown and recovery data from PM-67 (176 ft from PM-65).

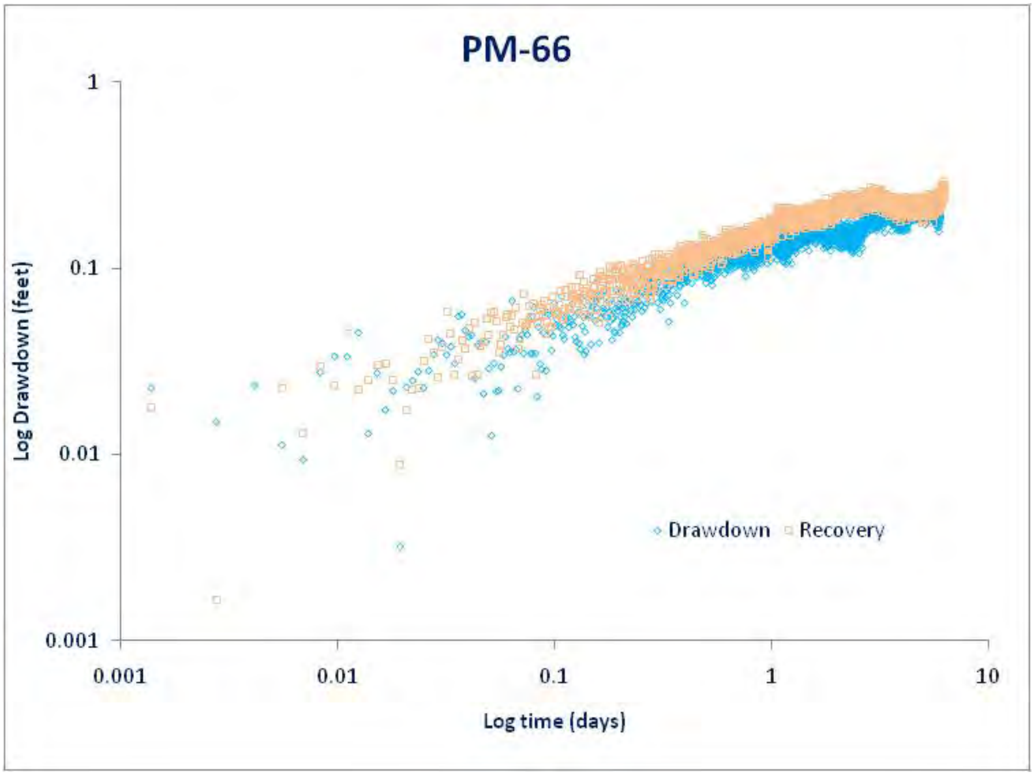

Figure PM-A4. Log-log plot of drawdown and recovery data from PM-66 (441 ft from PM-65).

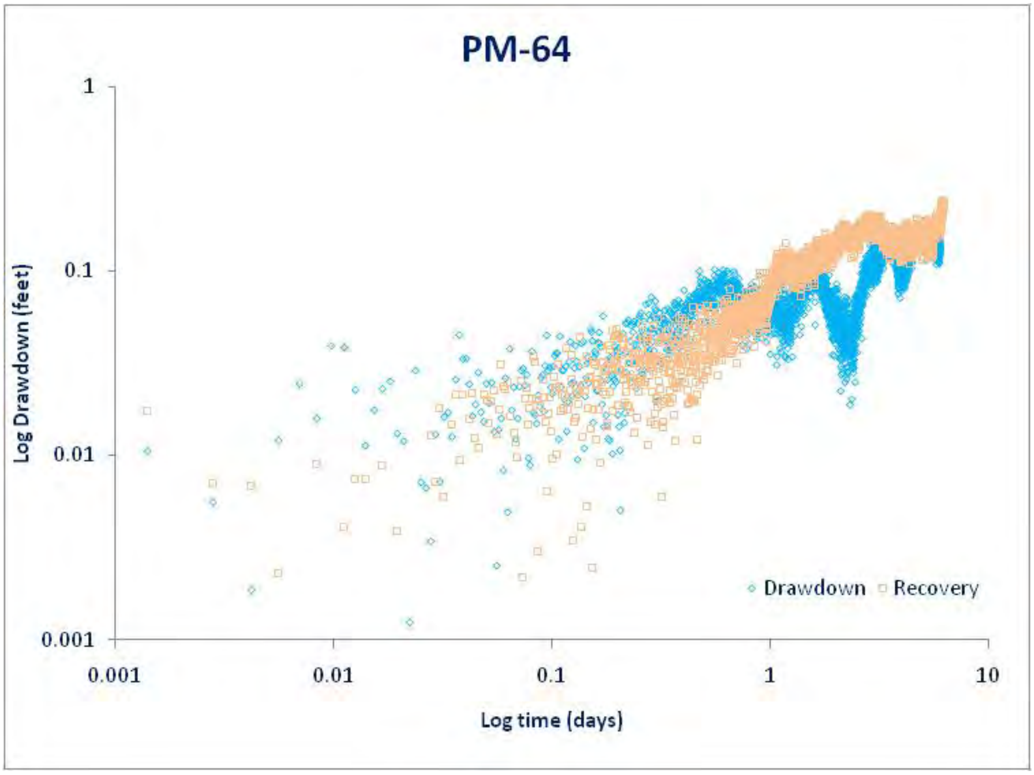

Figure PM-A5. Log-log plot of drawdown and recovery data from PM-64 (447 ft from PM-65).

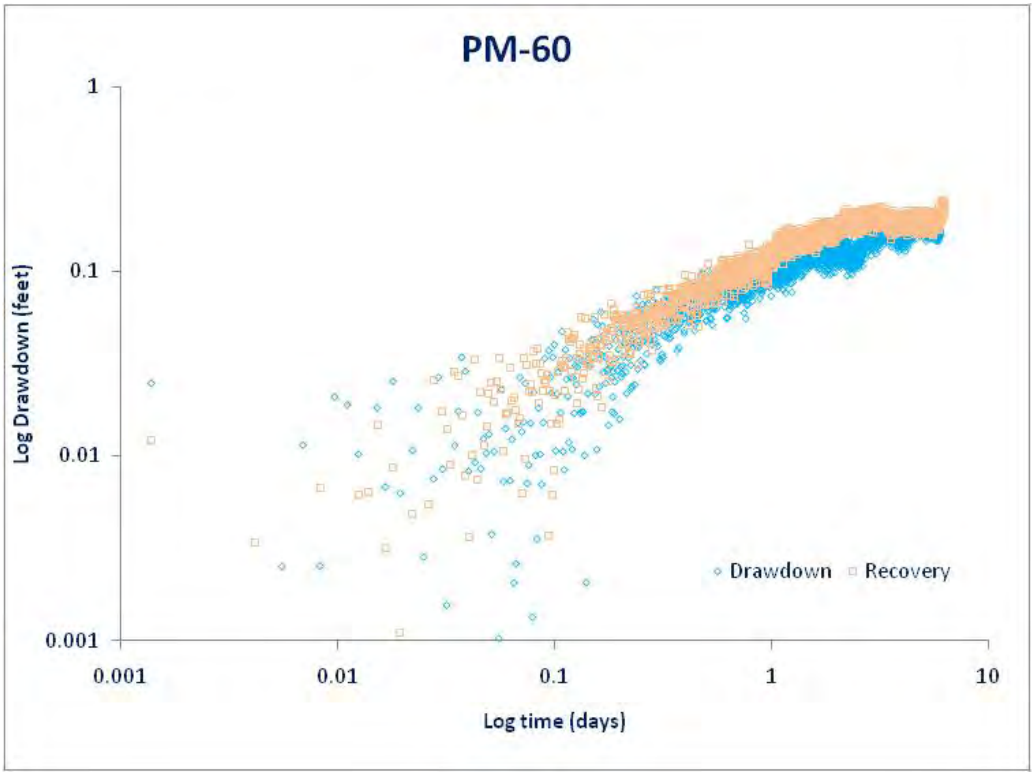

Figure PM-A6. Log-log plot of drawdown and recovery data from PM-60 (741 ft from PM-65).

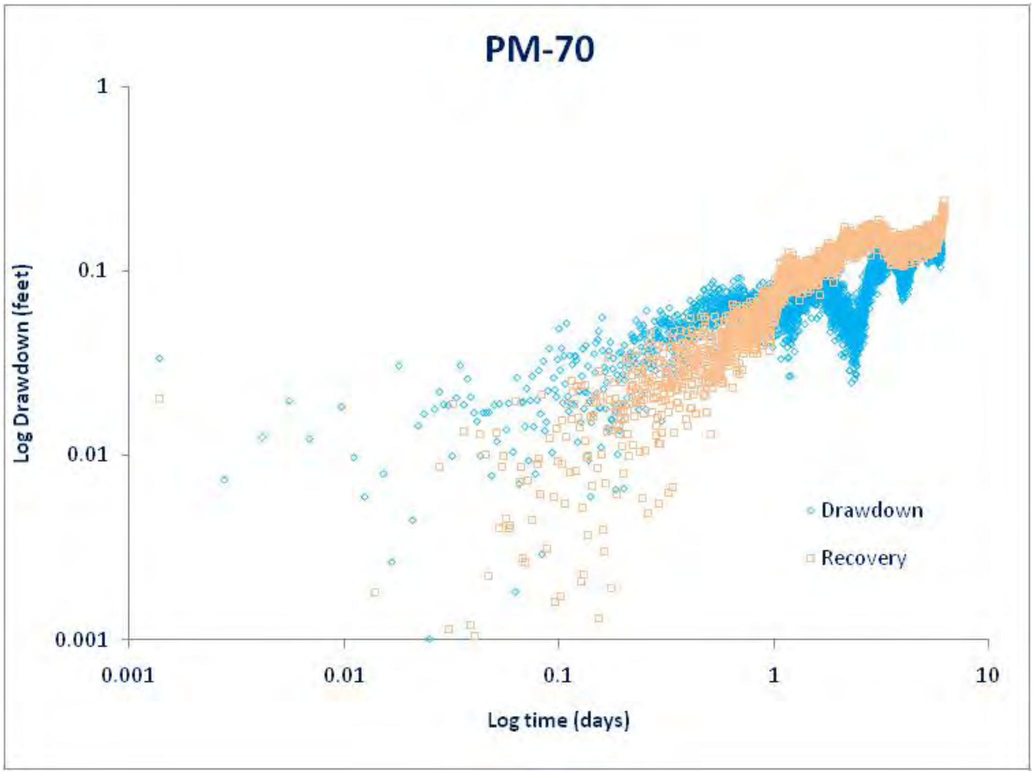

Figure PM-A7. Log-log plot of drawdown and recovery data from PM-70 (668 ft from PM-65).

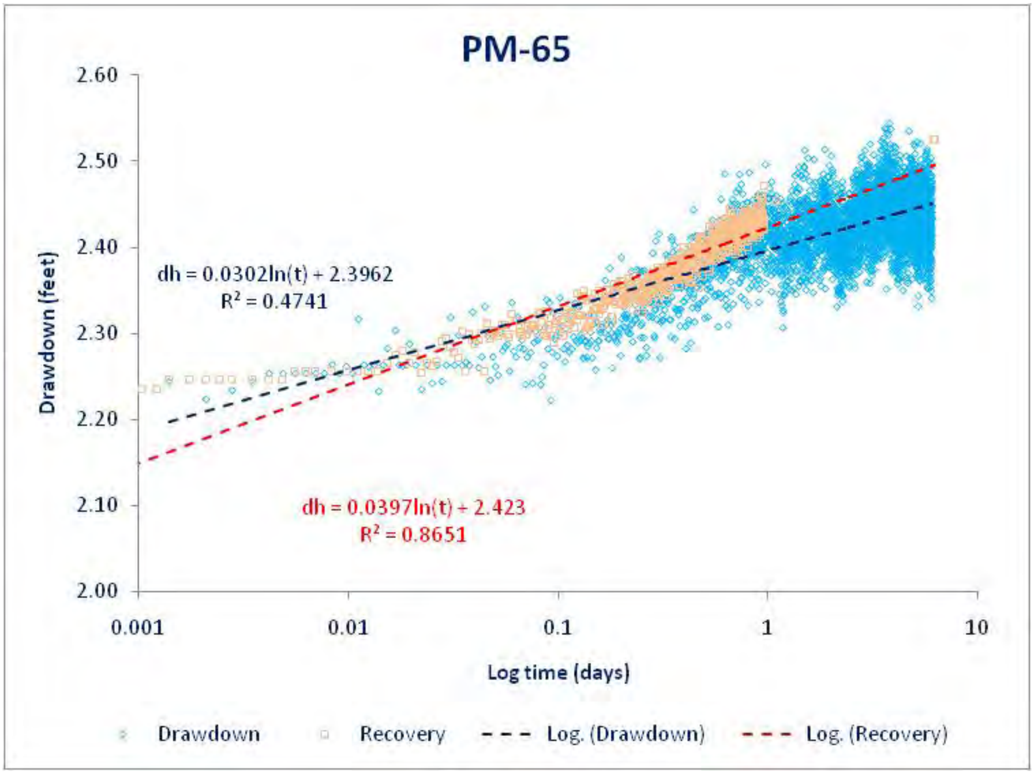

Figure PM-A8. Semi-log plot of drawdown and recovery data from PM-65 (pumping well).

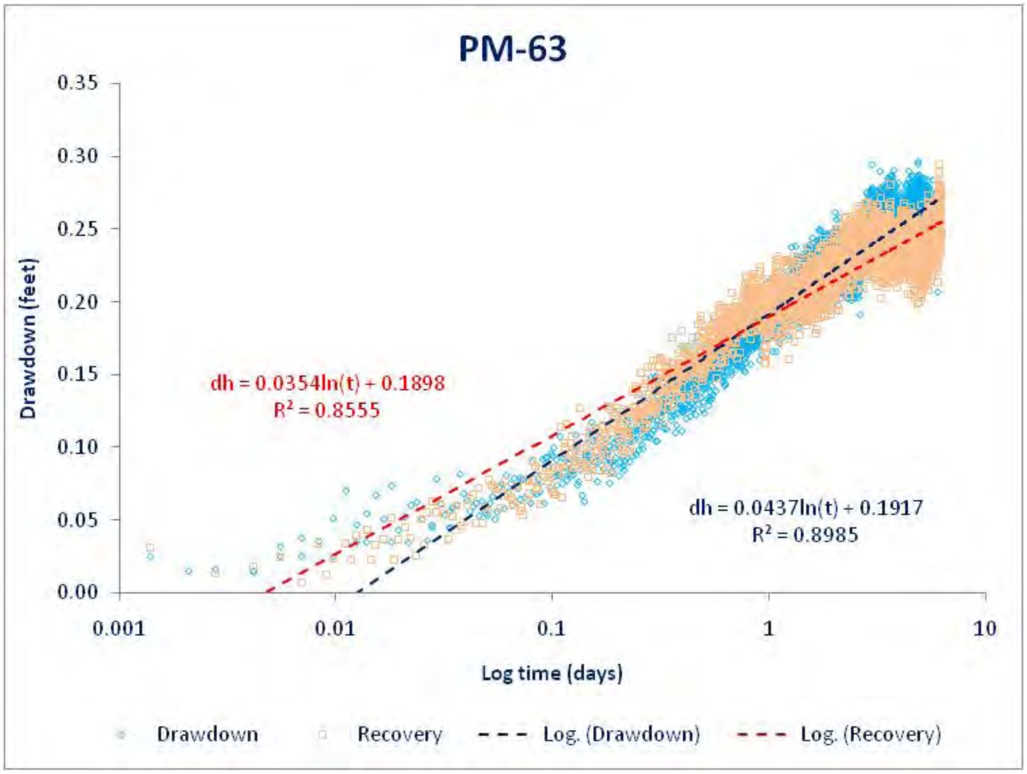

Figure PM-A9. Semi-log plot of drawdown and recovery data from PM-63 (178 ft from PM-65).

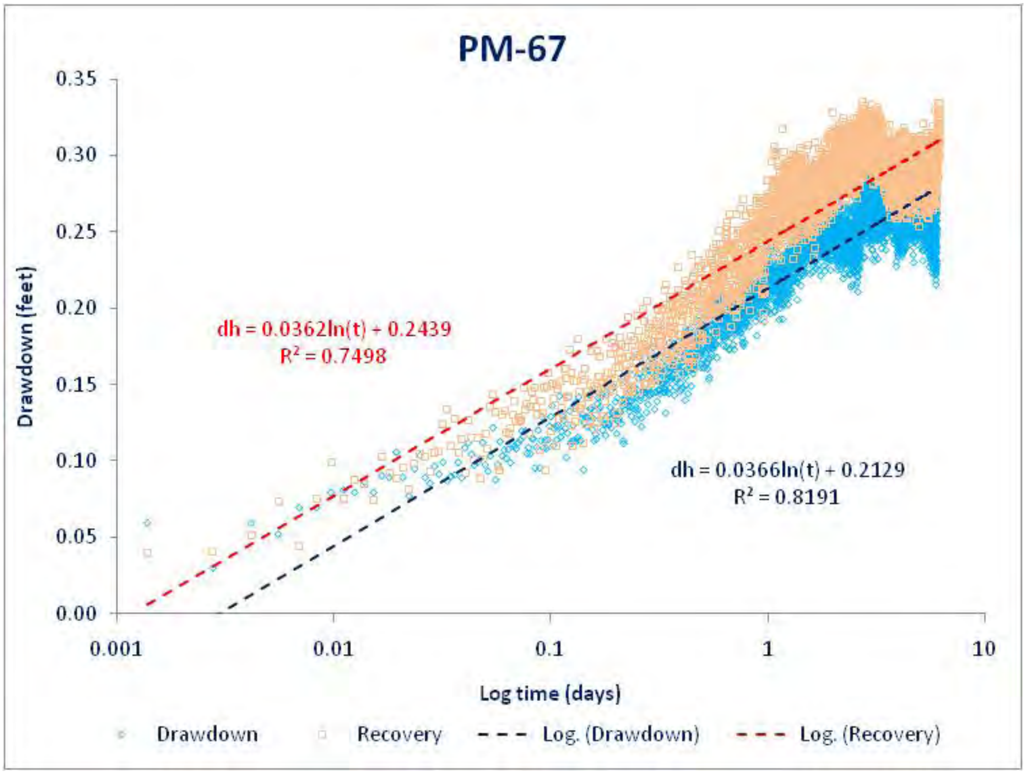

Figure PM-A10. Semi-log plot of drawdown and recovery data from PM-67 (176 ft from PM-65).

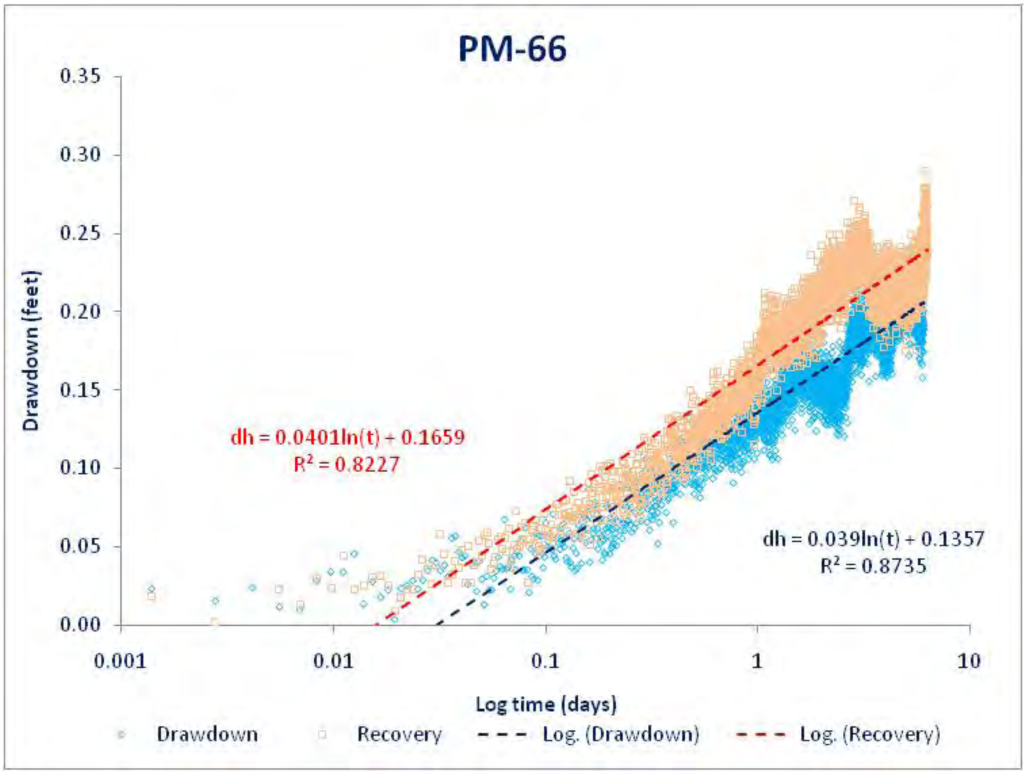

Figure PM-A11. Semi-log plot of drawdown and recovery data from PM-66 (441 ft from PM-65).

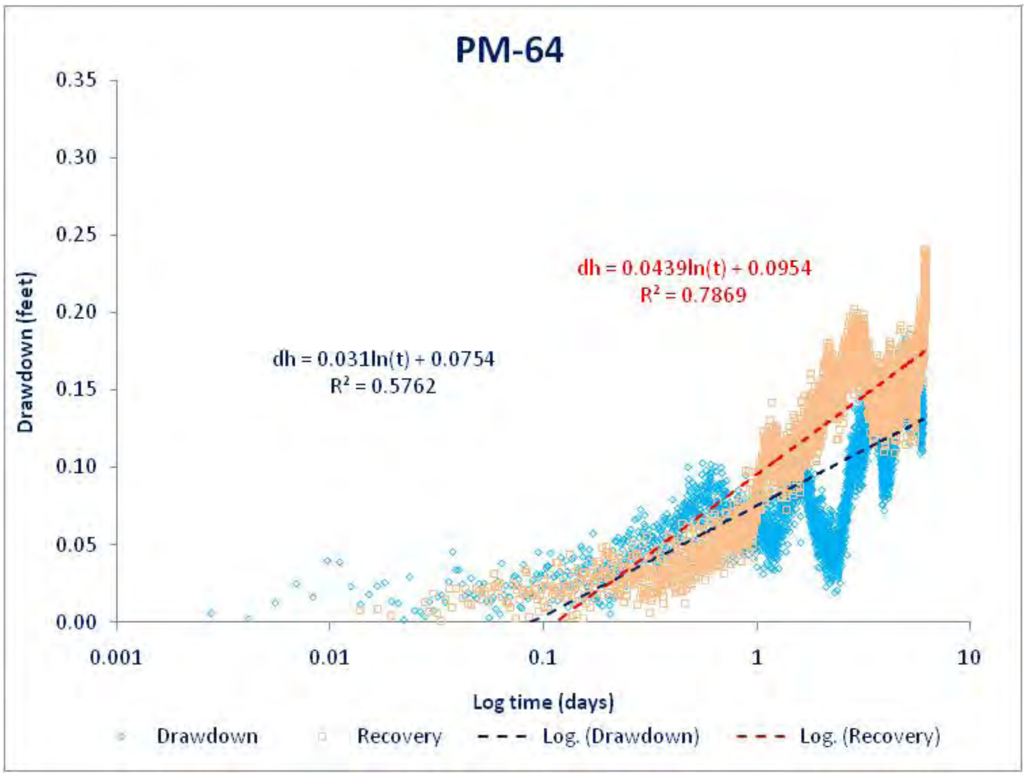

Figure PM-A12. Semi-log plot of drawdown and recovery data from PM-64 (447 ft from PM-65).

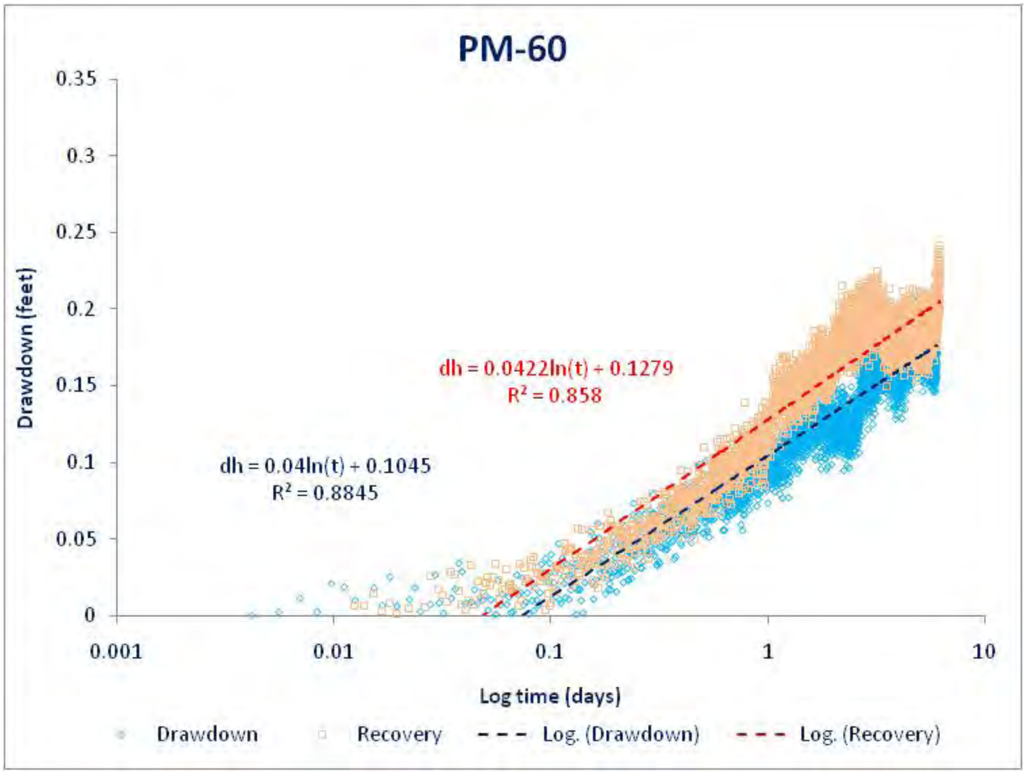

Figure PM-A13. Semi-log plot of drawdown and recovery data from PM-60 (742 ft from PM-65).

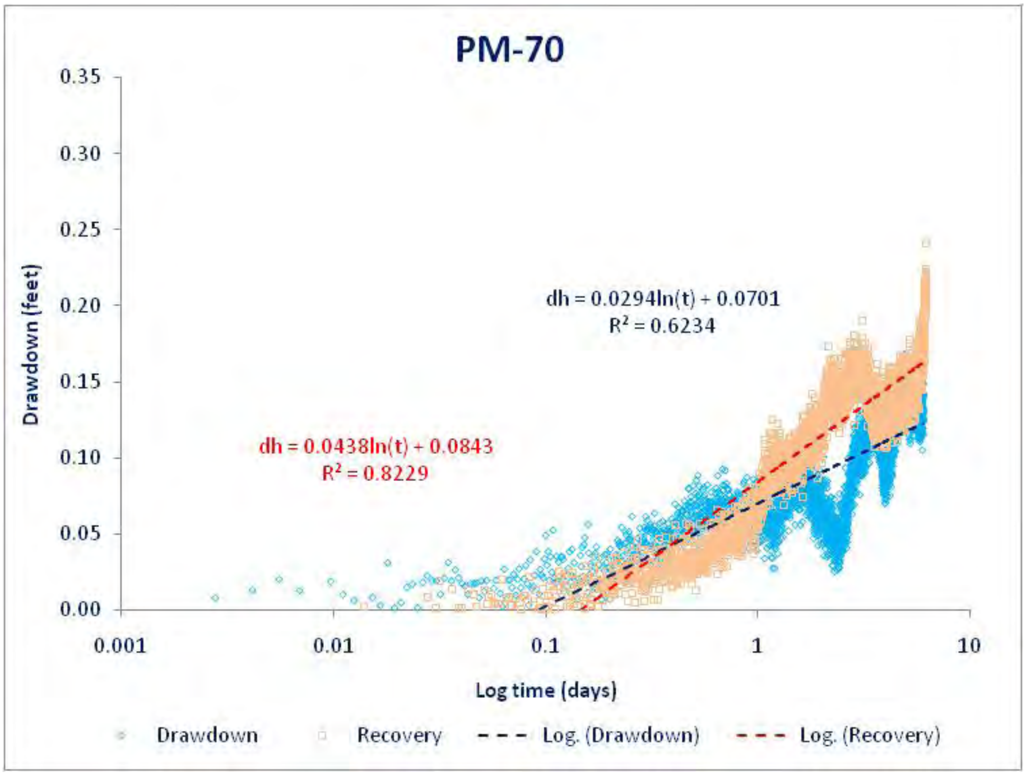

Figure PM-A14. Semi-log plot of drawdown and recovery data from PM-70 (668 ft from PM-65).

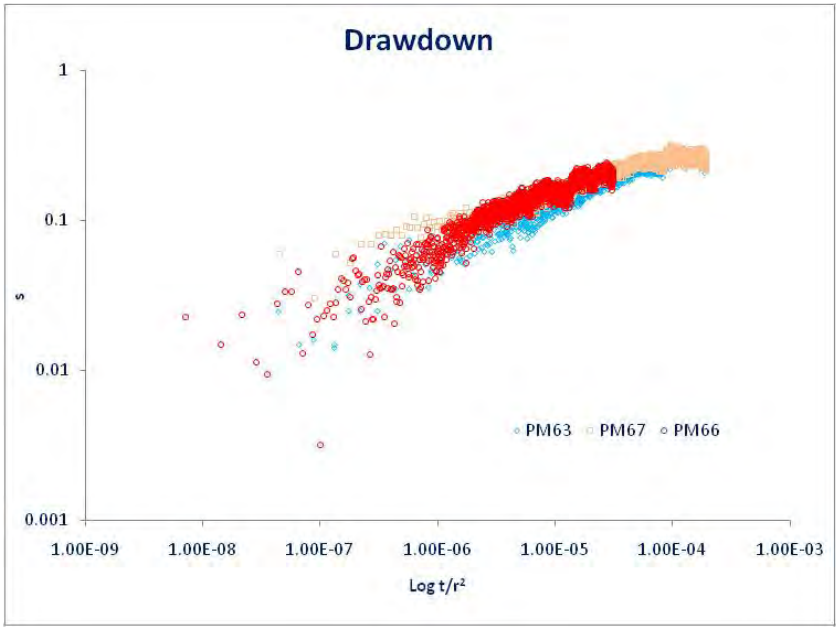

Figure PM-A15. Log-log plot of drawdown (s, ft) data from PM-63, PM-67, and PM-66 vs. time since pumping started (t, days) divided by distance to PM-65 squared (r^2, ft^2). The fact that these values plot on top of each other indicates that the aquifer is isotropic and that no outside stress disproportionately affected one well.

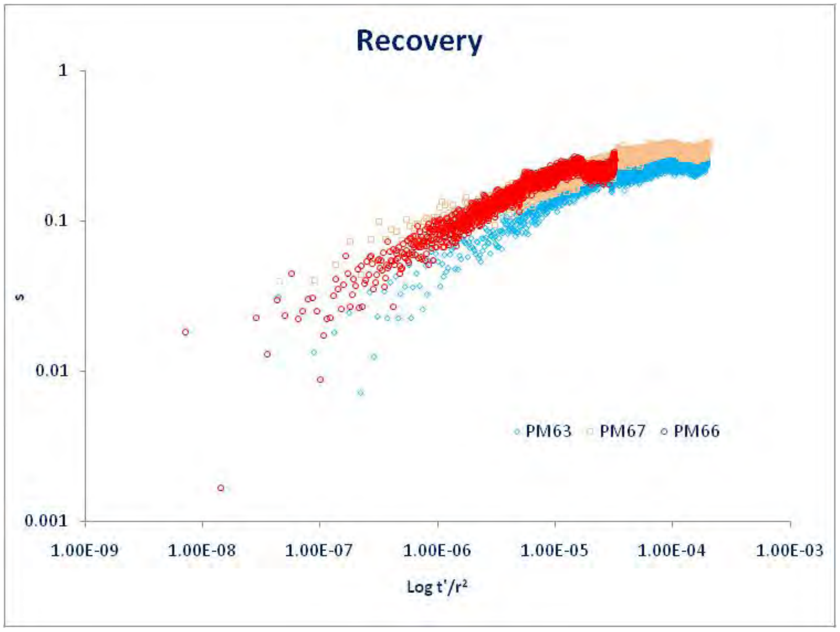

Figure PM-A16. Log-log plot of drawdown (s, ft) data from PM-63, PM-67, and PM-66 vs. time since pumping ended (t', days) divided by distance to PM-65 squared (r^2, ft^2). The fact that these values plot on top of each other indicates that the aquifer is isotropic and that no outside stress disproportionately affected one well.

HELENA VALLEY FAULT AQUIFER TEST—SPOKANE AND GREYSON FORMATIONS

HELENA VALLEY FAULT
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
May-June 2010

ANALYSIS OF FAULT AND AQUIFER PROPERTIES USING STEP TESTS AND CONSTANT-RATE TESTS

Background

The following is an analysis of step tests and constant-rate tests the MBMG conducted using wells installed on the property of Diamond Hills Estates. These wells are located near the Helena Valley Fault, with wells HVF-1 and HFV-2 on the south side of the major break in slope (fault?), and well HVF-3 on the north side. There are no homes on this parcel, and the nearest home is approximately 2,450 ft to the east.

The test's purpose was to determine the effect that the Helena Valley Fault may have on the flow system. Depending on the nature of the fault, it may act as a barrier boundary, a recharge boundary, or neither.

Three 6-in wells—HVF-1, HVF-2, and HVF-3 (GWIC IDs 258401, 258402, and 258597 respectively)—were installed in early April 2010. A MBMG hydrogeologist was present for their installation; cuttings were described in detail, and completion details were verified. A pre-existing well is located approximately 1,050 ft southwest (Shallow Diamond Hills; GWIC 253818). Well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu) by using the GWIC ID (table HVF1).

A transducer was deployed in the Shallow Diamond Hills well on January 8, 2010. Transducers were installed in wells HVF-2 and HVF-3 on May 12, 2010, and removed on June 5. The transducer in HVF-1 was installed on May 17, and removed on June 1, 2010.

Location

The test area is located in the North Hills, at the northern end of Applegate Drive. This site is located in Township 12 N., Range 3 W., Section 30, NE¼ NW¼ SW¼ NW¼, in Lewis and Clark County, Montana (figs. HVF1, HVF2).

Geology

The aquifers tested are within fractured Spokane Formation and Greyson Formation rocks. Also evaluated is the effect of the Helena Valley Fault on groundwater flow. The Spokane Formation has been described as "argillite and siltite with very thin limestone and quartz sandstone in the uppermost and lowest parts," and the Greyson as "siltite and argillite with quartzite in the uppermost part" (Thamke, 2000).

The approximate location of the fault was determined based on previous mapping, changes in topographic slope, rock type and vegetation, and spring locations (figs. HVF3–HVF5); however, the presence of colluvial materials masks the actual fault trace at the test site. Although the fault is mapped as a single feature, it is likely to be a fault zone, rather than a single distinct plane.

Table HVF1

Well Designations, Locations, and Completion Information

Helena Valley Fault Aquifer Test—May–June 2010

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 5/17/2010 (ft below/above [-] MP)	Groundwater Elevation 5/17/10 (ft-amsl)	Comments
258401	HVF-1	46.7586937	-112.0386578	4324.70	255	-7.11	4331.81	South Well; Artesian
258402	HVF-2	46.7589301	-112.0384789	4338.30	265	6.44	4331.86	Middle Well
258597	HVF-3	46.7591647	-112.0381867	4367.53	260	36.33	4331.20	North Well Bottom 20 ft plugged
253818	Shallow Diamond Hills	46.7566545	-112.0405959	4267.17	92.35	24.35	4242.82	Nearby observation well

ft-amsl = ft above mean sea level

ft below/above MP = ft below/above (-) measuring point

* = Horizontal Datum is NAD83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

Distances Between Wells

HVF1-HVF2 = 89 ft

HVF1-HVF3 = 189 ft

HVF2-HVF3 = 101 ft

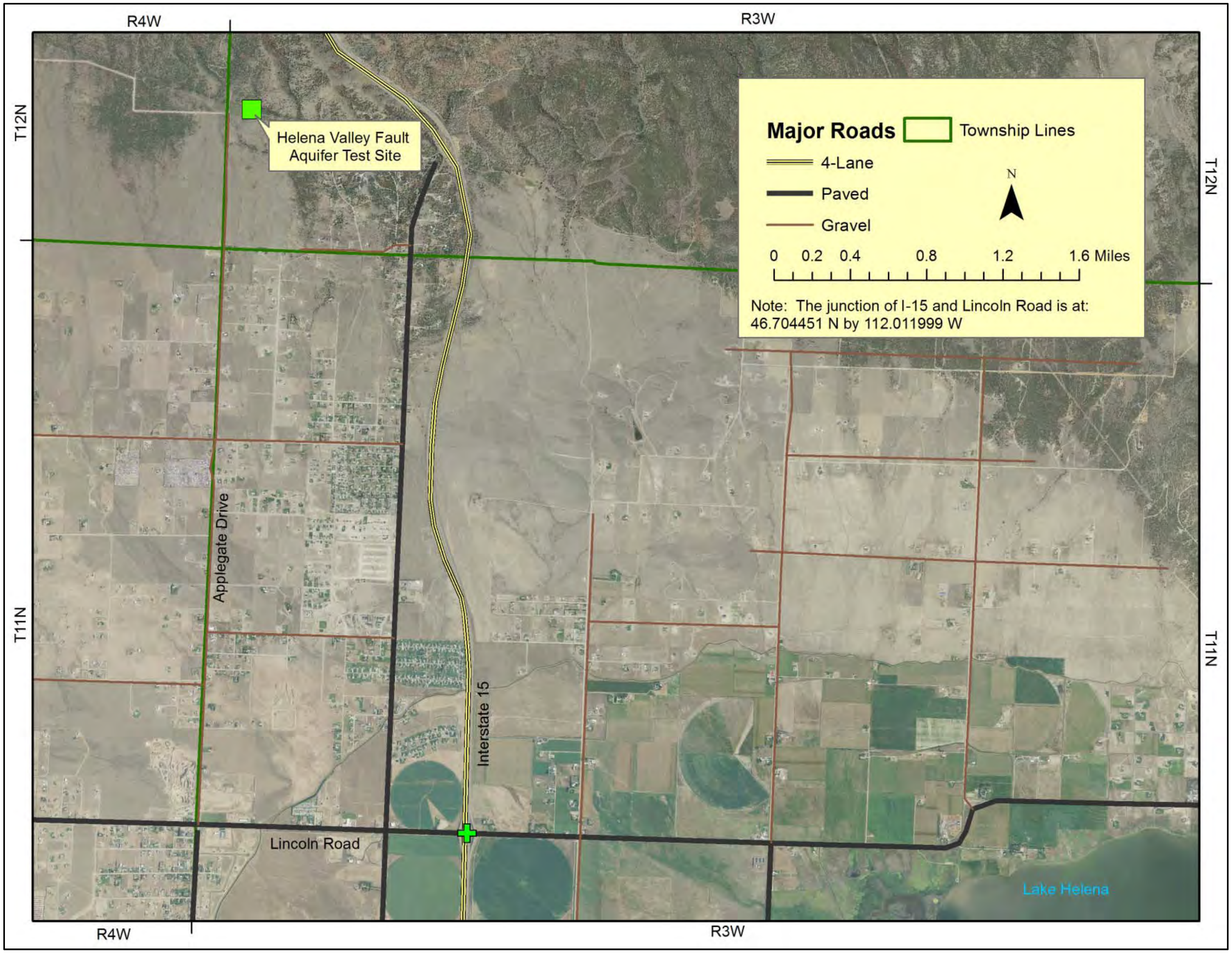

Figure HVF1. Location of the Helena Valley Fault Aquifer test site, May–June 2010.

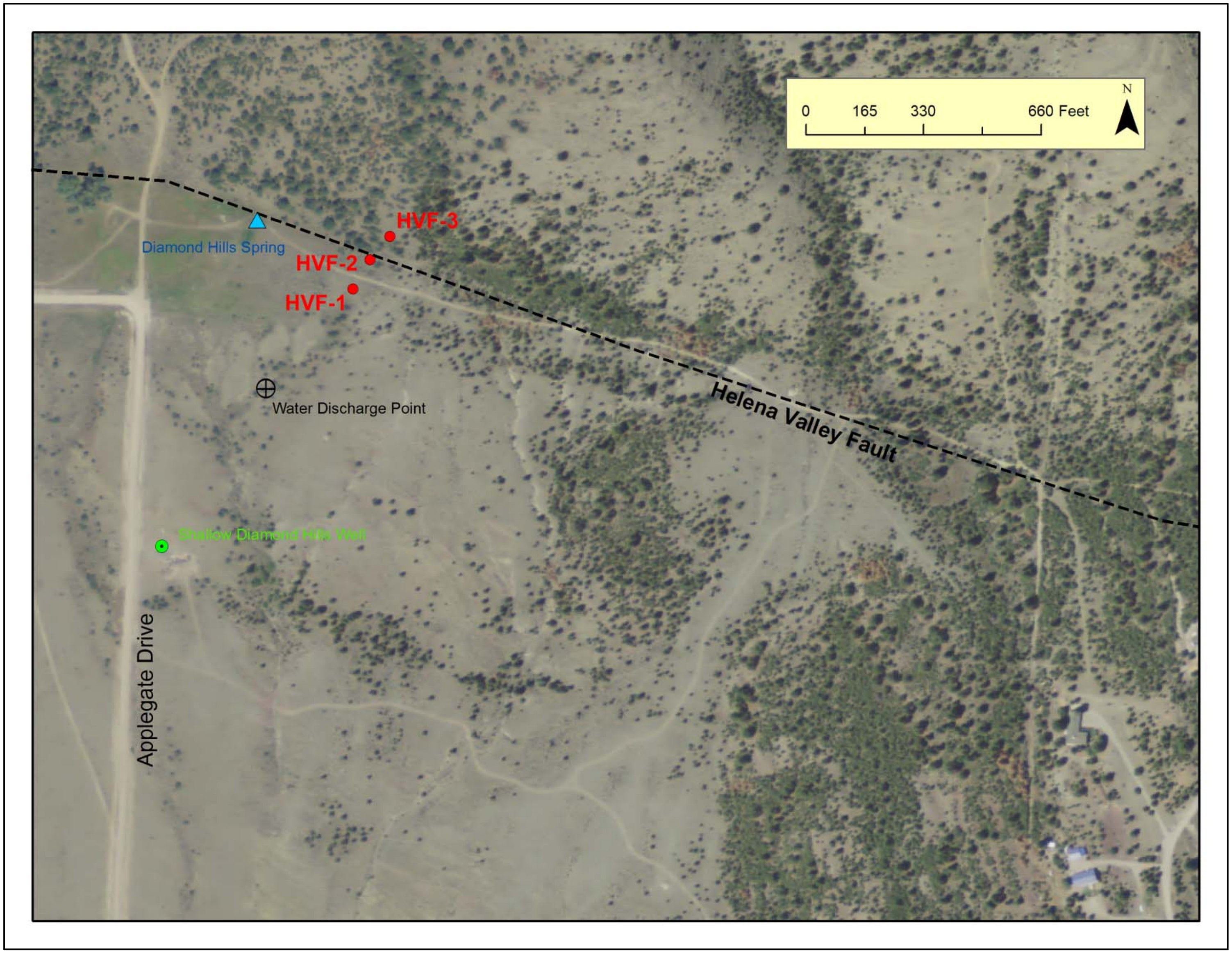

Figure HVF2. Site layout for the Helena Valley Fault Aquifer test site, May–June 2010. HVF-2 is located at 46.7589301°N latitude and 112.0384789°W longitude.

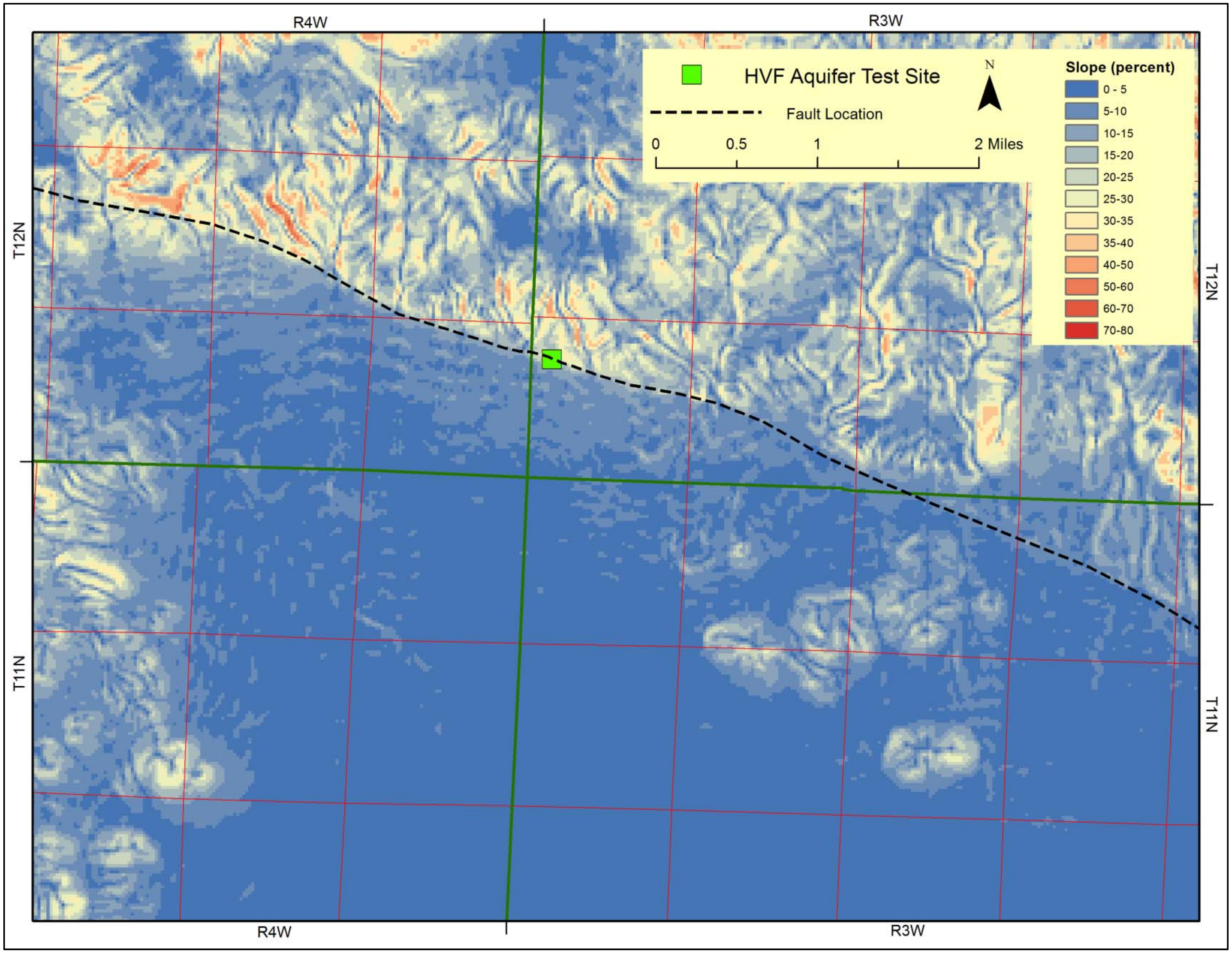

Figure HVF3. Changes in topographic slope are seen at the Helena Valley Fault Aquifer test site.

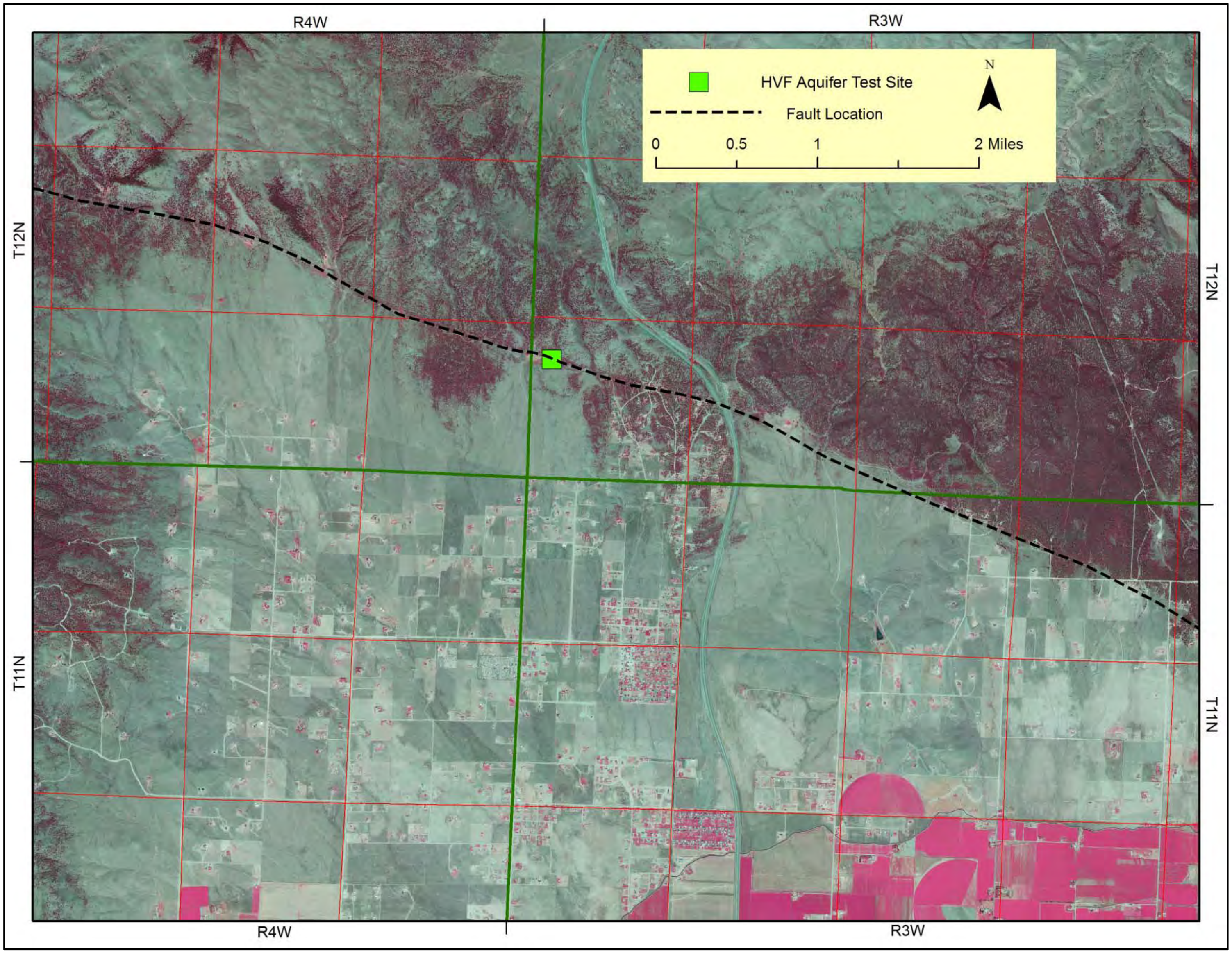

Figure HVF4. Changes in vegetation are seen at the Helena Valley Fault Aquifer test site.

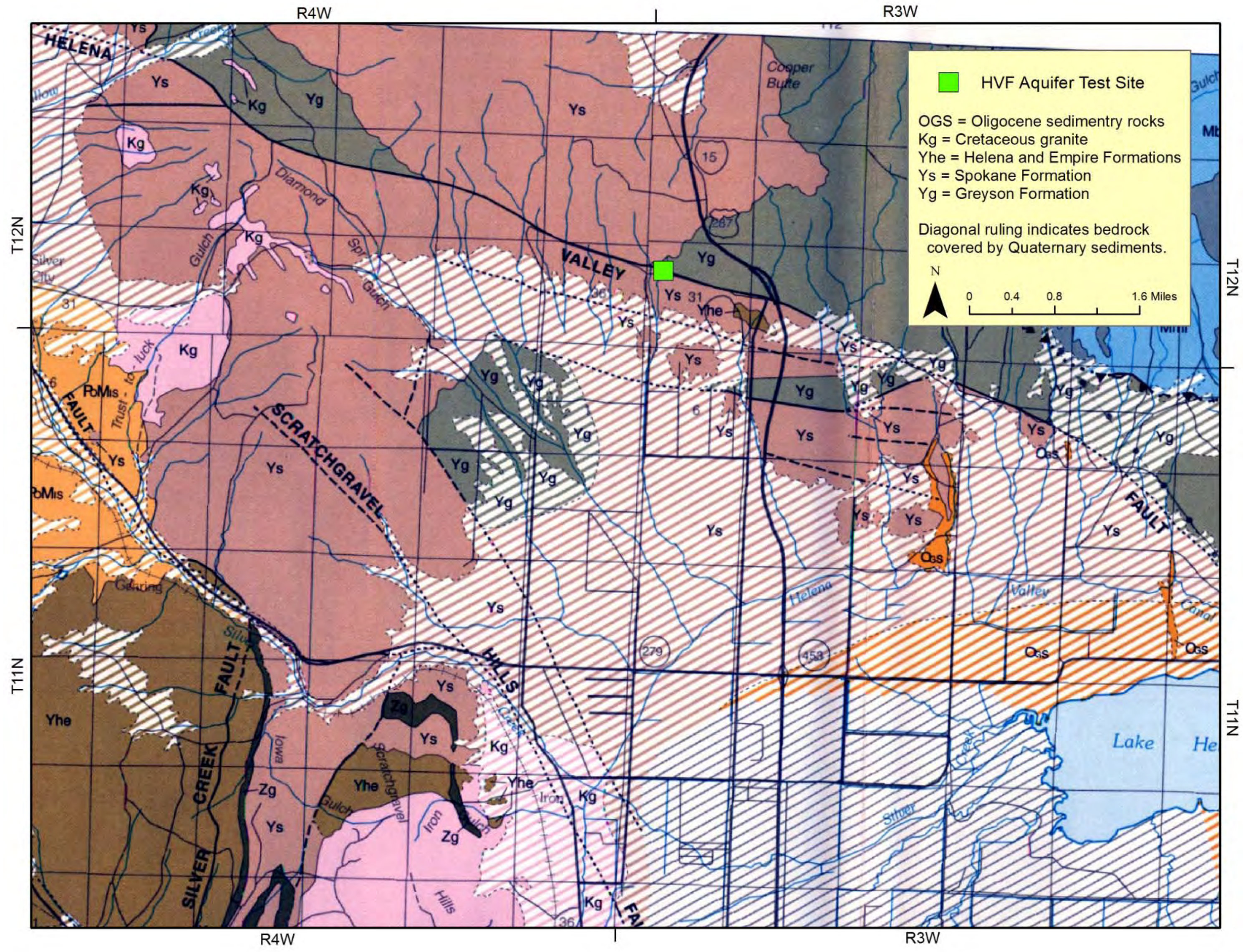

Figure HVF5. Geologic map of the Helena Valley Fault Aquifer test area (from Reynolds, 2000).

The Helena Valley Fault is a strike slip fault with right-lateral offset (geologic units to the north of the fault are offset to the east). According to Thamke (2000), "the Helena Valley Fault Zone at the base of the North Hills consists of a series of faults, parallel to the main strand, that offset the Greyson and Spokane Formations against one another.…The overall impact of the zone is to displace a major segment of the Earth's crust relatively eastward on the north side of the fault zone, and westward on the south side."

Along faults, zones of high secondary permeability can be created due to shear (i.e. highly fractured rocks); however, on the fault plain where the units actually slip past each other, the rock can be ground so finely that it resembles clay (fault gouge) to create a barrier to flow. According to Freeze and Cherry (1979), faults "…can play many roles. Faults that have developed thick zones of sheared and broken rock with little fault gouge may be highly permeable, while those that possess a thin (but continuous) layer of gouge may form almost impermeable barriers." Because of uncertainty about the Helena Valley Fault's hydrogeologic significance, this test site was established to help better understand its hydrologic function.

Well Details

Three 6-in-diameter steel-cased wells were installed. Each well was tested using a step test, followed by a constant-rate test. A step test at HVF-3 was conducted on May 17, 2010. A day later on May 18 an 8-h constant-rate pumping test was conducted. HVF-1 was pumped for a step test on May 19, 2010. An 8-h constant-rate pumping test at HVF-1 was conducted on May 20. On May 21, 2010 a step test at HVF-2 was conducted. HVF-2 was again pumped for 97 h between May 24 and May 28, 2010. During this test, the pump shut off for three brief periods (45 min, 11 min, and 7 min, all on May 26) due to generator problems.

HVF-1 was drilled to a total depth of 255 ft into the Spokane Formation. Due to borehole caving, 6-in steel casing was installed to total depth. The 6-in steel was perforated from 237 to 255 ft; however, based on field notes, the productive zone is only 3 ft thick. HVF-1 is an artesian well, with the static water level rising to about 7 ft above ground surface. A temporary stand pipe was installed on top of a sealing cap so that water levels could be measured for the tests. A Baker pitless adapter has since been installed. That the well was artesian clearly indicates that the aquifer is confined.

HVF-2 was drilled to a total depth of 265 ft in the Spokane Formation. Due to borehole caving, 6-in steel casing was installed to total depth. The 6-in steel was perforated from 245 to 265 ft; however, field notes indicate that the productive zone is only 5 ft thick. The static water level in this well was approximately 6 ft below ground surface.

HVF-3 was drilled to a total depth of 260 ft in the Greyson Formation. The bottom 20 ft of this hole was sealed with bentonite chips. Six-in steel casing was run to total depth (260 ft). The 6-in steel was perforated from 70 to 140 ft; however, the most productive interval was a fractured zone between 70 and 110 ft. The static water level was approximately 35 ft below ground surface.

The shallow Diamond Hills well is an unused pre-existing well located southwest of the test site. This well is 92 ft deep, and has a static water level approximately 25 ft below ground surface.

Pre-test depth to water (DTW) readings show that groundwater elevations were between 4,331.20 and 4,331.86 ft above mean sea level (ft-amsl). The Diamond Hills well had a pre-test groundwater elevation of 4,242.82 ft-amsl. These results and the overall North Hills potentiometric surface (Waren and other, 2012) indicated that there is generally flow to the south; however, the gradient reverses locally across the fault (fig. HVF6). Pre-test monitoring showed that groundwater levels were stable.

Methodology

The aquifer tests were conducted by the MBMG. The pumping rate was monitored throughout the test using a flow meter that was verified through use of a bucket and stopwatch when the flow rate was less than 30 gpm; however, when the pumping rate reached more than 30 gpm, hand measurements became impractical. Discharge was controlled using a gate valve. Discharge water was diverted approximately 300 ft southwest of the test site, and away from the monitored wells.

Vented and unvented pressure transducers were used to record water levels. HVF-3 had a vented transducer rated at 15 psig (34.61 ft; accuracy ±0.02 ft; resolution 0.002 ft). HVF-2 had two transducers: a vented transducer rated at 15 psig (34.61 ft; accuracy ±0.02 ft; resolution 0.002 ft), and an unvented transducer rated at 43 psig (100 ft; accuracy ±0.1 ft; resolution 0.01 ft). HVF-1 had an unvented transducer rated at 13 psig (30 ft; accuracy ±0.03 ft; resolution 0.003 ft). The Shallow Diamond Hills well also had an unvented transducer rated at 13 psig (30 ft; accuracy ±0.03 ft; resolution 0.003 ft). Data from all unvented transducers were corrected for atmospheric barometric pressure variation using data from a barologger.

Manual water-level readings were recorded at each well prior to placing transducers, and recorded periodically during the test, during recovery, and prior to uninstalling the transducers. The manual measurements were used to verify transducer response. All water-level data are available from GWIC by using the well’s GWIC ID (http://mbmggwic.mtech.edu/) (fig. HVF7).

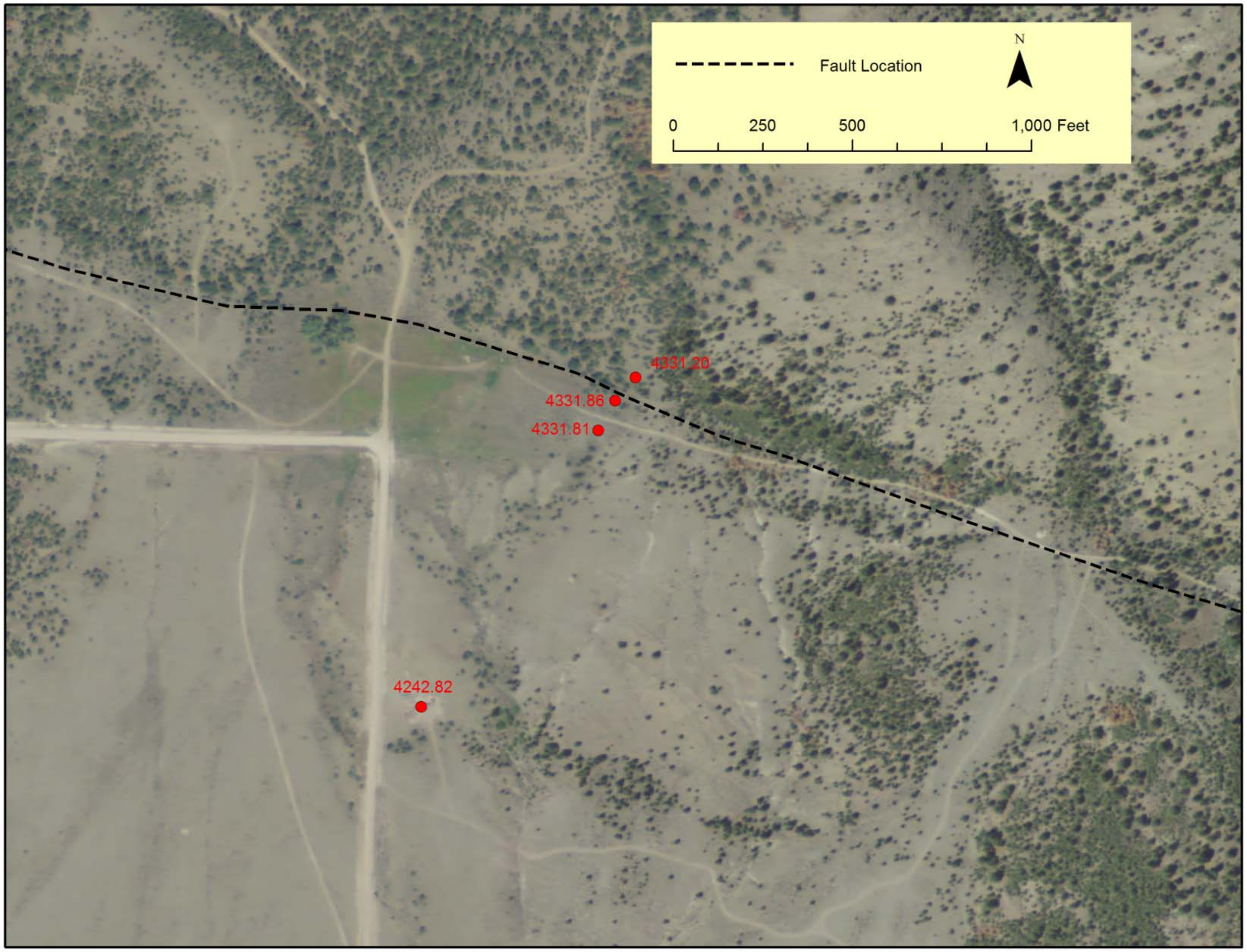

Figure HVF6. Groundwater elevations measured on May 17, 2010 prior to the start of the first step test.

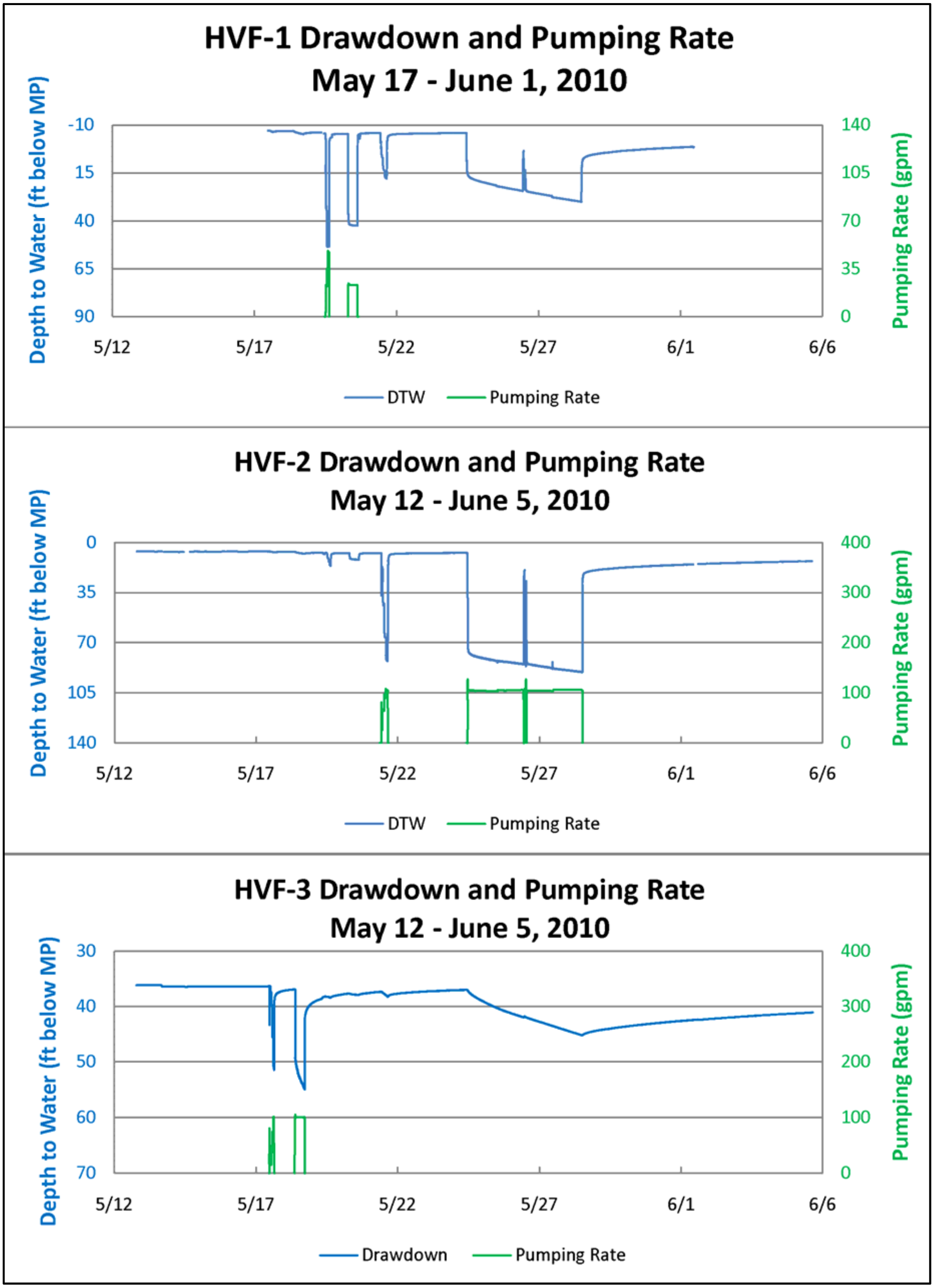

Figure HVF7. Comparison of water levels and pumping rates for the HVF wells during the aquifer testing periods.

Climatic Conditions/Background Water Levels

Conditions during the test were wet and cool; 2.80 in of precipitation was recorded at the Helena Airport between May 15 and June 5, 2010 (22 d; fig. HVF8). The mean annual precipitation at the test site is approximately 13 in (P. Farnes, written comun., 2010), so the area received approximately 22 percent of average annual precipitation during the tests. The average temperature recorded at the Helena Airport between May 15 and June 5, 2010 was 51.6°F. The minimum temperature during this time was 33.1°F and the maximum was 81.0°F. Due to the relatively cool temperatures during the testing period evapotranspiration (ET) was likely minimal.

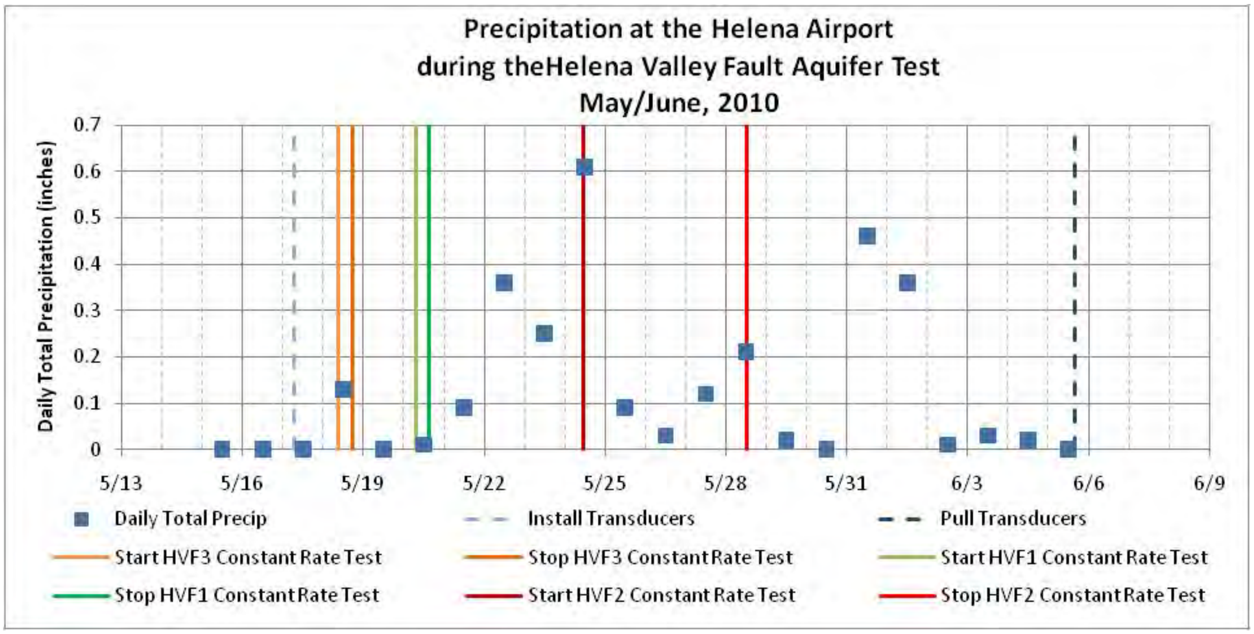

Figure HVF8. Daily precipitation totals during the Helena Valley Fault Aquifer test. There were two major events, with 1.22 in between 5/22 and 5/24 and 0.82 in between 5/31 and 6/1.

The combination of significant precipitation and limited ET indicate that recharge to groundwater may have occurred during the test. The hydrograph for the Shallow Diamond Hills well (GWIC 253818) supports this possibility as 2.4 ft of water-level rise occurred between May 24 and May 28 (fig. HVF9). However, hydrographs from nearby wells provide contradictory information. For example, the Foley well (GWIC 211387), located approximately 1.1 mi southeast, shows no noticeable water-level change (fig. HVF10). The Valley Construction well (GWIC 237331), located approximately 1.4 mi west, also shows no noticeable change (fig. HVF11). It appears that despite the observed rise in GWIC well 253818, a significant regional recharge event did not occur during the test period.

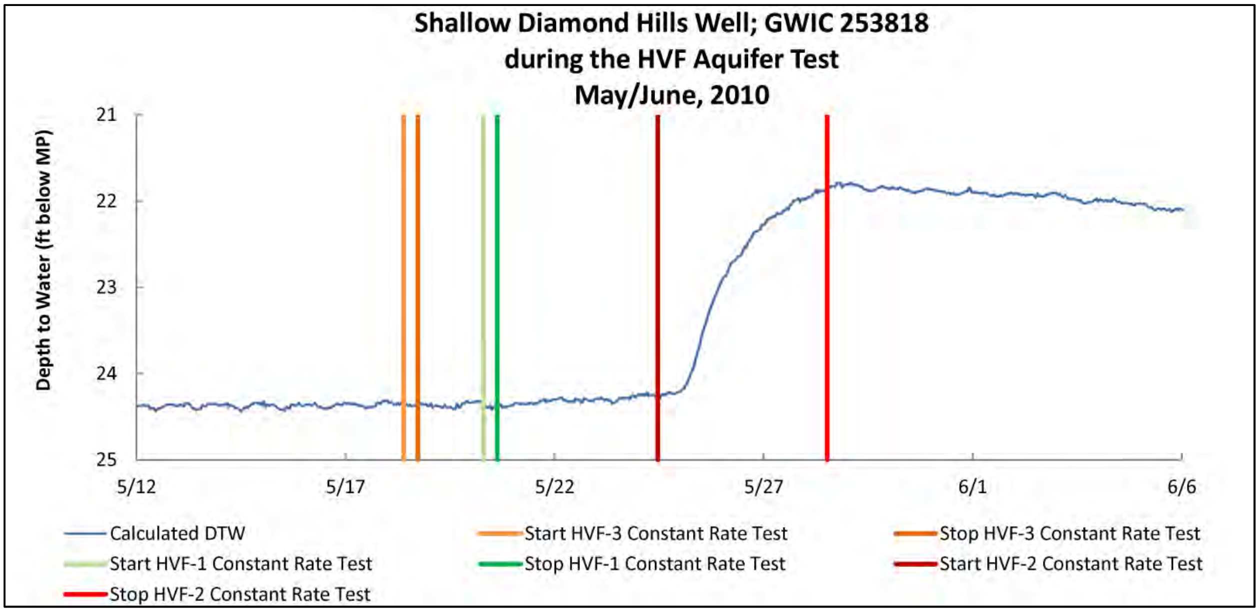

Figure HVF9. Water levels in the Shallow Diamond Hills well, located approximately 1,050 ft southwest of the test site. There is a substantial rise in water level between May 24 and May 28. The water-level rise appears to be due to infiltration of water discharged by the pumping tests.

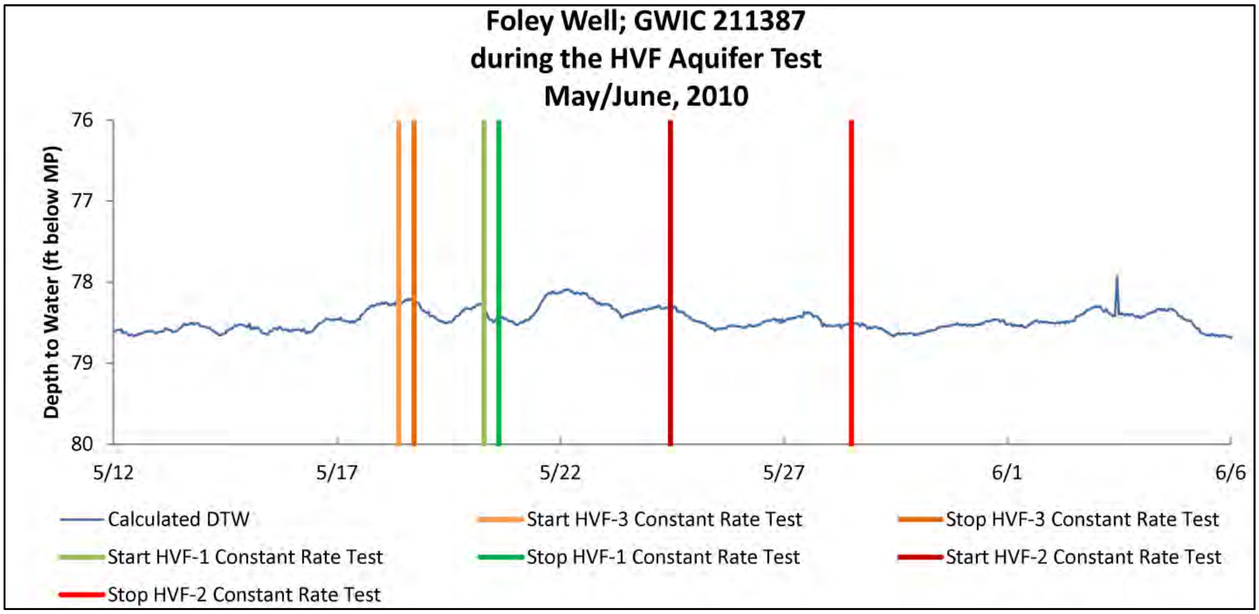

Figure HVF10. Water levels in the Foley well, located approximately 1.1 mi southeast of the test site. Changes in water level are not apparent.

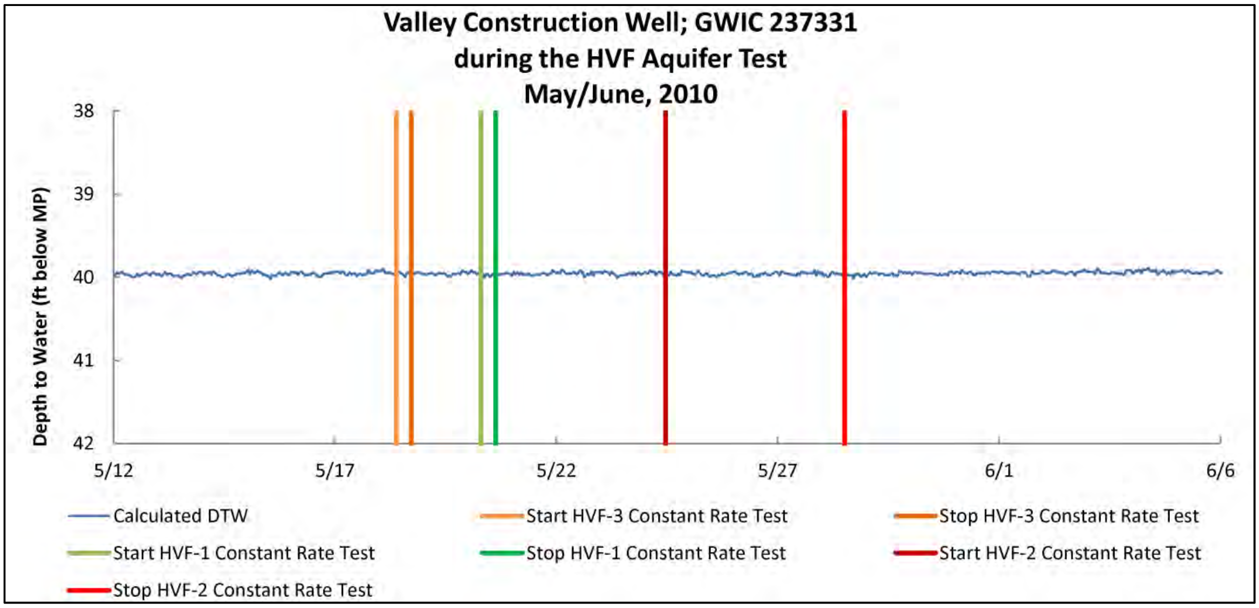

Figure HVF11. Water levels in the Valley Excavating well, located approximately 1.4 mi west from the test site. Changes in water level are not apparent.

If a significant recharge event did not occur, the question remains as to why the water level in the Shallow Diamond Hills well rose by 2.4 ft. The following facts need to be considered: (1) substantially fractured bedrock is exposed at the land surface, (2) discharge from the aquifer test entered an ephemeral drainage approximately 630 ft uphill from the shallow Diamond Hills well (fig. HVF2), (3) the drainage receiving discharge comes as close as 250 ft to the shallow Diamond Hills well, and (4) water was observed in the drainage at least 300 ft below the discharge point. It appears likely that water discharged from the HVF-2 constant-rate aquifer test recharged the bedrock aquifer as it infiltrated through the drainage bottom, and this recharge was recorded in the Shallow Diamond Hills well.

Step Tests

HVF-3

On May 17, 2010, a step test was conducted on HVF-3 to determine an appropriate constant-rate test discharge rate (table HVF2; fig. HVF12). Based on the step test results, approximately 100 gpm was a reasonable discharge for the constant-rate test. As discussed below, the actual weighted-average rate for the constant-rate test was 100.1 gpm. Assuming that the perforations provided approximately 0.05 ft^2 of open area per foot of pipe, the entrance velocity at 100 gpm would be about 0.06 ft/s, which is below the threshold of 0.1 ft/s recommended by Heath (1983).

Table HVF2
HVF-3 Step Test Summary—May 17, 2010
Helena Valley Fault Aquifer Test

Start Step	End Step	Rate (Q, gpm)	Max Drawdown (s, ft)	Q/s
12:18	13:03	15	1.20	12.50
13:03	13:47	37	3.52	10.51
13:47	14:36	73	9.05	8.07
14:36	15:40	101	15.07	6.70

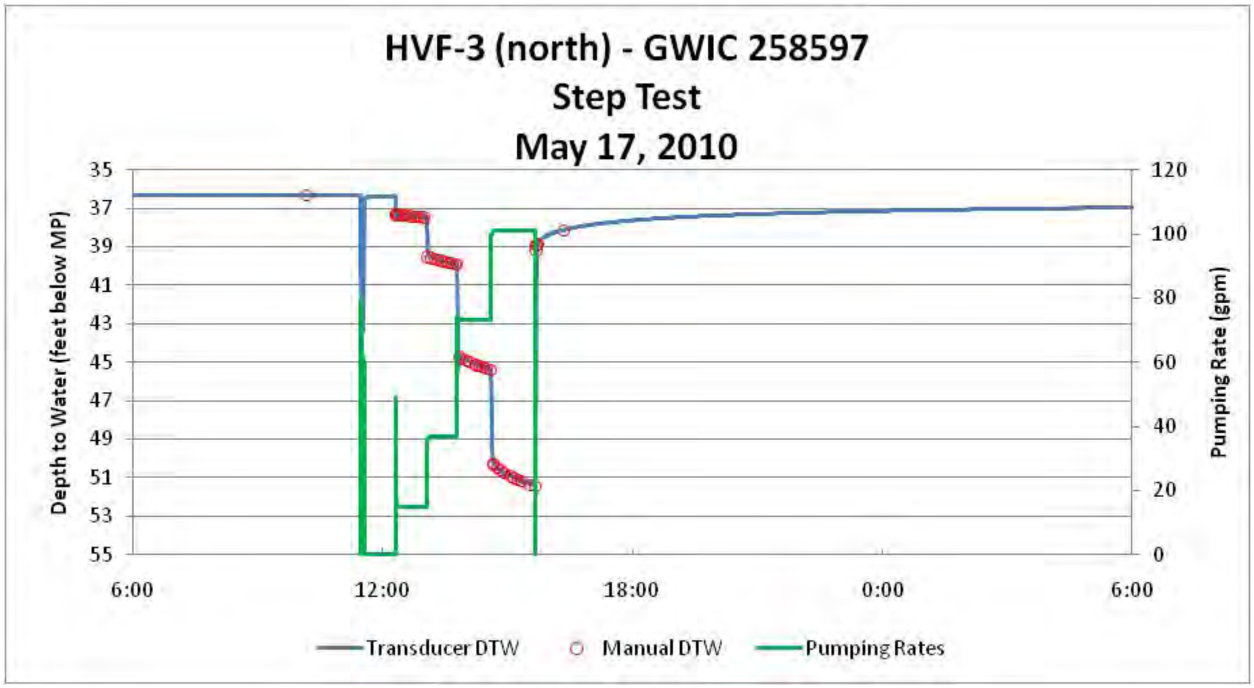

Figure HVF12. Water levels and pumping rates in HVF-3 during step test.

Data obtained during the step test also allow the specific capacity (discharge per unit of drawdown, Q/s) of the well to be determined at different pumping rates. This information can then be used to estimate the maximum rate that the well can be pumped, without exceeding a target drawdown value (fig. HVF13). Given that the top of the perforated interval is 70 ft below ground surface (bgs), the static water level is at 35 ft bgs, and that it is typically desired that the pumping water level stay at least 10 ft above the top of perforations, the target drawdown in this well is 25 ft. Using the calculated relationship, the estimated maximum drawdown would occur at a pumping rate of 146 gpm. The rather high production rate is unusual for bedrock wells in this area, particularly given the limited amount of drawdown to work with.

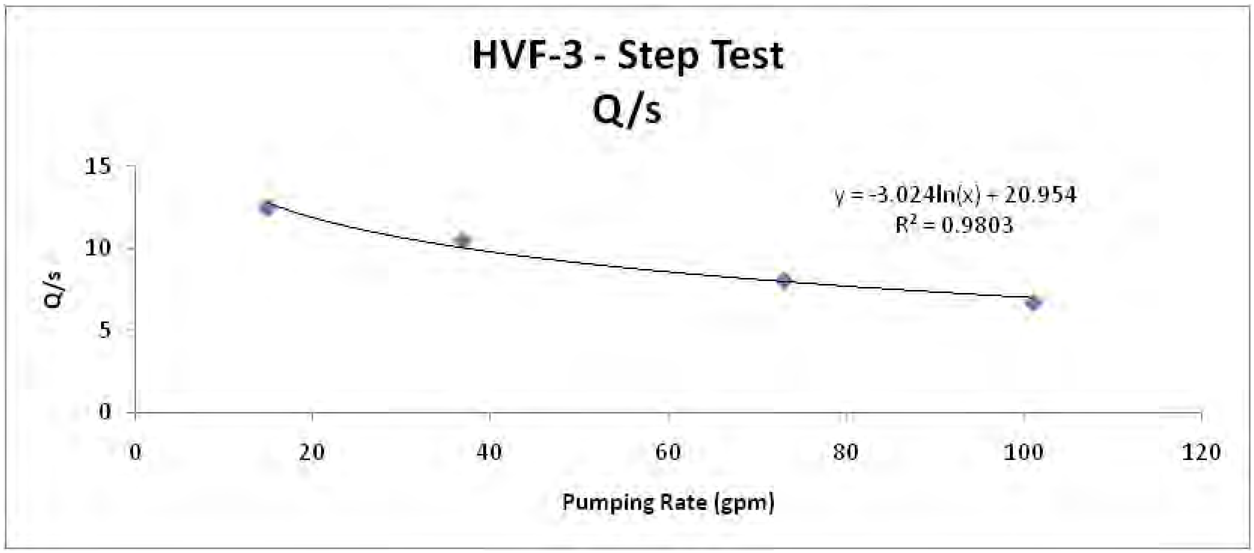

Figure HVF13. Specific capacity (Q/s) vs. pumping rate (Q) for HVF-3. This relationship can be used to estimate the maximum pumping rate for the well.

While this approach generally allows the long-term potential of a well to be estimated, data from the step and constant-rate tests show that at the 100 gpm pumping rate water levels do not stabilize but continue to drop. Flow barriers limiting the lateral extent of the aquifer being pumped is a likely reason and is supported by the well's relatively slow recovery, and proximity to the fault. It took 1 h and 17 min for 90 percent recovery from the step test to be achieved. Also supporting the presence of flow barriers is that little drawdown occurred in HVF-2 (0.66 ft) or HVF-1 (0.82 ft) during the step test at HVF-3.

HVF-1

On May 19, 2010, a step test was conducted on HVF-1 to determine an appropriate pumping rate (table HVF3; fig. HVF14). Based on this information it was determined that approximately 22 gpm was a reasonable rate for the constant-rate test. As discussed below, the actual weighted-average rate for the constant-rate test was 23.1 gpm. Assuming that the perforations provided approximately 0.05 ft^2 of open area per foot of pipe, the entrance velocity at 23 gpm would be about 0.06 ft/s, which is below the threshold of 0.1 ft/s recommended by Heath (1983).

Table HVF3

HVF-1 Step Test Summary—May 19, 2010

Helena Valley Fault Aquifer Test

Start Step	End Step	Rate (Q, gpm)	Max Drawdown (s, ft)	Q/s
11:52	12:20	2.9	2.95	0.98
12:20	13:20	22	40.70	0.54
13:20	14:10	35	77.54	0.45
14:10	15:10	47	120.33	0.39

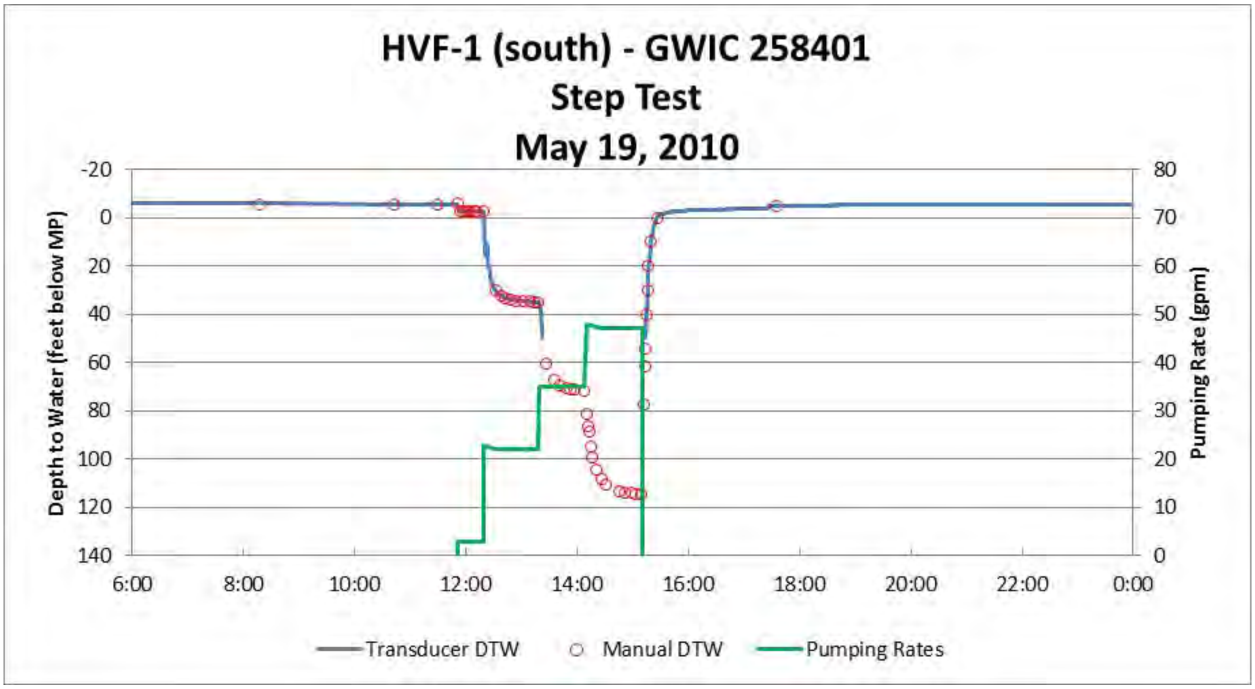

Figure HVF14. Water levels and pumping rates in HVF-1 during the step test.

Specific capacities were determined at different pumping rates (fig. HVF15). Given that the top of the perforated interval is at 237 ft below ground surface (bgs), that the static water level is at 7 ft above ground, and that it is typically desired that during pumping the water level stay at least 10 ft above the top of screen, the target drawdown is 234 ft. Using the calculated relationship, it is estimated that this drawdown would occur at a pumping rate of 70 gpm, which is a rather high production rate for bedrock wells in this area.

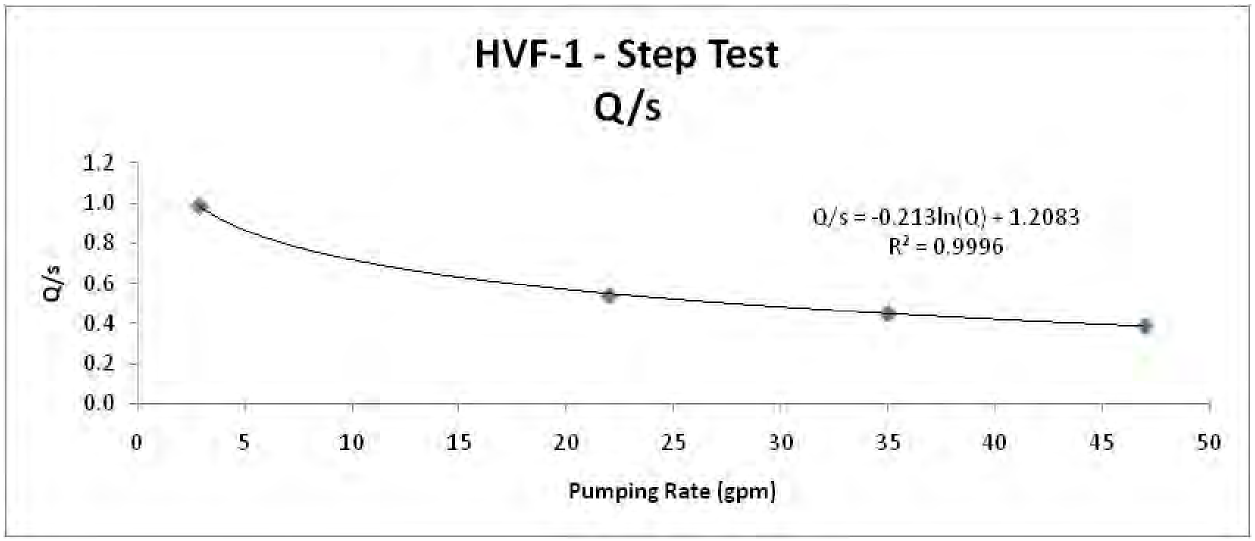

Figure HVF15. Specific capacity (Q/s) vs. pumping rate (Q) for HVF-1. This relation can be used to estimate the well's maximum pumping rate.

Water levels in HVF-1 appear to stabilize during the step and constant-rate tests, indicating that flow barriers do not exhibit a strong influence at these pumping rates; however, pumpage in HVF-1 does reveal an apparent flow barrier between HVF-2 and HVF-3, given the difference in observed drawdown in these wells. During the step test, HVF-2 experienced 8.99 ft of drawdown, while HVF-3 only experienced 0.18 ft of drawdown. The effect of the flow barrier on HVF-1 is limited because it took only 9 min for HVF-1 to achieve 90 percent recovery from the step test.

HVF-2

On May 21, 2010, a step test was conducted on HVF-2 to determine an appropriate pumping rate (table HVF4; fig. HVF16) for a constant-rate test. Based on the test results, approximately 105 gpm was a reasonable rate. As discussed below, the actual weighted-average discharge for the constant-rate test was 103.8 gpm. Assuming that the perforations provided approximately 0.05 ft^2 of open area per foot of pipe, the entrance velocity at 104 gpm would be about 0.23 ft/s, which is above the threshold of 0.1 ft/s recommended by Heath (1983). As such, tests pumping this well may violate the assumption of laminar flow. While this may impact quantitative analysis of the test data, it does not impact the lack of drawdown across the fault.

Specific capacities were determined at different pumping rates (fig. HVF17). Given that the top of the perforated interval is 245 ft bgs, that the static water level is at 6 ft below ground, and that it is typically desired that during pumping the water level stay at least 10 ft above the top of screen, a target drawdown is 228 ft. Using the calculated relationship, it is estimated that a pumping rate of 200 gpm would be necessary to attain this drawdown.

Table HVF4
HVF-2 Step Test Summary—May 21, 2010
Helena Valley Fault Aquifer Test

Start Step	End Step	Rate (Q, gpm)	Max Drawdown (s, ft)	Q/s
10:20	11:10	26	10.52	2.47
11:10	12:28	64	36.52	1.75
12:28	13:57	90	60.19	1.50
13:57	15:50	105	75.34	1.39

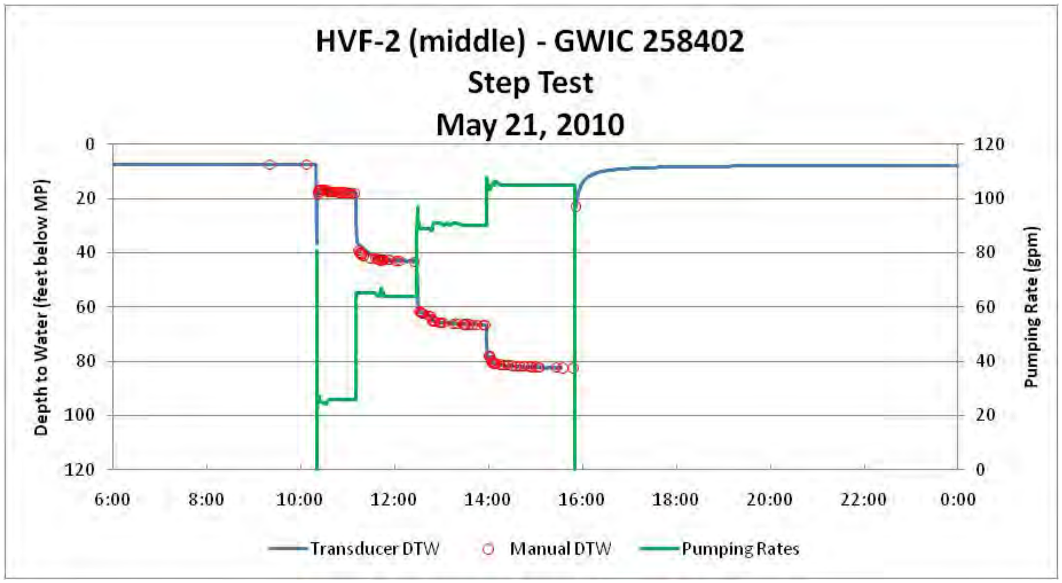

Figure HVF16. Water levels and pumping rates in HVF-2 during step test.

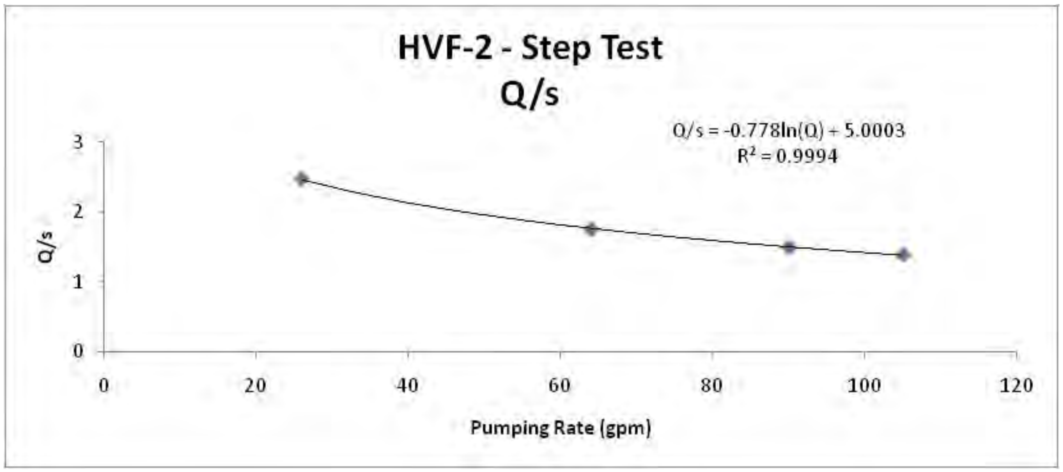

Figure HVF17. Specific capacity (Q/s) vs. pumping rate (Q) for HVF-2. This relationship can be used to determine the maximum pumping rate for the well.

Although water levels appeared to stabilize during the step test, water levels during the constant-rate test did not level off as much as expected. The failure to level off indicates that flow barriers are limiting flow to the well at these discharge rates, so the estimated maximum rate of 200 gpm likely overestimates HVF2's long-term yield. There again appears to be a barrier between HVF-2 and HVF-3 given the differences in observed drawdown in these wells during the step test. HVF-2 experienced a maximum drawdown of 75.34 ft, HVF-1 experienced a maximum drawdown of 23.92 ft, and HVF-3 experienced a maximum drawdown of 0.90 ft. The effect of this barrier is limited because only 8 min were needed for HVF-2 to achieve 90 percent recovery from step test pumpage.

Constant-Rate Tests

HVF-3 (Test 1)

The constant-rate test for HVF-3 started at 09:19 and ended at 17:27 on May 18, 2010, for a total pumping time of 8 h and 8 min. The time-weighted average pumping rate was 100.1 gpm. The maximum recorded pumping rate was 105 gpm (for a short period at the start of the test) and the minimum recorded rate was 99 gpm (fig. HVF18). Thus the maximum deviation from average was 4.9%. The maximum recorded drawdown in HVF-3 was 18.04 ft. Drawdown in well HVF-3 rapidly increased at the beginning of the test, but as pumping continued the rate slowed markedly. Water levels continued to drop steadily through the end of the test. After pumping ceased, well HVF-3 exhibited a rapid initial recovery; however, 12 h and 53 min were needed to reach 90 percent recovery (fig. HVF19).

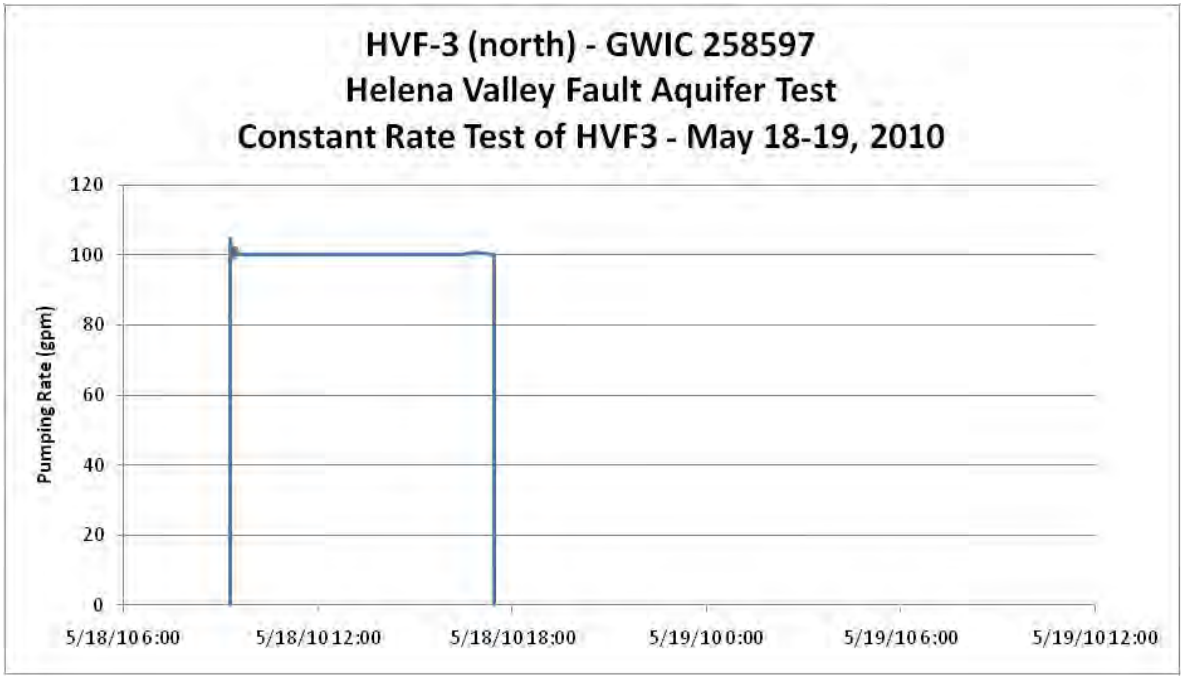

Figure HVF18. Pumping rate vs. time during constant-rate test of HVF-3.

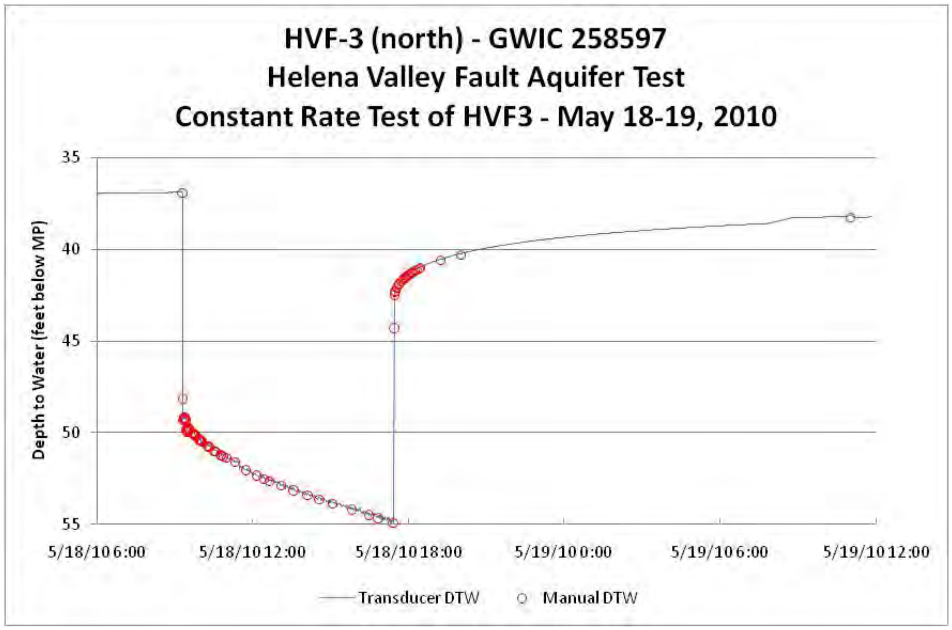

Figure HVF19. Water levels in HVF-3 during a constant-rate pumping test.

Evaluation of change in head vs. time for the drawdown and recovery portions of this test shows curves that indicate that a barrier boundary has been encountered (Freeze and Cherry, 1979). Rather than forming a straight line, the water-level curve continues to steepen (fig. HVF20). Given the presence of this boundary, the assumption of radial flow is not applicable and quantitative analysis of the data would not be appropriate.

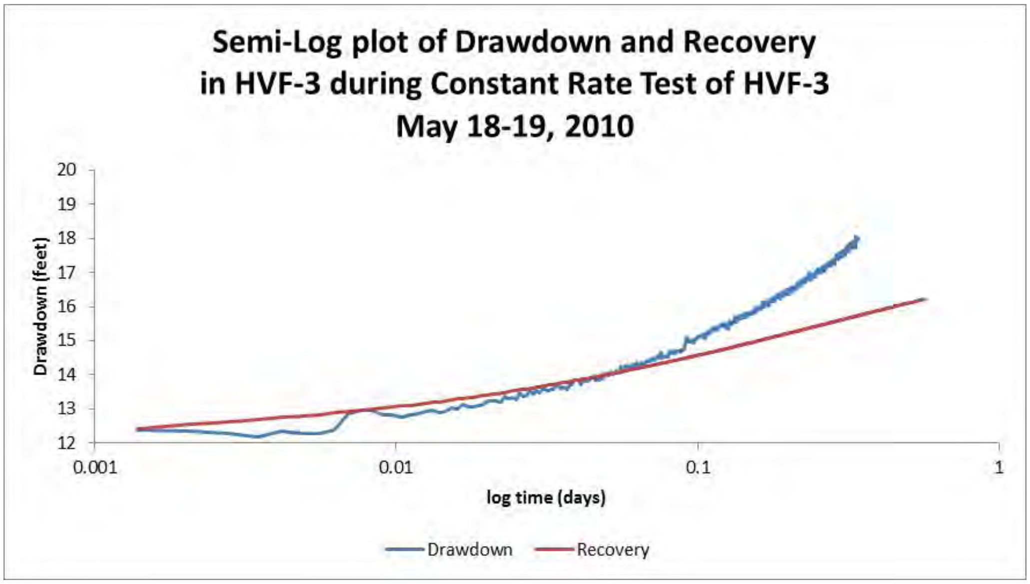

Figure HVF20. Semi-log plot of drawdown and recovery vs. log time. If no boundaries were encountered the drawdown data would form a straight line. Instead, the drawdown data continue to curve upward, indicating a barrier.

During the test at HVF-3, drawdown was seen in HVF-2 and HVF-1 (figs. HVF21, HVF22). While the presence of a significant boundary prevents the quantitative analysis of these data, it is informative to note that maximum drawdown in HVF-2 was 1.38 ft, while HVF-1 experienced 1.69 ft of drawdown. It is not clear why HVF-1, which is 100 ft more distant from HVF-3 than HVF-2, should have the greater drawdown, but this same pattern was observed during the step test. The complex nature of materials and fractures within the fault zone apparently cause HVF-3 to be hydraulically better connected with HVF-1 than it is with HVF-2.

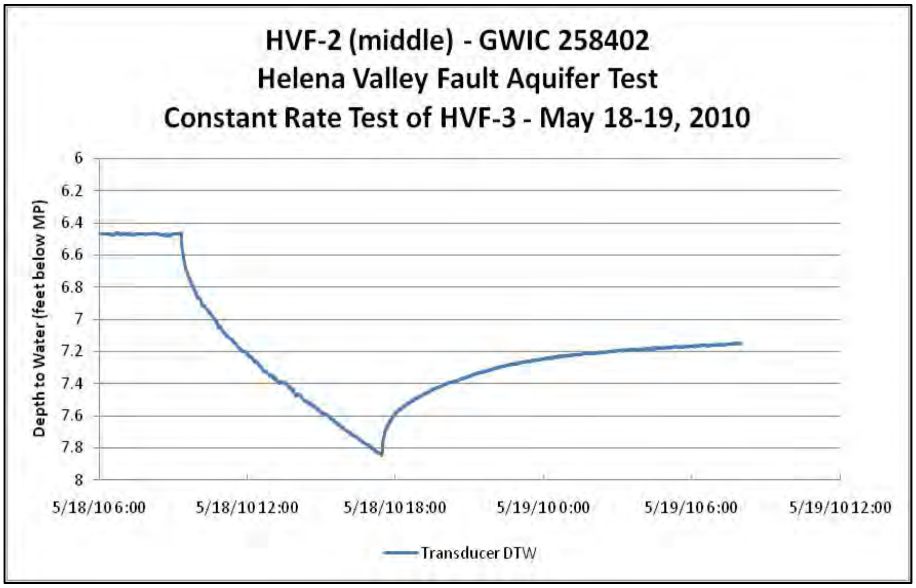

Figure HVF21. Water levels in HVF-2 during constant-rate test of HVF-3.

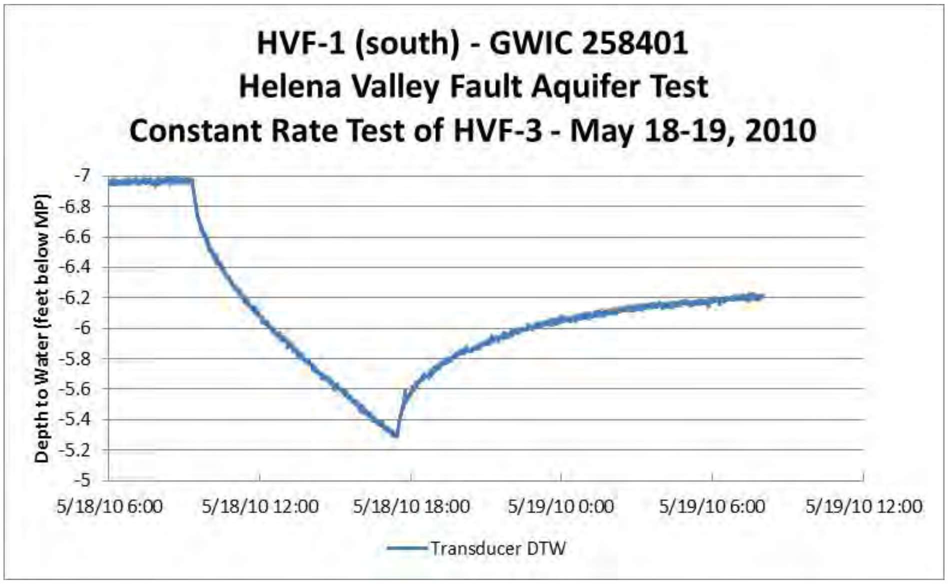

Figure HVF22. Water levels in HVF-1 during constant-rate test of HVF-3.

HVF-1 (Test 2)

The constant-rate test for HVF-1 started at 07:06 and ended at 15:06 on May 20, 2010, for a total pumping time of 8 h. The time-weighted average pumping rate was 23.1 gpm. The maximum recorded pumping rate was 24 gpm (for a short period at the start of the test) and the minimum recorded pumping rate was 21 gpm (fig. HVF23). Thus the maximum deviation from average was 9.0%. The maximum recorded drawdown was 47.94 ft. Drawdown in well HVF-1 rapidly increased at the beginning of the test, but as pumping continued the rate slowed markedly. Water levels were falling slightly at the end of the test, dropping 0.07 ft over the last hour. After pumping ceased, well HVF-1 exhibited a rapid recovery, and 10 min were needed to reach 90 percent recovery (fig. HVF24).

Evaluation of drawdown and recovery plots for HVF-1 shows that a recharge boundary was encountered after about 12 min of pumping. It appears that effects from the borehole and from disturbance of the formation during drilling are seen up to about 3 min into the test (fig. HVF25). Due to these influences, aquifer properties are not calculated.

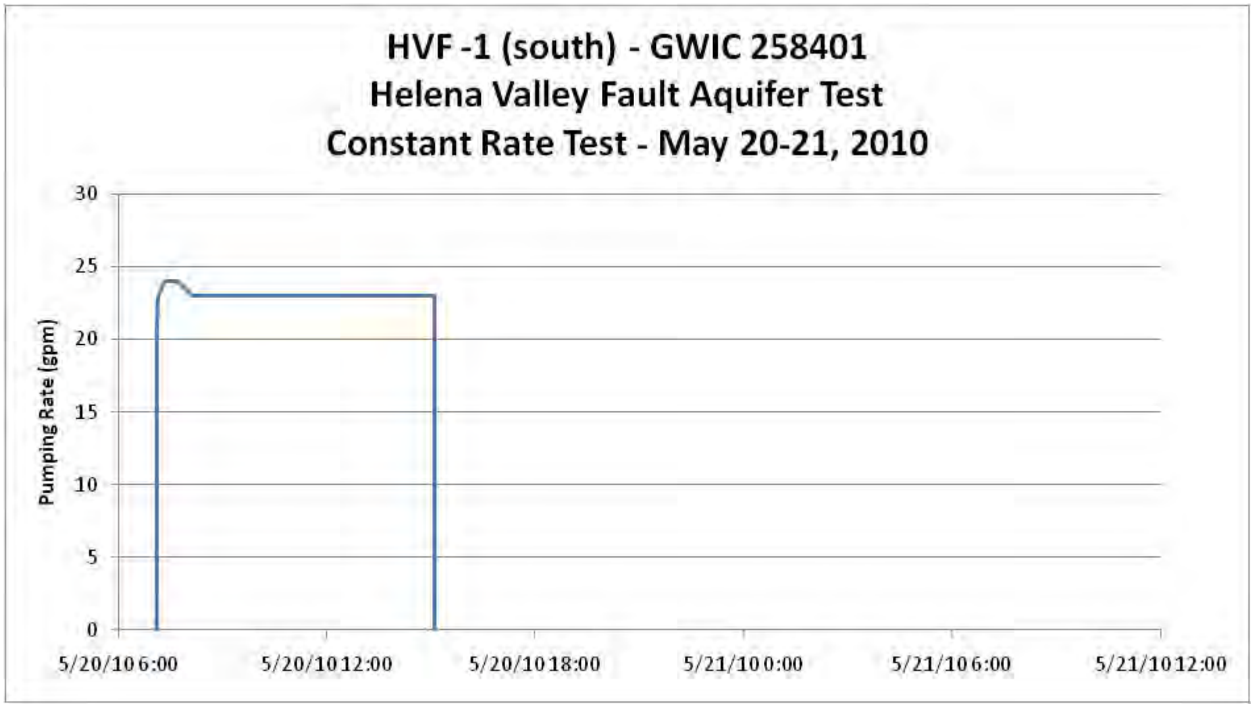

Figure HVF23. Pumping rate vs. time during constant-rate test of HVF-1.

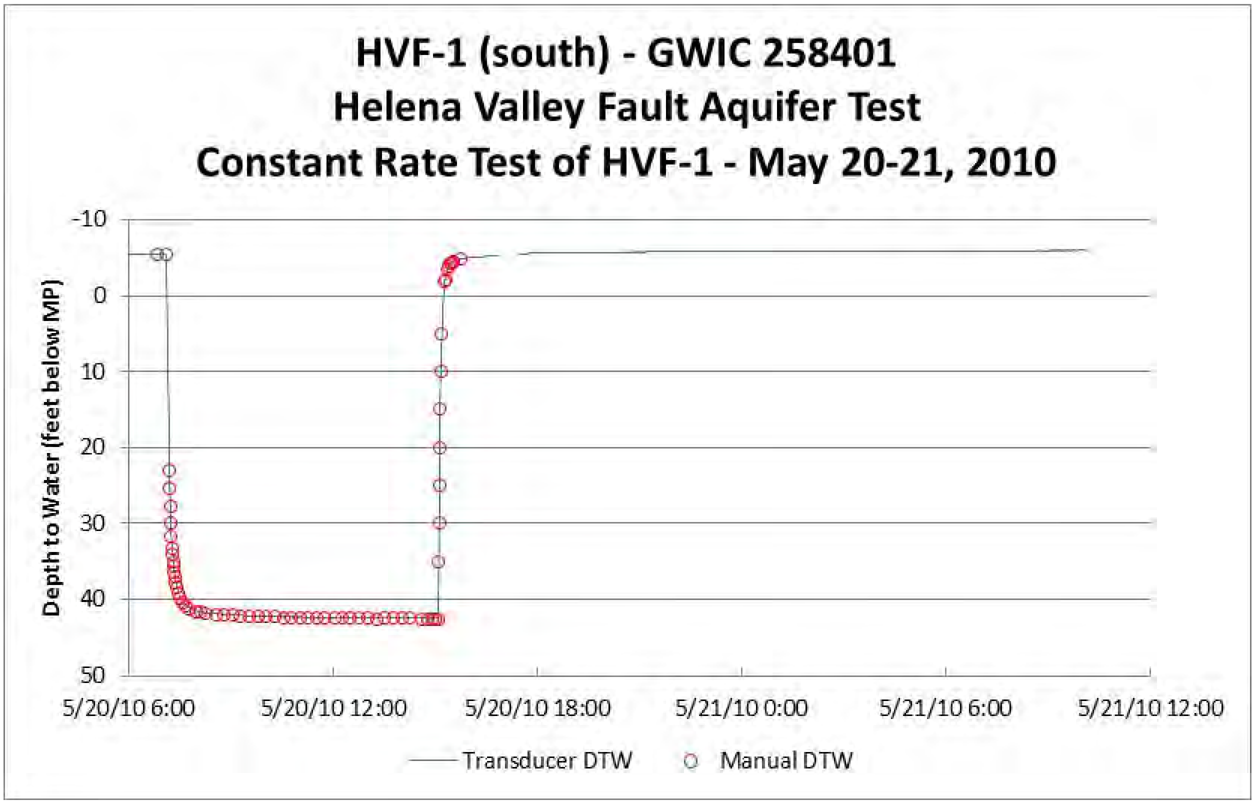

Figure HVF24. Water levels in HVF-1 during constant-rate test of HVF-1.

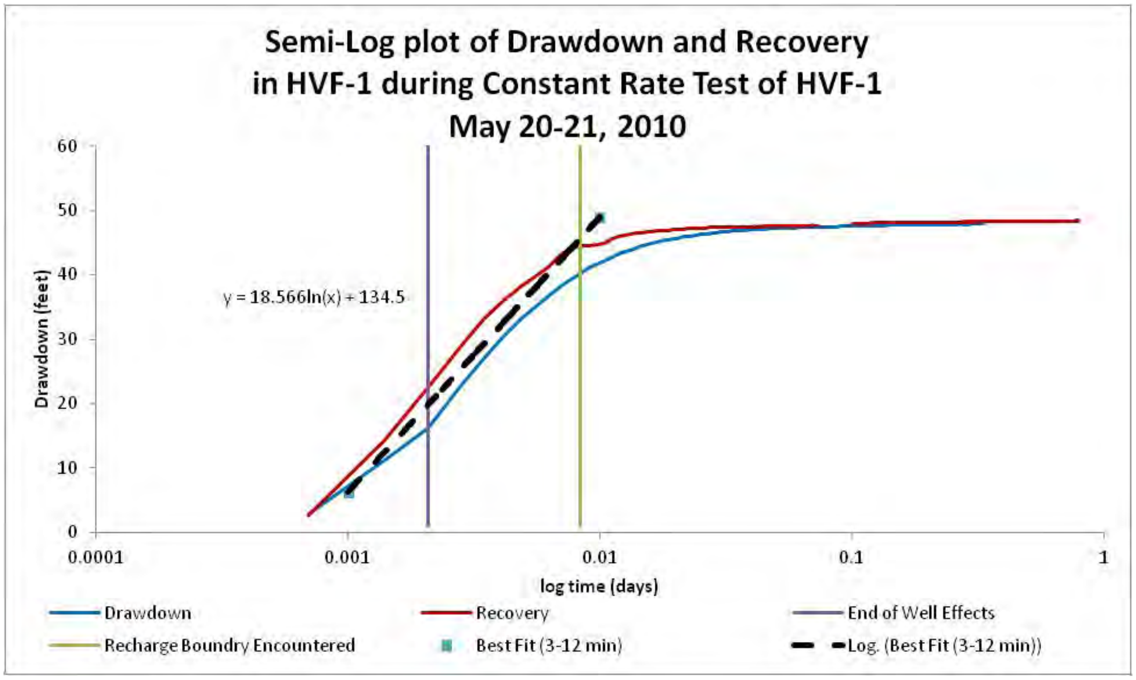

Figure HVF25. Semi-log plot of drawdown and recovery vs. time. If no boundaries are encountered drawdown data will form a straight line. The data form a straight line up to about 12 min into the test; however, the first 3 min of data are impacted by borehole effects. The curve flattens after 12 min of pumping due to the intersection of the drawdown cone with a recharge source, likely a more permeable fractured zone.

During this test, drawdown caused by pumping in HVF-1 was seen in both HVF-2 and HVF-3 (figs. HVF26, HVF27). The maximum drawdown in HVF-2 was 4.69 ft, while in HVF-3 it was 0.44 ft. When these data are plotted on a Cooper–Jacob composite plot (dh vs. t/r^2; fig. HVF28), the differences in how these wells respond to pumping becomes clear. HVF-2 is in direct communication with HVF-1; however, the effects of a recharge boundary are also seen in the data from HVF-2. HVF-3 is not in direct communication with HVF-1, thus a barrier boundary is located between HVF-2 and HVF-3.

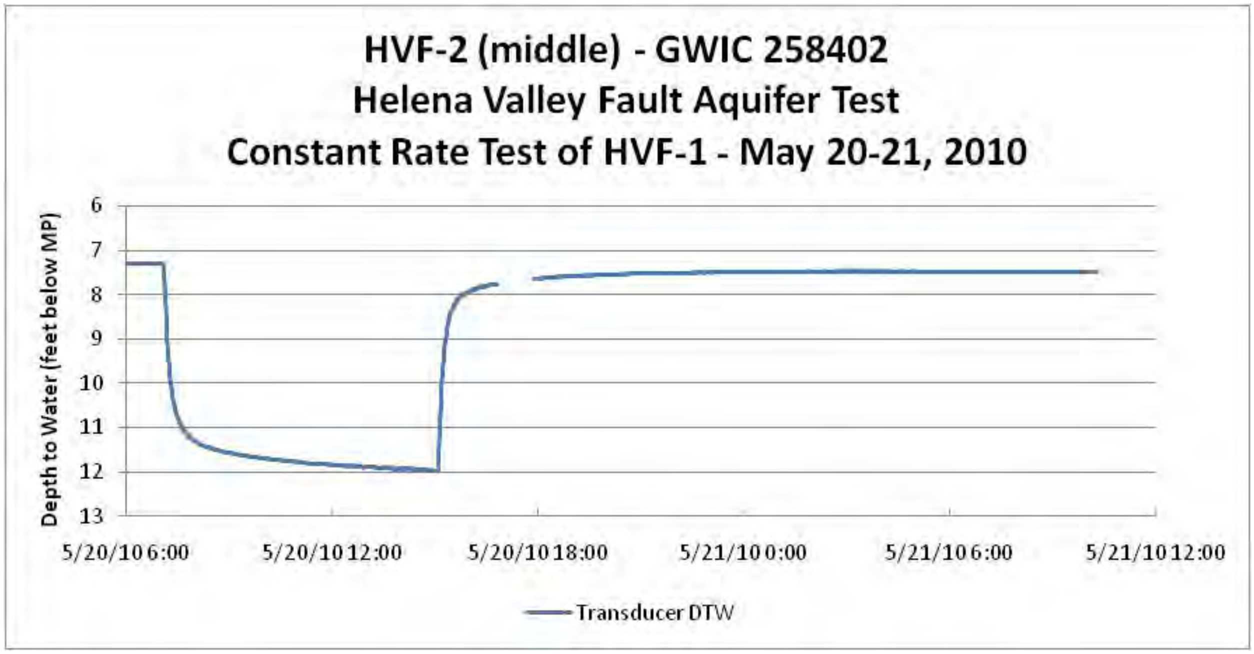

Figure HVF26. Water levels in HVF-2 during constant-rate test of HVF-1.

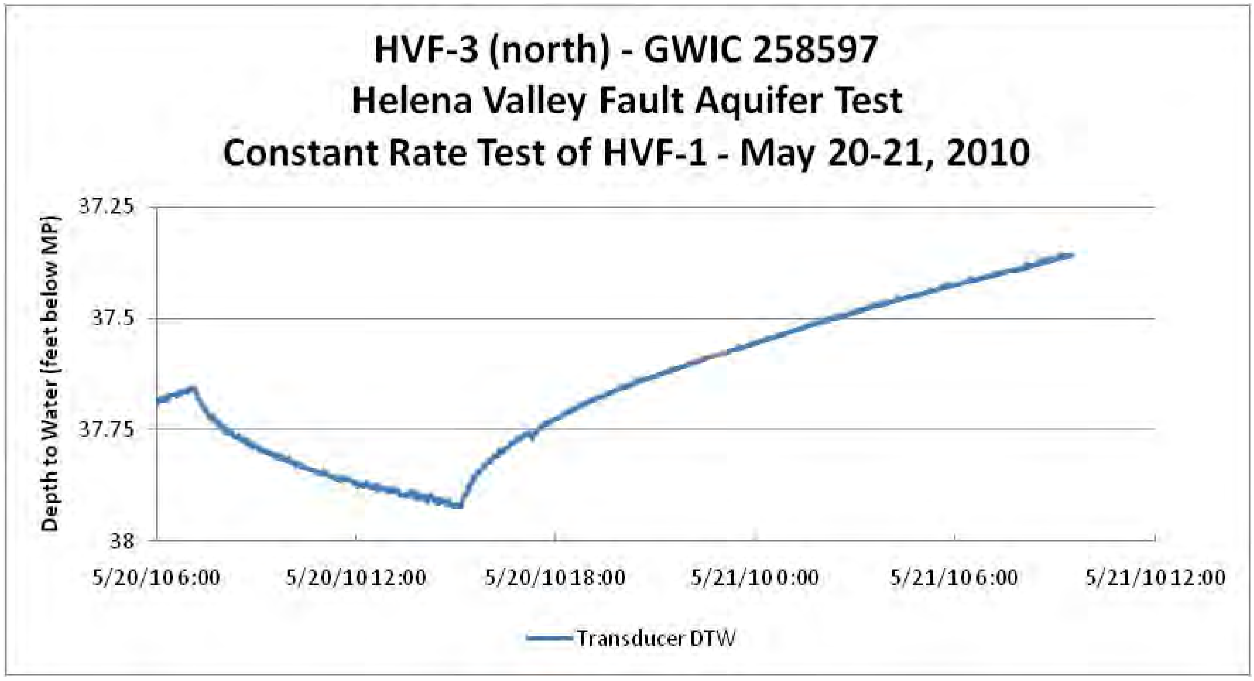

Figure HVF27. Water levels in HVF-3 during constant-rate test of HVF-1. Water levels in HVF-3 were recovering from the HVF-3 constant-rate test during the HVF-1 test; however, since the data were not used quantitatively they were not detrended.

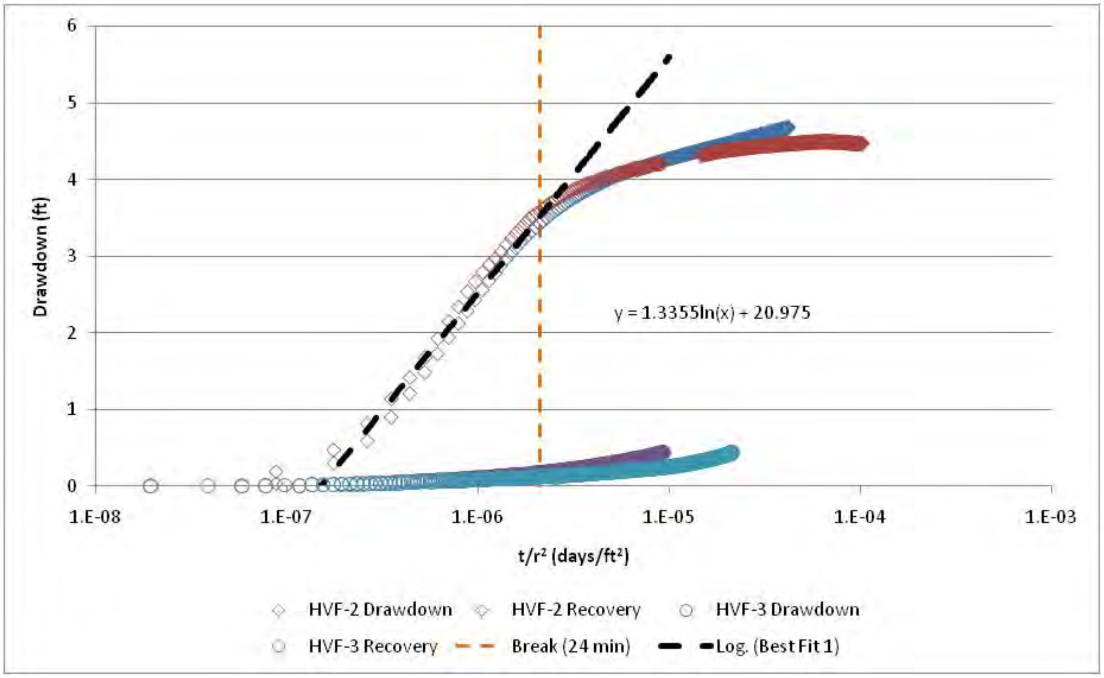

Figure HVF28. Composite plot of drawdown vs. time divided by distance squared. In an ideal setting (isotropic and with no barrier) the data from HVF-2 and HVF-3 would form a single straight line. The slope change in data from HVF-2 shows that a recharge boundary is encountered. The minimal response in HVF-3 water levels shows that there is a barrier between HVF-2 and HVF-3.

HVF-2 (Test 3)

The constant-rate test for HVF-2 started at 11:13 on May 24, 2010 and ended at 12:25 on May 28, for a total pumping time of 4 d, 1 h, and 12 min. The time-weighted average pumping rate was 103.8 gpm. The maximum recorded pumping rate was 127 gpm and the minimum recorded pumping rate was 0 gpm. The 0 gpm values were recorded on May 26, 2010 during three time intervals (10:50–11:35 a.m., 12:25–12:28 p.m., and 12:54–13:01 p.m.), when there were generator problems (fig. HVF29). The maximum recorded drawdown in HVF-2 was 83.31 ft. Drawdown in well HVF-2 rapidly increased at the beginning of the test but as pumping continued the rate slowed markedly. Water levels were falling slightly at the end of the test, dropping 0.12 ft during the last hour. After pumping ceased, HVF-2 exhibited a rapid initial recovery; however, 2 d, 19 h, and 36 min were needed to reach 90 percent recovery (fig. HVF30).

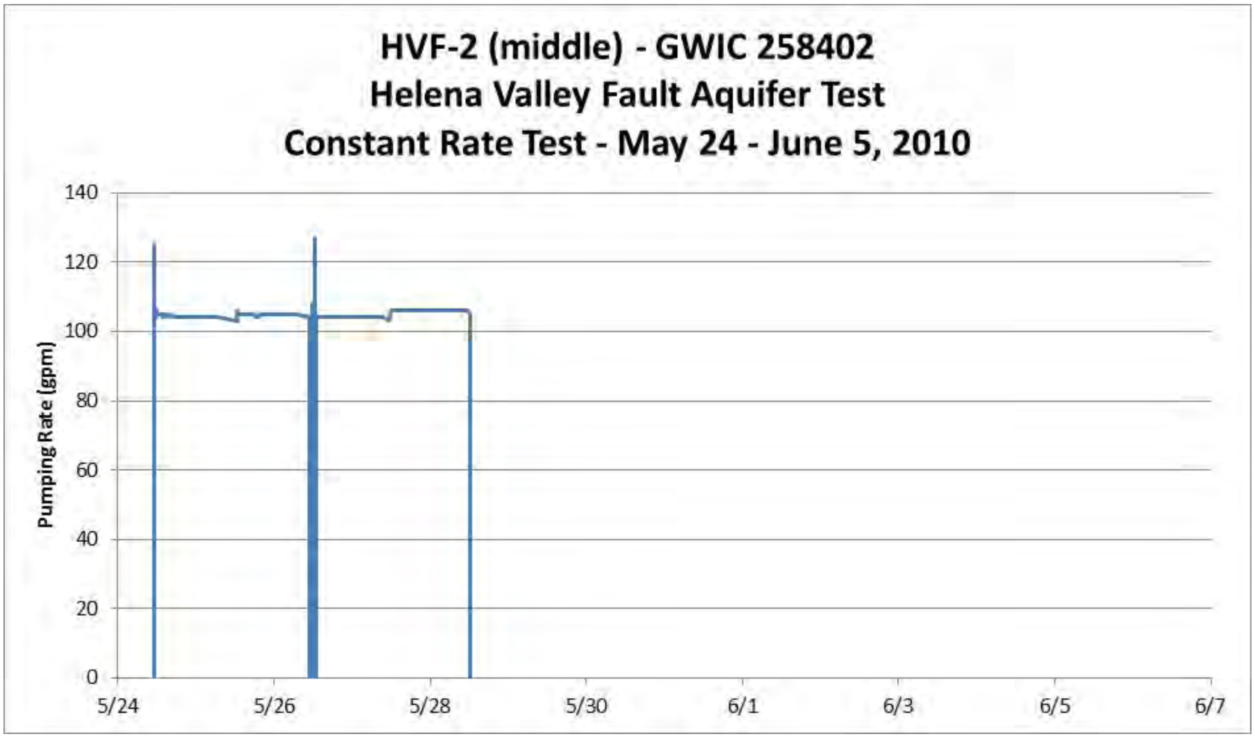

Figure HVF29. Pumping rate vs. time during constant-rate test of HVF-2.

Evaluation drawdown and recovery in the pumping well indicate that this aquifer is semi-confined, because it appears that there is gravity drainage (fig. HVF31). As pumping continues, gravity drainage slows and the curves steepen upward as the drawdown cone encounters a barrier boundary. Thus it appears that the materials on the south side of the fault are draining until about 1 d, and then the effects of the barrier boundary are seen. In any case, a meaningful calculation of T does not appear possible because borehole effects are quickly followed by gravity drainage, which is then followed by effects from the barrier boundary. It is likely that during the middle portion of the test the results are affected by both gravity drainage and the barrier boundary. As such, quantitative analysis of the data from the pumping well is not reasonable.

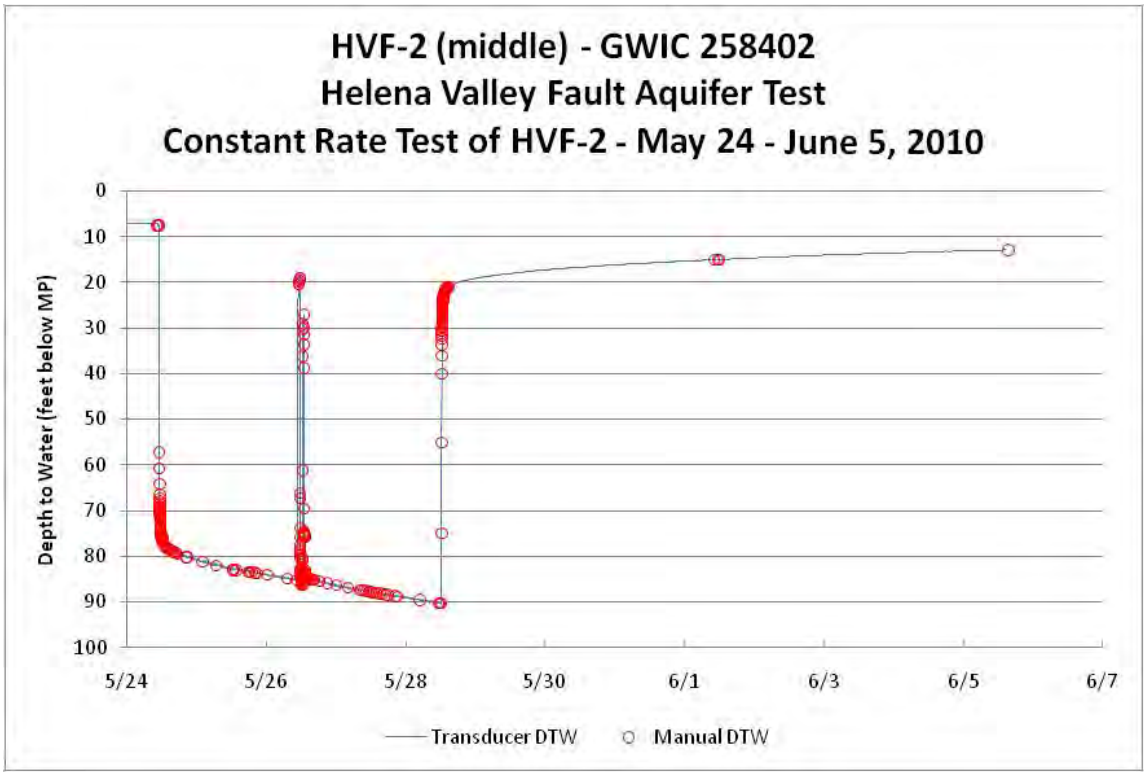

Figure HVF30. Water levels in HVF-2 during constant-rate test of HVF-2.

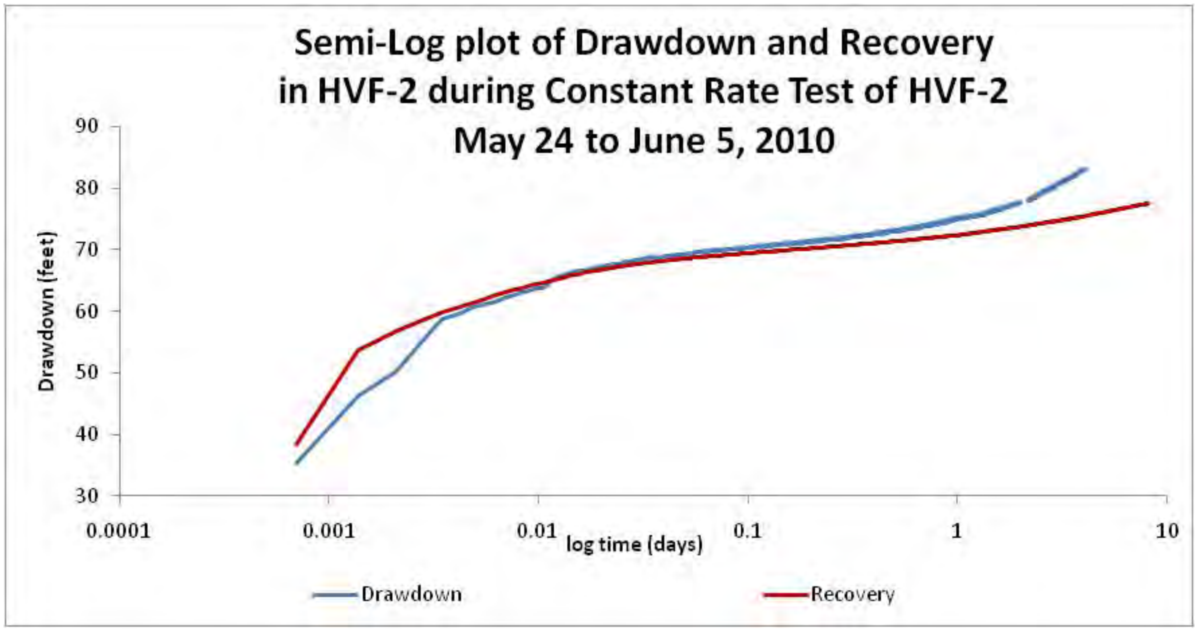

Figure HVF31. Semi-log plot of drawdown and recovery vs. time. If no boundaries were encountered the data would form straight lines. The curves flatten (gravity drainage) and then steepen (barrier boundary).Quantitative analysis of these data is not reasonable.

During this test, drawdown occurs in monitoring wells HVF-1 and HVF-3 (figs. HVF32, HVF33). Maximum drawdown in HVF-1 was 36.03 ft, while drawdown in HVF-3 was only 8.25 ft. When the drawdown values are plotted on a Cooper–Jacob composite plot (dh vs. t/r^2 ; fig. HVF34), the different responses to pumping between each well is clear. HVF-2 is in direct communication with HVF-1; however, a recharge boundary is encountered after 18 min of pumping. HVF-3 is not in direct communication with HVF-2, thus a barrier boundary is located between HVF-2 and HVF-3.

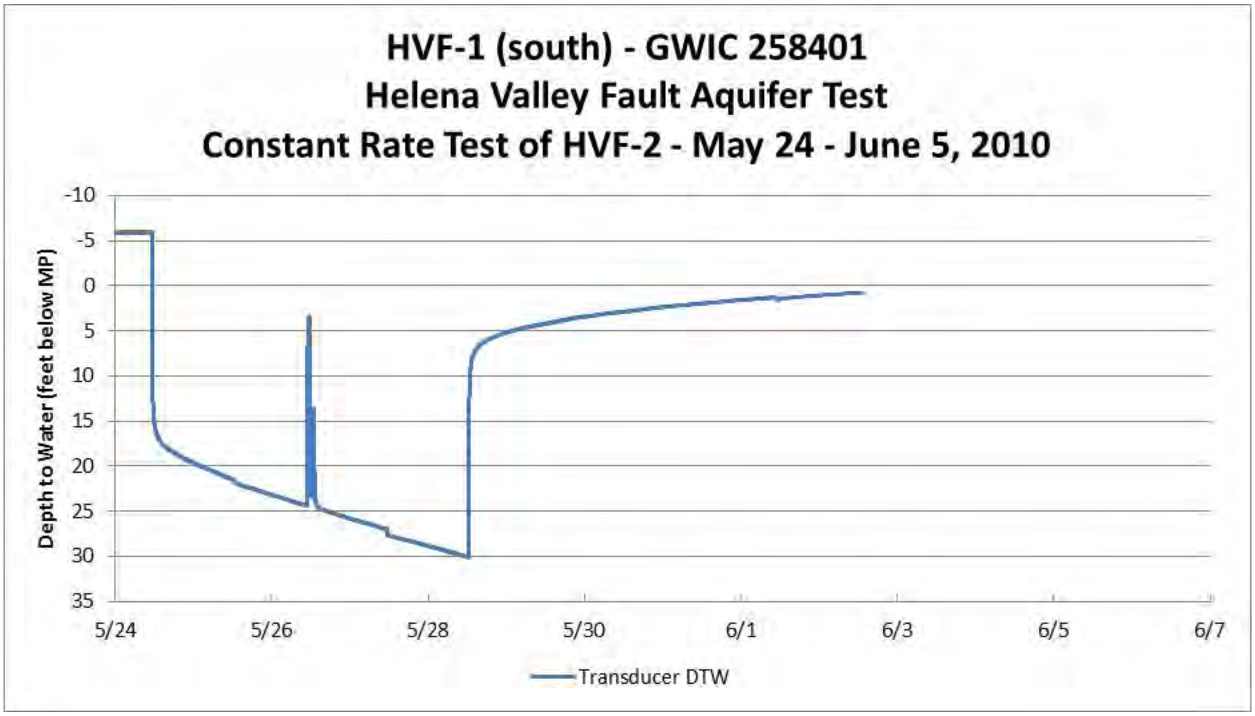

Figure HVF32. Water levels in HVF-1 during constant-rate test of HVF-2.

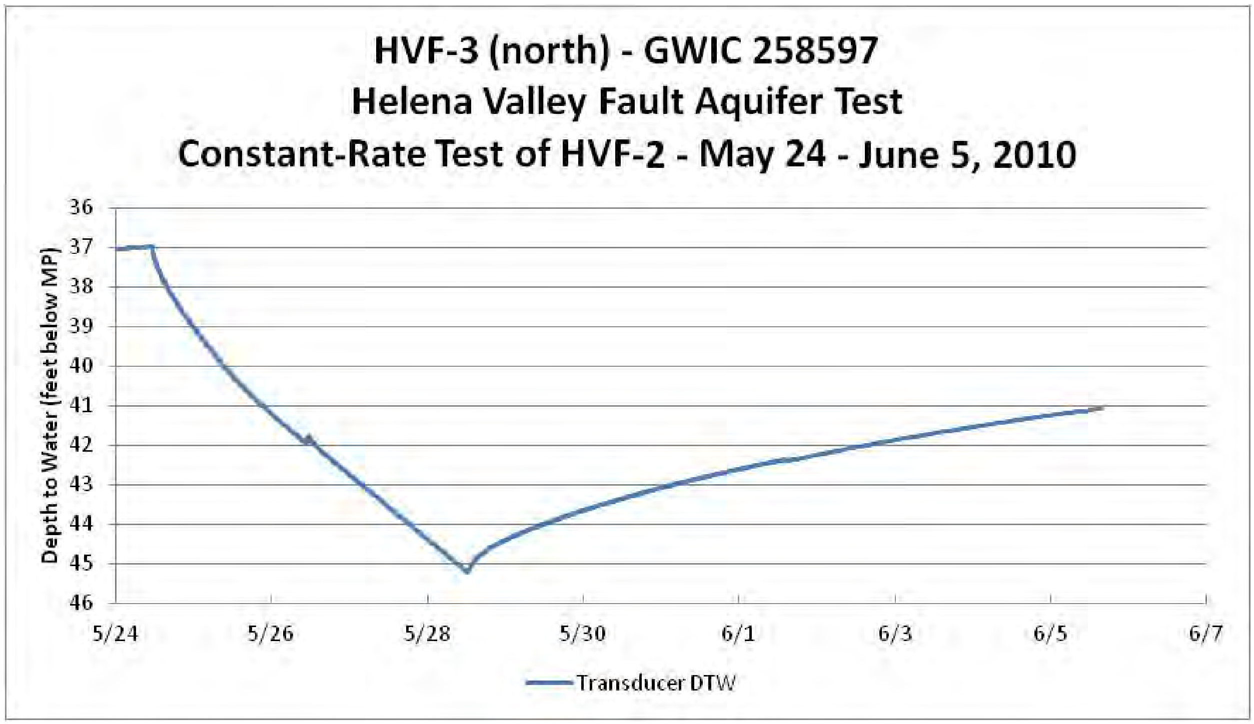

Figure HVF33. Water levels in HVF-3 during constant-rate test of HVF-2.

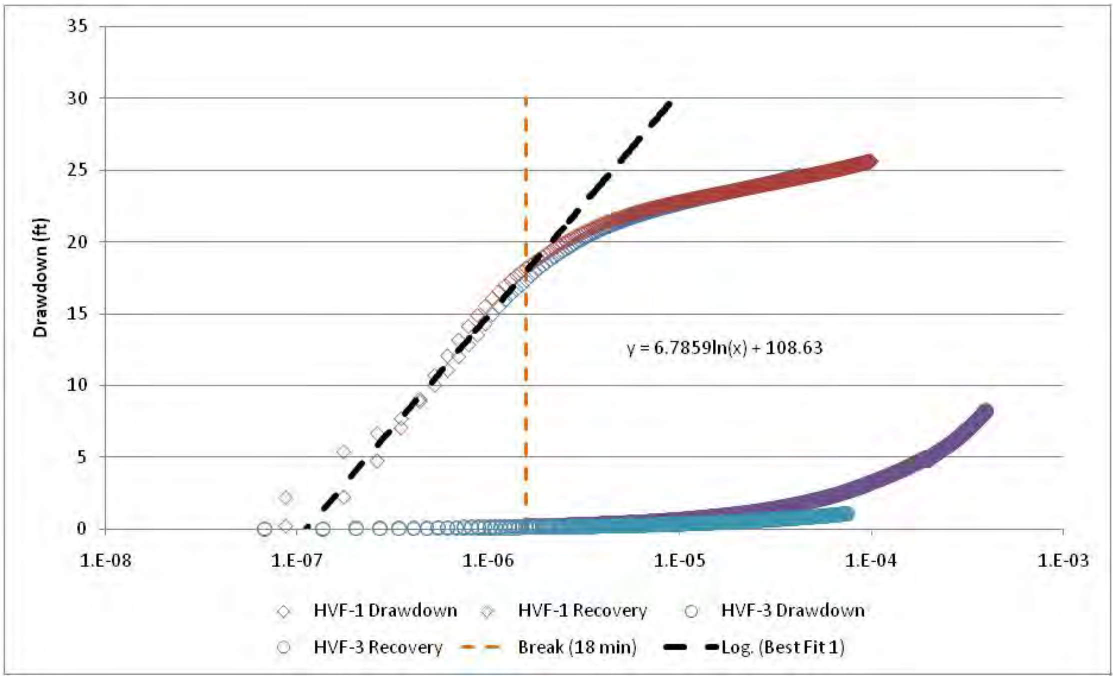

Figure HVF34. Composite plot of drawdown vs. time divided by distance squared. Ideally the data from both wells would form a single straight line. The decrease in slope in the data from HVF-1 shows that the drawdown cone encounters a recharge boundary. The minimal response in HVF-3 shows that there is a barrier boundary between HVF-2 and HVF-3.

Conclusions

It is clear that the Helena Valley Fault at this location forms a barrier to flow, likely due to the fault being gouge filled. It is not impermeable, because drawdown was observed on the opposite sides of the fault from the pumping wells; however, it has a substantial effect on the ease with which water moves through this area. A permeable zone (open fractures or higher fracture density) also appears to be associated with the fault, which allows wells installed near the fault to be more highly productive than most bedrock wells in this area. However, these wells recover from pumping more slowly than expected, which implies that although the fracture zone near the fault is productive, it receives limited recharge. Water can be pumped from the zone at a high rate; however, the duration for which this high rate can be maintained is limited.

Due to the barrier created by the fault, and the recharge obtained from highly fractured zones, aquifer properties are not quantified.

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VALLEY EXCAVATING AQUIFER TEST—
SPOKANE FORMATION

VALLEY EXCAVATING
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
June 2010

STEP TEST
AND
144-HOUR (6-DAY) CONSTANT-RATE TEST

Background

The following is an analysis of a step test and a 144 h (6 d) constant-rate pumping test performed using wells installed on the property of Valley Excavating. There is no development or groundwater usage near the test site.

This test was designed to determine the transmissivity, storativity, and anisotropy of the Spokane Formation aquifer at this location. One 4-in-diameter pumping well (PW1) and five 2-in-diameter observation wells (OW1, OW2, OW3, OW4, and OW5) were installed for the test. A MBMG geologist was present for the well installation; cuttings were described in detail, and completion details verified. For every 5 ft of borehole in PW1, samples of cuttings were composited, described, and retained for long-term storage at the MBMG. For the observation wells composite cuttings were collected and described for each 10-ft interval. A pre-existing well at this site (GWIC 237331), located away from the new wells, was included in the long-term monitoring network and used to evaluate antecedent trends prior to the aquifer tests. Well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu) and are identified by using the GWIC ID. A summary of well-completion details is provided in table VX1.

Transducers were deployed in the six wells for the duration of the test. Measurable drawdown was recorded in all wells.

Location

The test area is located in the northern part of the Helena Valley, near the upper end of dissected pediments about 0.5 mi south of the break in slope and vegetative change that marks the trace of the Helena Valley Fault. Valley Excavating operates a bedrock quarry approximately 0.2 mi east of this site. All wells are located in Township 12 N., Range 4 W., Section 35, NW¼ NE¼, in Lewis and Clark County, Montana (figs. VX1, VX2).

Geology

The aquifer tested is the Spokane Formation (fig. VX3). This unit is described by Reynolds (2000) as “argillite and siltite with very thin limestone and quartz sandstone in the uppermost and lowest parts.” Cuttings descriptions indicate that the formation at the test site is composed of reddish-brown and greenish-gray argillite consistent with exposures seen in the nearby quarry. Evaluation of fractures observed in the quarry walls indicates that the major fracture trend is approximately N15W. There are many less continuous fractures oriented roughly perpendicular to the main fracture set, which results in material removed from the quarry tending to be blocky (fig. VX4).

Shallow magnetic-survey information became available for an area approximately 0.5 mi west of the aquifer test site in March 2011 (fig. VX5). This information shows a more detailed view of the structure in this area. The orientations of major lineaments from the magnetic survey are consistent with the fracture orientations in the quarry. This image also shows the fractured and faulted nature of the rocks.

Table VX1

Well Designations, Locations, and Completion Information

Valley Excavating Aquifer Test—June 2010

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Altitude$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 6/9/10 (ft below MP)	Groundwater Altitude 6/9/10 (ft-amsl)	Distance from PW1 (ft)	Bearing from PW1 (degrees)	Comments
254356	PW1	46.7619121	-112.0734183	4353.80	200	79.37	4274.43	---	---	Pumping Well
254357	OW1	46.7618452	-112.0733844	4352.48	200	78.08	4274.40	25.4	S15E	Observation Well
254359	OW2	46.7616545	-112.0732864	4347.15	200	72.52	4274.63	99.4	S15E	Observation Well
254360	OW3	46.7619320	-112.0733221	4355.22	200	80.63	4274.59	24.8	N85E	Observation Well
254361	OW4	46.7619981	-112.0730350	4354.44	200	79.97	4274.47	100.5	N85E	Observation Well
257001	OW5	46.7618836	-112.0733253	4353.46	120	78.77	4274.69	25.1	S65E	Shallow Observation Well
237331	PreExisting	46.7600876	-112.0680216	4276.95	200	39.90	4237.05	1510	S65E	Unused well - Background

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

* = Horizontal Datum is NAD83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

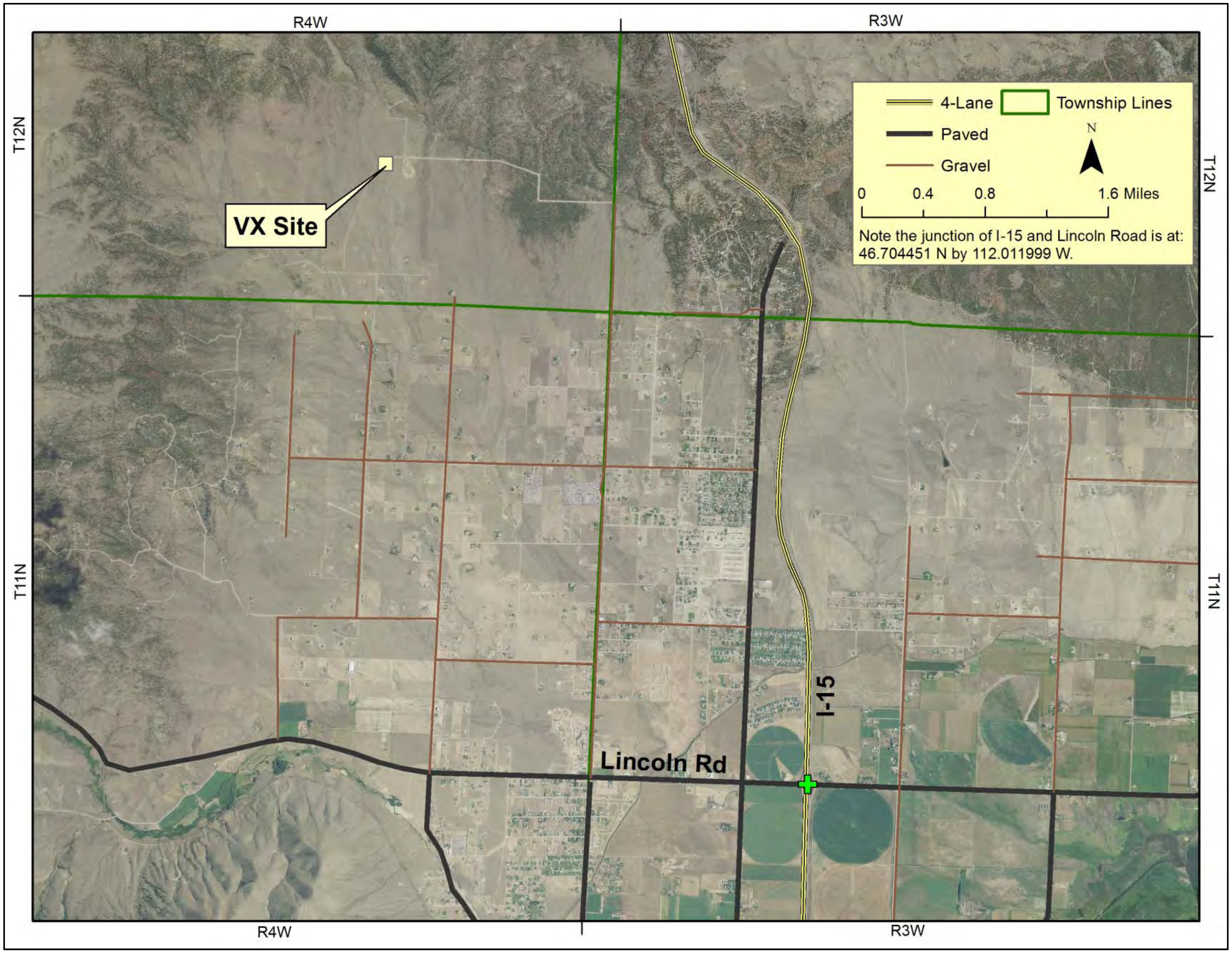

Figure VX1. Location of the Valley Excavating Aquifer test site, June 2010. The green cross is at 46.704451^{o}N latitude and 112.011999^{o}W longitude.

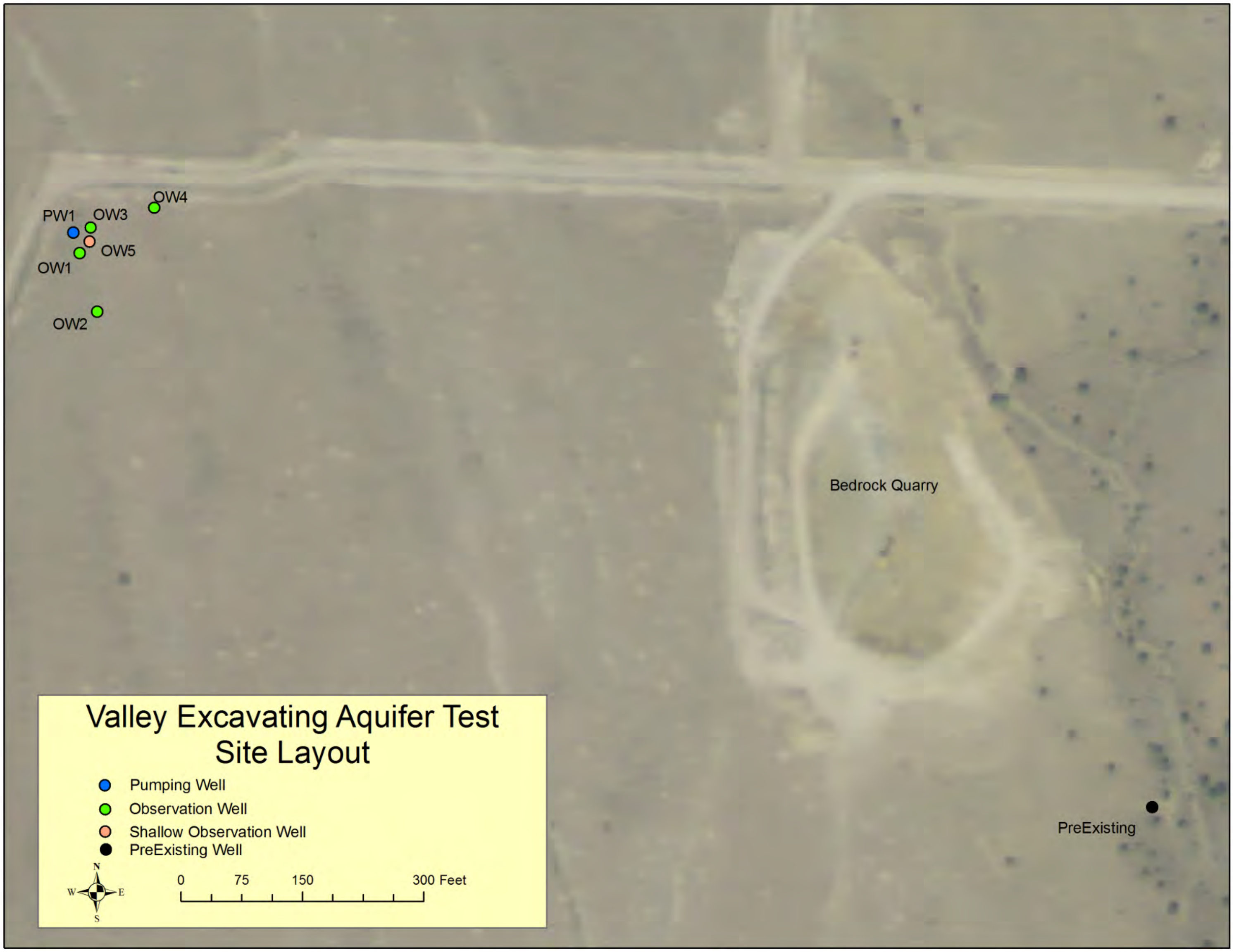

Figure VX2. Site layout for the Valley Excavating Aquifer test, June 2010.

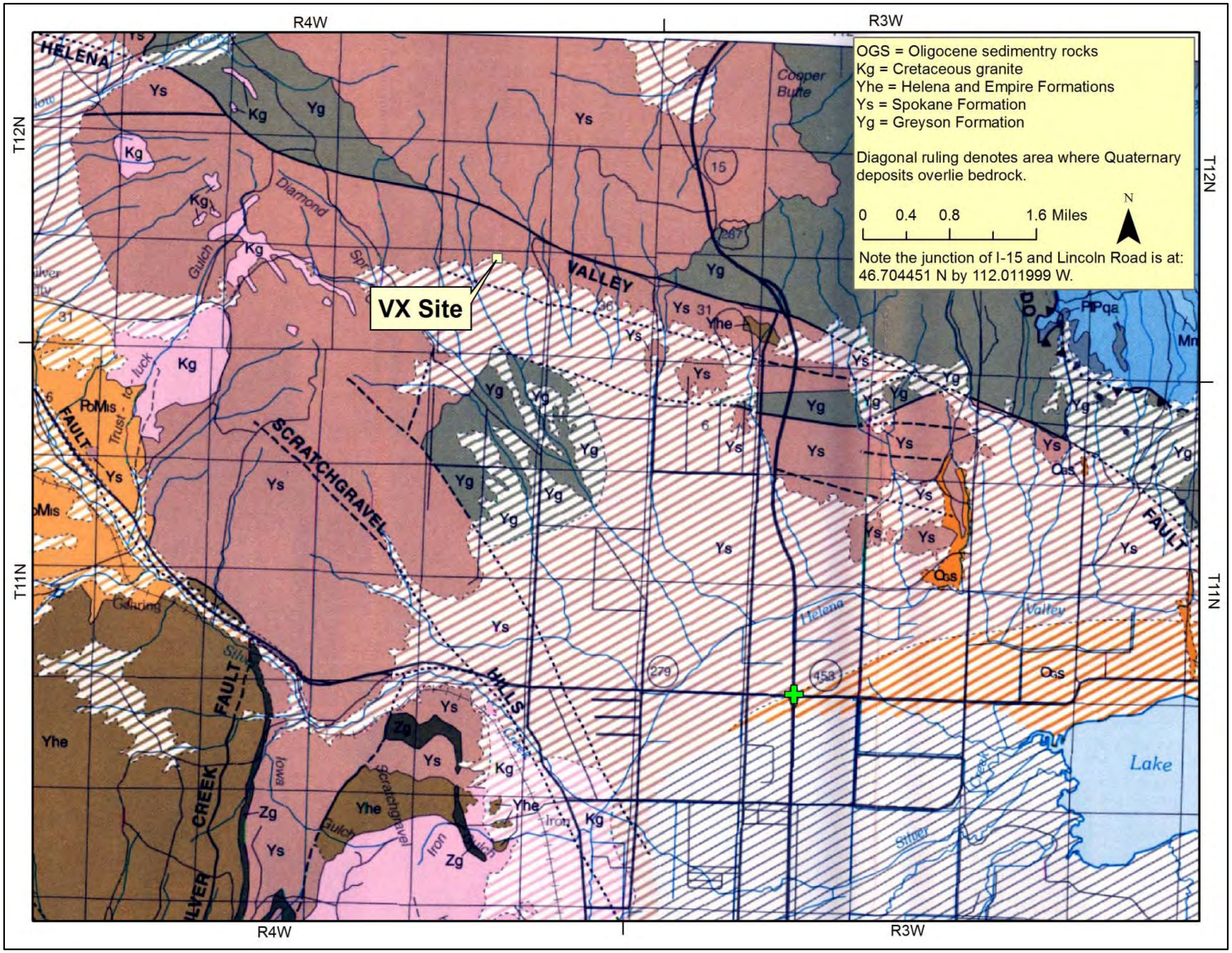

Figure VX3. Geologic Map of the Valley Excavating Aquifer test area (from Reynolds, 2000). The green cross is at 46.704451°N latitude and 112.011999°W longitude.

Figure VX4. Spokane Formation exposed in the Valley Excavating Quarry.

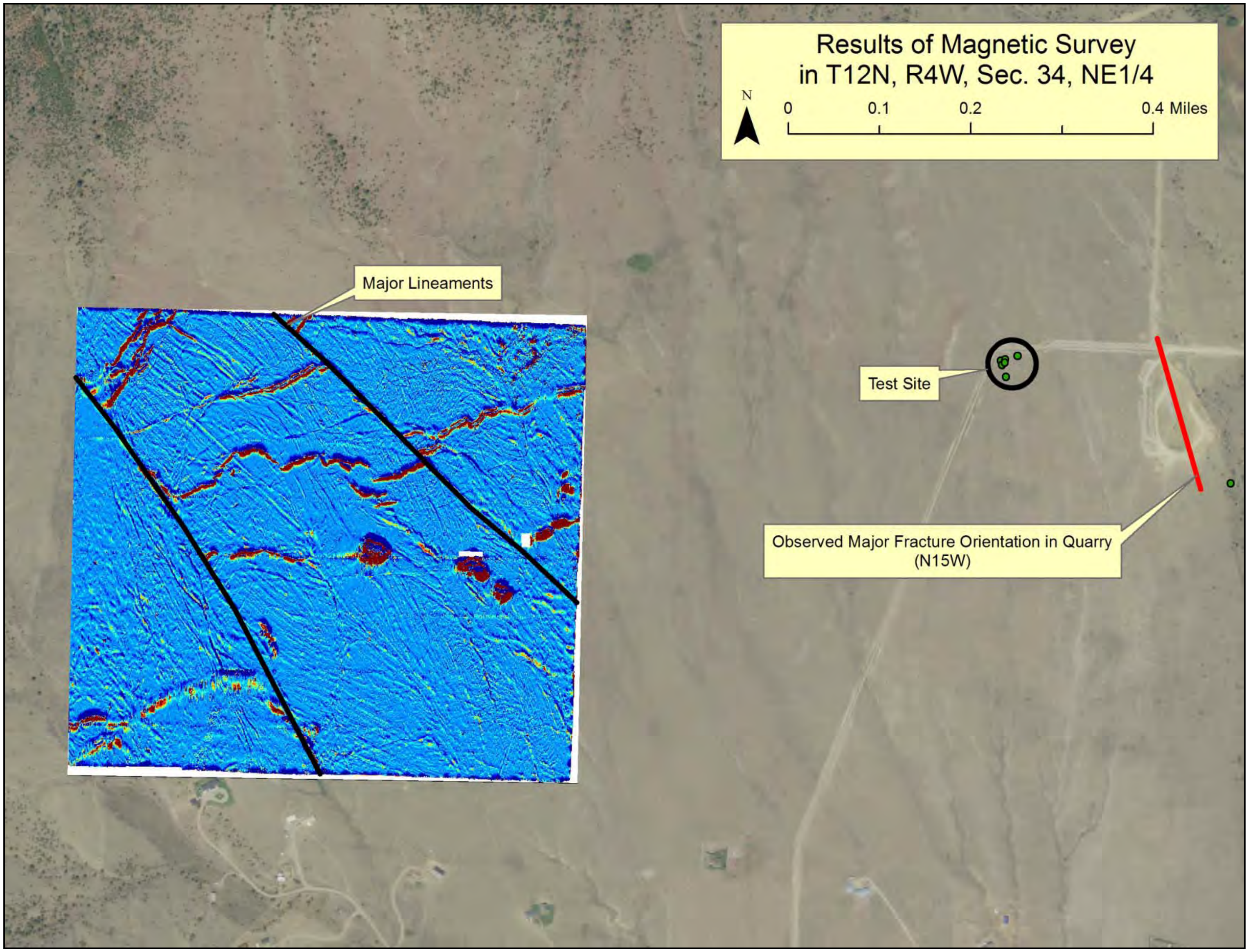

Figure VX5. Comparison of VX site to shallow magnetic survey results.

There are no known faults in the immediate vicinity of the test site; however, the Helena Valley Fault is located approximately 0.35 mi to the north, and an unnamed fault is mapped 0.29 mi to the south.

Well Details

One 4-in-diameter PVC-cased well was installed at this site to serve as the pumping well (PW1, GWIC 254356). This well has a total depth of 200 ft. Five 2-in PVC observation wells (OW1, OW2, OW3, OW4, and OW5; GWIC IDs 254357, 254359, 254360, 254361, and 257001 respectively) were also installed. Observations wells 1, 3, and 5 are approximately 25 ft from the pumping well. Observation wells 2 and 4 are approximately 100 ft from the pumping well. Observation wells 1, 2, 3, and 4 are 200 ft deep and OW5 is 120 ft deep (fig. VX2). This site is relatively flat, with a ground surface altitude of approximately 4,350 ft. Static water level is approximately 80 ft below ground (~4,270 ft amsl). In order to test anisotropy based on the observed fracture orientations in the rock quarry, the 200-ft-deep observation wells are either on a bearing N15W from the pumping well (in line with the main fractures; OW1 and OW2) or N75E (perpendicular to the main fractures; OW3 and OW4). The 120-ft observation well (OW5) was placed between these at a bearing of N60W (fig. VX2).

There is an unused pre-existing well located on the east of the quarry (well 237331; approximately 1,510 ft from PW1), which provided information on antecedent trends. A transducer was installed in this well on January 25, 2010, and it collected data until July 21, 2011. During the test, water levels in well 237331 rose by 0.05 ft (fig. VX6).

Pre-test depth to water (DTW) readings show groundwater altitudes were between 4,274.40 and 4,274.69 ft above mean sea level (ft-amsl). These results indicate that there is generally flow to the southeast (fig. VX7), which is further supported by the groundwater elevation in the pre-existing well. Pre-test monitoring shows that groundwater levels were stable (figs. VX8 to VX13).

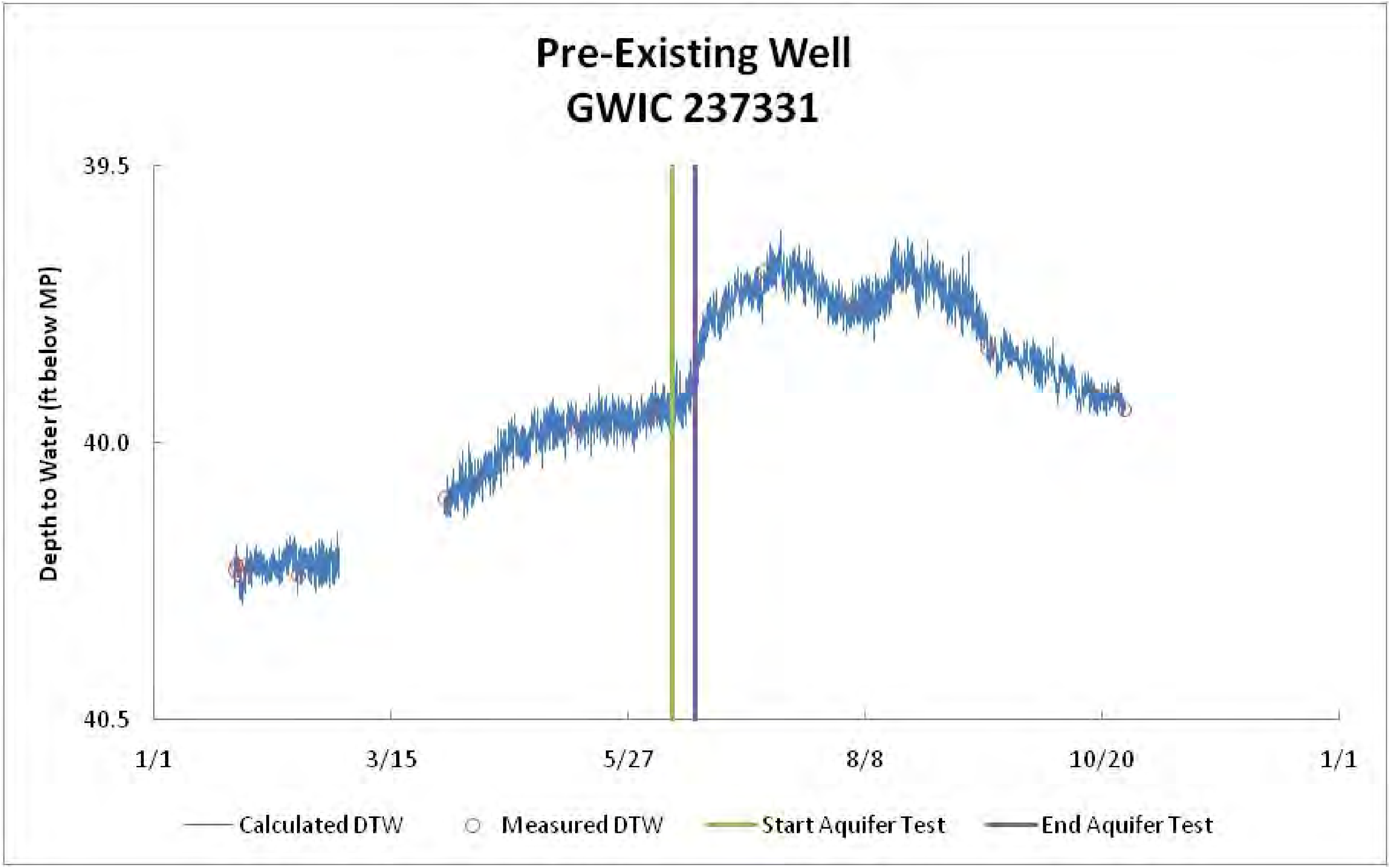

Figure VX6. Hydrograph of pre-existing well during 2010 provides background for the Valley Excavating aquifer test.

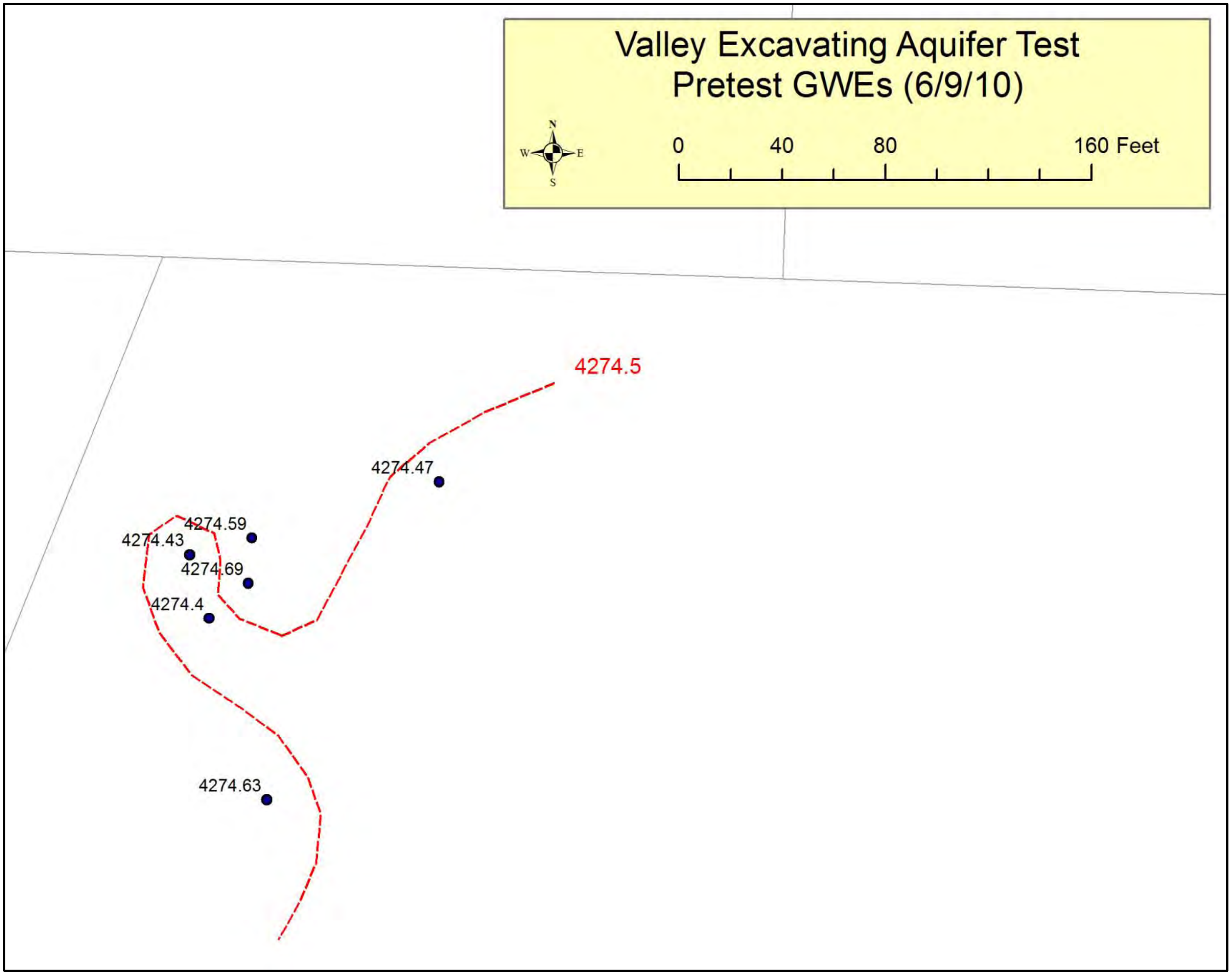

Figure VX7. Groundwater elevation (ft amsl) measured on June 9, 2010, prior to the start of the step test.

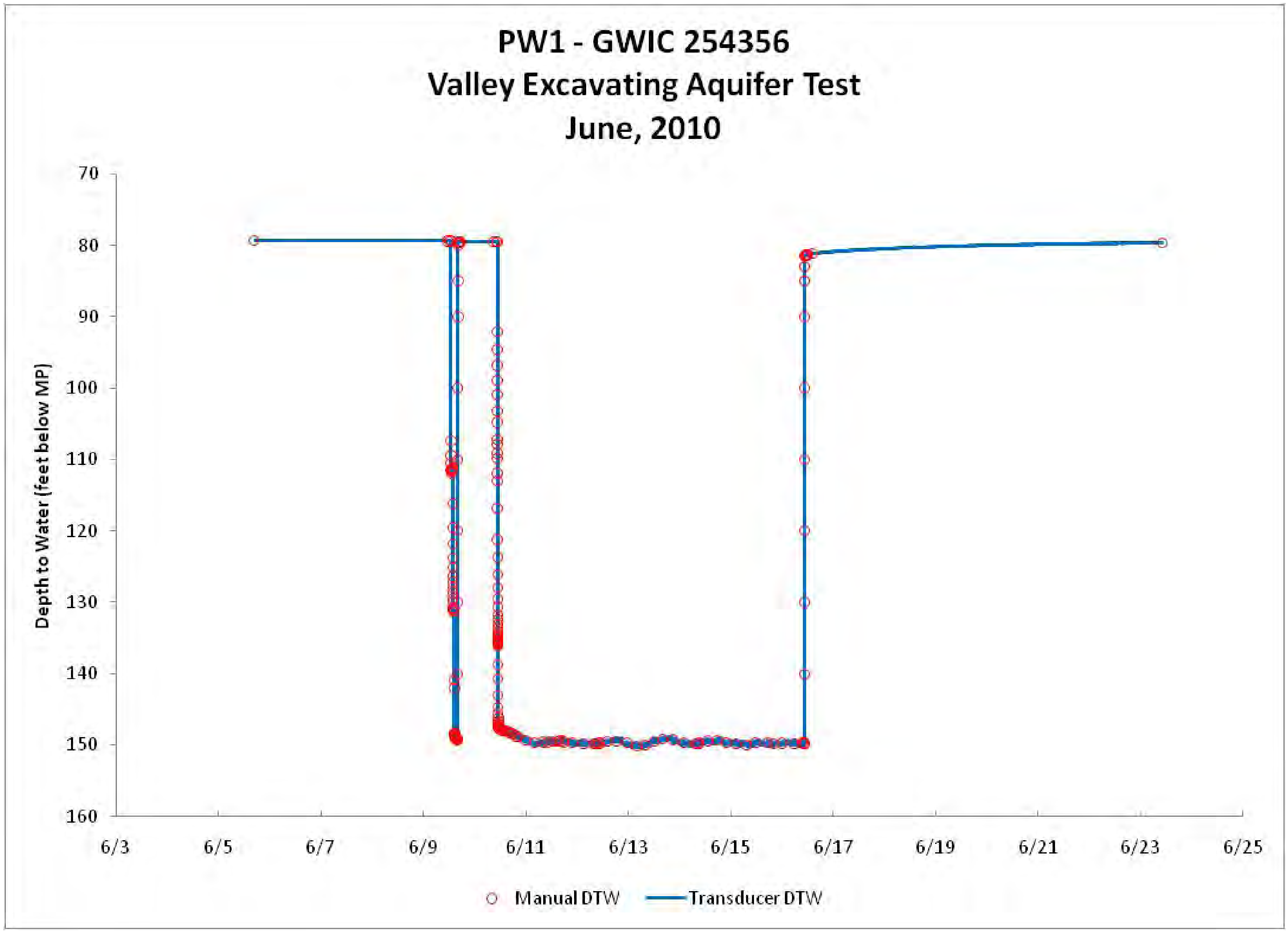

Figure VX8. Depth to water readings [DTW; ft below measuring point (MP)] in well PW1 (pumping well; 200 ft deep) during the Valley Excavating Aquifer test.

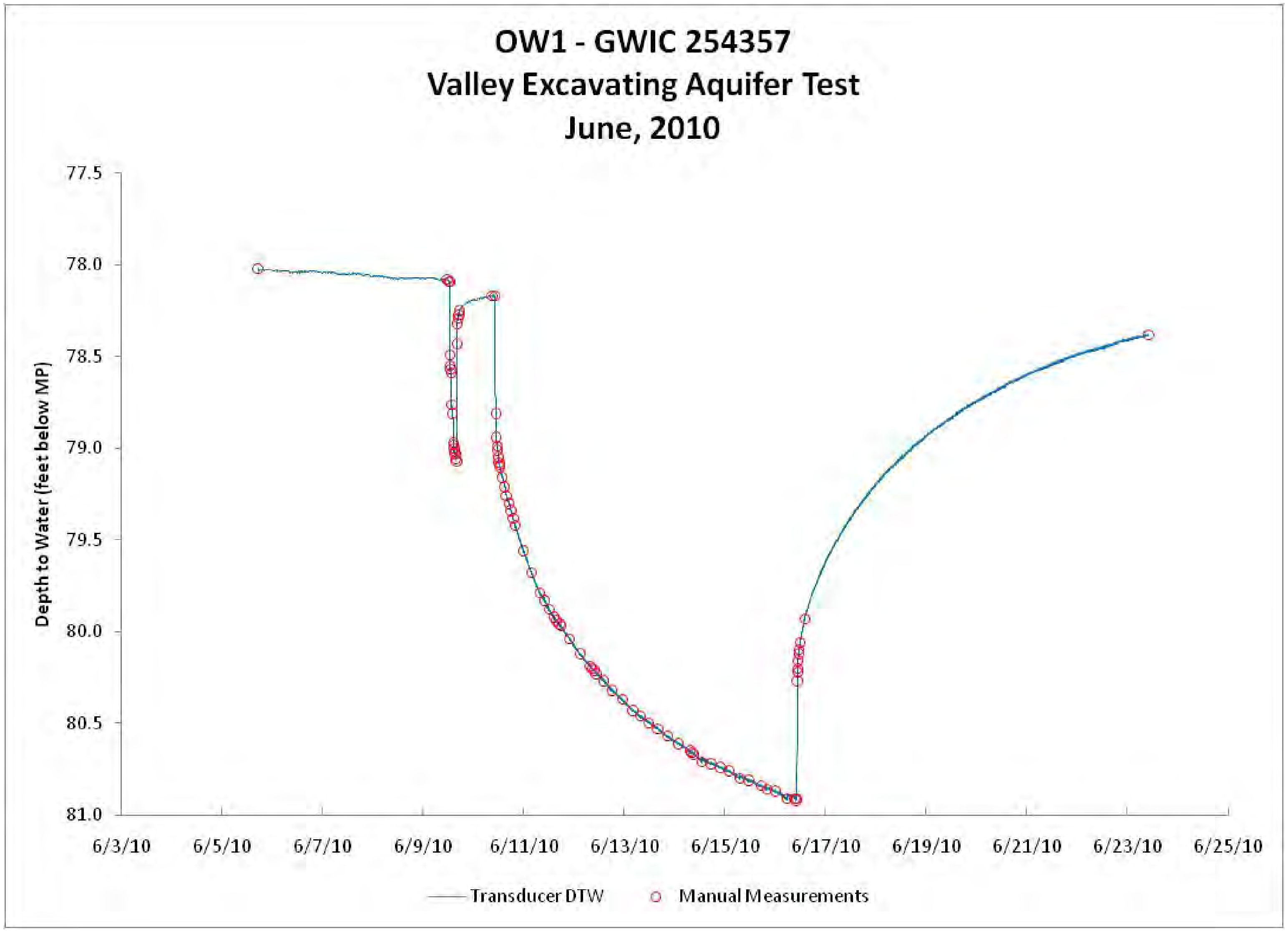

Figure VX9. Depth to water readings (ft below MP) in well OW1 (25.4 ft S15E of PW1; 200 ft deep) during the Valley Excavating Aquifer test.

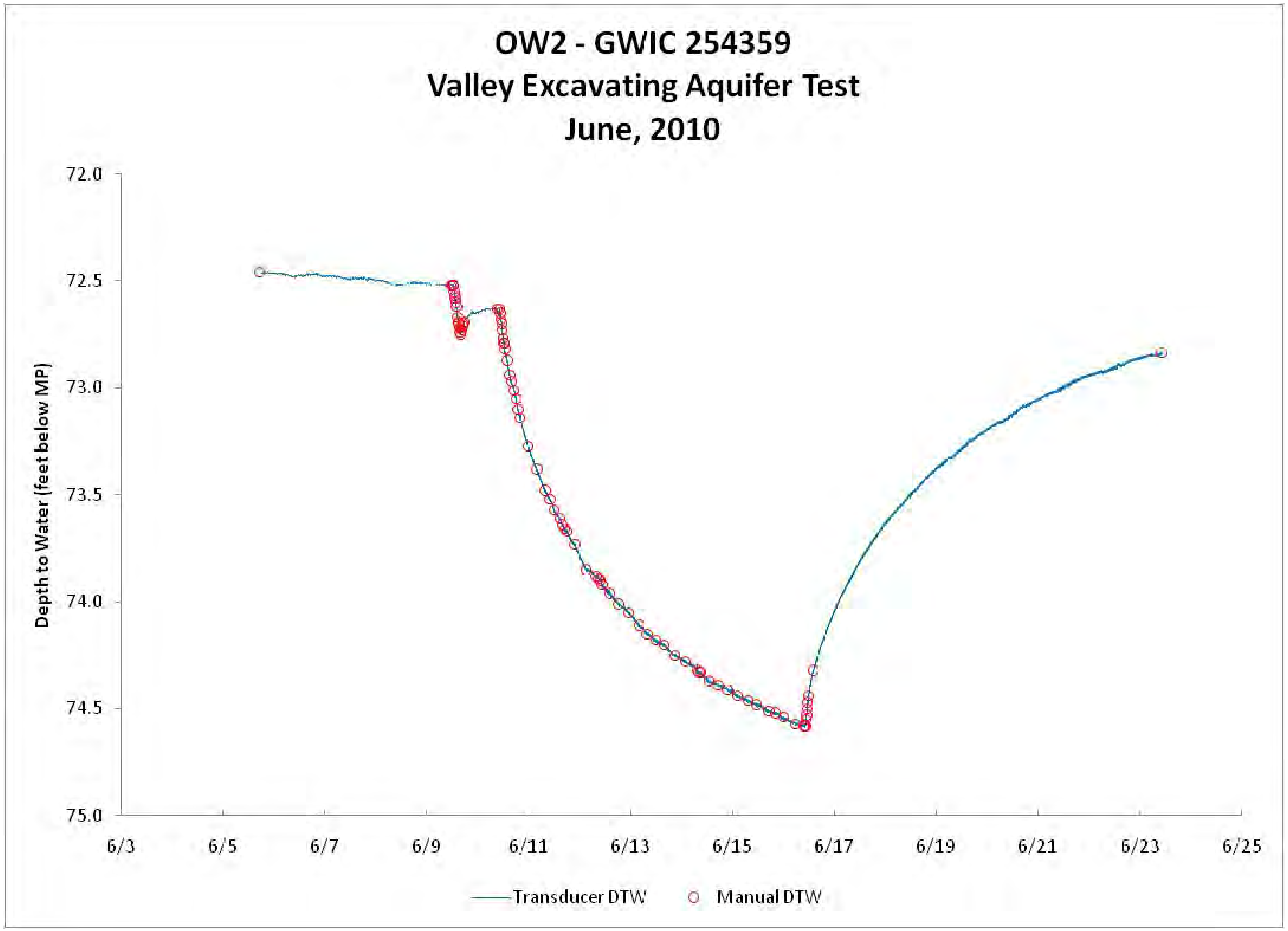

Figure VX10. Depth to water readings (ft below MP) in Well OW2 (99.4 ft S15E of PW1; 200 ft deep) during the Valley Excavating Aquifer test.

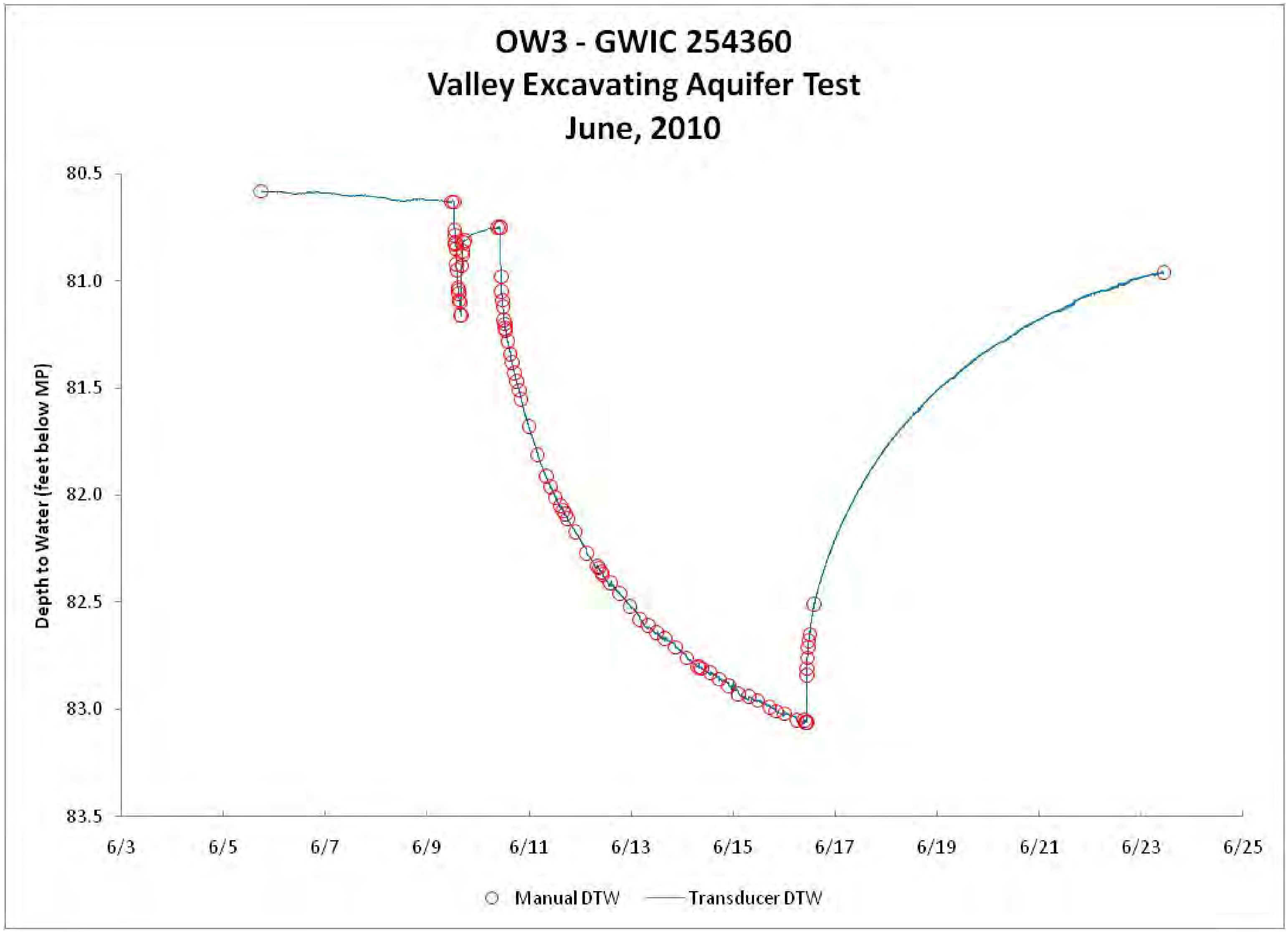

Figure VX11. Depth to water readings (ft below MP) in well OW3 (24.8 ft N85E of PW1; 200 ft deep) during the Valley Excavating Aquifer test.

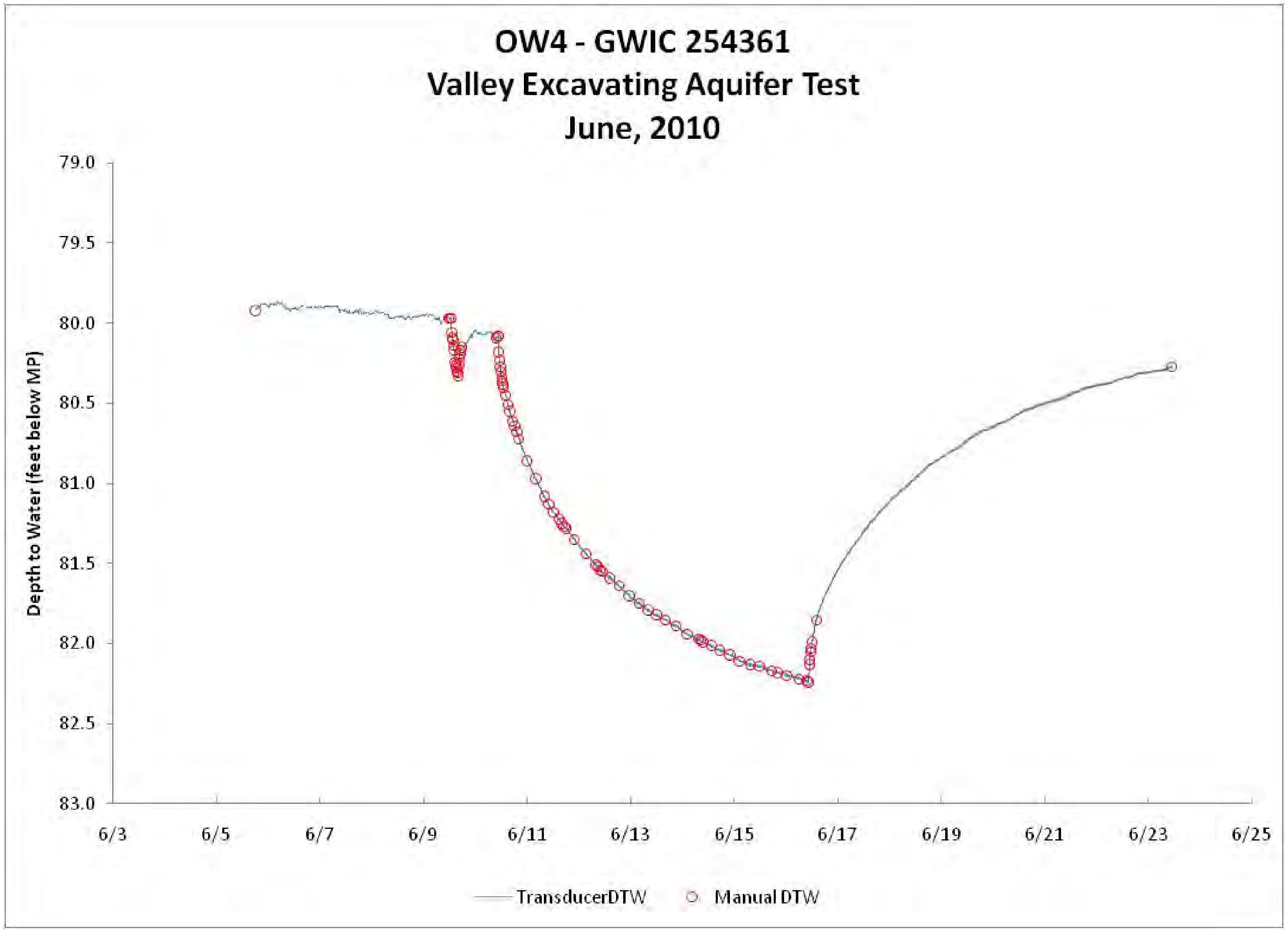

Figure VX12. Depth to water readings (ft below MP) in well OW4 (100.5 ft N85E of PW1; 200 ft deep) during the Valley Excavating Aquifer test.

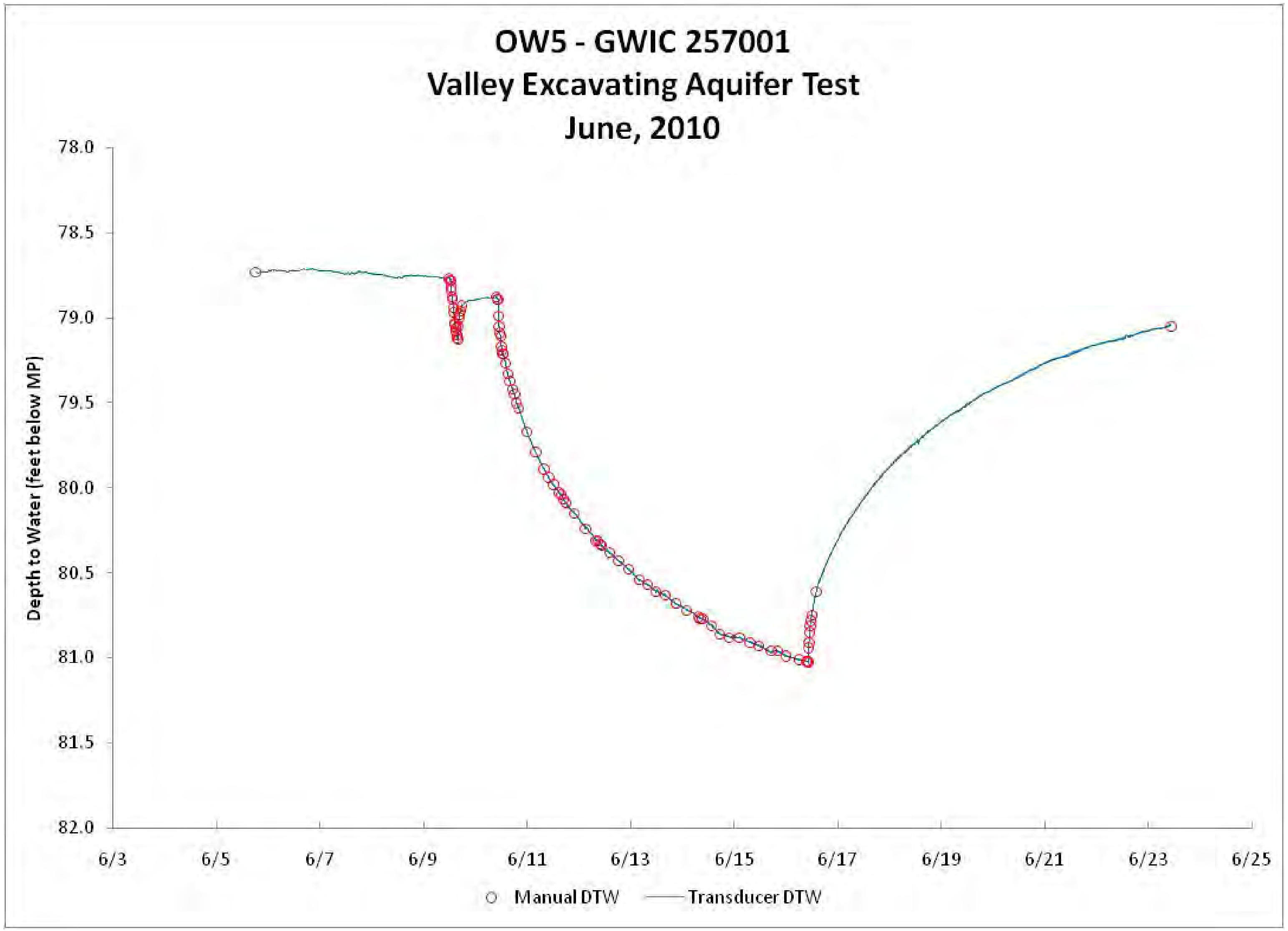

Figure VX13. Depth to water readings (ft below MP) in well OW5 (25.1 ft S65E of PW1; 120 ft deep; shallow well) during the Valley Excavating Aquifer test.

Methodology

This pumping test was conducted by the MBMG. The pumping rate was monitored throughout the test using a calibrated 5-gallon bucket and stopwatch, with each recorded value being the average of at least three measurements. A totalizing flow meter was also used to monitor flow. The bucket and stopwatch measurements were consistently about 2 gpm higher than flow meter values during the constant-rate test; however, flow meter readings were taken much more frequently. Therefore, the flow meter readings were adjusted upward to match their average with the average of the more reliable manual measurements (fig. VX14). Discharge was controlled using a gate valve. The discharge from the pumping well (PW1) was diverted approximately 300 ft south of the pumping well, and away from all monitored wells.

Vented pressure transducers were used to record water levels in the pumping well (PW1) and four of the observation wells (OW1, OW2, OW3, and OW5). An unvented pressure transducer was installed in observation well OW4. A barologger was also installed in OW4, and data from this logger were used to correct for barometric effects. The transducer used in the pumping well (PW1) is rated at 100 psig (230.7 ft), has a manufacturer reported accuracy of ±0.05 percent of the rated pressure (±0.11 ft), and a resolution of ±0.005 percent of the rated pressure (0.011 ft). The other four vented transducers are rated at 15 psig (34.61 ft) and have a manufacturer-reported accuracy of ±0.05 percent of the rated pressure (±0.017 ft), and a resolution of ±0.005 percent of the rated pressure (0.001 ft). The unvented transducer used in OW4 is rated at 30 psig (35 ft) and has a manufacturer-reported accuracy of ±0.1 percent of the rated pressure (±0.035 ft), and a resolution of ±0.01 percent of the rated pressure (0.0035 ft).

Manual water-level measurements were recorded for all wells prior to placing transducers, and were recorded periodically during the test, during recovery, and prior to removing the transducers. These manual measurements were used to verify transducer response. All water level data are available from GWIC by using the GWIC ID numbers (http://mbmggwic.mtech.edu/) and accessing the aquifer tests.

Transducers were placed in all wells on June 5, 2010, to determine antecedent trends. The pumping portion of the tests ran from June 9 to June 16. All transducers were left in place until June 23.

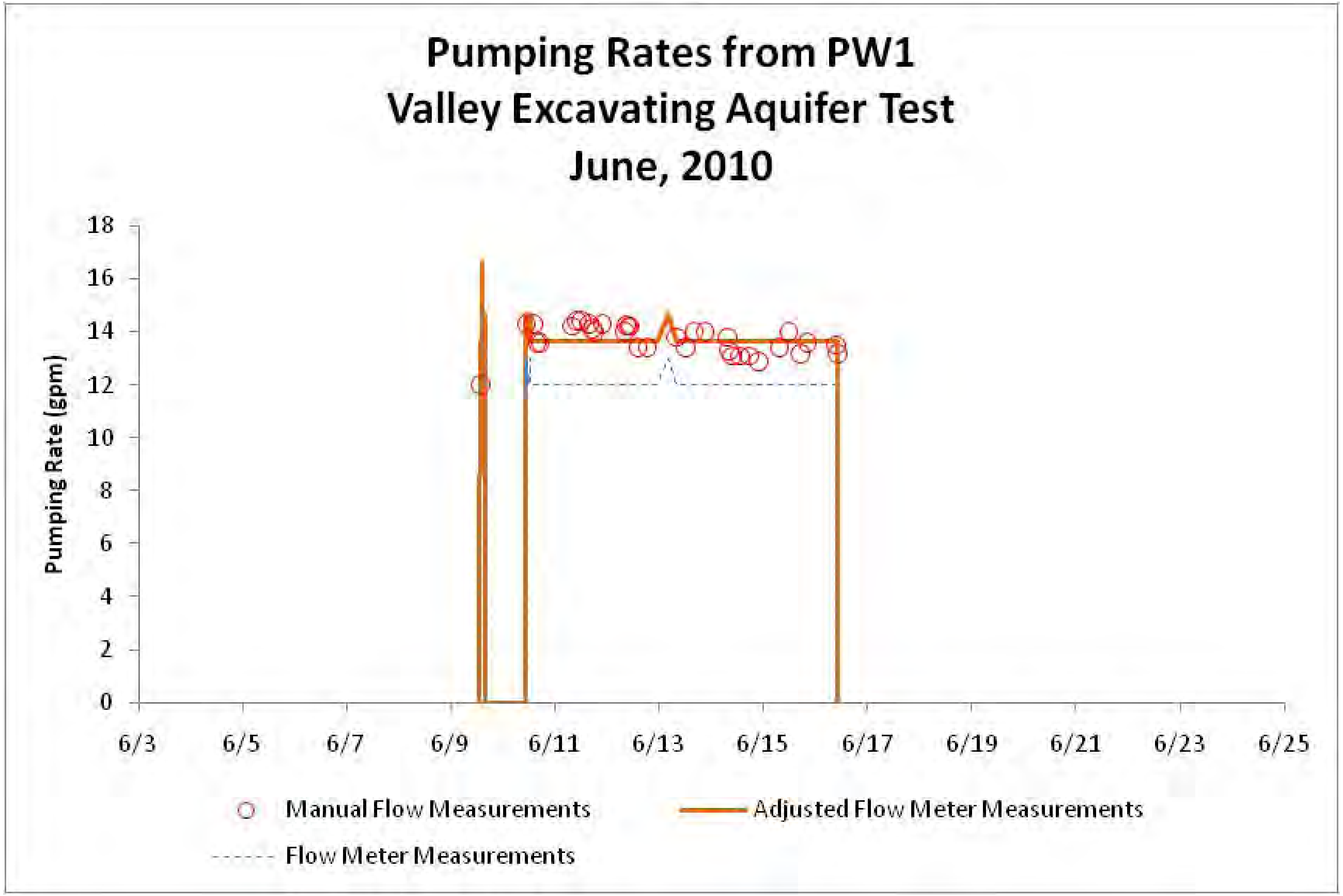

Figure VX14. Pumping rates from PW1 (flow meter readings adjusted for manual measurements) during the Valley Excavating Aquifer test.

Step Test

On the afternoon of June 9, 2013, a step test was conducted on PW1 to determine an appropriate pumping rate (fig. VX15). Time steps, pumping rates, and maximum drawdown are shown in table VX2. Because the pump was set at 160 ft below ground, it was desired that the long-term pumping rate not cause water levels to drop below 150 ft. As such, a rate of approximately 14 gpm was selected, and valves were set accordingly. As discussed below, the actual weighted average rate for the constant-rate test was 13.7 gpm. PW1 was constructed with a 4-in 20-slot screen 20 ft long. Thus, the entrance velocity at 14 gpm would be 0.005 ft/s, which is well below the 0.1 ft/s threshold recommended by Heath (1983) for laminar flow.

Table VX2
PW1 - Step Test Summary
Valley Excavating Aquifer Test—June 9, 2010

Start Step	End Step	Rate (Q, gpm)	Maximum Drawdown (s, ft)	Specific Capacity (gpm/ft)
12:45	13:32	8.6	31.83	0.27
13:32	14:20	12.0	52.16	0.23
14:20	16:00	14.7	69.84	0.21

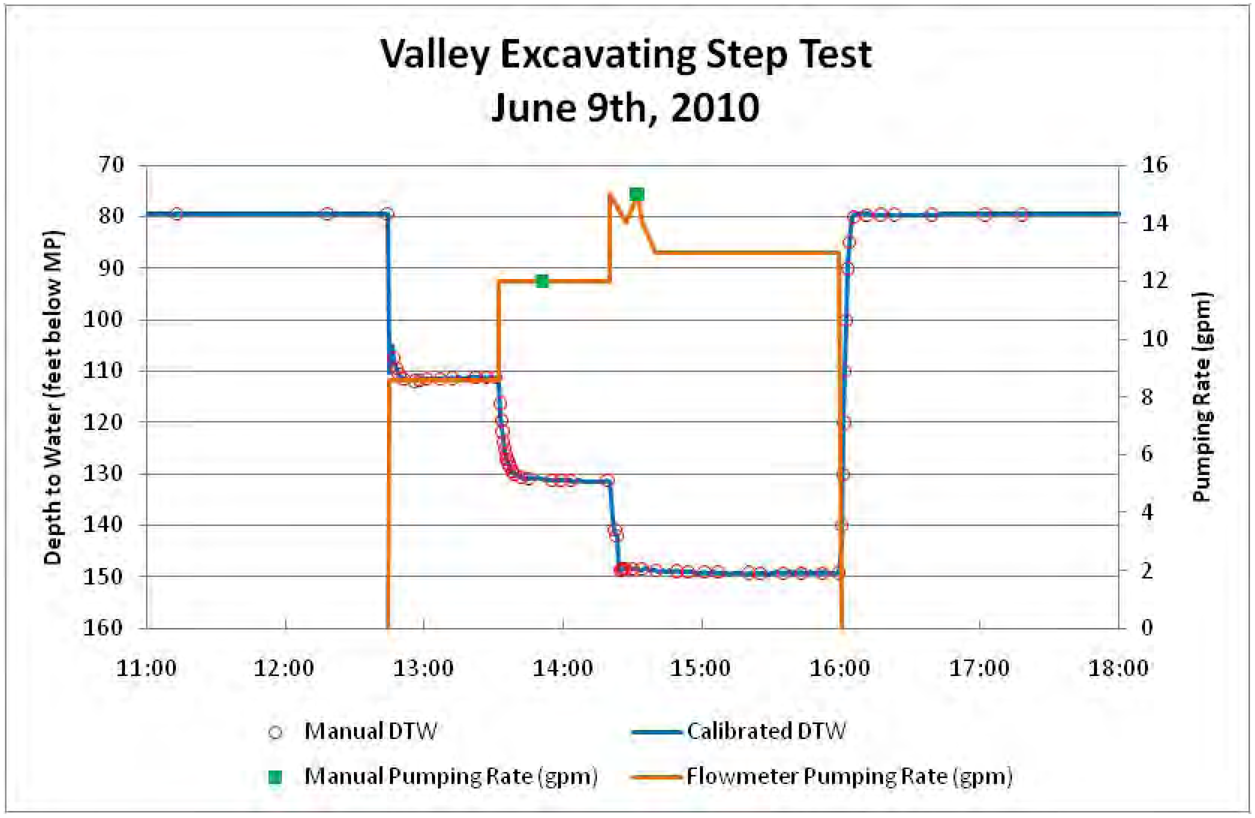

Figure VX15. Depth to water in PW1, and pumping rates recorded during step test.

The data obtained during the step test also allow the specific capacity (discharge per unit of drawdown, Q/s) of the well to be determined at different pumping rates (fig. VX16). This information can then be used to estimate the maximum rate that the well can be pumped without exceeding a target drawdown. Given that the top of the screen is at 179 ft below ground surface (bgs), the static water level is at 80 ft bgs, and it is typically desired that the pumping water level stay at least 10 ft above the top of screen, the target drawdown (s) is 89 ft and would be achieved by pumping PW1 at 17 gpm.

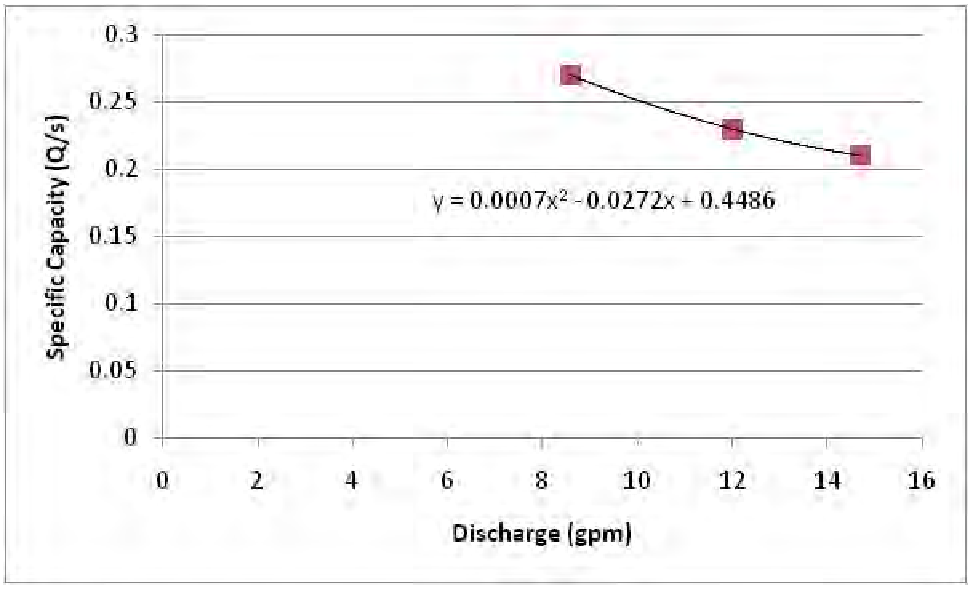

Figure VX16. Specific capacity (Q/s) vs. pumping rate (Q) for PW1. This relation can be used to determine the maximum pumping rate for the well.

The data from this step test can be simulated using the known pumping rates and the T and S values determined during the constant-rate test (figs. VX-B1 and VX-B2 in appendix VX-B).

Constant-Rate Test Analysis

The constant-rate test started at 10:30 am on June 10, and ended at 10:30 am on June 16, 2010 for a total pumping time of 144 h. The time-weighted average pumping rate was 13.7 gpm. The maximum recorded pumping rate was 14.4 gpm and the minimum recorded pumping rate was 12.9 gpm. Thus, the maximum deviation from average was 6.1 percent. The maximum recorded drawdown in well PW1 was 70.83 ft. Drawdown in well PW1 showed a rapid initial increase, but the rate slowed as pumping continued. Drawdown was still increasing slightly at the end of the test. After pumping ceased, well PW1 exhibited rapid recovery, with water levels reaching 90 percent recovery in less than 5 min.

Drawdown in all observation wells mirrored the drawdown in the production well except that the magnitude was less, and more time was required for 90 percent recovery. Maximum drawdown values in each well (table VX3; figs. VX17, VX18) show that the magnitude of drawdown was not strongly influenced by direction (i.e., there is little anisotropy).

Table VX3
Maximum Drawdown Values—Constant-Rate Test
Valley Excavating Aquifer Test—June 2010

Well	**Maximum Drawdown (ft)**	**Distance from PW1 (ft)**
PW1	70.83	—
OW1	2.74	25.4
OW2	1.92	99.4
OW3	2.28	24.8
OW4	2.16	100.5
OW5	2.14	25.1
Pre-existing	0.00	1,507

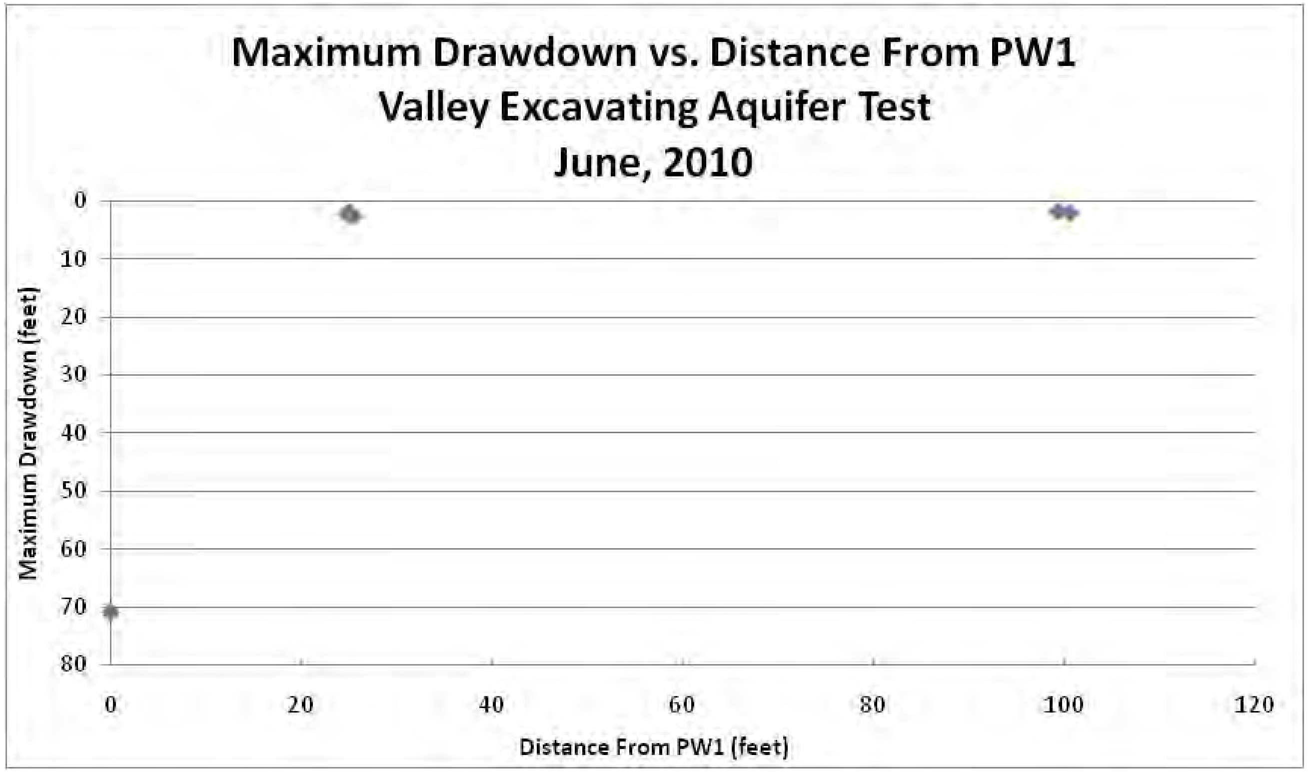

Figure VX17. Maximum drawdown (ft) observed during the Valley Excavating Aquifer test (pre-existing well not included).

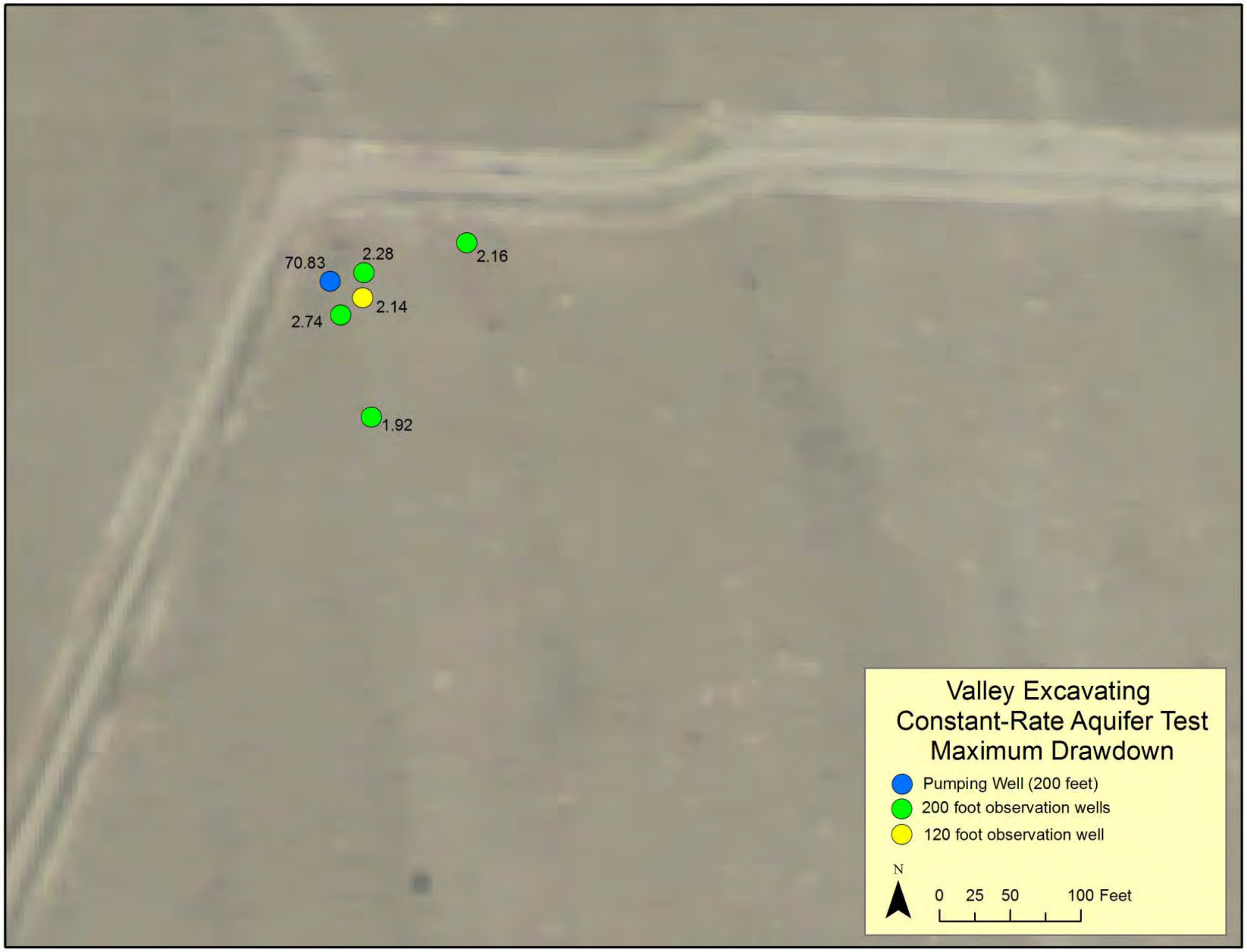

Figure VX18. Maximum drawdown (ft) observed during the Valley Excavating Aquifer test.

Data from the 144-h aquifer test were analyzed using multiple methods to determine aquifer transmissivity and storage values. Evaluation of log-log plots of drawdown vs. time shows a weak unconfined response (figs. VX-A1–VX-A6; Freeze and Cherry, 1979, pg 346). Data from OW1 were analyzed using the Neuman method for unconfined aquifers (Neuman, 1975, ASTM Standard D5920-96, 2005) and the Cooper–Jacob straight-line method (Cooper and Jacob, 1946; Jacob, 1950; Fetter, 1994; and ASTM Standard D4105-96, 2008). This analysis showed that when data after 1 d are used, the results are identical. Therefore, the Cooper–Jacob method alone was used to interpret data from all other wells, and only data collected after 1 d were considered. Analysis plots are included as appendix VX-A.

The geometric mean of the transmissivity values (T) is 360 ft^2/d. Results ranged from 332 to 391 ft^2/d. Given that the saturated thickness in PW1 is 120 ft, the geometric mean hydraulic conductivity (K) = 3.0 ft/d (fig. VX19; table VX4). The drawdown data from the pumping well (PW1) were not analyzed due to excessive noise.

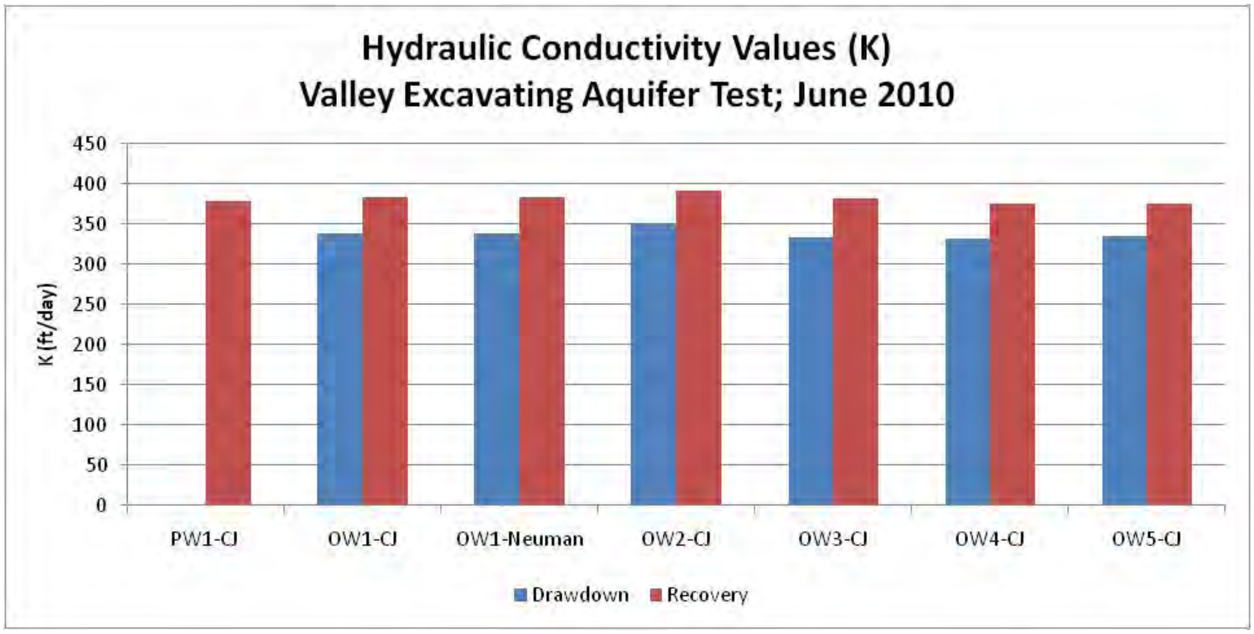

Figure VX19. Hydraulic conductivity values calculated from Valley Excavating Aquifer test data.

Table VX4
Transmissivity and Hydraulic Conductivity Values
Calculated using the Cooper–Jacob and Neuman Methods
Valley Excavating Aquifer Test—June 2010

Well	Transmissivity (T, ft^2/d)		Hydraulic Conductivity (K, ft/d)	
	Drawdown	Recovery	Drawdown	Recovery
PW1 - CJ	***	378	***	3.15
OW1-CJ	338	382	2.82	3.18
OW1 - Neuman	338	382	2.82	3.18
OW2 - CJ	351	390	2.93	3.25
OW3 - CJ	334	381	2.78	3.18
OW4 - CJ	332	375	2.76	3.12
OW5 - CJ	334	375	2.78	3.13
Geometric Mean T		360	Geometric Mean K	3.00
Minimum T		332	Minimum K	2.76
Maximum T		391	Maximum K	3.26

K is calculated using a saturated thickness of 120 ft, as seen in PW1.
*** = Indicates too much noise to make a reliable calculation.

The average of the storage coefficients (S) is 0.113, and results ranged from 0.015 to 0.269 (fig. VX20; table VX5). The wide range is believed to be dependent on fractures with high S values from wells that intersect substantial fractures connected to the pumping well, and low values from those that do not. Note that S in the two wells furthest from PW1 (OW2 and OW4) are substantially lower than S in wells near PW1, emphasizing the dependence on interconnected fractures. These low values (~0.02) more likely represent the formation's bulk storativity because the values integrate a relatively long flow path.

The data from the observation wells were also evaluated using a Cooper–Jacob Composite Plot (fig. VX21), where all observation wells can be plotted as drawdown (dh) vs. time divided by distance squared (t/r^2). In an ideal setting, all observations would fall on a single straight line when drawdown is on an arithmetic scale and t/r^2 is on a logarithmic scale. The slope of the straight line gives the transmissivity, and the X intercept is used to calculate storativity. The slope of the late time data for all wells is consistent; however, the X intercept is variable. Since the X intercept reflects storativity, this again demonstrates the dependence of storage on the fracture pattern. From the consistent slopes $T = 350$ ft^2/d. Given a saturated thickness of 120 ft, $K = 2.9$ ft/d. Using the highest and lowest X intercepts, storativity values were estimated to be between 0.01 and 0.32.

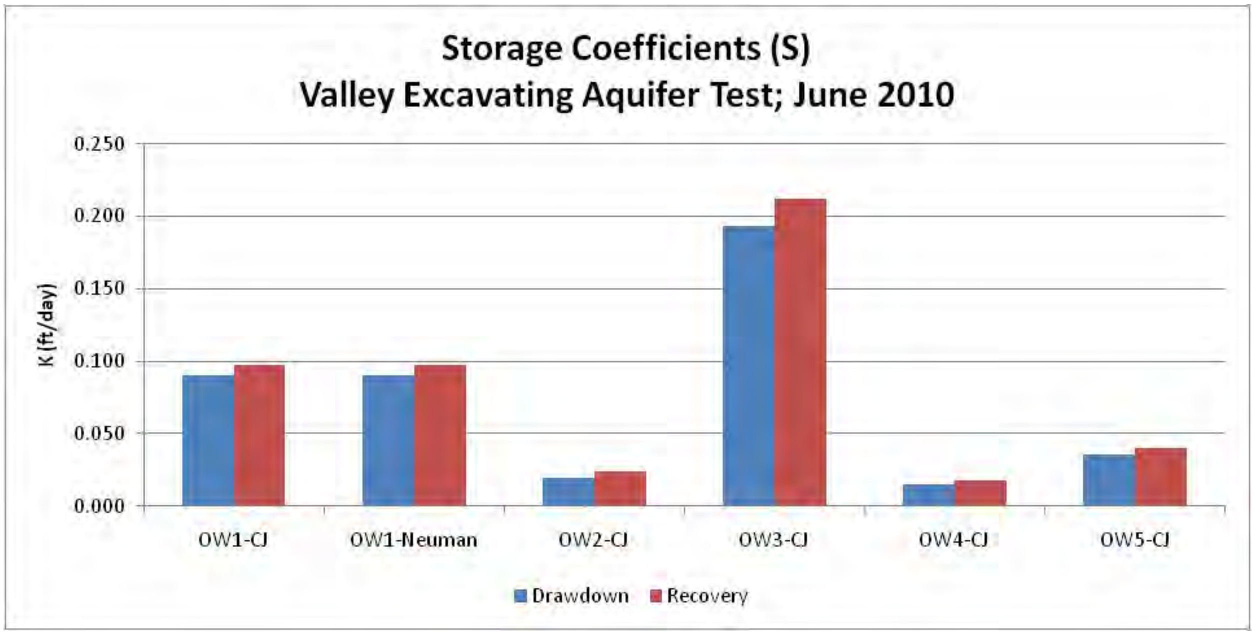

Figure VX20. Storage coefficients calculated from Valley Excavating Aquifer test data.

Table VX5
Storage Coefficients
Calculated using the Cooper–Jacob and Neuman Methods
Valley Excavating Aquifer Test—June 2010

Well	**Storage Coefficient (S)**	
	Drawdown	**Recovery**
OW1-CJ	0.090	0.097
OW1 - Neuman	0.090	0.097
OW2-CJ	0.019	0.024
OW3-CJ	0.193	0.212
OW4-CJ	0.015	0.018
OW5-CJ	0.036	0.040
	Average S	0.08
	Minimum S	0.015
	Maximum S	0.212

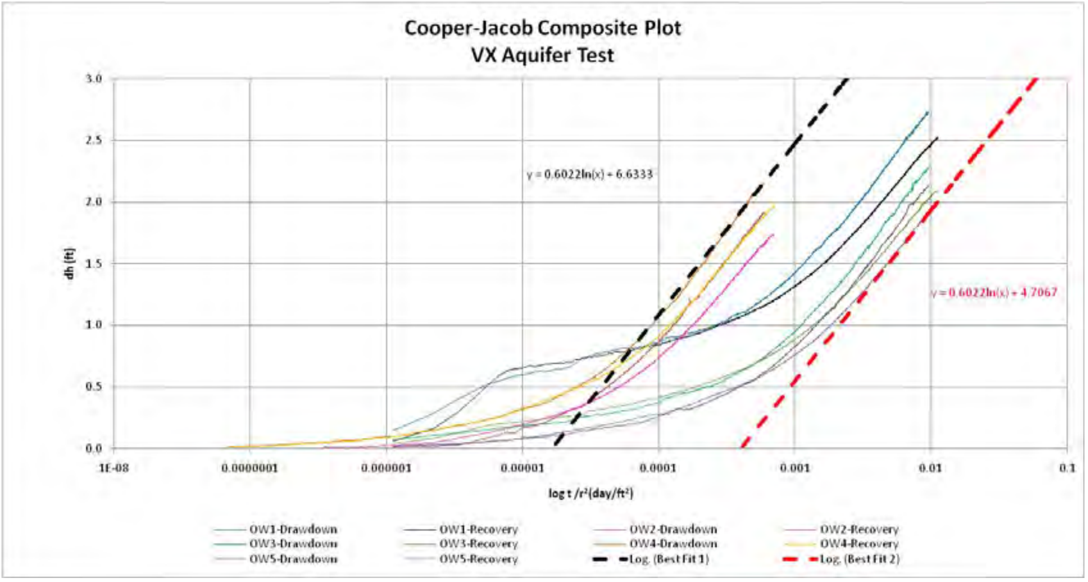

Figure VX21. Cooper–Jacob composite plot.

The Valley Excavating test data were also analyzed using AQTESOLV, which resulted in T = 350 ft^2/d, and storativity values ranged from 0.012 to 0.30 (appendix VX-B).

The recovery data were also assessed using the Cooper–Jacob (1946) straight line analysis method. The plotted recovery data are shown in figure VX22. A line was fit to the data, using the best straight-line portion of the curves, and with the x-intercept at 1 (x=1, y=0), to avoid the effects of boundaries (drawdown should go to zero as time becomes infinite, unless boundaries affect the data). In this analysis T = 333 ft^2/d and K = 2.8 ft/d.

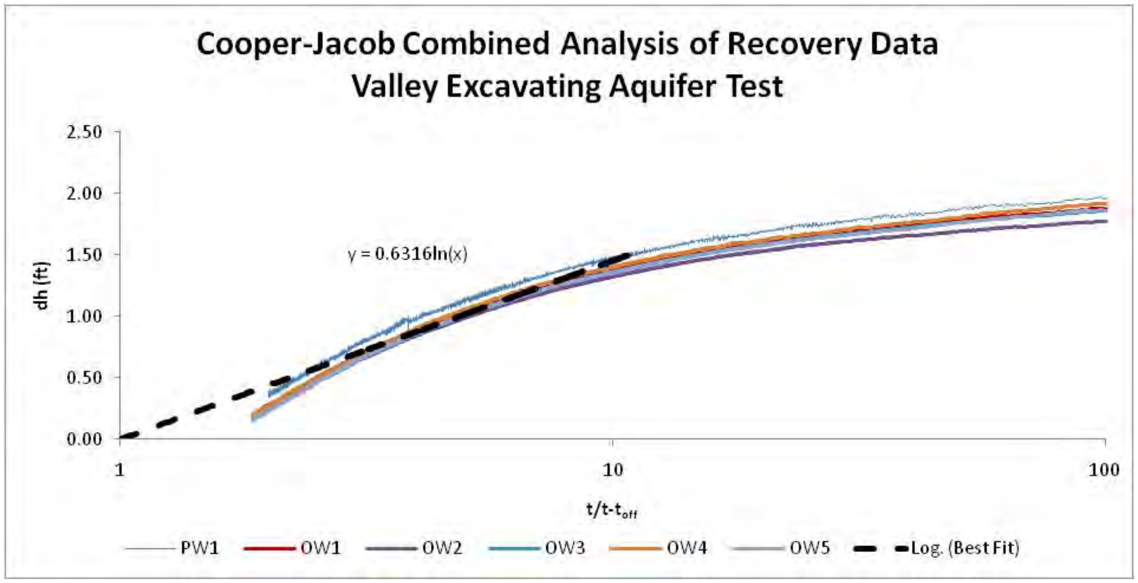

Figure VX22. Cooper–Jacob analysis of recovery data.

Summary

Analysis of this aquifer test indicates that the Spokane Formation at this site has a transmissivity (T) of about 350 ft^2/d, and a hydraulic conductivity (K) of about 3 ft/d. Storativity values (S) vary, ranging from 0.01 to 0.2. Storativity values apparently depend on the fracture geometry between the observation and pumping wells. A representative bulk S value is approximately 0.02. Because T is determined by the total volume of aquifer pumped, those values are much more consistent. Based on evaluation of the drawdown curves and the resulting storativity values, this aquifer is considered to be semi-confined to unconfined at this location. The aquifer also appears to be isotropic and approximates a porous media (despite the fracture pattern). Vertical flow barriers were not evident in the analyses.

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APPENDIX VX-A

LOG-LOG AND SEMI-LOG PLOTS OF DRAWDOWN
VS.
TIME

FOR THE

VALLEY EXCAVATING AQUIFER TEST

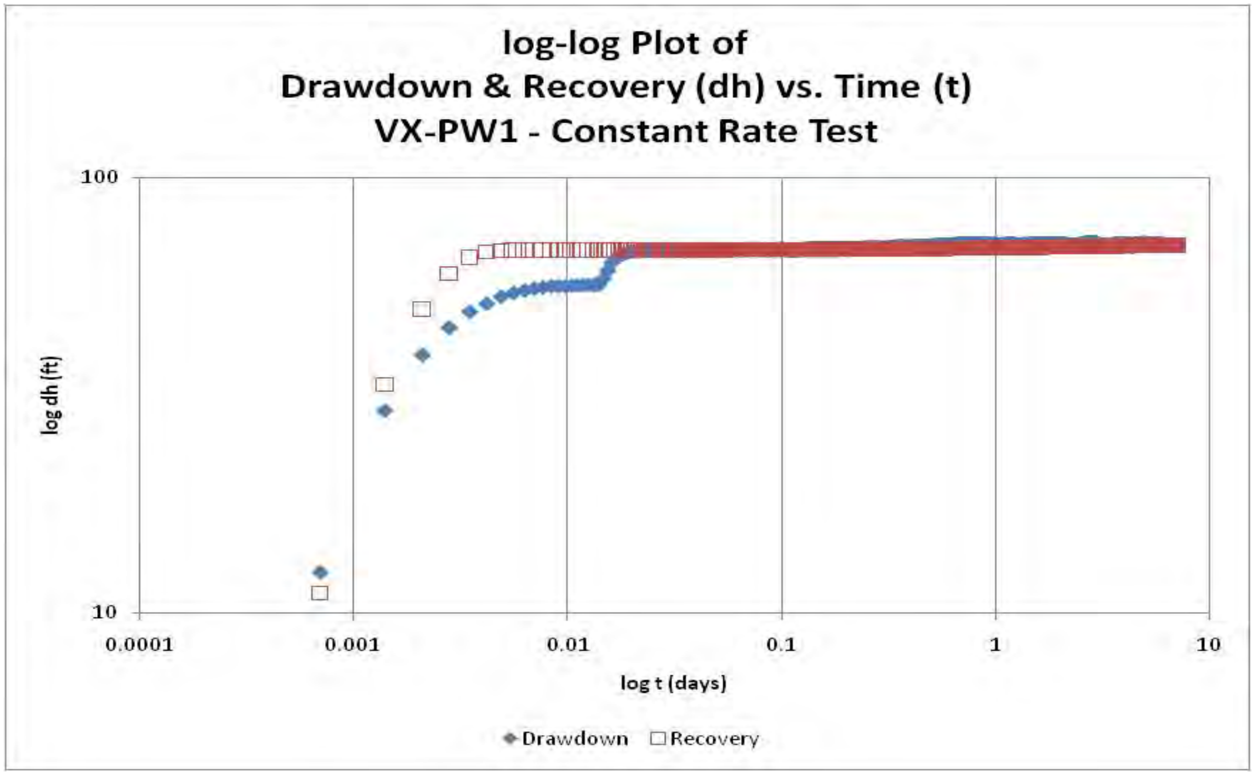


Figure VX-A1. Log-log plot of drawdown and recovery data from Valley Excavating PW1 (pumping well).

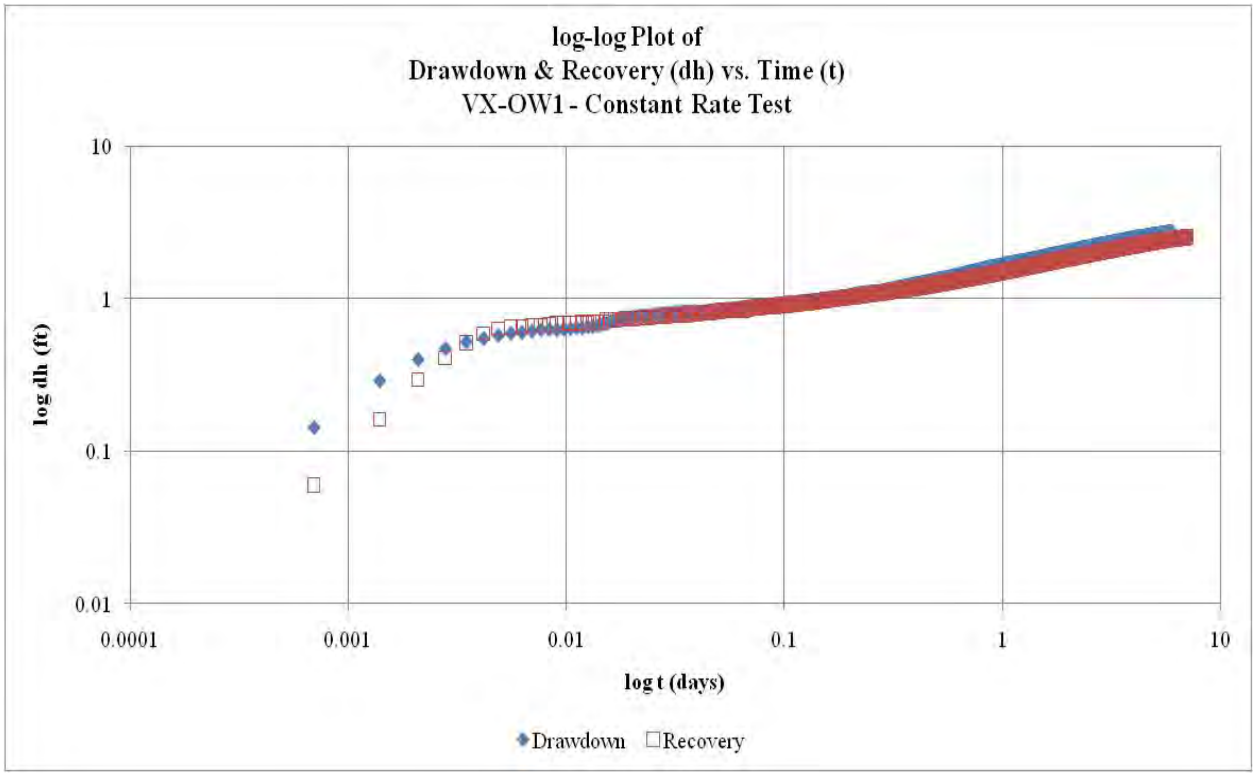


Figure VX-A2. Log-log plot of drawdown and recovery data from Valley Excavating OW1 (25.4 ft from PW1).

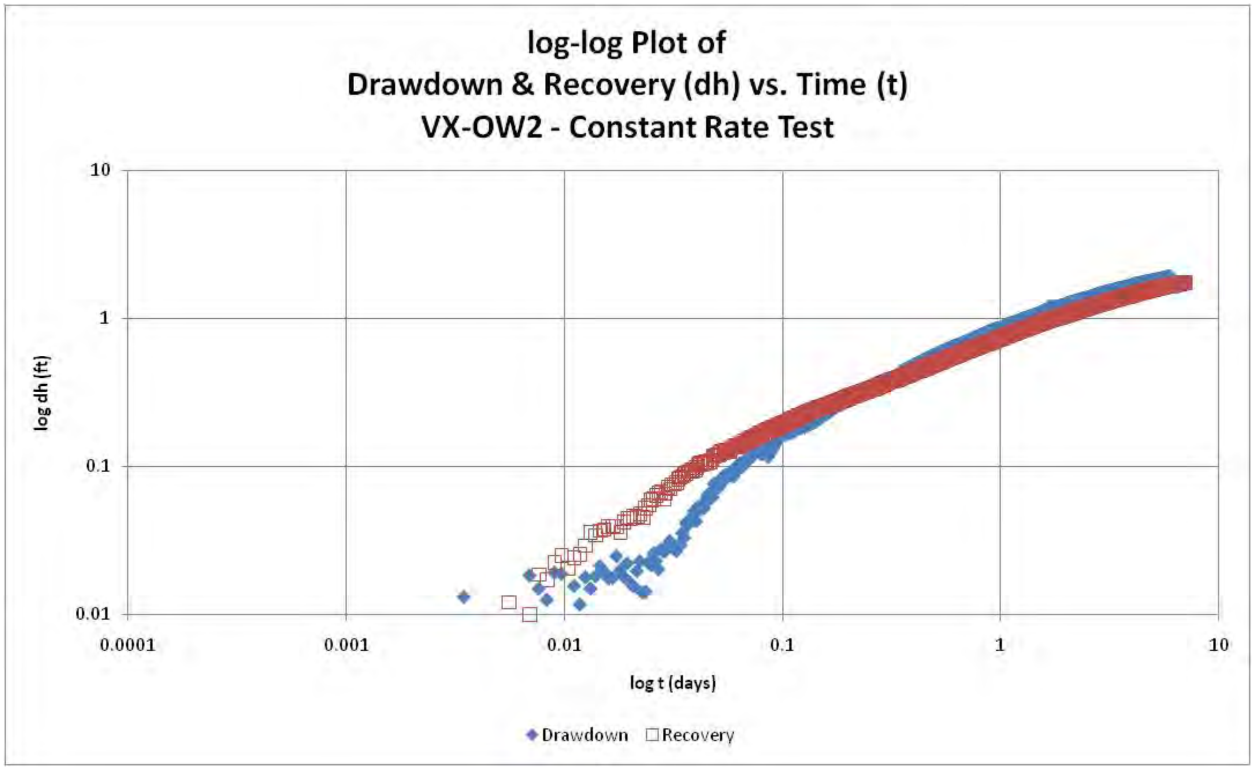


Figure VX-A3. Log-log plot of drawdown and recovery data from Valley Excavating OW2 (99.4 ft from PW1).

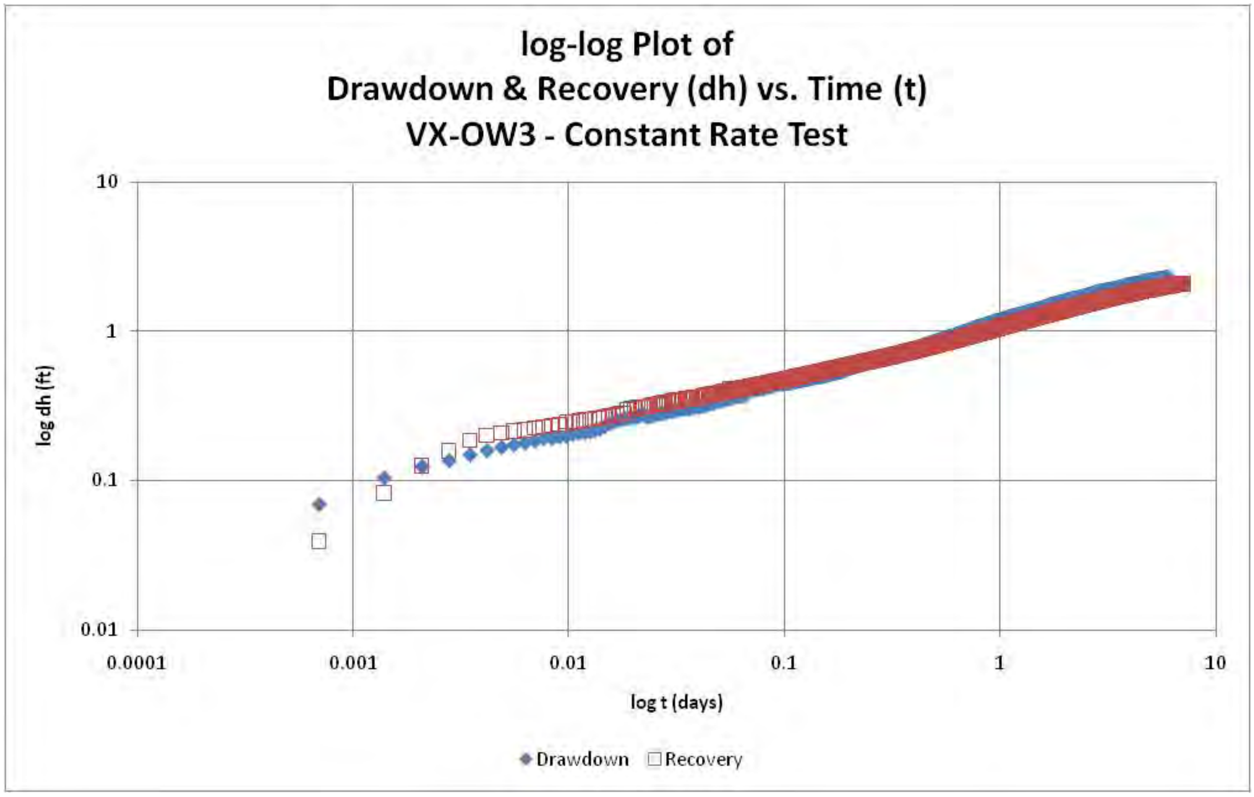


Figure VX-A4. Log-log plot of drawdown and recovery data from Valley Excavating OW3 (24.8 ft from PW1).

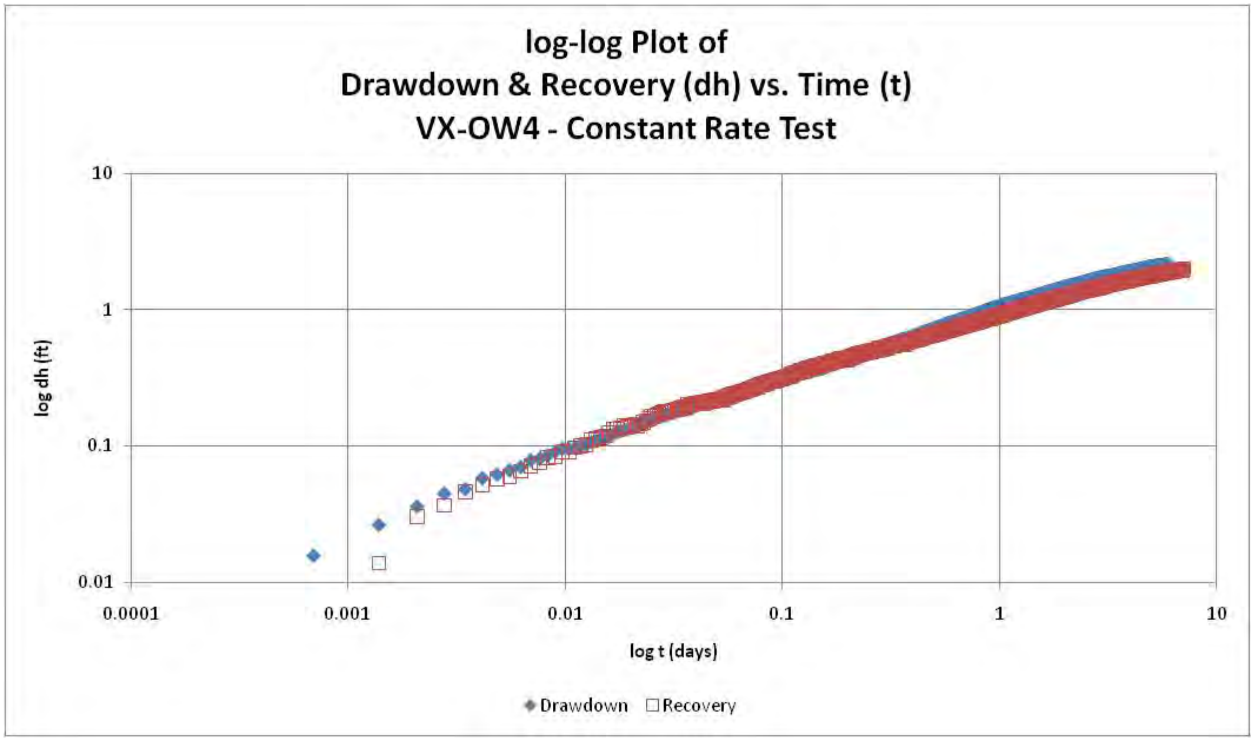


Figure VX-A5. Log-log plot of drawdown and recovery data from Valley Excavating OW4 (100.5 ft from PW1).

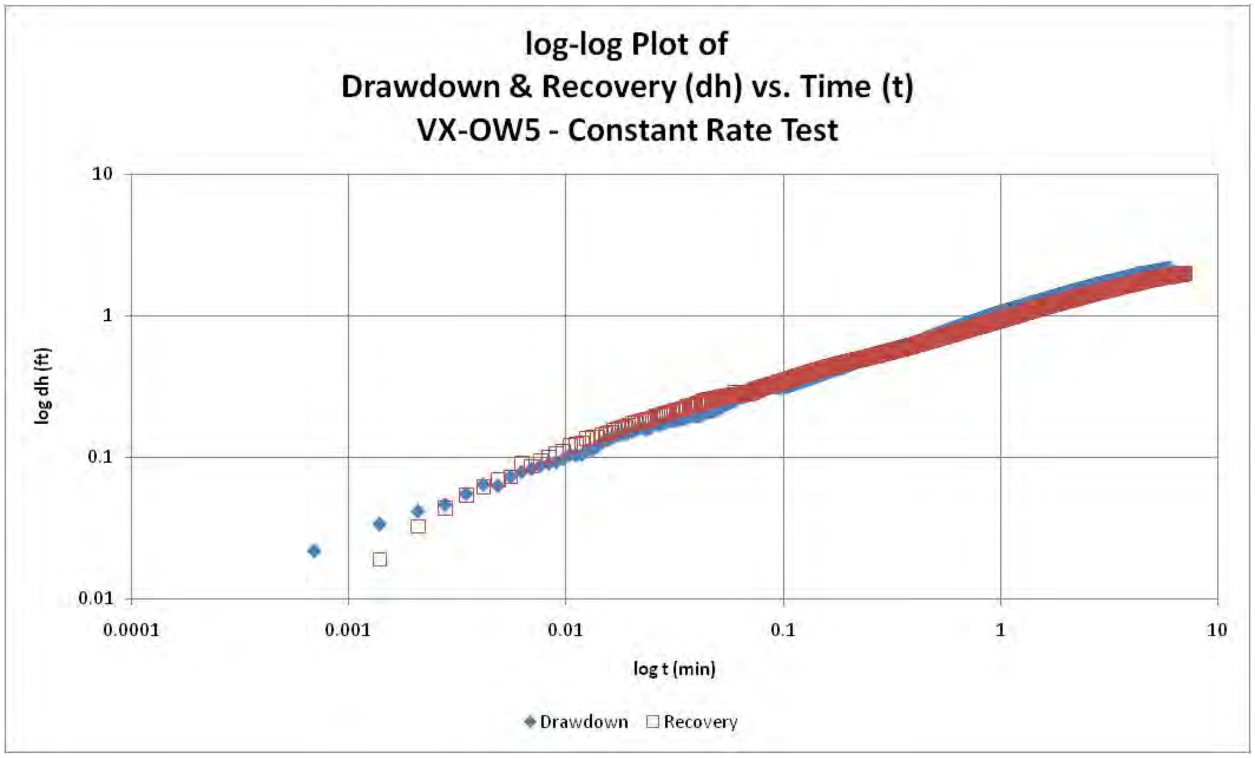


Figure VX-A6. Log-log plot of drawdown and recovery data from Valley Excavating OW5 (25.1 ft from PW1).

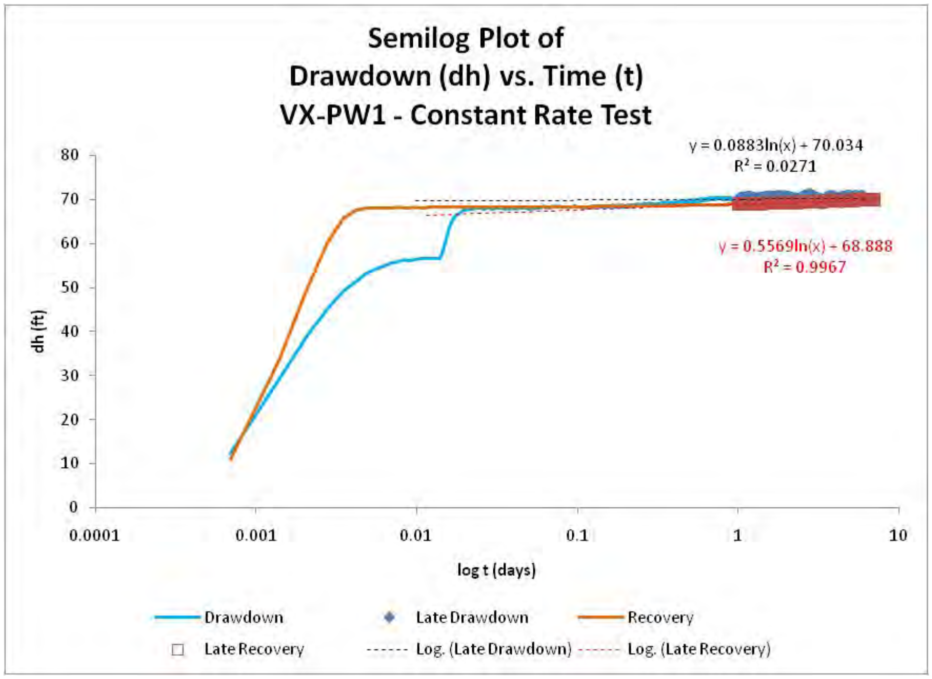


Figure VX-A7. Semi-log plot of Valley Excavating drawdown and recovery data (Cooper–Jacob method) from PW1 (pumping well). Only recovery data were analyzed. Late data (>1 d) used in analysis.

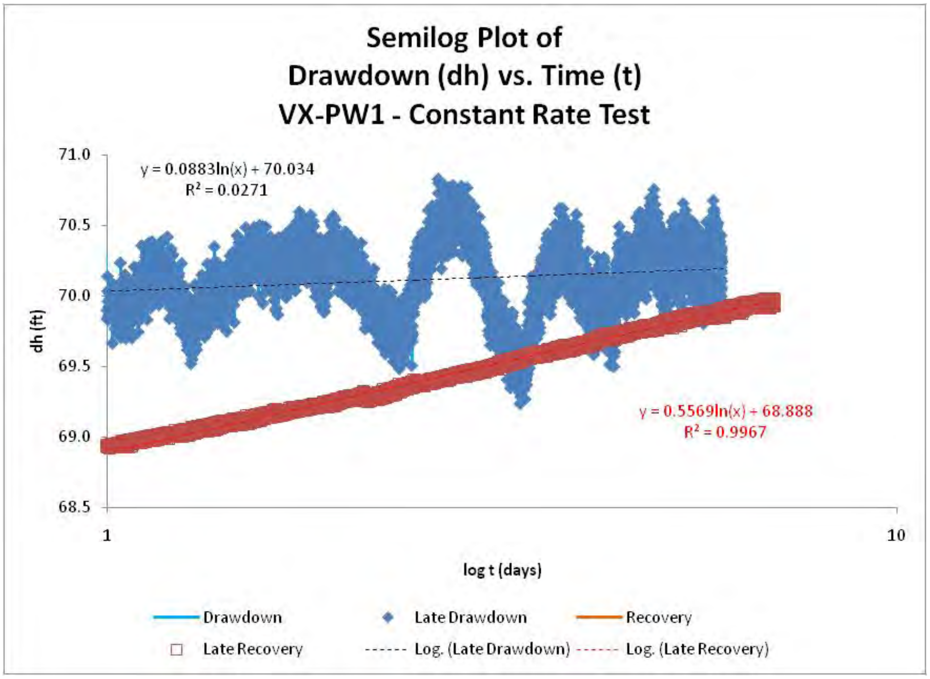


Figure VX-A8. Close up of late Valley Excavating data on semi-log plot of drawdown and recovery data (Cooper–Jacob method) from PW1 (pumping well). Only recovery data were analyzed.

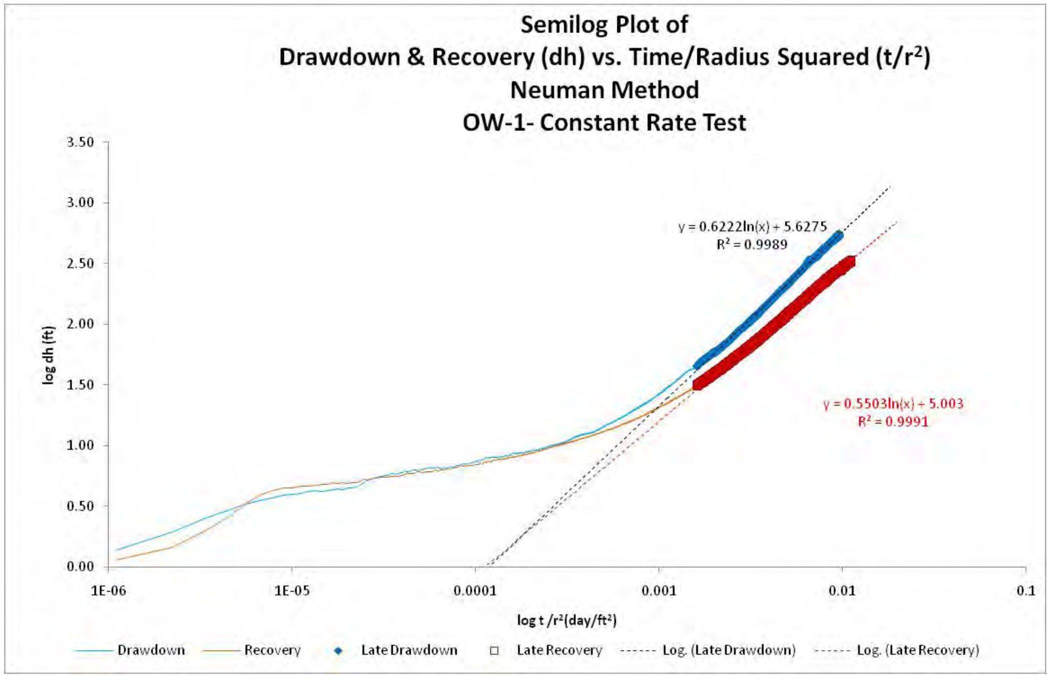


Figure VX-A9. Semi-log plot of drawdown and recovery data from Valley Excavating OW1 vs. time/distance squared (Neuman method) (25.4 ft from PW1). Late data are >1 d.

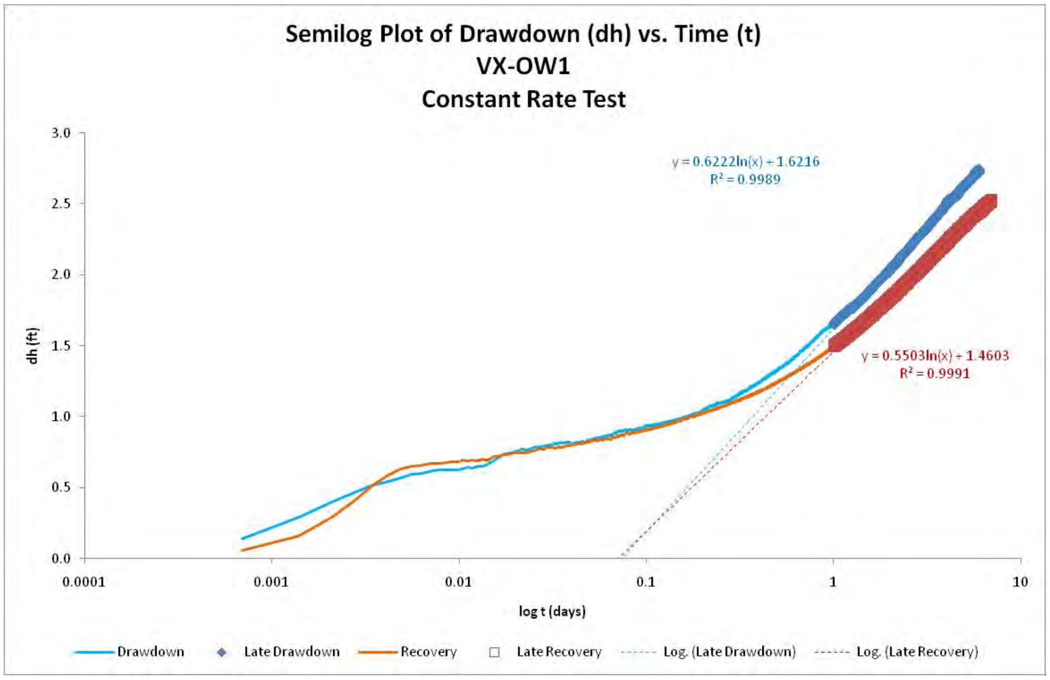


Figure VX-A10. Semi-log plot of drawdown and recovery data (Cooper–Jacob method) from Valley Excavating OW1 (25.4 ft from PW1).

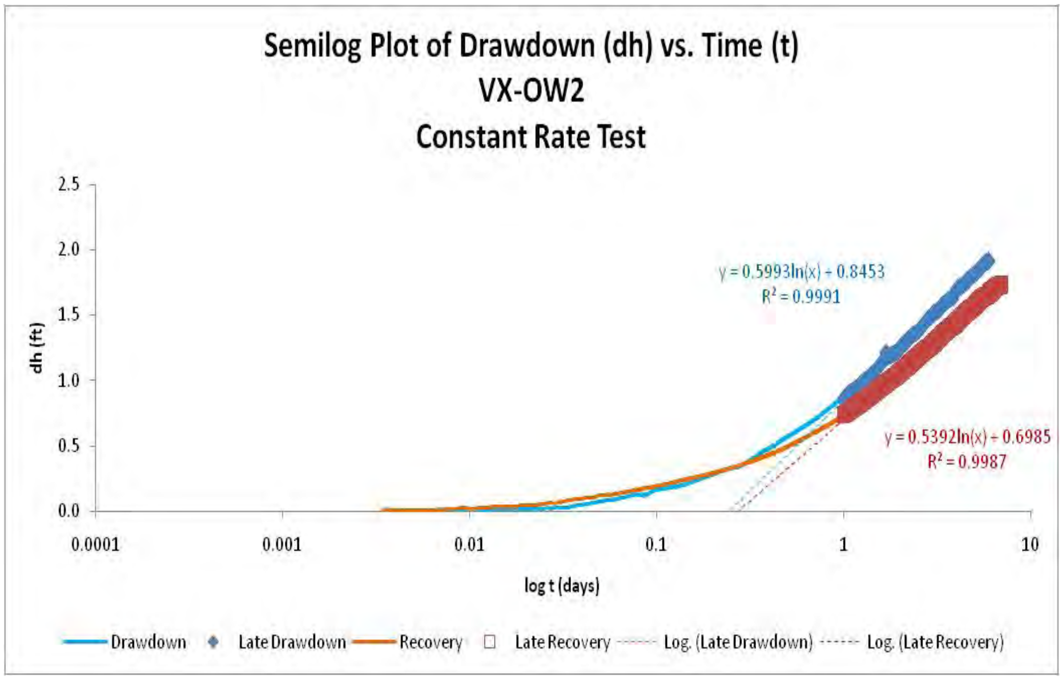


Figure VX-A11. Semi-log plot of drawdown and recovery data (Cooper–Jacob method) from Valley Excavating OW2 (99.4 ft from PW1).

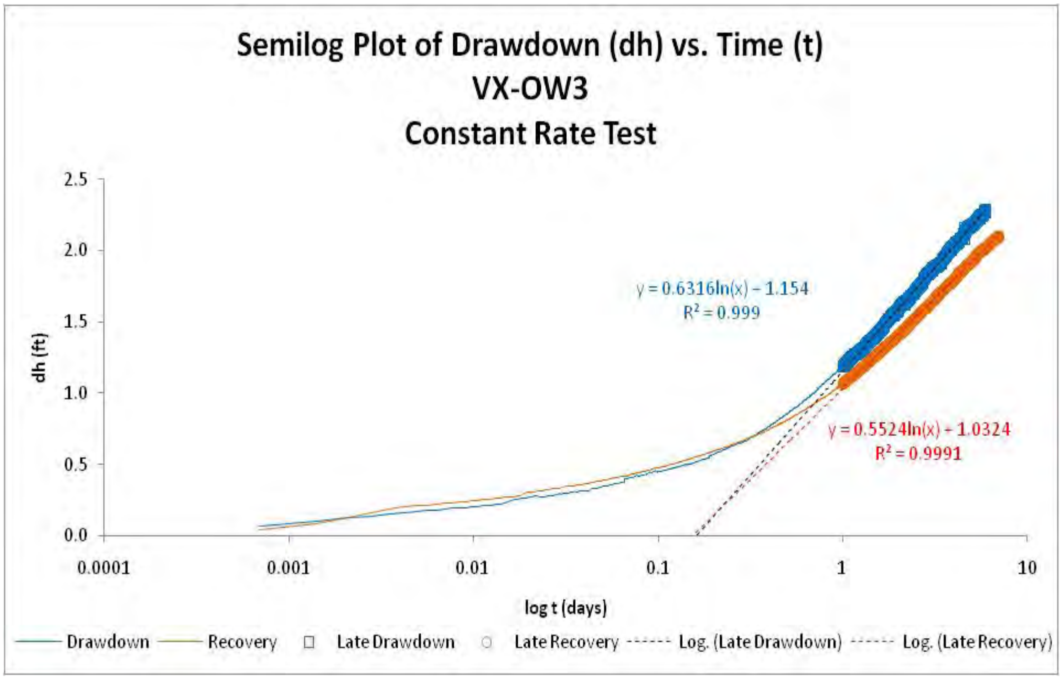


Figure VX-A12. Semi-log plot of drawdown and recovery data (Cooper–Jacob method) from Valley Excavating OW3 (24.8 ft from PW1).

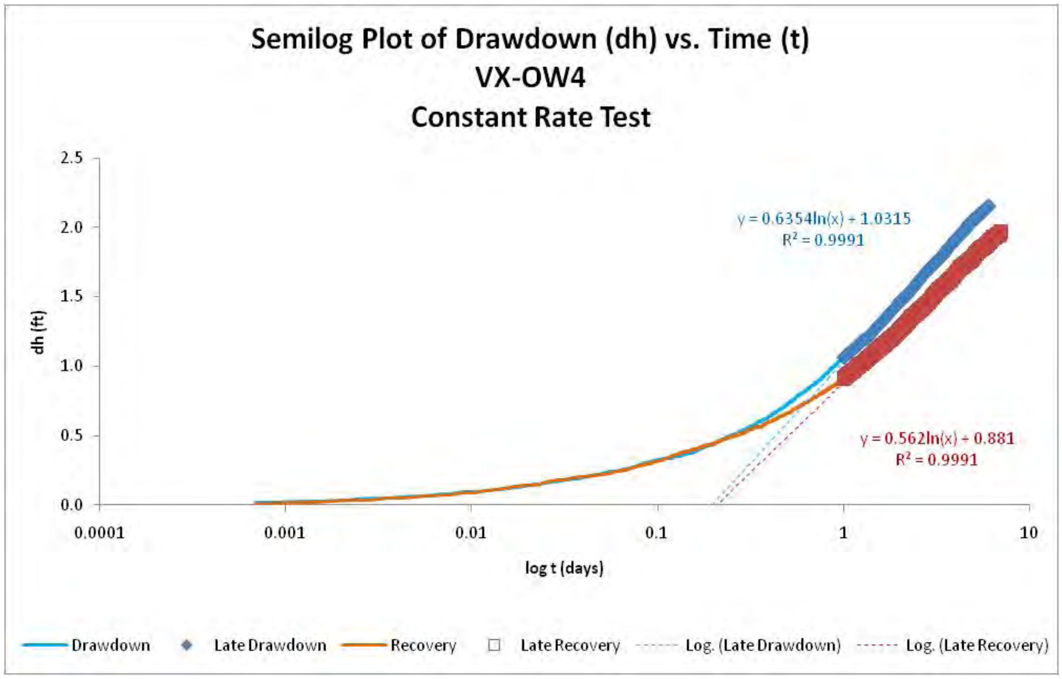


Figure VX-A13. Semi-log plot of drawdown and recovery data (Cooper–Jacob method) from Valley Excavating OW4 (100.5 ft from PW1).

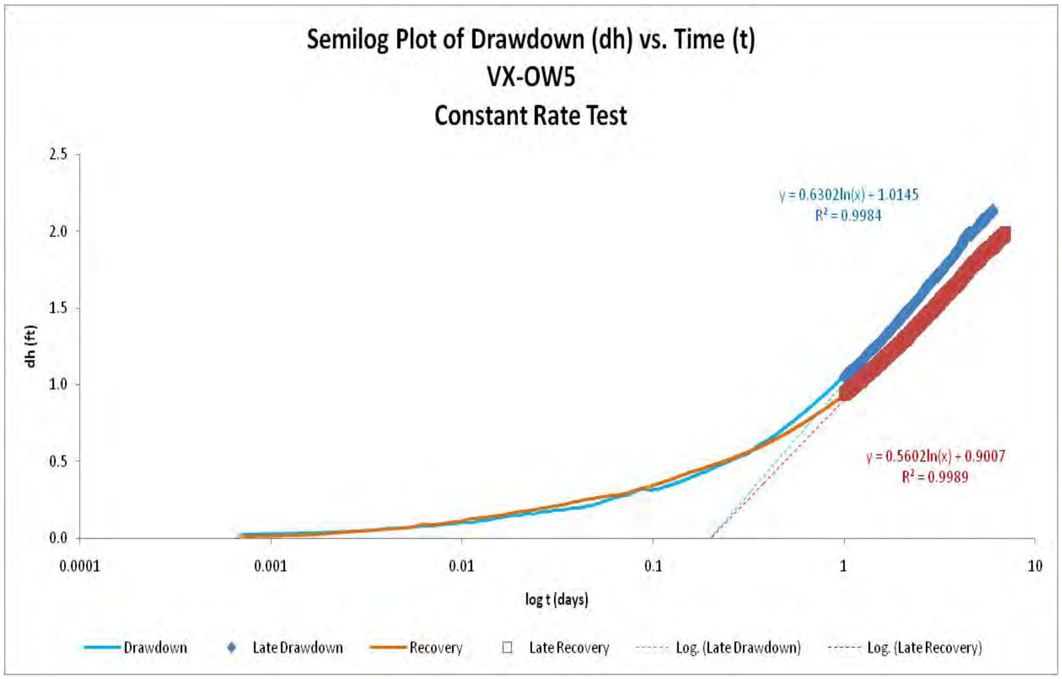
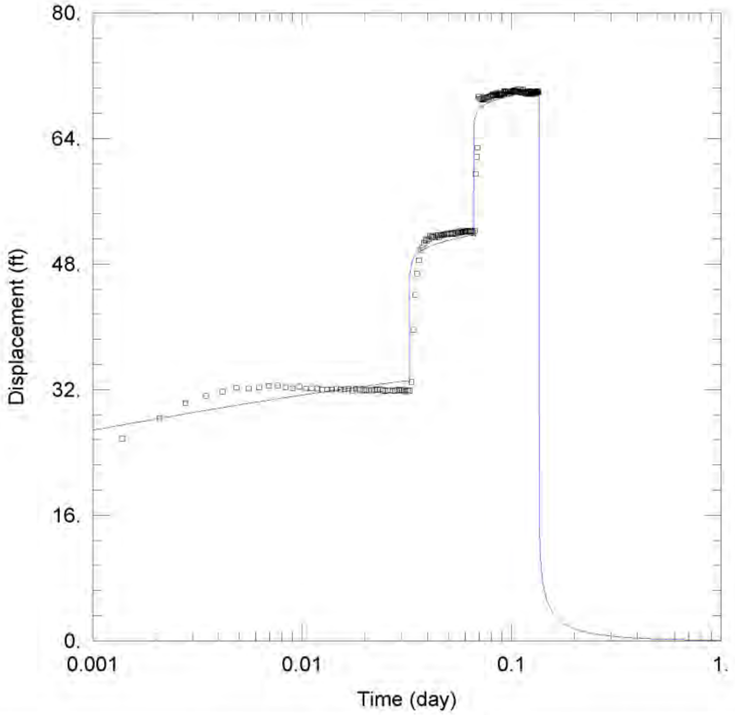


Figure VX-A14. Semi-log plot of drawdown and recovery data (Cooper–Jacob method) from Valley Excavating OW5 (25.1 ft from PW1).

APPENDIX VX-B
RESULTS FROM
AQTESOLV
ANALYSIS
FOR THE
VALLEY EXCAVATING AQUIFER TEST



VX AQUIFER TEST

Data Set: M:\Gwip\Projects\North Hills\Data\VX-Pumptest\Aqtesolv\A-1_Steptest\VX_Steptest_Theis.aqt
Date: 02/18/11 Time: 09:07:30

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ PW1	0	0

SOLUTION

Aquifer Model: Confined

Solution Method: Theis (Step Test)

T = 350. ft^2/day

S = 0.054

Sw = 1.58

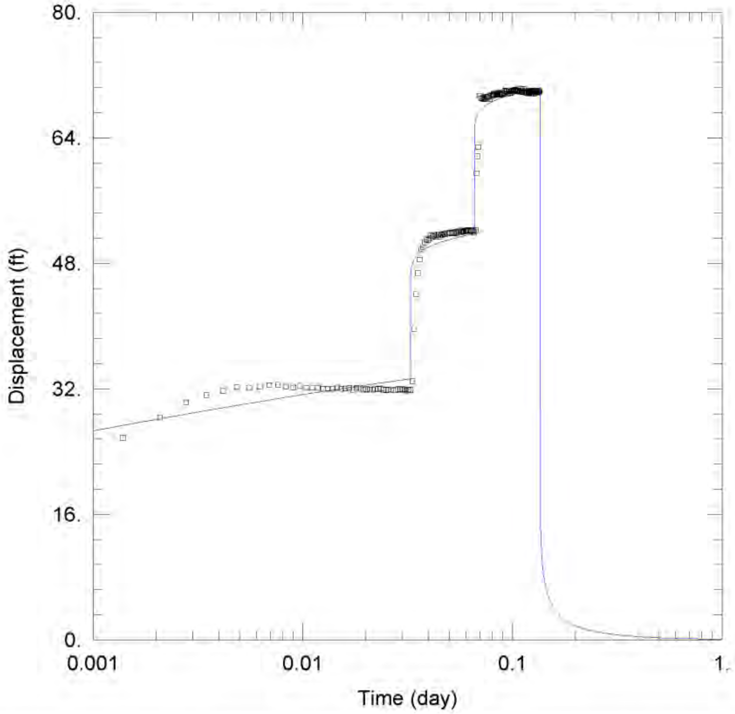
C = 5.253E-6 day^2/ft^5

P = 1.936

Step Test Model: Jacob-Rorabaugh

$s(t) = 0.0162Q + 5.253E\text{-}6Q^{1.936}$

Figure VX-B1. Step test simulation using T and S values determined during the drawdown portion of the Valley Excavating constant-rate test.



VX AQUIFER TEST

Data Set: M:\Gwip\Projects\North Hills\Data\VX-Pumptest\Aqtesolv\A-1_Steptest\VX_Steptest_Theis.aqt
Date: 02/18/11 Time: 09:47:35

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ PW1	0	0

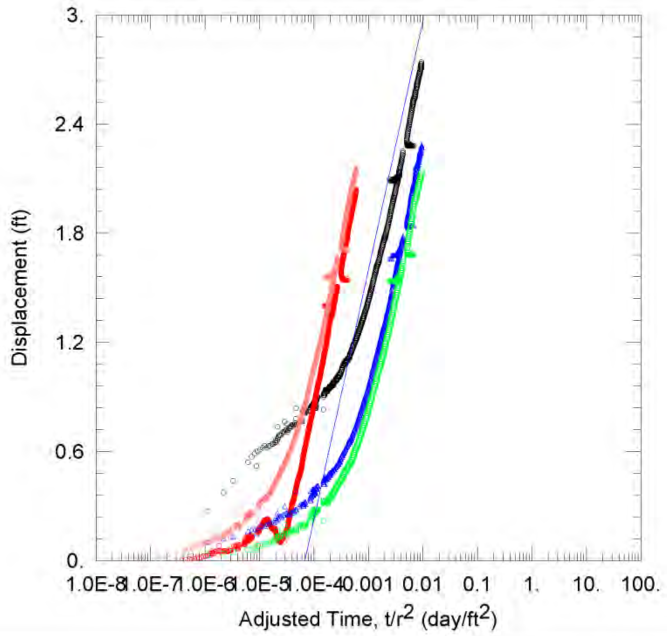
SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 350. ft^2/day
S = 0.0806
Sw = 1.768
C = 5.681E-6 day^2/ft^5
P = 1.923

Step Test Model: Jacob-Rorabaugh
$s(t) = 0.01661Q + 5.681E\text{-}6Q^{1.923}$

Figure VX-B2. Step test simulation using T and S values determined during the recovery portion of the Valley Excavating constant-rate test.



VX AQUIFER TEST

Data Set: M:\...\VX_Drawdown_CJ.aqt
Date: 02/18/11 Time: 09:00:38

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

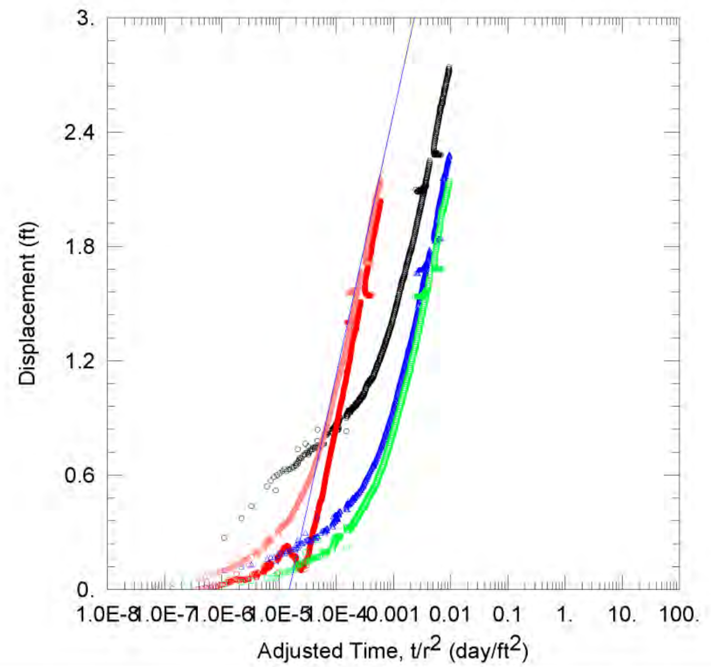
Observation Wells

Well Name	X (ft)	Y (ft)
○ OW1	0	-25
○ OW2	0	-100
○ OW3	25	0
○ OW4	100	0
○ OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined
Solution Method: Cooper-Jacob
T = 350. ft^2/day
S = 0.05424

Figure VX-B3. Cooper–Jacob analysis of composite drawdown data from the Valley Excavating test, solving for overall best fit.



VX AQUIFER TEST

Data Set: M:\...\VX_Drawdown_CJ.aqt
Date: 02/18/11 Time: 09:01:56

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

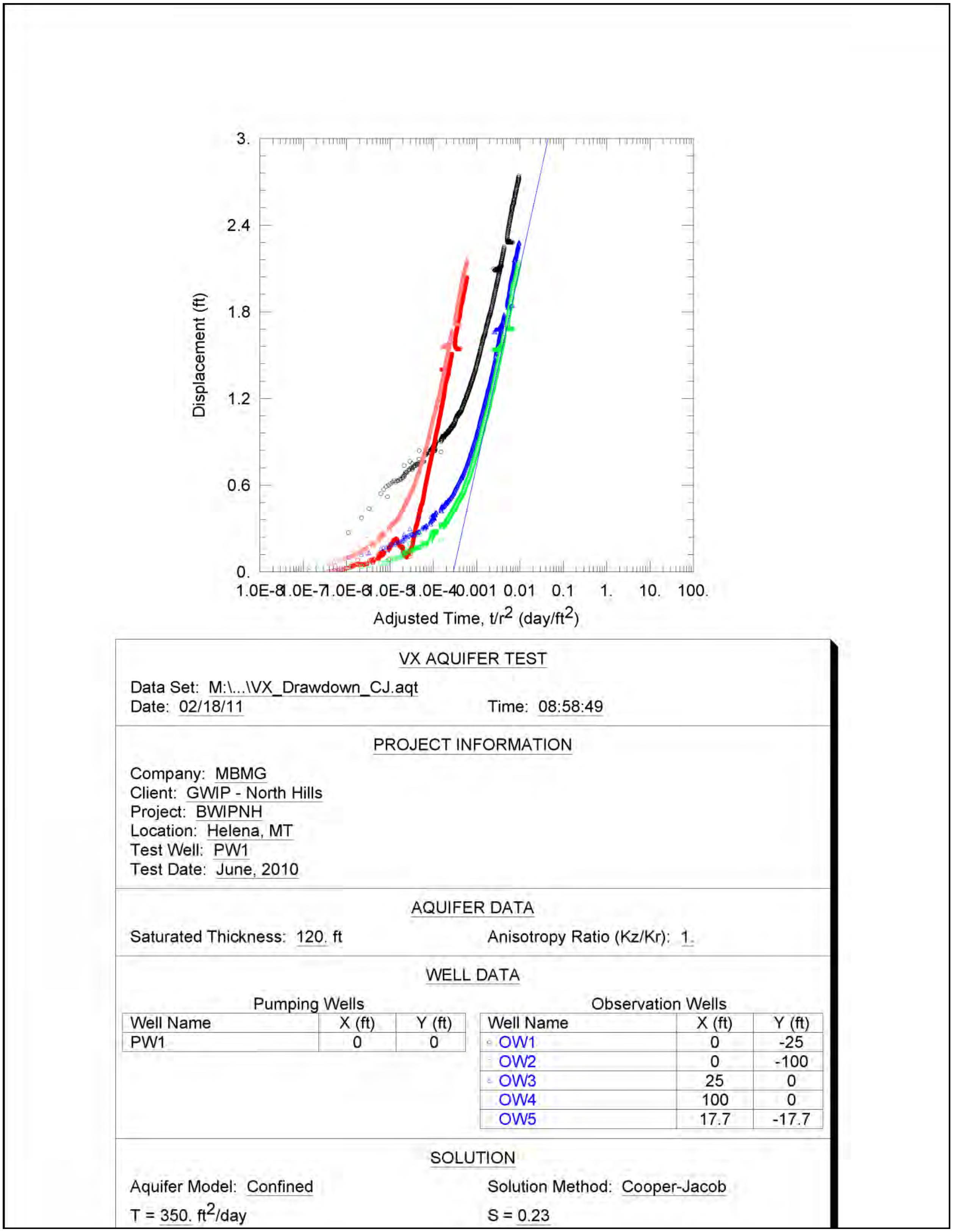
Observation Wells

Well Name	X (ft)	Y (ft)
OW1	0	-25
OW2	0	-100
OW3	25	0
OW4	100	0
OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob
T = 350. ft^2/day S = 0.012

Figure VX-B4. Cooper–Jacob analysis of composite Valley Excavating drawdown data, solving for minimum S.



VX AQUIFER TEST

Data Set: M:\...\VX_Drawdown_CJ.aqt
Date: 02/18/11 Time: 08:58:49

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

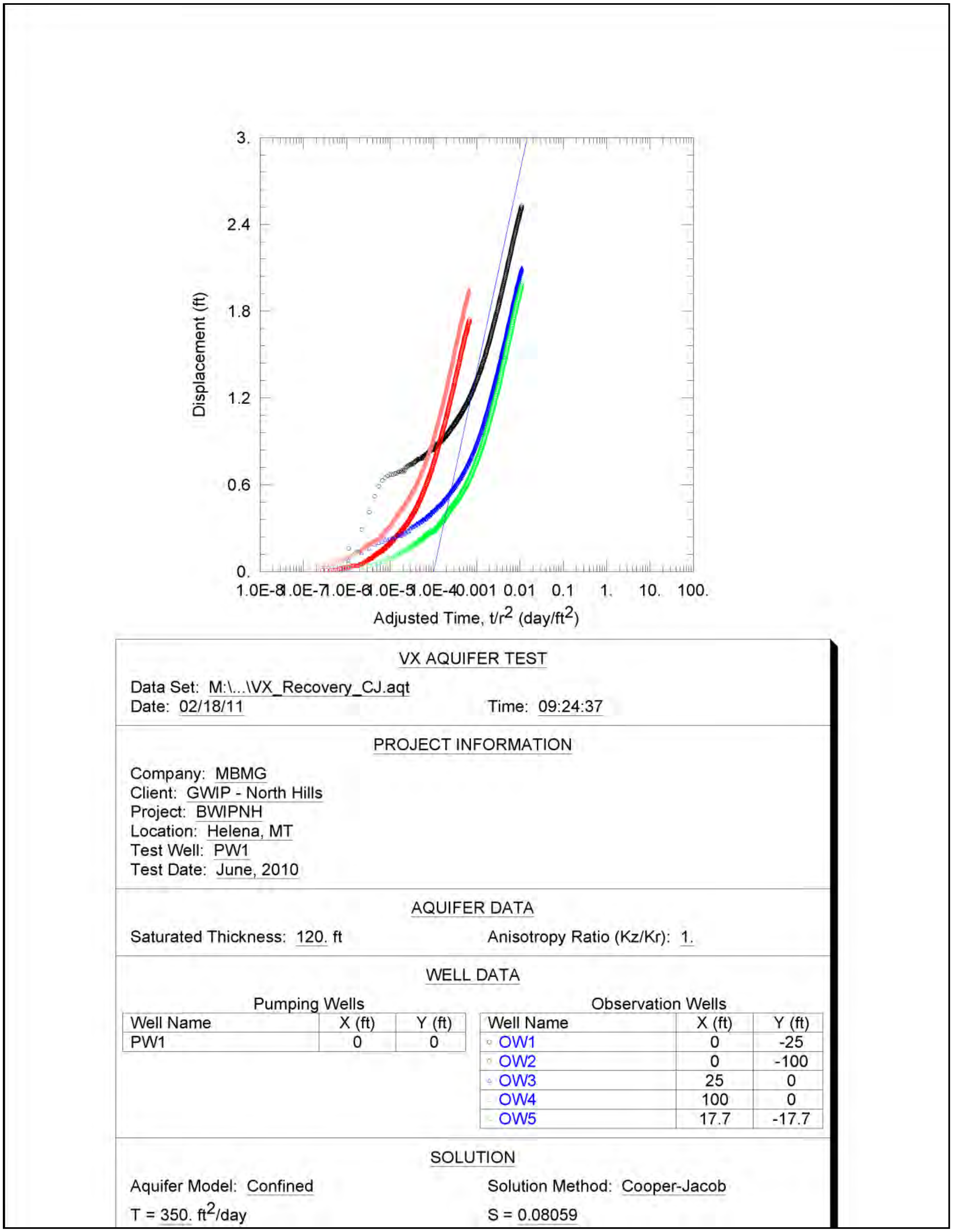
Well Name	X (ft)	Y (ft)
○ OW1	0	-25
OW2	0	-100
△ OW3	25	0
OW4	100	0
OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined
Solution Method: Cooper-Jacob

$T = 350.\ ft^2/day$
S = 0.23

Figure VX-B5. Cooper–Jacob analysis of Valley Excavating composite drawdown data, solving for maximum S.



VX AQUIFER TEST

Data Set: M:\...\VX_Recovery_CJ.aqt
Date: 02/18/11 Time: 09:24:37

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

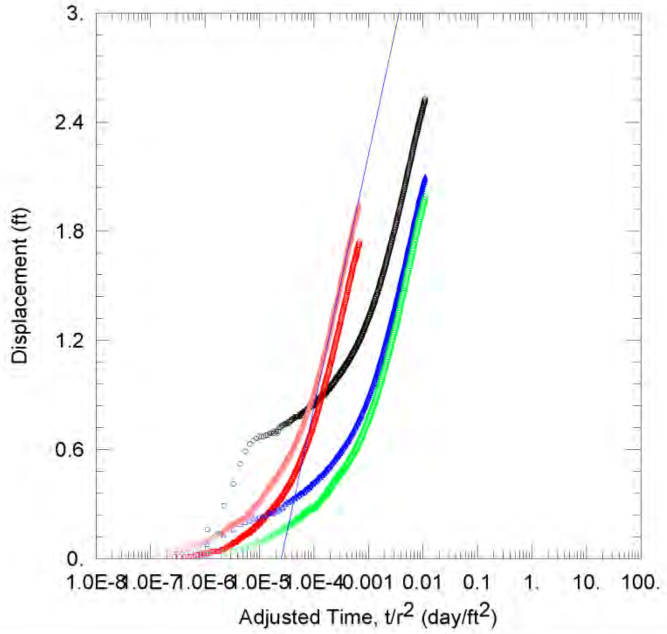
Well Name	X (ft)	Y (ft)
○ OW1	0	-25
○ OW2	0	-100
○ OW3	25	0
○ OW4	100	0
○ OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob

T = 350. ft^2/day S = 0.08059

Figure VX-B6. Cooper–Jacob analysis of composite Valley Excavating recovery data, solving for overall best fit.



VX AQUIFER TEST

Data Set: M:\...\VX_Recovery_CJ.aqt
Date: 02/18/11 Time: 09:25:33

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

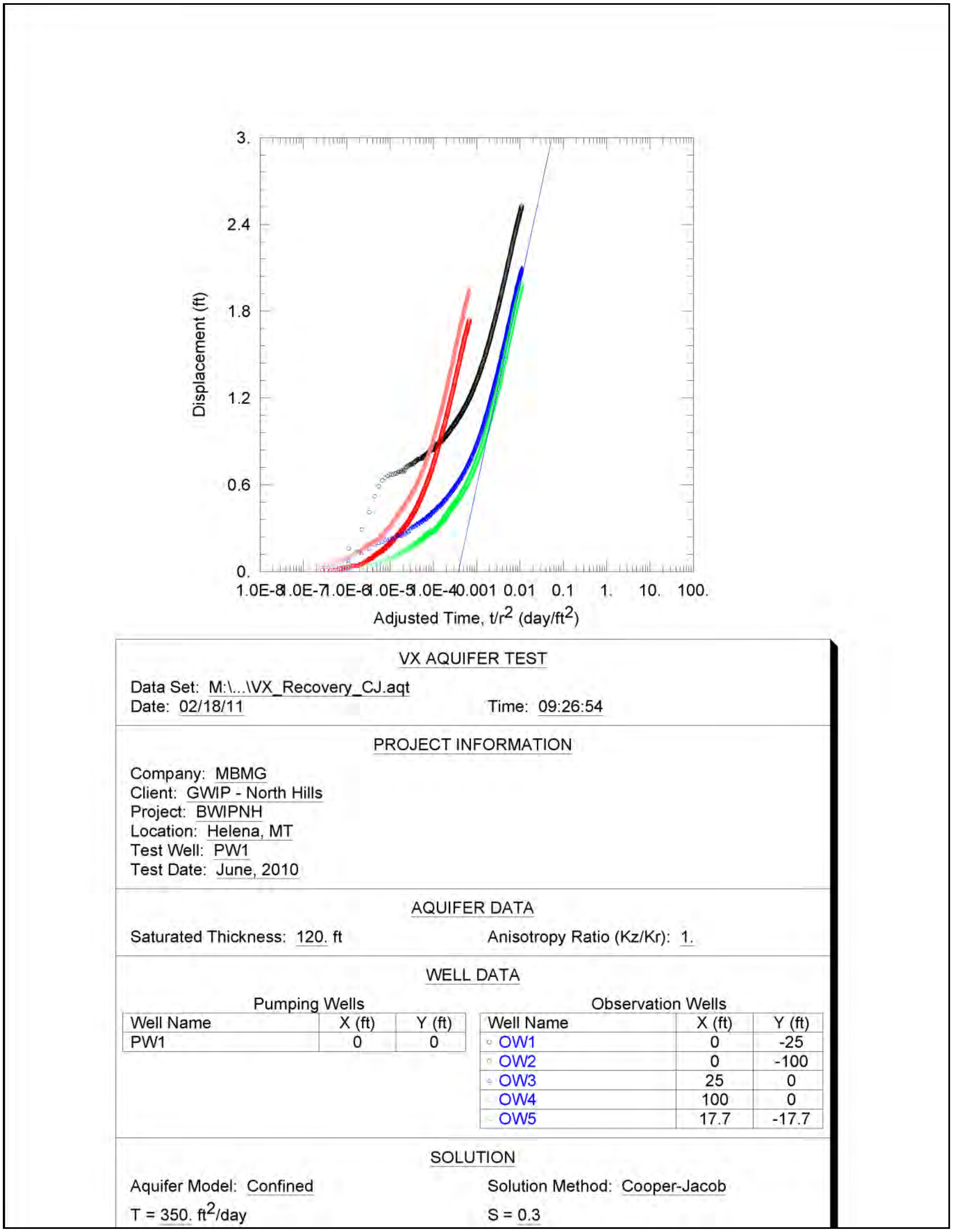
Well Name	X (ft)	Y (ft)
○ OW1	0	-25
○ OW2	0	-100
○ OW3	25	0
○ OW4	100	0
○ OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob

$T = 350.\ ft^2/day$ S = 0.02

Figure VX-B7. Cooper–Jacob analysis of Valley Excavating composite recovery data, solving for minimum S.



VX AQUIFER TEST

Data Set: M:\...\VX_Recovery_CJ.aqt
Date: 02/18/11 Time: 09:26:54

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hills
Project: BWIPNH
Location: Helena, MT
Test Well: PW1
Test Date: June, 2010

AQUIFER DATA

Saturated Thickness: 120. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PW1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
○ OW1	0	-25
○ OW2	0	-100
○ OW3	25	0
○ OW4	100	0
○ OW5	17.7	-17.7

SOLUTION

Aquifer Model: Confined Solution Method: Cooper-Jacob

T = 350. ft^2/day S = 0.3

Figure VX-B8. Cooper–Jacob analysis of composite Valley Excavating recovery data, solving for maximum S.

O’REILLY AQUIFER TEST— GREYSON FORMATION

O’REILLY
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
March 2011

STEP TEST
AND
24-HOUR CONSTANT-RATE TEST

Background

The following is an analysis of a step test and a 24-h constant-rate pumping test performed using wells installed on the O'Reilly property in the North Hills study area. There is no development or groundwater usage in the immediate area of this aquifer test. The nearest residence is approximately 1,100 ft west of the test site, and homes in this area are on lots of 20 acres or more.

This test was designed to allow the vertical movement of water through the bedrock aquifer to be evaluated. One deep 4-in-diameter pumping well (ORD; GWIC 257066) and one shallow 4-in-diameter observation well (ORS; GWIC 257067) were installed at this site in July 2010. A MBMG geologist was present during installation; cuttings were described in detail, and completion details verified. Composite cuttings samples were collected, and described for each 5-ft interval in each well. Well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu); wells are identified by GWIC ID. A summary of completion details are provided in table OR1.

Transducers were deployed in these wells in August 2010 for long-term monitoring at a rate of one reading per hour. These background data are available on GWIC. The transducers were reprogrammed for 1-min intervals for the aquifer tests. Measurable drawdown was recorded in both wells.

Location

The test area is located in the northern part of the Helena Valley, on the dissected pediment, north of Lincoln Road and east of Interstate 15. Both wells are located in Township 11 N., Range 3 W., section 8, SW¼ NE¼ , in Lewis and Clark County, Montana (figs. OR1, OR2).

Geology

This area has been mapped as Spokane Formation (fig. OR3); however, cuttings and nearby outcrop indicate that the aquifer tested is the Greyson Formation. This unit is described by Reynolds (in Thamke, 2000) as "Siltite and argillite with quartzite in the uppermost part."

There are no known faults in the immediate vicinity of the test site; however, there is a mapped fault approximately 1,000 ft to the north, and it is suspected that another colluvium covered fault is located approximately 1,000 ft to the south (see Purcell Aquifer Test Report).

Table OR1

Well Designations, Locations, and Completion Information

O'Reilly Aquifer Test—March 2011

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 3/21/11 (ft below MP)	Groundwater Elevation 3/21/11 (ft-amsl)	Distance from ORD (ft)	Comments
257066	ORD	46.7294773	-112.0075062	3867.99	260	22.54	3845.45	—	Deep Pumping Well
257067	ORS	46.7294810	-112.0076250	3868.73	45	22.81	3845.92	30	Shallow Observation Well

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

* = Horizontal Datum is NAD83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

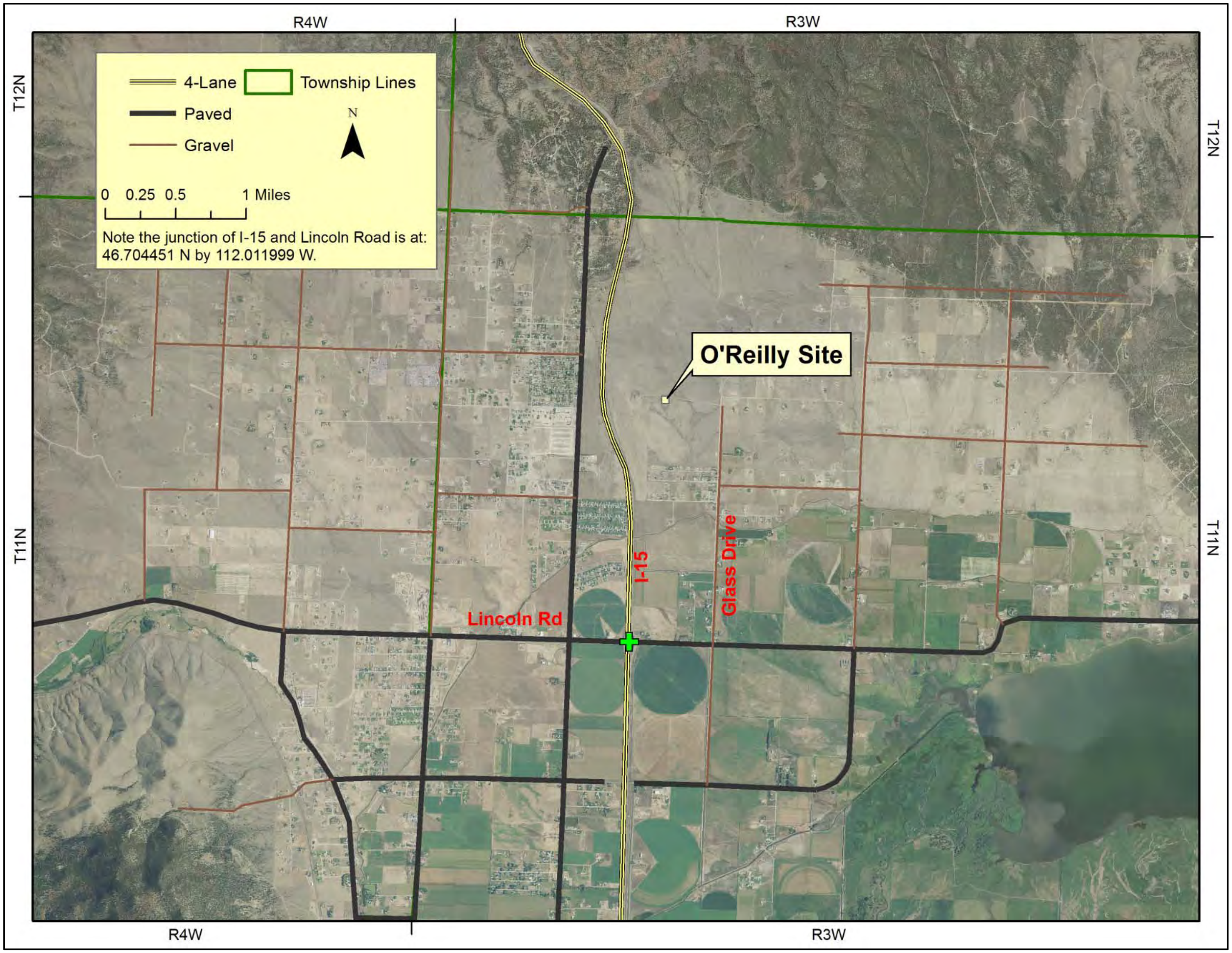


Figure OR1. Location of the O'Reilly Aquifer test site. The green cross at the junction of Lincoln Road and Interstate 15 is at 46.704451° N latitude and 112.011999° W longitude.

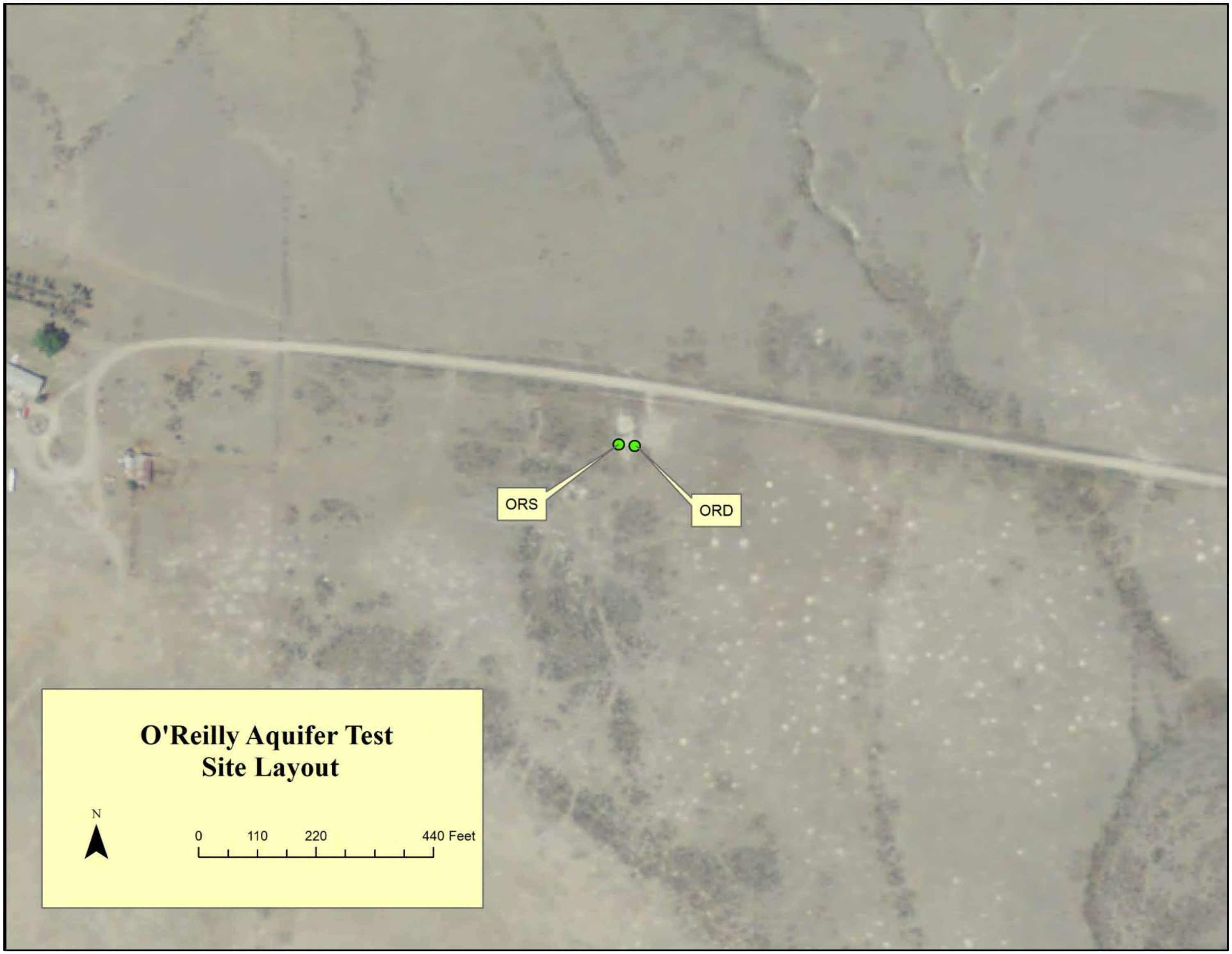


Figure OR2. Site layout for the O’Reilly Aquifer test. The site is located in T. 11 N., R. 3 W., section 8. ORD (well 257066) is located at 46.7294773° N latitude and 112.0075062° W longitude.

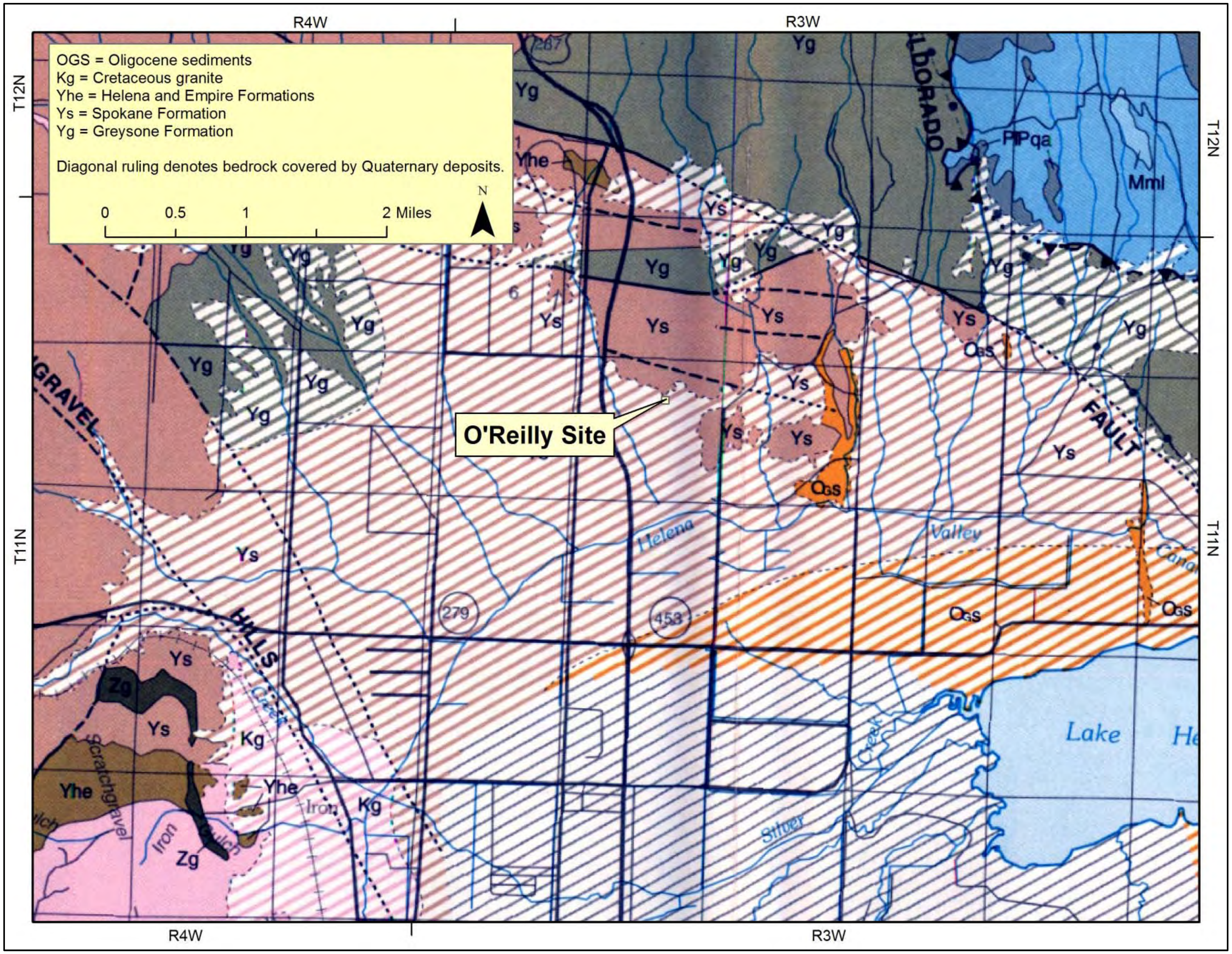


Figure OR3. Geologic map of the O'Reilly Aquifer test area. Geologic map prepared by Reynolds for Thamke, 2000.

Well Details

One 4-in-diameter PVC-cased well was installed at this site to serve as the pumping well (ORD, GWIC 257066). This well has a total depth of 260 ft. One 4-in-diameter PVC observation well (ORS, GWIC 257067) was installed 30 ft west of ORD. This well is 45 ft deep. This site is relatively flat, with a ground surface elevation of approximately 3,866 ft. Static water levels in both wells were approximately 23 ft below ground surface (~3,846 ft amsl) at the time of the test.

Transducers were placed in these wells in August 2010, and water levels were recorded hourly (fig. OR4). These data show that between October 2010 and March 2011, water levels rose by approximately 3 ft, apparently in response to non-irrigation season pumping rates. Water-level changes occur at the same time in both wells although deep well fluctuations are somewhat greater in magnitude than in the shallow well, suggesting that the storativity is somewhat lower in the deep zone. Groundwater elevations are nearly identical, suggesting a direct hydrologic connection.

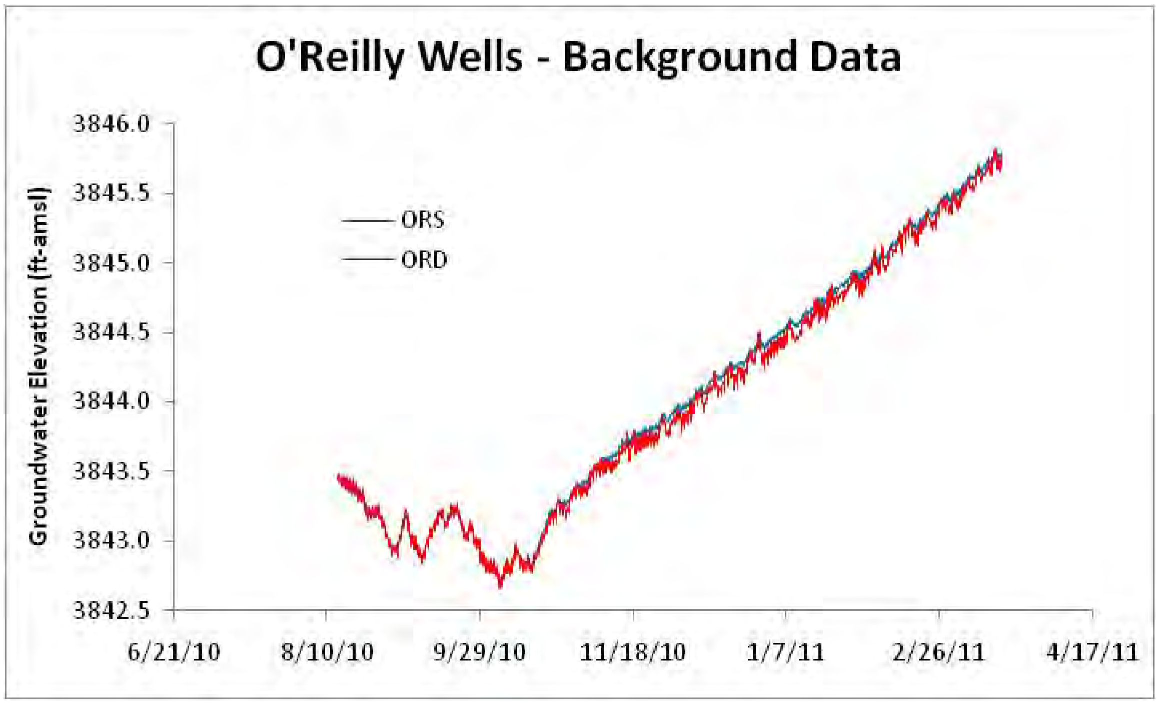


Figure OR4. Hydrographs from August 2010 to March 2011 provide background water levels for the O’Reilly site.

Pretest depth to water (DTW) readings at the test site show groundwater elevations between 3,845.45 and 3,845.92 ft above mean sea level (ft-amsl), showing that there is little difference between the water levels in these wells. Water levels returned to near their starting levels following the test, indicating that compensation for antecedent trends is not needed (figs. OR5, OR6).

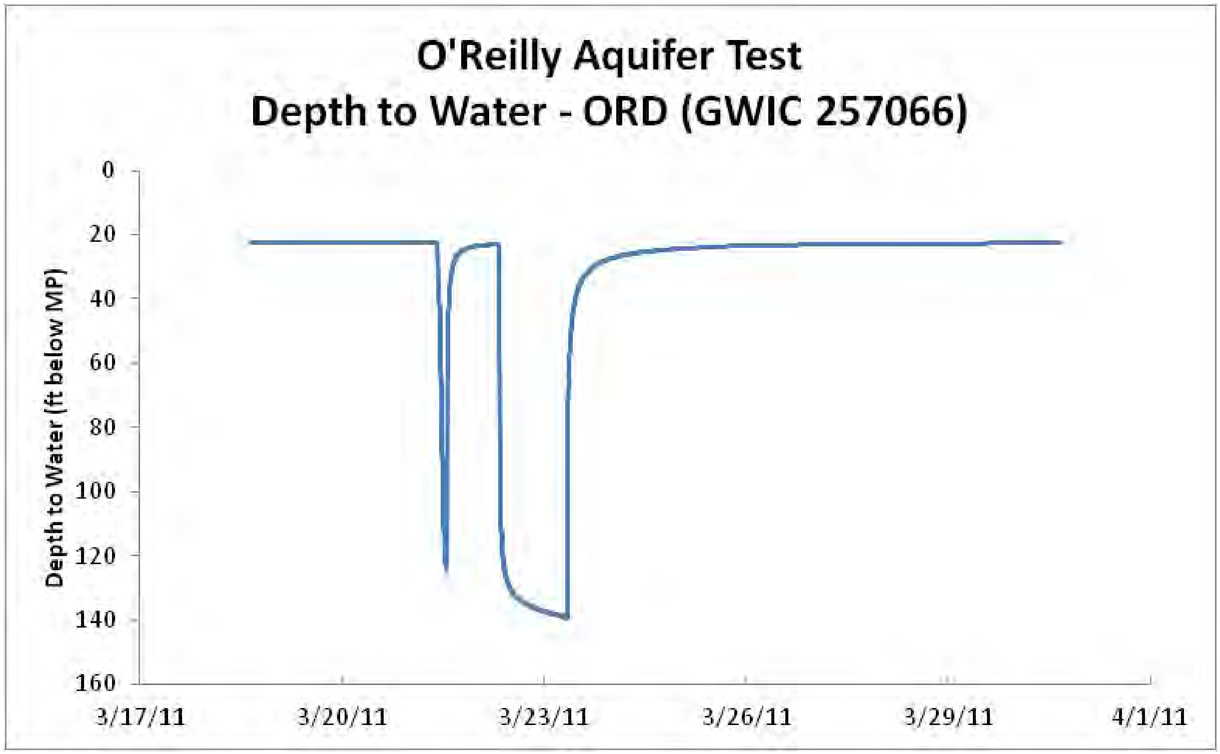


Figure OR5. Depth to water readings [DTW; ft below measuring point (MP)] in well ORD (pumping well; 260 ft deep) during the O'Reilly Aquifer test.

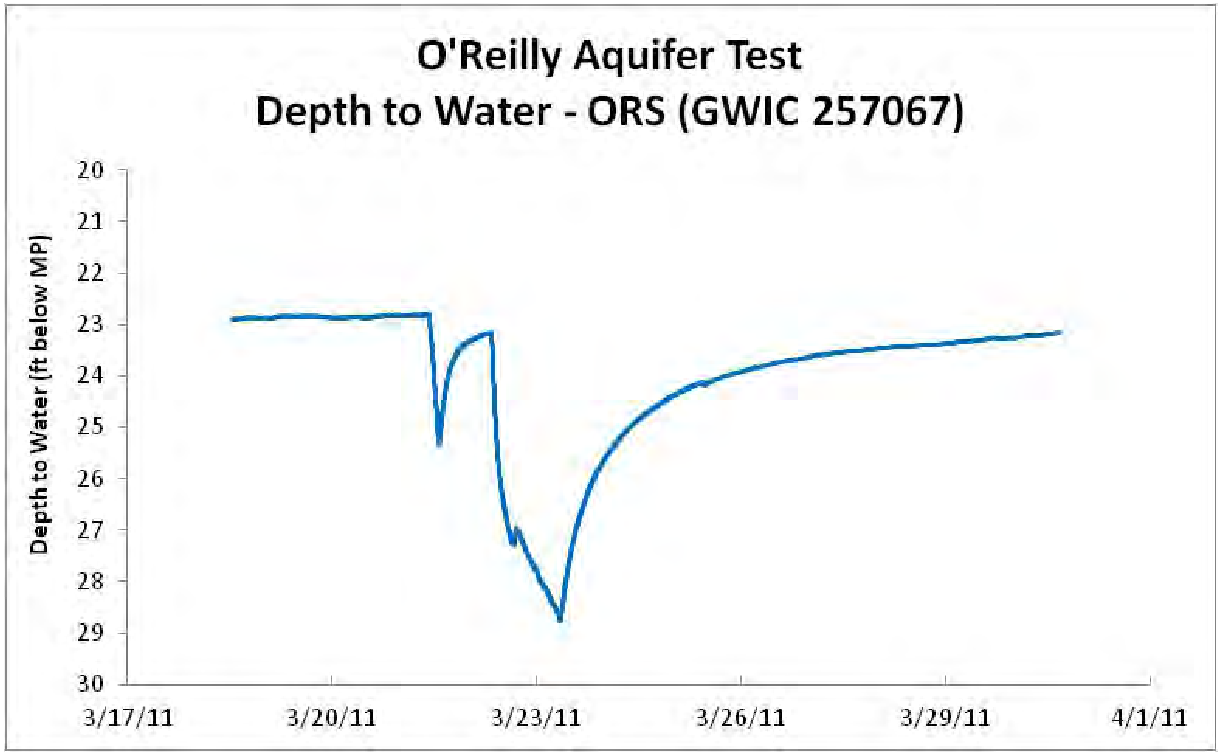


Figure OR6. Depth to water readings (ft below MP) in ORS (30 ft west of ORD; 45 ft deep) during the O'Reilly Aquifer test.

Methodology

The pumping rate was monitored throughout the test using a totalizing flow meter and an orifice bucket flow meter with a transducer in the piezometer tube (fig. OR7). The flow meter was checked using bucket and stopwatch during the early part of the step test; however, when the pumping rate reached more than 30 gpm, hand measurements became impractical. When measurements using the flow meter and the bucket and stopwatch were concurrent, there was good agreement in the flow rates. Discharge was controlled using a gate valve. The discharge water was diverted approximately 200 ft south of the pumping well and away from the shallow observation well.

Non-vented pressure transducers were used to record water levels in the pumping well (ORD), the observation well (ORS), and in the orifice bucket flow meter. All transducers are rated at 30 psig (35 ft), have a manufacturer-reported accuracy of ±0.1% of the rated pressure (±0.03 ft), and a resolution of ±0.01% of the rated pressure (0.003 ft). The transducer in the pumping well was above water during part of the step test and was lowered during the constant-rate test.

Manual readings of water levels were made for all wells prior to placing transducers, and were made periodically during the test, during recovery, and prior to transducer removal. These manual measurements were used to verify transducer response. All water-level data are available from GWIC by using the GWIC ID (http://mbmggwic.mtech.edu/).

The transducers, which had been recording at one reading per hour for long-term monitoring of these wells, were set to record at one reading per minute on March 18, 2011, to determine antecedent trends. The step test was conducted on March 21. The 24-h constant-rate test was conducted between March 22 and March 23. All transducers were left in place, recording one reading per minute until March 25, 2011. Following the test, the transducers were reset to record at 1-h intervals. Recovery data through March 30 are used in this analysis.

Step Test

On March, 21, 2011, a step test was conducted on ORD to determine an appropriate pumping rate (table OR2; fig. OR8). Because the pump was set at 220 ft below ground, it was desired that the long-term pumping rate not cause water levels to drop below 200 ft below ground. The last step of the step test was with the valve fully open, and as such represents the maximum capacity of the equipment on site. At maximum capacity, drawdown was less than 200 ft below ground and the constant-rate test was conducted with the valve fully open. As discussed below, the weighted average rate for the constant-rate test was 45.9 gpm. ORD was constructed with a 4-in 40-slot screen 20 ft long. Thus, the entrance velocity at 46 gpm would be 0.009 ft/s, which is well below the 0.1 ft/s threshold recommended by Heath (1983) for laminar flow.

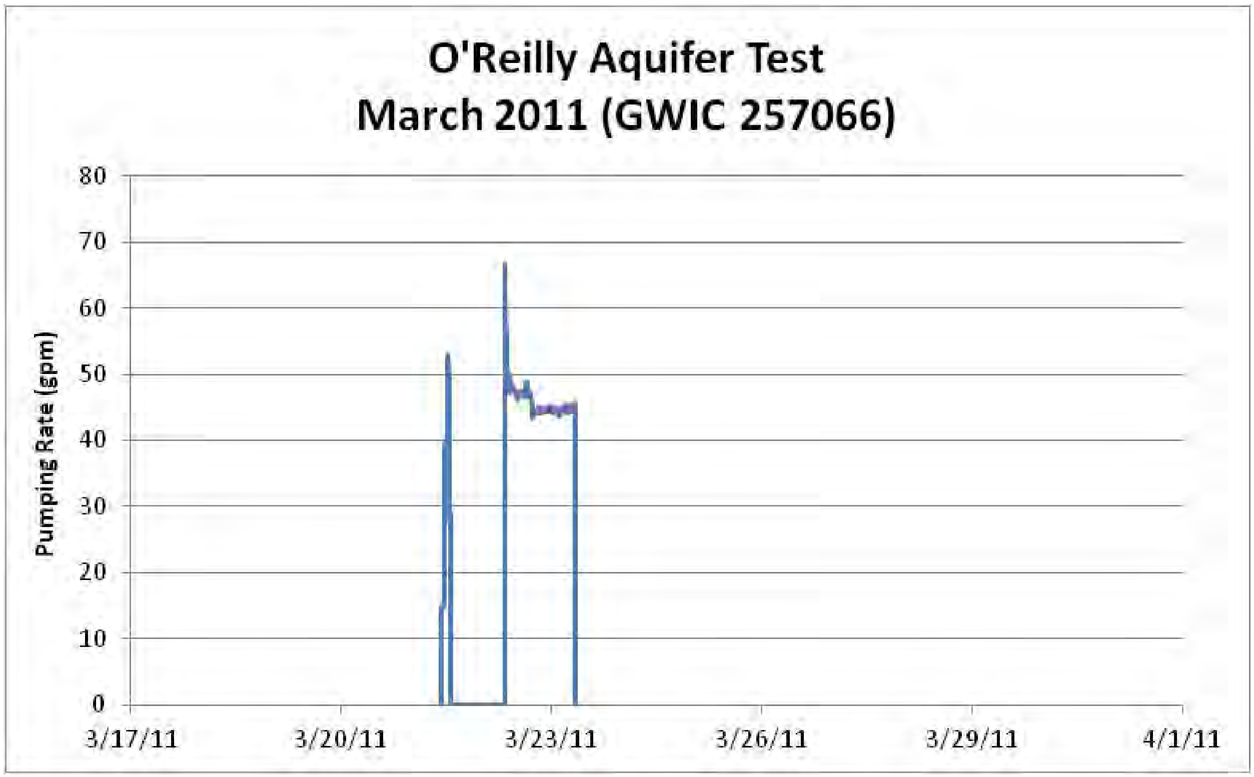


Figure OR7. Pumping rates from ORD during the O'Reilly Aquifer test.

Table OR2
ORD—Step Test Summary
O'Reilly Aquifer Test—March 21, 2010

Start Step	End Step	Rate (Q, gpm)	Maximum Drawdown (s, ft)	Specific Capacity (Q/s)
10:20	11:22	14.9	22.81	0.65
11:22	12:20	39.5	72.80	0.54
12:20	13:20	51.1	102.27	0.50

The data obtained during the step test allow the specific capacity (discharge per unit of drawdown, Q/s) of ORD to be determined at different pumping rates. This information was used to determine the maximum rate that the well could be pumped without exceeding a target drawdown value (fig. OR9). Given that the top of the screen is at 240 ft below ground surface (bgs), that the static water level is at 23 ft bgs, and that it is typically desired that the pumping water level stay at least 10 ft above the top of the screen, the target drawdown was 208 ft. Using the step test data, this drawdown would occur at a pumping rate of 97 gpm. Given that the water level continued to decline at a steady rate at the end of the constant-rate test, and that it did not fully stabilize during any of its steps, the step test likely overestimates the well's potential long-term yield.

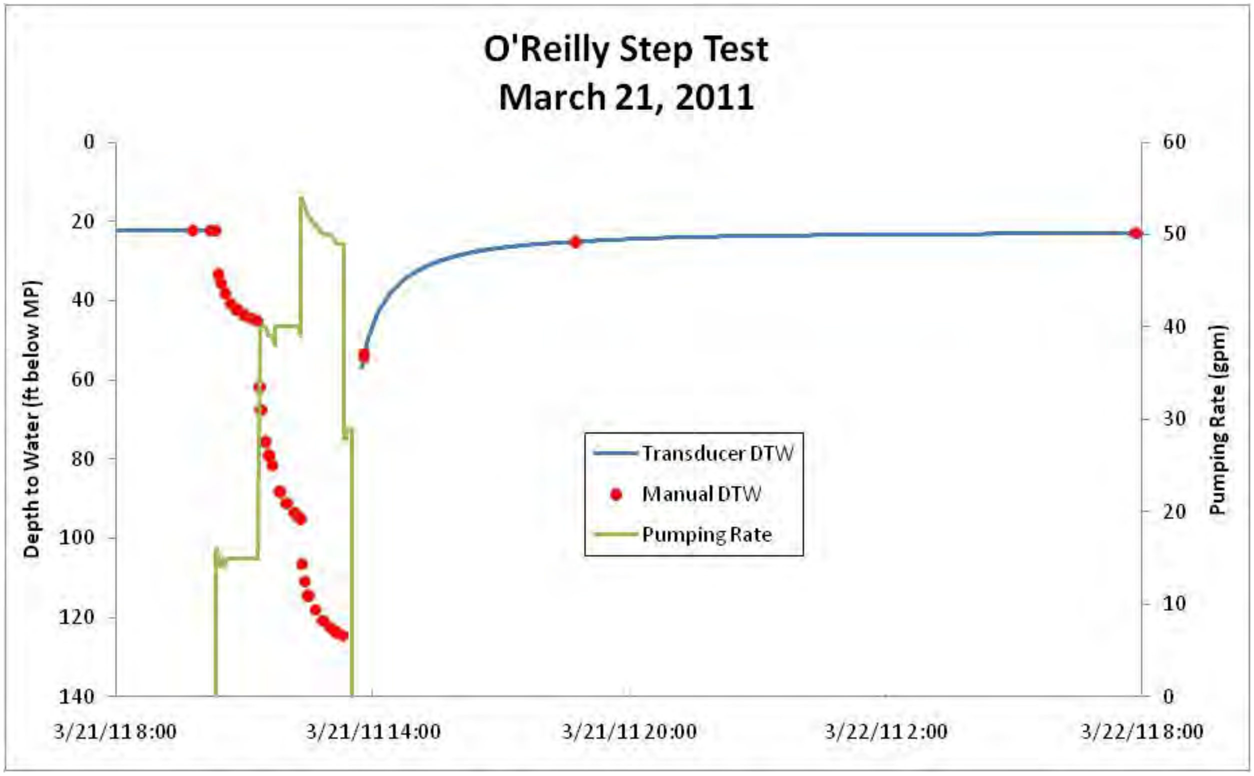


Figure OR8. Depth to water in ORD and pumping rates recorded during the step test.

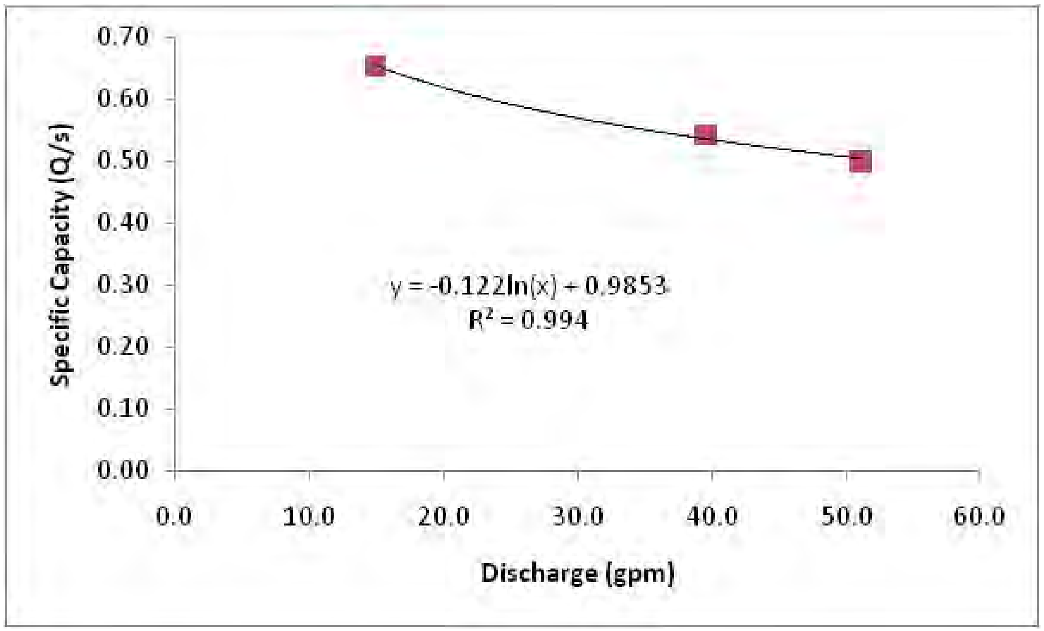


Figure OR9. Specific capacity (Q/s) vs. pumping rate (Q) for ORD. This relationship can be used to estimate the well's likely maximum pumping rate.

The data from this step test can be simulated with AQTESOLV using the known pumping rates and T and S values determined during the constant-rate test (appendix OR-A).

Constant-Rate Test Analysis

The constant-rate test started at 8:15 am on March 22, 2011 and ended at 8:20 am on March 23, for a total pumping time of 24 h and 5 min. The time-weighted average pumping rate was 45.9 gpm. The maximum recorded pumping rate was 66 gpm (for a short period at the start of the test) and the minimum recorded rate was 44 gpm. Thus the maximum deviation from average was 44 percent. Due to variable rate, analysis was conducted using AQTESOLV software.

The maximum recorded drawdown in well ORD was 116.53 ft. Drawdown in well ORD showed a rapid initial increase but the rate slowed as pumping continued. Drawdown increased during the last hour by 0.18 ft. After pumping ceased, ORD initially recovered rapidly; however, 5 h were needed to reach 90 percent recovery.

Drawdown in ORS generally mirrored drawdown in the production well except that the magnitude was less, and more time was required to reach 90 percent recovery. At just over 8 h into the test, a rise in water levels, confirmed by manual measurements, was observed in ORS that was not observed in ORD. This rise may also be related to the transition from confined to unconfined conditions because the water level dropped below the confining layer at the time of the recovery. This rise makes analysis of the data from the observation well difficult; however, late time data allow analysis of bulk unconfined aquifer properties. The maximum drawdown in ORS was 5.56 ft.

Data from the 24-h aquifer test were analyzed using multiple analysis methods to determine the aquifer parameters, including transmissivity and storage coefficient (appendix OR-A). It was determined that the most appropriate T is approximately 250 ft^2/d, which equates to a hydrologic conductivity of 1.0 ft/d. An S of 0.09 was determined.

Summary

Analysis of this aquifer test indicates that there are no vertical barriers to flow in the bedrock at this site.

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ASTM, 2008, Standard test method (analytical procedure) for determining transmissivity and storage coefficient of nonleaky confined aquifers by the modified Theis nonequilibrium method, D4105-96 (Reapproved 2008).

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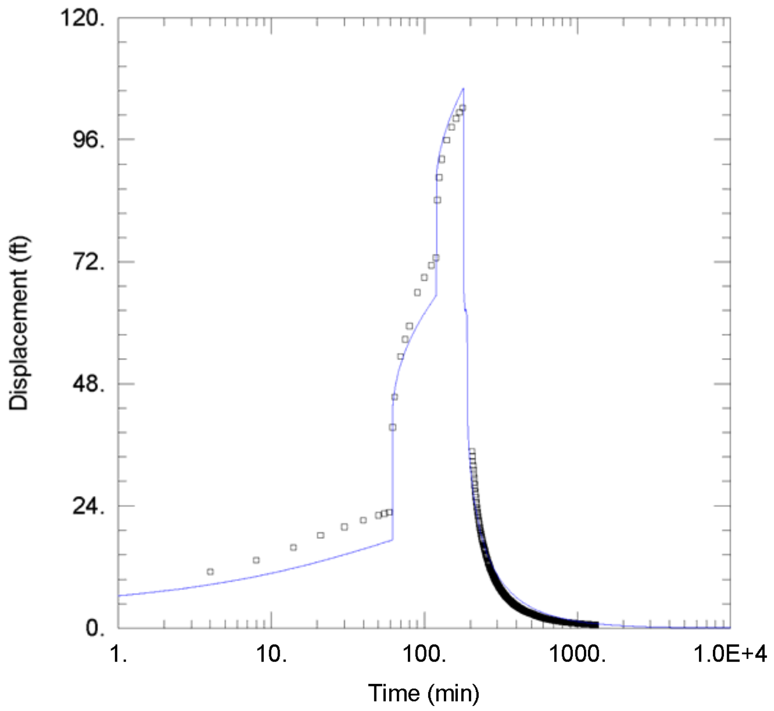
APPENDIX OR-A—
RESULTS FROM

AQTESOLV

ANALYSIS

O’REILLY AQUIFER TEST



OR STEP TEST

Data Set: M:\...\ORD_Step_2.aqt
Date: 04/10/12 Time: 13:20:48

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/21/11

AQUIFER DATA

Saturated Thickness: 260. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ ORD	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Dougherty-Babu

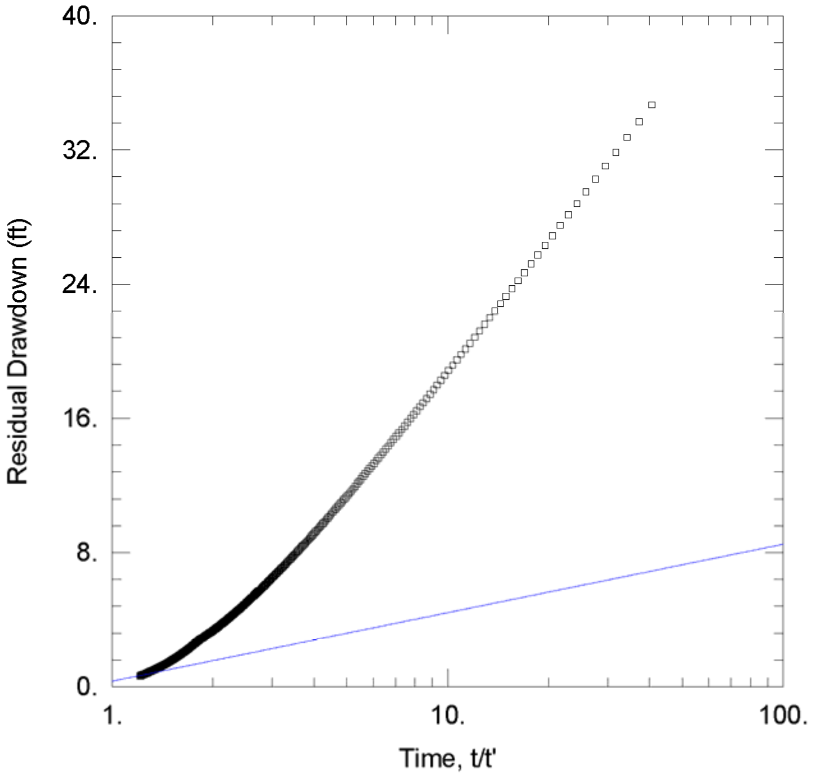
T = 250. ft^2/day
Kz/Kr = 1.
r(w) = 0.25 ft
C = 1. min^2/ft^5

S = 0.088
Sw = -4.064
r(c) = 0.1666 ft
P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min

s(t) = 1.178Q + 1.$Q^{2.}$
W.E. = 97.02% (Q from last step)

Figure OR-A1. Step test simulation using the T and S values determined from the O'Reilly constant-rate test, using the Dougherty-Babu method.



OR STEP TEST

Data Set: M:\...\ORD_Step_2.aqt
Date: 04/10/12 Time: 13:21:54

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/21/11

AQUIFER DATA

Saturated Thickness: 260. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

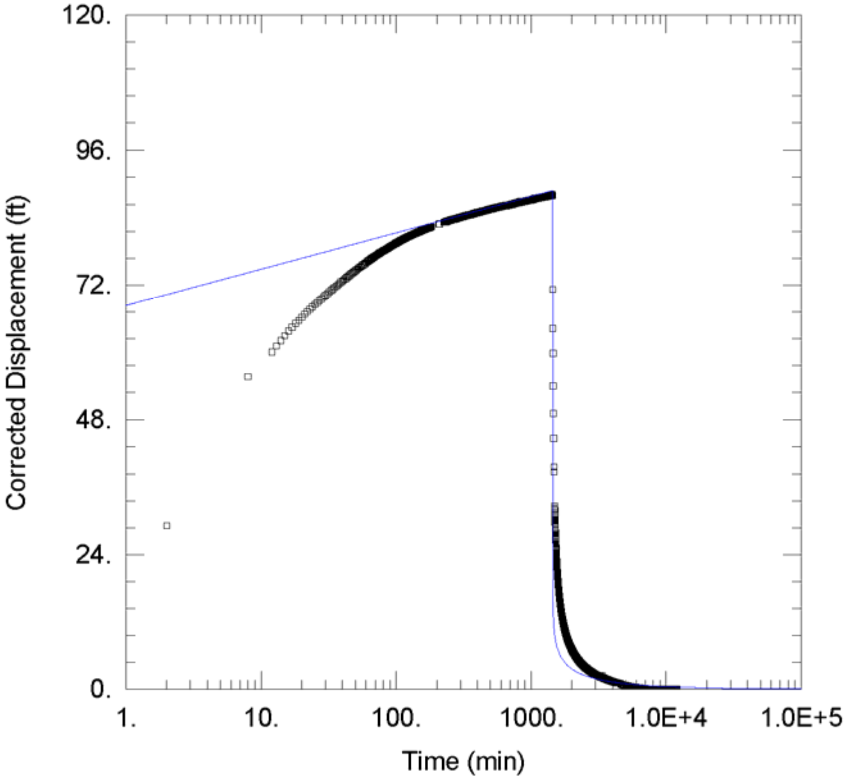
Well Name	X (ft)	Y (ft)
▫ ORD	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 250. ft^2/day
S/S' = 0.8318

Figure OR-A2. Step test recovery simulation using the T value determined from the O’Reilly constant-rate test, using the Theis method.



OR CONSTANT RATE TEST

Data Set: M:\...\ORD_CR_2.aqt
Date: 04/10/12 Time: 13:32:22

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/22/11 - 3/23/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

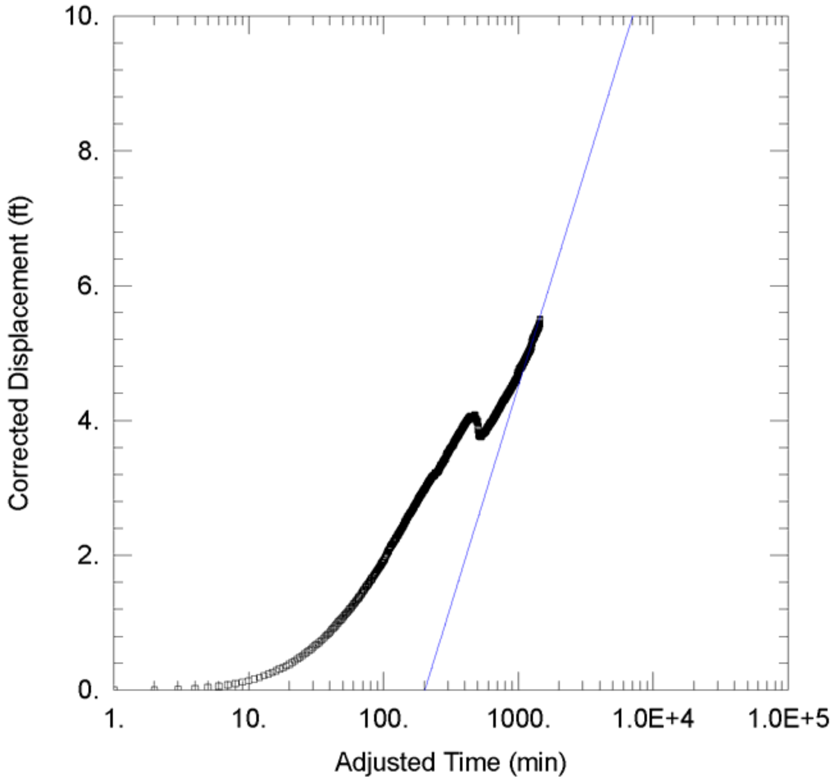
Well Name	X (ft)	Y (ft)
▫ ORD	0	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 250. ft^2/day
S = 1.143E-11
Kz/Kr = 1.
b = 240. ft

Figure OR-A3. O’Reilly constant-rate test simulation of ORD using the Theis method. Note that the S value here is not representative, because ORD is the pumping well.



OR CONSTANT RATE TEST

Data Set: M:\...\ORS_CR_2.aqt
Date: 04/10/12 Time: 13:29:02

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/22/11 - 3/23/11

AQUIFER DATA

Saturated Thickness: 240. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

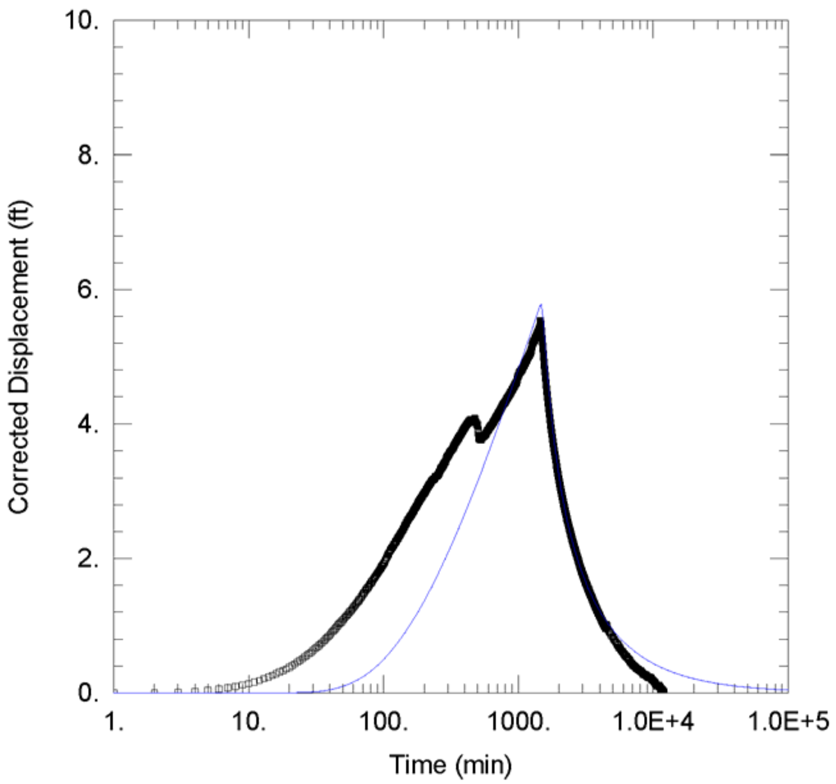
Well Name	X (ft)	Y (ft)
▫ ORS	30	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Cooper-Jacob

T = 250. ft^2/day
S = 0.088

Figure OR-A4. O’Reilly constantrate test simulation of ORS using the Cooper–Jacob method.



OR CONSTANT RATE TEST

Data Set: M:\...\ORS_CR_2.aqt
Date: 04/10/12 Time: 13:29:34

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/22/11 - 3/23/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

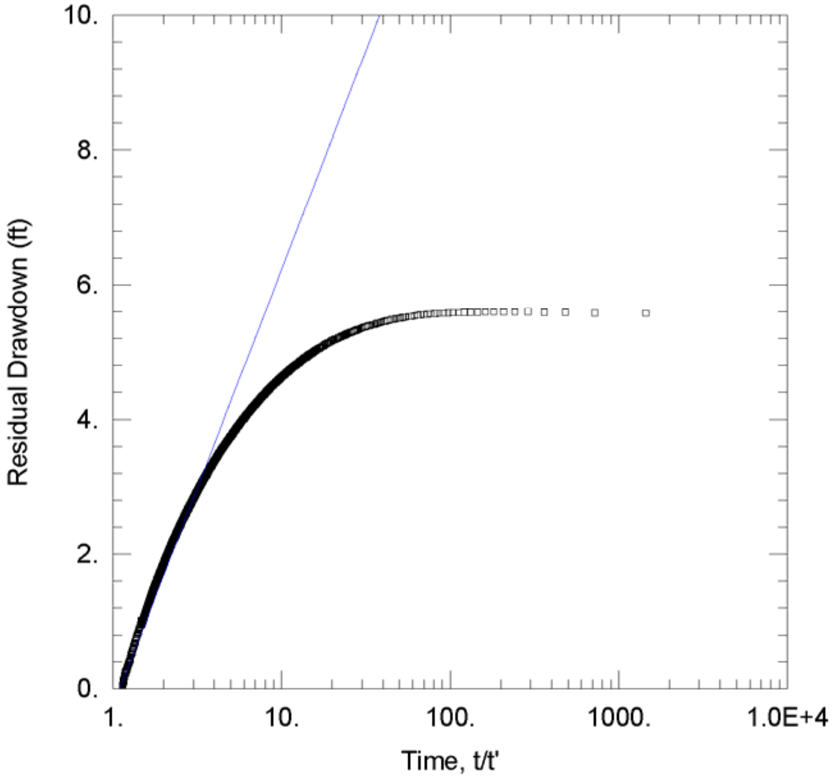
Well Name	X (ft)	Y (ft)
▫ ORS	30	0

SOLUTION

Aquifer Model: Unconfined
Solution Method: Theis

T = 250. ft^2/day
S = 0.088
Kz/Kr = 1.
b = 240. ft

Figure OR-A5. O’Reilly constant-rate test simulation of ORS using the Theis method.



OR CONSTANT RATE TEST

Data Set: M:\...\ORS_CR_2.aqt
Date: 04/10/12 Time: 13:30:08

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: ORD
Test Date: 3/22/11 - 3/23/11

AQUIFER DATA

Saturated Thickness: 240. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
ORD	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ ORS	30	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 250. ft^2/day
S/S' = 1.1

Figure OR-A6. O’Reilly constant-rate test recovery simulation using the Theis method.

PURCELL AQUIFER TEST—
HELENA FORMATION

PURCELL
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
March 2011

STEP TEST
AND
24-HOUR CONSTANT-RATE TEST

Background

The following is an analysis of a step test and a 24-h constant-rate pumping test performed in March 2011, using wells installed on the Purcell property in the North Hills Study Area. There are several residences in the area; the closest used well is approximately 600 ft from the pumping well. Homes in this area are on lots of 20 acres or more.

This test was designed to evaluate the hydrogeologic function of a suspected fault. One 5-in-diameter pumping well (PS; GWIC 257065) was installed at this site south of the suspected fault in July 2010. A MBMG geologist was present for the installation of PS; cuttings were described in detail, and completion details verified. For every 5 ft of borehole, samples of cuttings were composited, described, and retained for long-term storage at the MBMG. At this site there is a pre-existing well north of the suspected fault (PN; GWIC 176012) and another well located to the west of PS (PF; GWIC 64771). The well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu) and can be accessed by using their GWIC IDs. A summary of completion details is provided in table P1 and in appendix P-A.

A transducer was deployed in PN in March 2010 for long-term monitoring. This same well was also monitored by Madison (2006) between 2004 and 2006. Background data are available on GWIC. A transducer was deployed in PS on March 18, 2011, immediately following installation of the pump. The transducers in both wells were programmed to collect measurements at 1-min intervals for the duration of the test.

Location

The test area is located in the northern part of the Helena Valley, on the dissected pediment, north of Lincoln Road and east of Interstate 15. The wells are located in Township 11 N., Range 3 W., Section 9, NW¼ SW¼, in Lewis and Clark County, Montana (figs. P1, P2).

Geology

This area has been mapped as the Spokane Formation (Reynolds, 2000); however, cuttings and nearby bedrock outcrop indicate that the aquifer tested is actually the Helena Formation (fig. P3). The Helena Formation is described by Schmidt and others (1994) as "cyclic interlayers of clastic, dolomite, and limestone beds."

There is a mapped fault approximately 2,500 ft to the north of the well locations. It is also suspected that a fault exists at this site due to observed changes in slope, soils, the sudden appearance of bedrock, and the presence of bedrock springs. The suspected fault runs roughly east–west, and is located between wells PS and PN (fig. P2).

Table P1

Well Designations, Locations, and Completion Information

Purcell Aquifer Test—March 2011

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation^{+} (ft-amsl)	Total Depth (ft below MP)	Depth to Water 3/21/11 (ft below MP)	Groundwater Elevation 3/21/11 (ft-amsl)	Distance from PS (ft)	Comments
257065	PS	46.7236443	-111.9936754	3828.88	360	84.39	3744.49	—	Pumping Well
176012	PN	46.7245951	-111.9941215	3842.00	140	51.10	3790.90	364	North Observation Well
64771	PF	46.7236591	-111.9959389	3832.39	135	48.91	3783.48	568	West Observation Well

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

* = Horizontal Datum is NAD83

$^{+}$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

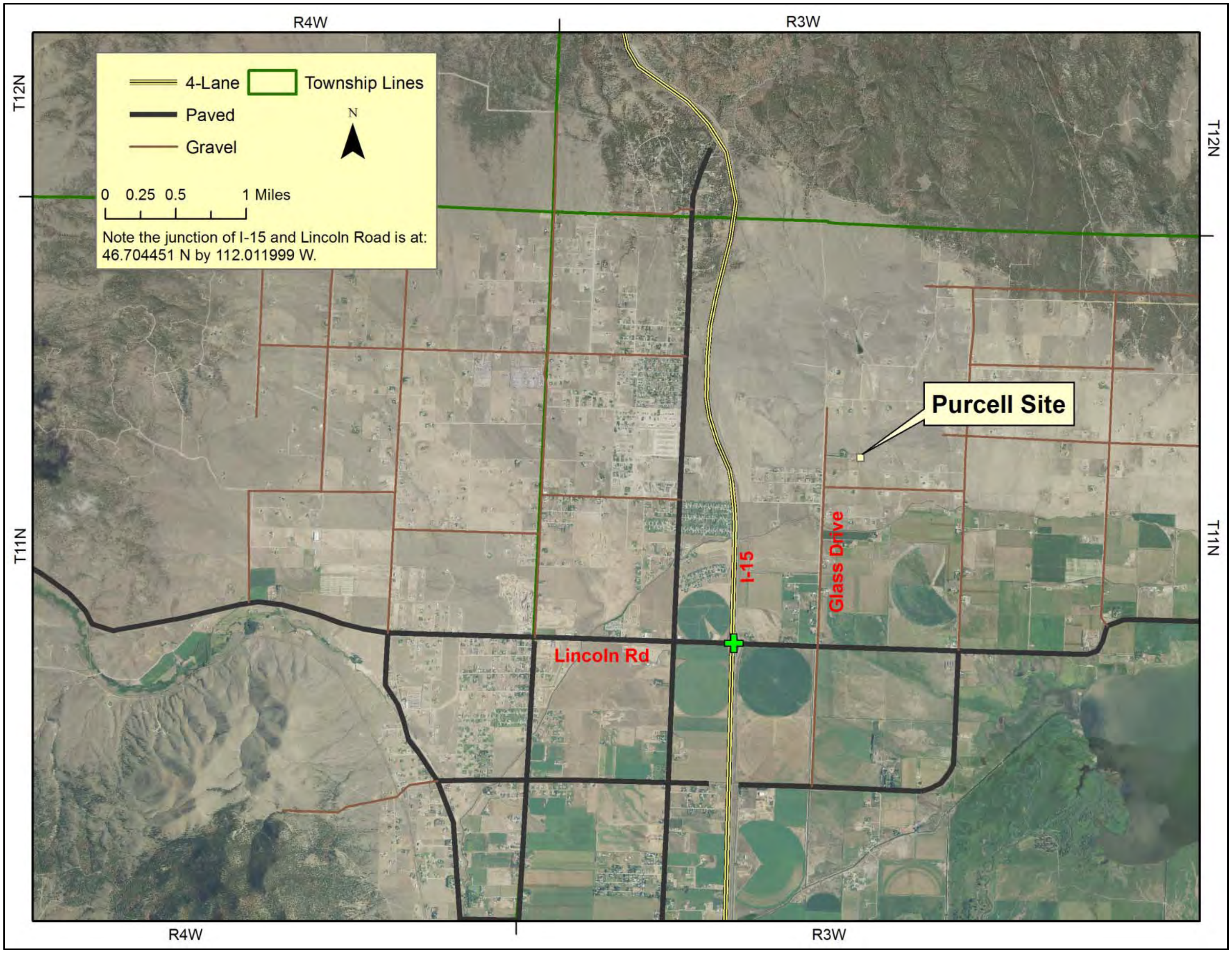


Figure P1. Location of the Purcell Aquifer test site. The green cross located at the junction of Interstate 15 and Lincoln Road is at latitude 46.704451°N and longitude 112.011999°W.

Figure P2. Site layout for the Purcell Aquifer test.

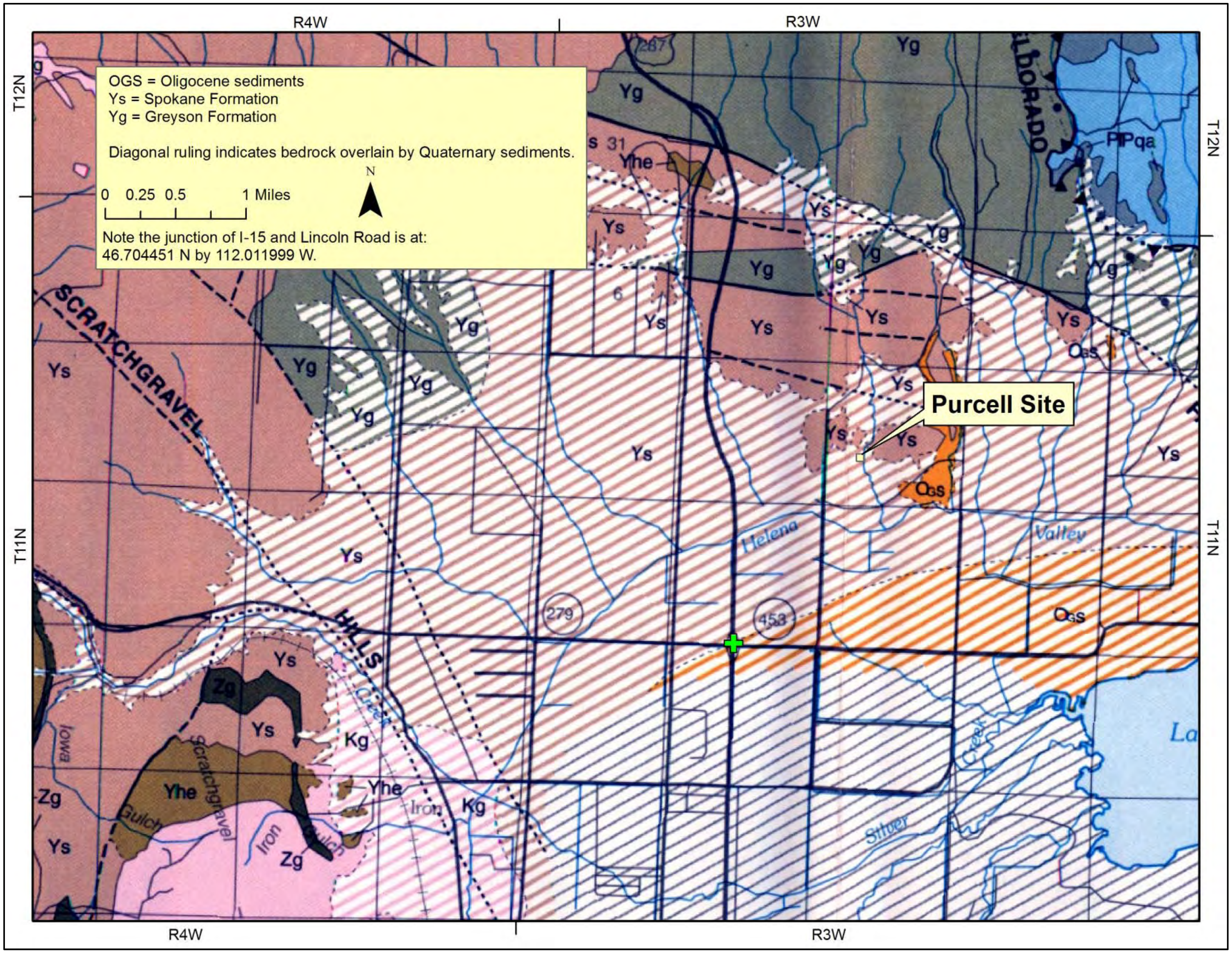


Figure P3. Geologic map of the Purcell Aquifer test area (Reynolds, 2000).

Well Details

One 5-in steel-cased well was installed at this site to serve as the pumping well (PS). This well has a total depth of 360 ft. There is a preexisting well to the north of the fault (PN), which is a 6-in unlined well with a total depth of 140 ft. The well log for PN reports its yield to be 2 gpm, suggesting that it is completed in bedrock with few fractures. Another preexisting well (PF), a 5-in steel- cased well used to irrigate a hay field, is located to the west. PF has a reported yield of 95 gpm, which suggests that this well is completed in a highly fractured zone, potentially associated with a fault.

A transducer was placed in PN in March 2010, and water levels recorded hourly. Manual measurements have also been made at this well since January 2010. These data provide information on antecedent trends and show that between April 2010 and October 2010 groundwater levels declined by approximately 5 ft. Between October 2010 and March 2011 water levels rose by approximately 3 ft. The cycle portrays apparent response to relatively high groundwater withdrawals during the summer followed by recovery over the winter (fig. P4).

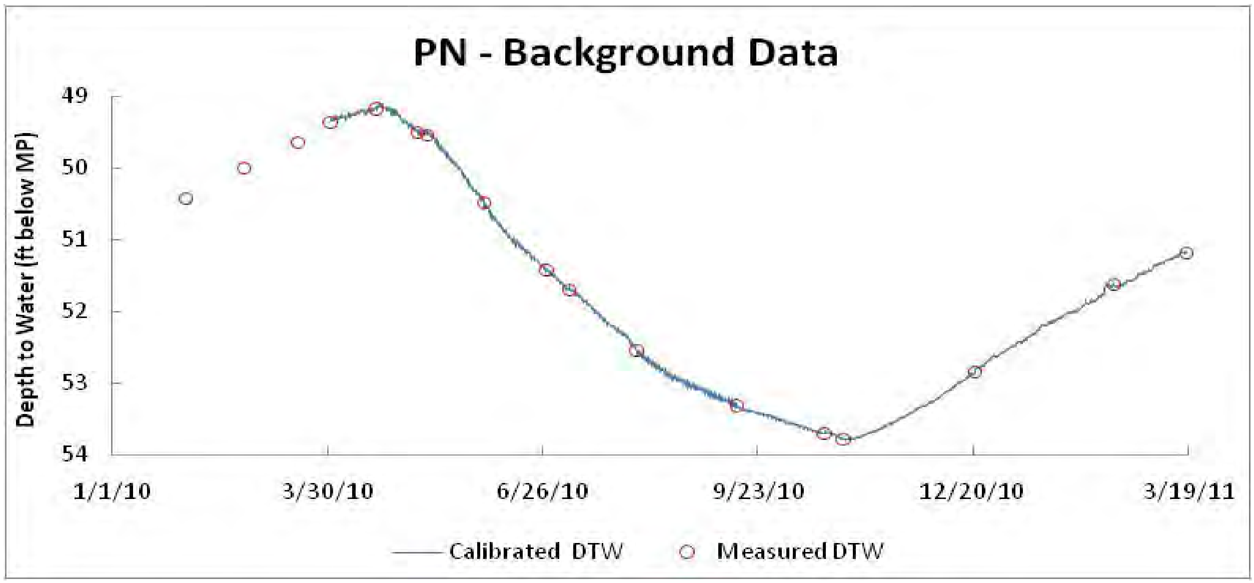


Figure P4. The hydrograph for PN from January 2010 to March 2011 shows seasonal variation in water levels.

Pretest depth to water (DTW) readings at the test site show groundwater elevations between 3744.49 and 3790.90 ft above mean sea level (ft-amsl). Along with water levels in nearby wells, these altitudes indicate groundwater flow is to the southeast; however, because the hydrologic gradient is much greater between PS and PN (0.13 ft/ft; unitless) than the overall gradient in this area (0.02; fig. P5), the data suggest that a barrier to flow is present. Short-term water levels were rising slightly prior to and throughout the test (figs. P6–P8).

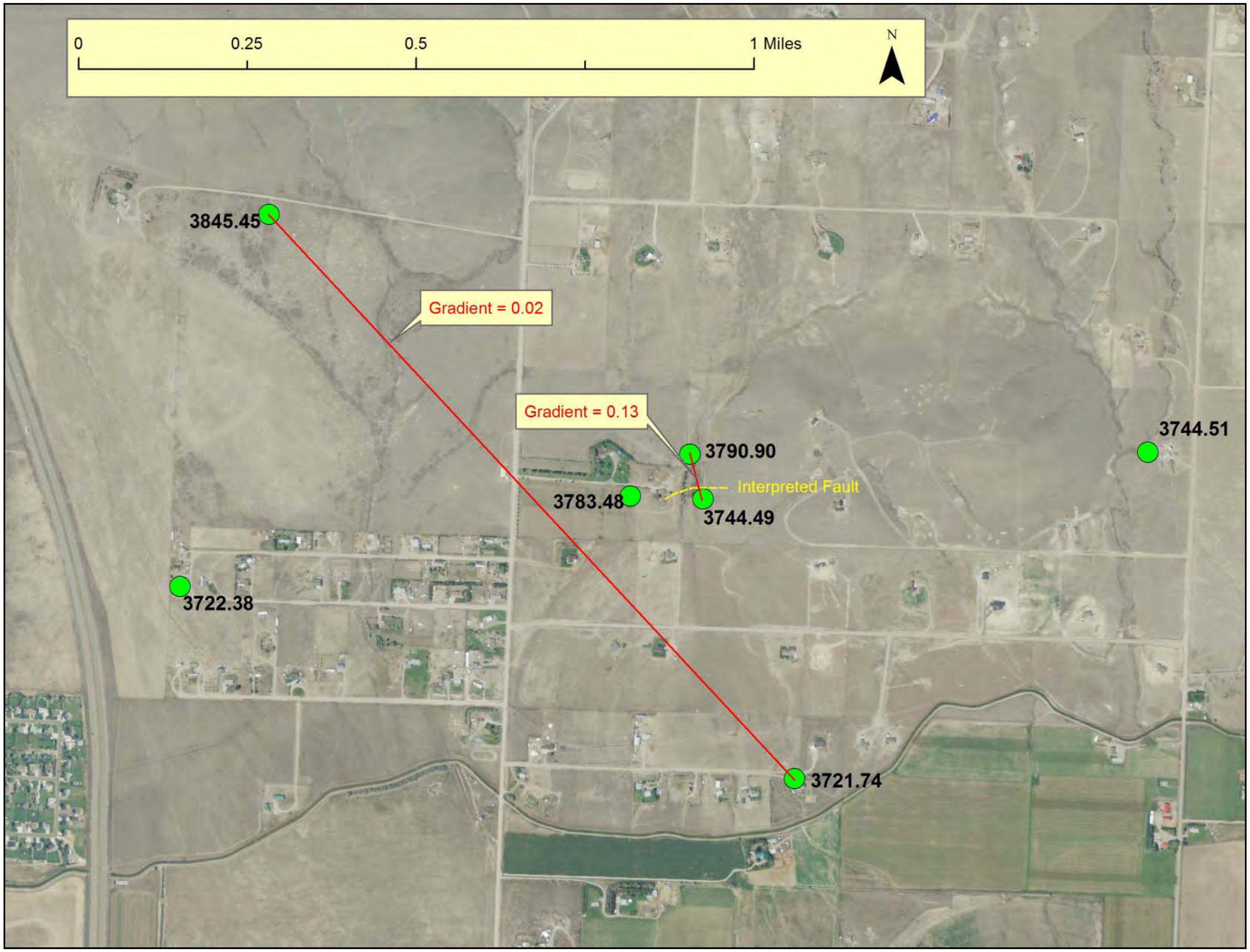


Figure P5. Static water-level elevations collected in March 2011 show that flow is to the southeast (GWIC wells 64740, 64771, 144726, 176012, 218593, 257066, and 257065). The steep hydrologic gradient in the area of the test site indicates that a barrier is present.

Methodology

The pumping rate was monitored throughout the test using a totalizing flow meter and an orifice bucket with a transducer in the piezometer tube (fig. P6). The flow meter was also checked using bucket and stopwatch measurements. When concurrent measurements were made, there was good agreement in the flow rates. Discharge was controlled using a gate valve, and discharge water was diverted approximately 200 ft south of the pumping well (PS) away from the observation wells.

Non-vented pressure transducers were used to record water levels in the pumping well (PS), the north observation well (PN), and in the orifice flow meter. All transducers were rated at 30 psia (35 ft), have a manufacturer-reported accuracy of ±0.1% of the rated pressure (±0.03 ft), and a resolution of ±0.01% of the rated pressure (0.003 ft). The original transducer placed in well PS was above water during part of the step test, so a second transducer was installed at a greater depth below land surface during the pumping portion of the constant-rate test. All transducer data were barometrically corrected.

The west well (PF) was measured using an e-tape, because its access port was too narrow to allow installation of a transducer.

Manual water-level readings were made in all wells prior to placing transducers and periodically during the test, during recovery, and prior to removing the transducers. The manual measurements were used to verify transducer response. All water-level data are available from GWIC by using the GWIC IDs (http://mbmggwic.mtech.edu/).

The transducers were set to record at one reading per minute and deployed on March 18, 2011, to determine antecedent trends. Deployment occurred immediately following the installation of the pump in PS. The step test was conducted on March 21. The constant-rate test was originally started on March 23 at 10:55 am; however, equipment problems stopped the test after 1 h and 7 min. At that time the pump was pulled and reset, and the well was allowed to recover. A second constant-rate test was started on March 24 at 8:50 am and ended on March 25 at 8:53 am. All transducers were left in place, recording one reading per minute, until March 30, 2011.

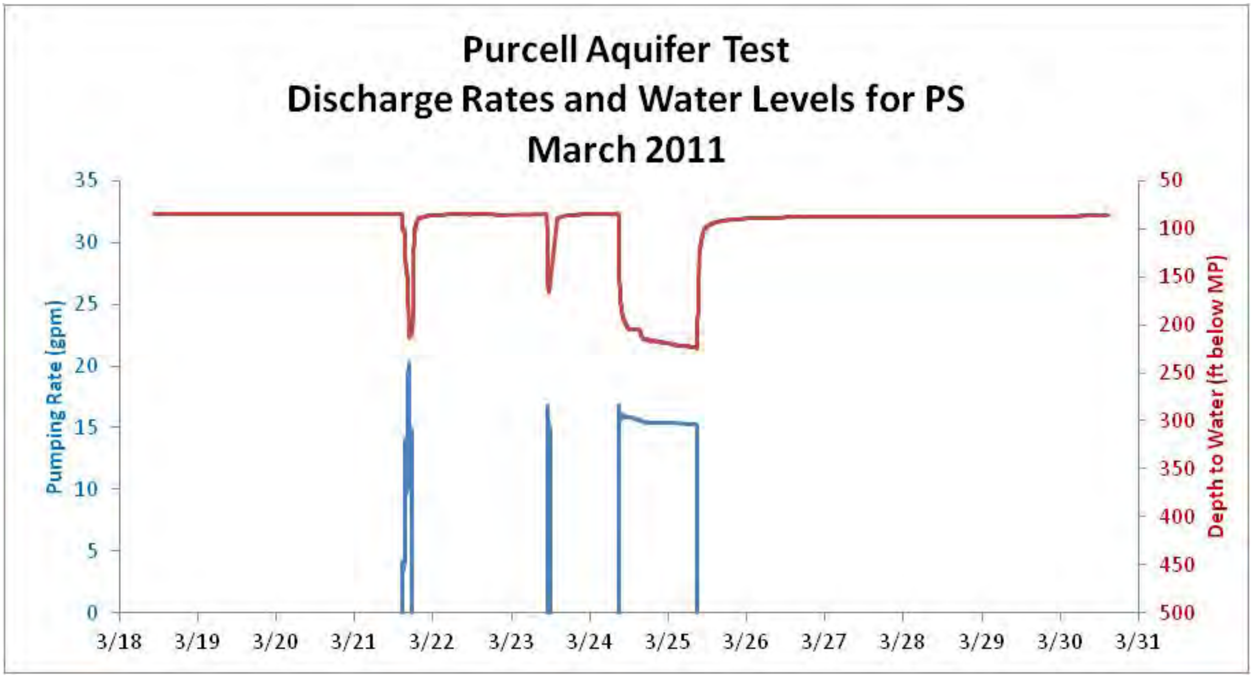


Figure P6. Pumping rates and water-level measurements from PS (pumping well) during the Purcell Aquifer test.

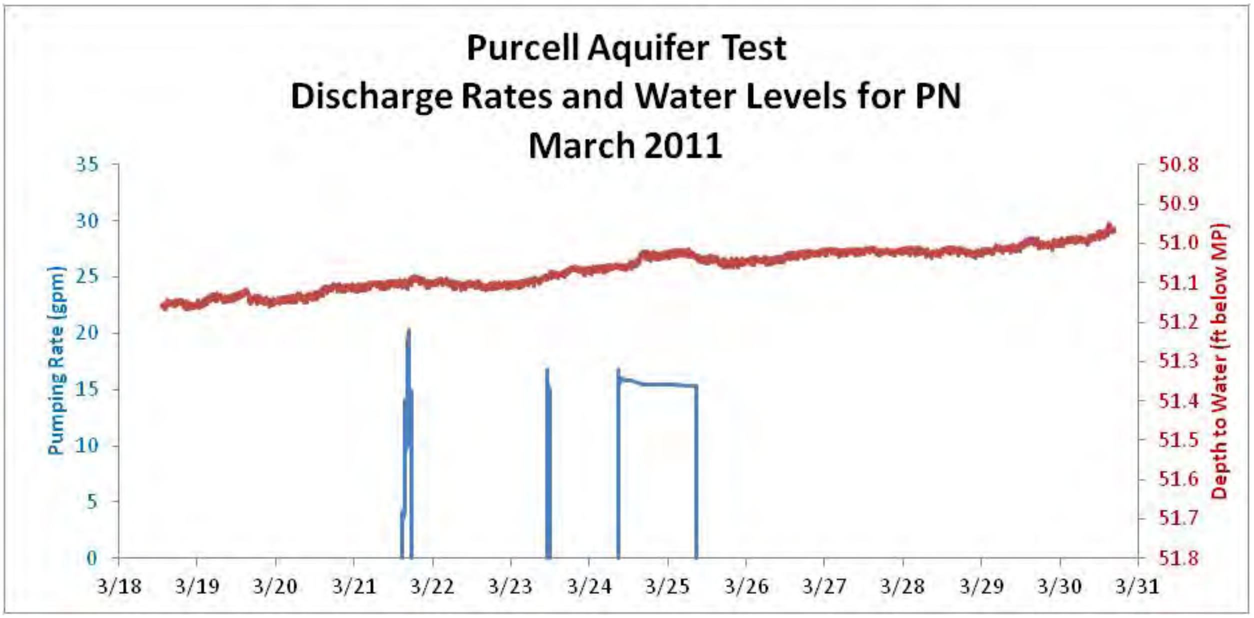


Figure P7. Water-level measurements in PN and pumping rates for PS during the Purcell Aquifer test.

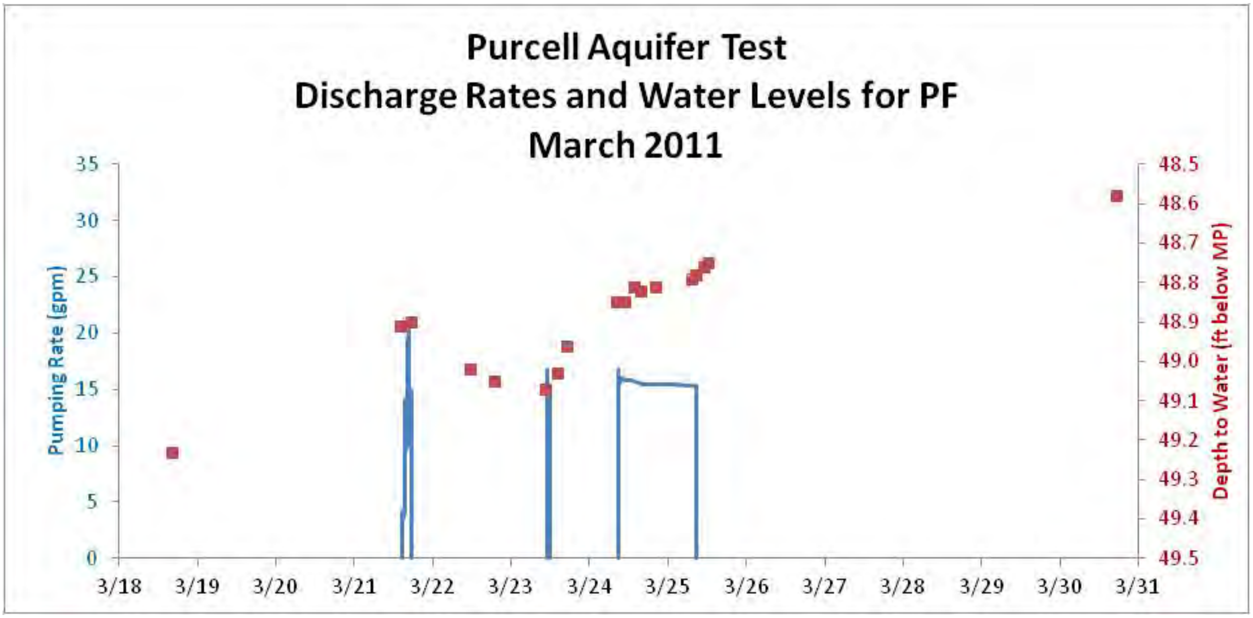


Figure P8. Water-level measurements in PF and pumping rates for PS during the Purcell Aquifer test.

Step Test

On March, 21, 2011, a step test was conducted on PS to determine an appropriate pumping rate (table P2; fig. P8). During the last step, it was determined that the rate of ~19 gpm was too high and would likely cause the water level to fall to the pump intake; thus after 20 min the rate was reduced to ~15 gpm. This reduction causes the data from the last step to have an irregular appearance. Because the pump was set at 235 ft below ground and the screen extends from the bottom up to 250 ft, it was desired that the long-term pumping rate not cause water levels to drop below 225 ft (140 ft of drawdown). Analysis of the step test data shows that this pumping water level would result in a pumping rate of about 16 gpm. As discussed below, the weighted-average rate for the constant-rate test was 15.5 gpm.

Table P2
PS—Step Test Summary
Purcell Aquifer Test—March 21, 2011

Start Step	End Step	Rate (Q, gpm)	Maximum Drawdown (s, ft)	Specific Capacity (gpm/ft)
14:34	15:23	4.0	18.60	0.21
15:23	16:23	10.2	66.57	0.15
16:23	17:45	14.8	125.35	0.12

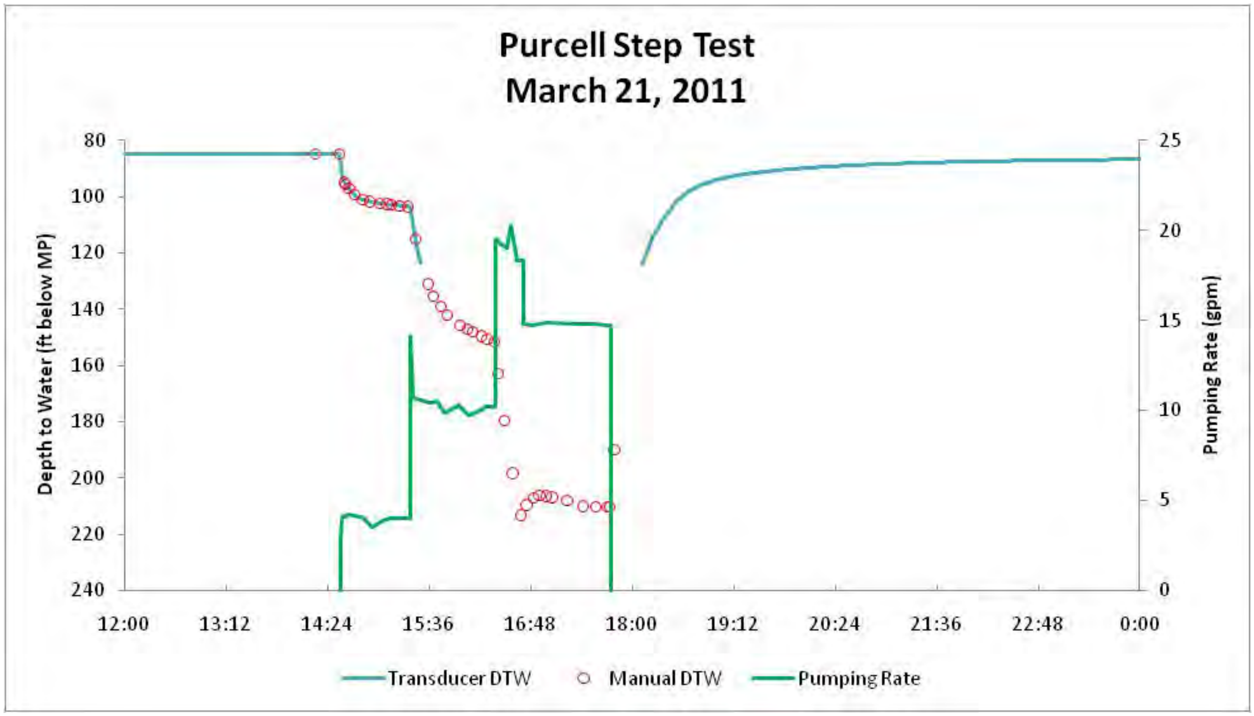


Figure P8. Depth to water in PS and pumping rates recorded during step test.

The data obtained during the step test also allow the specific capacity (SC, discharge per unit of drawdown, Q/s) of the well to be determined at different pumping rates. This information can be used to determine the maximum rate that the well can be pumped, without exceeding a target drawdown value (table P2; fig. P9). Given that the top of the screen is at 250 ft below ground surface (bgs), that the static water level is at 85 ft bgs, and that it is typically desired that the water level stay at least 10 ft above the top of screen and above the pump, this results in a target drawdown (s) of 155 ft. It is calculated that this drawdown is achieved at a pumping rate of about 17 gpm for PS; however, the pump would need to be set lower than it was for the aquifer test.

The data from this step test can be simulated with AQTESOLV using the known pumping rates and the T value determined during the constant-rate test (appendix P-B).

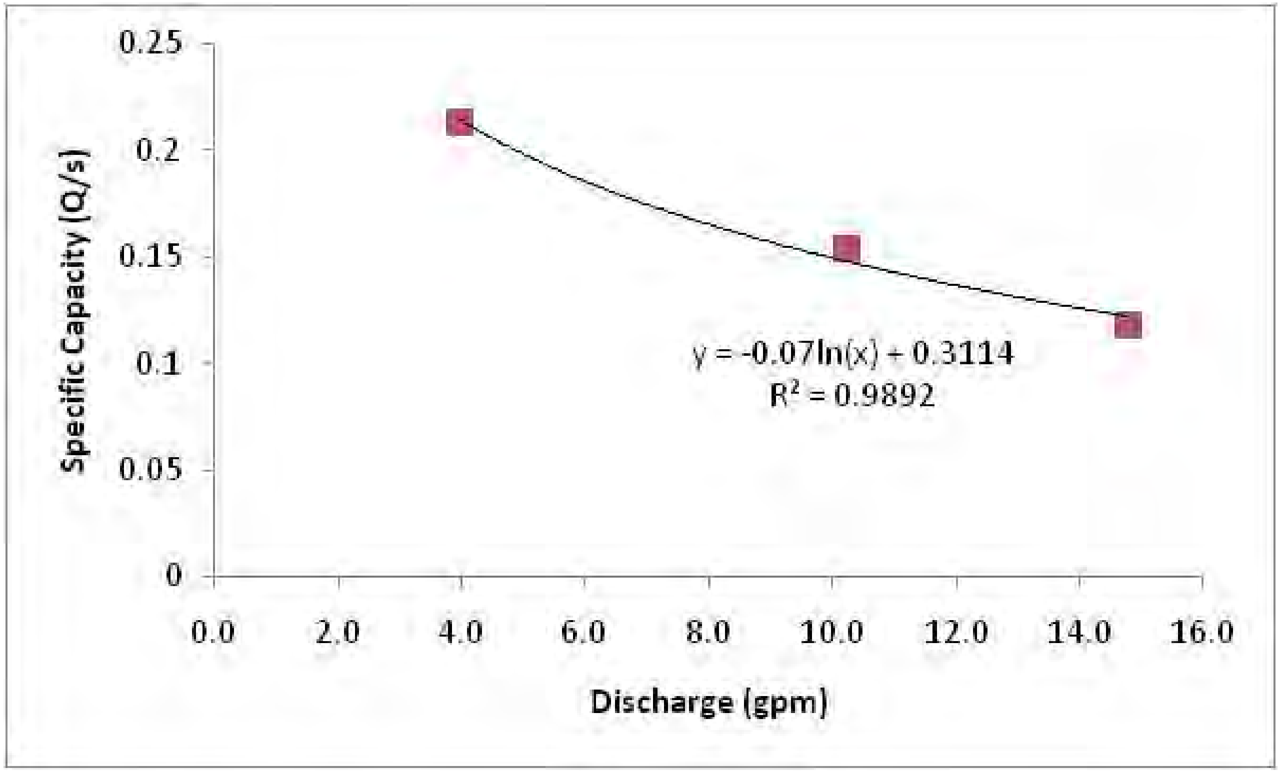


Figure P9. Specific capacity (Q/s) vs. pumping rate (Q) for PS. This relationship can be used to determine the maximum pumping rate for the well.

Constant-Rate Test Analysis

The constant-rate test was planned to start on March 23, 2012; however, after a brief pumping period, equipment problems forced the end of that test.

A new constant-rate test was started at 8:50 am on March 24, 2011, and ended at 8:53 am on March 25, for a total pumping time of 24 h and 3 min. The time-weighted average pumping rate was 15.5 gpm. The maximum recorded pumping rate was 16.8 gpm (for a short period at the start of the test) and the minimum recorded pumping rate was 15.2 gpm. Thus the maximum deviation from average was 8 percent. Data analysis was conducted using AQTESOLV software which allows for variable pumping rates. The maximum recorded drawdown in well PS was 138.62 ft. Water levels in well PS showed a rapid initial decline, followed by a period where the water level stabilized, then fell rapidly. The water level then followed a trend towards stabilizing. It is believed that the early stable portion results from the interception of a highly fractured zone (recharge source), and the following rapid decline is a result of a flow barrier being encountered. Both of these features could be explained by the drawdown cone expanding into a highly fractured zone adjacent to the fault, and then intersecting a low-permeability fault gouge. Later values represent the integration of the fractured zone, the fault, and a larger volume of surrounding country rock. Drawdown increased during the last hour by 0.29 ft. After pumping ceased, well PS exhibited a rapid initial recovery in water levels, and 2 h and 46 min were needed to reach 90 percent recovery. No drawdown was recorded in wells PN or PF.

Data from the 24-h aquifer test were analyzed using multiple analysis methods to determine aquifer parameter (appendix P-A). From early pumping data representing conditions before the recharge zone or the fault were intercepted by the cone of depression, the most appropriate transmissivity is approximately 70 ft^2/day, or a hydraulic conductivity of approximately 0.25 ft/day.

Summary

Analysis of this aquifer test indicates that there is a horizontal flow barrier at this site. No drawdown was seen in either observation well although pumping rate/duration and aquifer properties were sufficient to expect drawdown in the absence of a barrier. It is suspected that this barrier is a fault. It was also determined that the bedrock has a hydraulic conductivity (K) of about 0.25 ft/day; however, this value is from a relatively short period of pumping (~2 h), before the effects of boundaries are seen.

References

ASTM, 2008, Standard test method (field procedure) for withdrawal and injection well tests for determining hydraulic properties of aquifer systems, D4050-96 (Reapproved 2008).

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Hantush, M.S., 1960, Modification of the theory of leaky aquifers, Journal of Geophysical Research, v. 65, no. 11, p. 3713–3725.

Jacob, C.E., 1950, Flow of ground-water, *in* Engineering Hydraulics, Rouse, H., ed.: New York, N.Y., John Wiley Press.

Neuman, S.P., 1975, Analysis of pumping test data from anisotropic aquifers considering delayed gravity response, Water Resources Research, v. 11, no. 2, p. 329–342.

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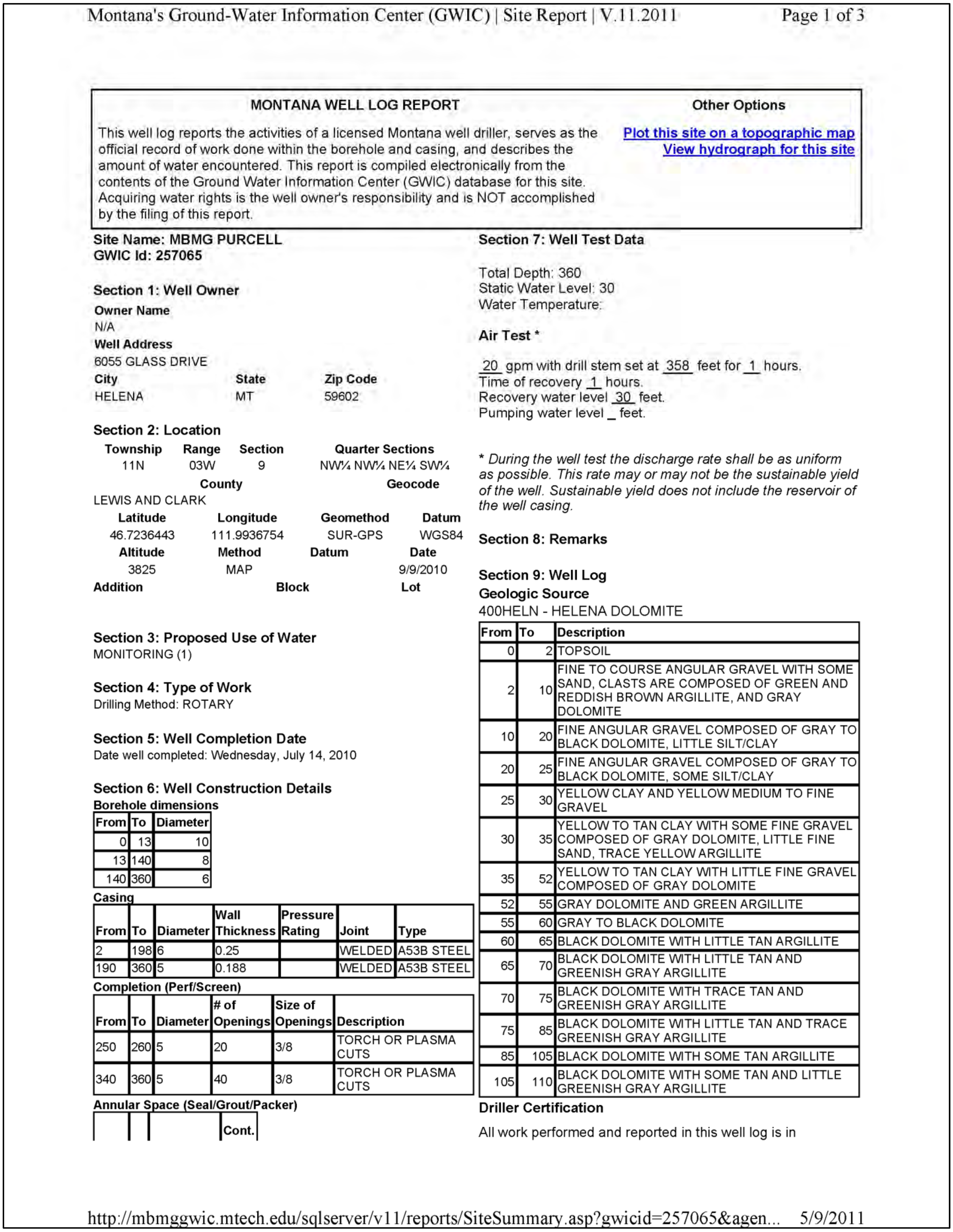
Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage, American Geophysical Union Transactions, v. 16, p. 519–524.

APPENDIX P-A—WELL LOGS



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MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site

Site Name: MBMG PURCELL
GWIC Id: 257065

Section 1: Well Owner

Owner Name
N/A
Well Address
6055 GLASS DRIVE

City	State	Zip Code
HELENA	MT	59602

Section 2: Location

Township	Range	Section	Quarter Sections
11N	03W	9	NW¼ NW¼ NE¼ SW¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7236443	111.9936754	SUR-GPS	WGS84

Altitude	Method	Datum	Date
3825	MAP		9/9/2010

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Wednesday, July 14, 2010

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	13	10
13	140	8
140	360	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
2	198	6	0.25		WELDED	A53B STEEL
190	360	5	0.188		WELDED	A53B STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
250	260	5	20	3/8	TORCH OR PLASMA CUTS
340	360	5	40	3/8	TORCH OR PLASMA CUTS

Annular Space (Seal/Grout/Packer)

			Cont.

Section 7: Well Test Data

Total Depth: 360
Static Water Level: 30
Water Temperature:

Air Test *

20 gpm with drill stem set at 358 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level 30 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

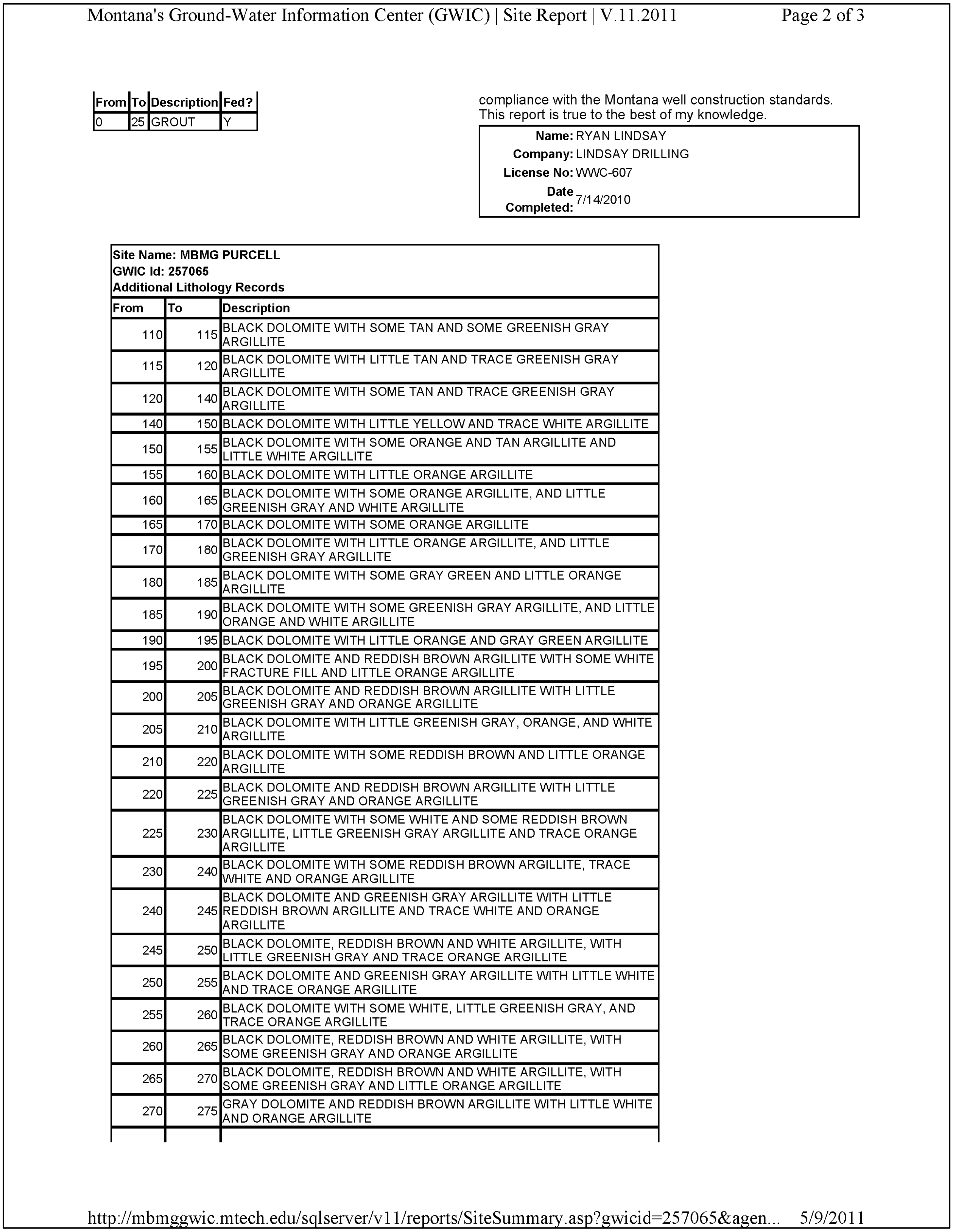
Geologic Source
400HELN - HELENA DOLOMITE

From	To	Description
0	2	TOPSOIL
2	10	FINE TO COURSE ANGULAR GRAVEL WITH SOME SAND, CLASTS ARE COMPOSED OF GREEN AND REDDISH BROWN ARGILLITE, AND GRAY DOLOMITE
10	20	FINE ANGULAR GRAVEL COMPOSED OF GRAY TO BLACK DOLOMITE, LITTLE SILT/CLAY
20	25	FINE ANGULAR GRAVEL COMPOSED OF GRAY TO BLACK DOLOMITE, SOME SILT/CLAY
25	30	YELLOW CLAY AND YELLOW MEDIUM TO FINE GRAVEL
30	35	YELLOW TO TAN CLAY WITH SOME FINE GRAVEL COMPOSED OF GRAY DOLOMITE, LITTLE FINE SAND, TRACE YELLOW ARGILLITE
35	52	YELLOW TO TAN CLAY WITH LITTLE FINE GRAVEL COMPOSED OF GRAY DOLOMITE
52	55	GRAY DOLOMITE AND GREEN ARGILLITE
55	60	GRAY TO BLACK DOLOMITE
60	65	BLACK DOLOMITE WITH LITTLE TAN ARGILLITE
65	70	BLACK DOLOMITE WITH LITTLE TAN AND GREENISH GRAY ARGILLITE
70	75	BLACK DOLOMITE WITH TRACE TAN AND GREENISH GRAY ARGILLITE
75	85	BLACK DOLOMITE WITH LITTLE TAN AND TRACE GREENISH GRAY ARGILLITE
85	105	BLACK DOLOMITE WITH SOME TAN ARGILLITE
105	110	BLACK DOLOMITE WITH SOME TAN AND LITTLE GREENISH GRAY ARGILLITE

Driller Certification

All work performed and reported in this well log is in

http://mbmggwic.mtech.edu/sqlserver/v11/reports/SiteSummary.asp?gwicid=257065&agen... 5/9/2011



From	To	Description	Fed?
0	25	GROUT	Y

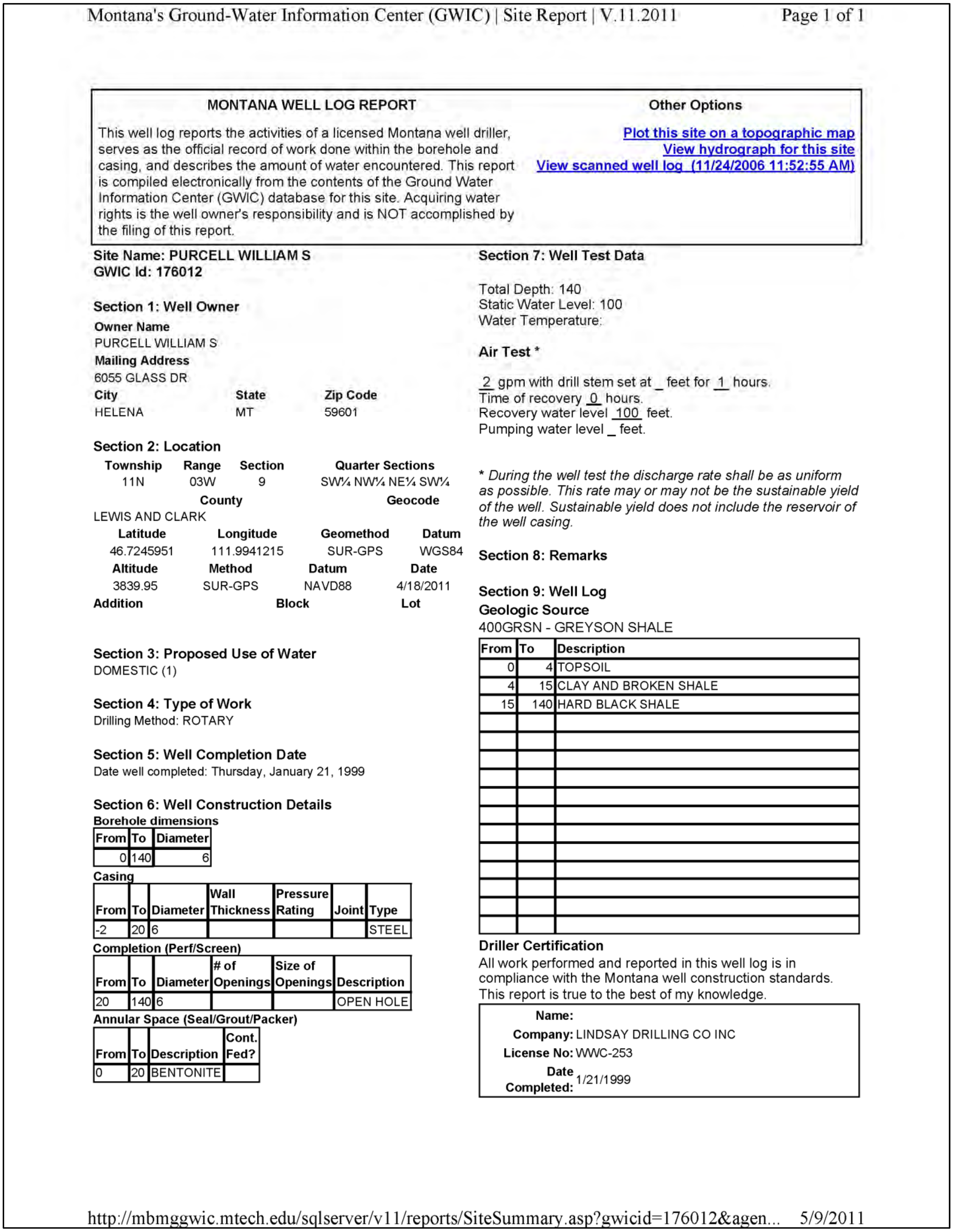
compliance with the Montana well construction standards.
This report is true to the best of my knowledge.

Name:	RYAN LINDSAY
Company:	LINDSAY DRILLING
License No:	WWC-607
Date Completed:	7/14/2010

Site Name: MBMG PURCELL
GWIC Id: 257065
Additional Lithology Records

From	To	Description
110	115	BLACK DOLOMITE WITH SOME TAN AND SOME GREENISH GRAY ARGILLITE
115	120	BLACK DOLOMITE WITH LITTLE TAN AND TRACE GREENISH GRAY ARGILLITE
120	140	BLACK DOLOMITE WITH SOME TAN AND TRACE GREENISH GRAY ARGILLITE
140	150	BLACK DOLOMITE WITH LITTLE YELLOW AND TRACE WHITE ARGILLITE
150	155	BLACK DOLOMITE WITH SOME ORANGE AND TAN ARGILLITE AND LITTLE WHITE ARGILLITE
155	160	BLACK DOLOMITE WITH LITTLE ORANGE ARGILLITE
160	165	BLACK DOLOMITE WITH SOME ORANGE ARGILLITE, AND LITTLE GREENISH GRAY AND WHITE ARGILLITE
165	170	BLACK DOLOMITE WITH SOME ORANGE ARGILLITE
170	180	BLACK DOLOMITE WITH LITTLE ORANGE ARGILLITE, AND LITTLE GREENISH GRAY ARGILLITE
180	185	BLACK DOLOMITE WITH SOME GRAY GREEN AND LITTLE ORANGE ARGILLITE
185	190	BLACK DOLOMITE WITH SOME GREENISH GRAY ARGILLITE, AND LITTLE ORANGE AND WHITE ARGILLITE
190	195	BLACK DOLOMITE WITH LITTLE ORANGE AND GRAY GREEN ARGILLITE
195	200	BLACK DOLOMITE AND REDDISH BROWN ARGILLITE WITH SOME WHITE FRACTURE FILL AND LITTLE ORANGE ARGILLITE
200	205	BLACK DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY AND ORANGE ARGILLITE
205	210	BLACK DOLOMITE WITH LITTLE GREENISH GRAY, ORANGE, AND WHITE ARGILLITE
210	220	BLACK DOLOMITE WITH SOME REDDISH BROWN AND LITTLE ORANGE ARGILLITE
220	225	BLACK DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY AND ORANGE ARGILLITE
225	230	BLACK DOLOMITE WITH SOME WHITE AND SOME REDDISH BROWN ARGILLITE, LITTLE GREENISH GRAY ARGILLITE AND TRACE ORANGE ARGILLITE
230	240	BLACK DOLOMITE WITH SOME REDDISH BROWN ARGILLITE, TRACE WHITE AND ORANGE ARGILLITE
240	245	BLACK DOLOMITE AND GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND TRACE WHITE AND ORANGE ARGILLITE
245	250	BLACK DOLOMITE, REDDISH BROWN AND WHITE ARGILLITE, WITH LITTLE GREENISH GRAY AND TRACE ORANGE ARGILLITE
250	255	BLACK DOLOMITE AND GREENISH GRAY ARGILLITE WITH LITTLE WHITE AND TRACE ORANGE ARGILLITE
255	260	BLACK DOLOMITE WITH SOME WHITE, LITTLE GREENISH GRAY, AND TRACE ORANGE ARGILLITE
260	265	BLACK DOLOMITE, REDDISH BROWN AND WHITE ARGILLITE, WITH SOME GREENISH GRAY AND ORANGE ARGILLITE
265	270	BLACK DOLOMITE, REDDISH BROWN AND WHITE ARGILLITE, WITH SOME GREENISH GRAY AND LITTLE ORANGE ARGILLITE
270	275	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE WHITE AND ORANGE ARGILLITE

275	285	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE WHITE AND ORANGE ARGILLITE
285	295	GRAY DOLOMITE AND WHITE ARGILLITE WITH SOME REDDISH BROWN ARGILLITE, AND LITTLE ORANGE ARGILLITE
295	300	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE WITH SOME WHITE AND LITTLE ORANGE ARGILLITE
300	305	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE WHITE ARGILLITE, AND TRACE ORANGE ARGILLITE
305	315	GRAY DOLOMITE WITH SOME REDDISH BROWN ARGILLITE, LITTLE WHITE ARGILLITE, AND TRACE ORANGE ARGILLITE
315	320	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE, WITH LITTLE WHITE AND TRACE ORANGE ARGILLITE
320	330	GRAY DOLOMITE AND REDDISH BROWN ARGILLITE WITH LITTLE WHITE AND TRACE ORANGE ARGILLITE
330	335	GRAY DOLOMITE, AND REDDISH BROWN AND WHITE ARGILLITE WITH LITTLE ORANGE ARGILLITE
335	340	GRAY DOLOMITE, AND REDDISH BROWN AND WHITE ARGILLITE WITH TRACE ORANGE ARGILLITE
340	360	GRAY DOLOMITE AND WHITE ARGILLITE, WITH LITTLE REDDISH BROWN AND ORANGE ARGILLITE



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MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned well log (11/24/2006 11:52:55 AM)

Site Name: PURCELL WILLIAM S
GWIC Id: 176012

Section 1: Well Owner

Owner Name
PURCELL WILLIAM S
Mailing Address
6055 GLASS DR

City	State	Zip Code
HELENA	MT	59601

Section 2: Location

Township	Range	Section	Quarter Sections
11N	03W	9	SW¼ NW¼ NE¼ SW¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7245951	111.9941215	SUR-GPS	WGS84

Altitude	Method	Datum	Date
3839.95	SUR-GPS	NAVD88	4/18/2011

Addition	Block	Lot

Section 3: Proposed Use of Water

DOMESTIC (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Thursday, January 21, 1999

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	140	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	20	6				STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
20	140	6			OPEN HOLE

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE	

Section 7: Well Test Data

Total Depth: 140
Static Water Level: 100
Water Temperature:

Air Test *

2 gpm with drill stem set at _ feet for 1 hours.
Time of recovery 0 hours.
Recovery water level 100 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
400GRSN - GREYSON SHALE

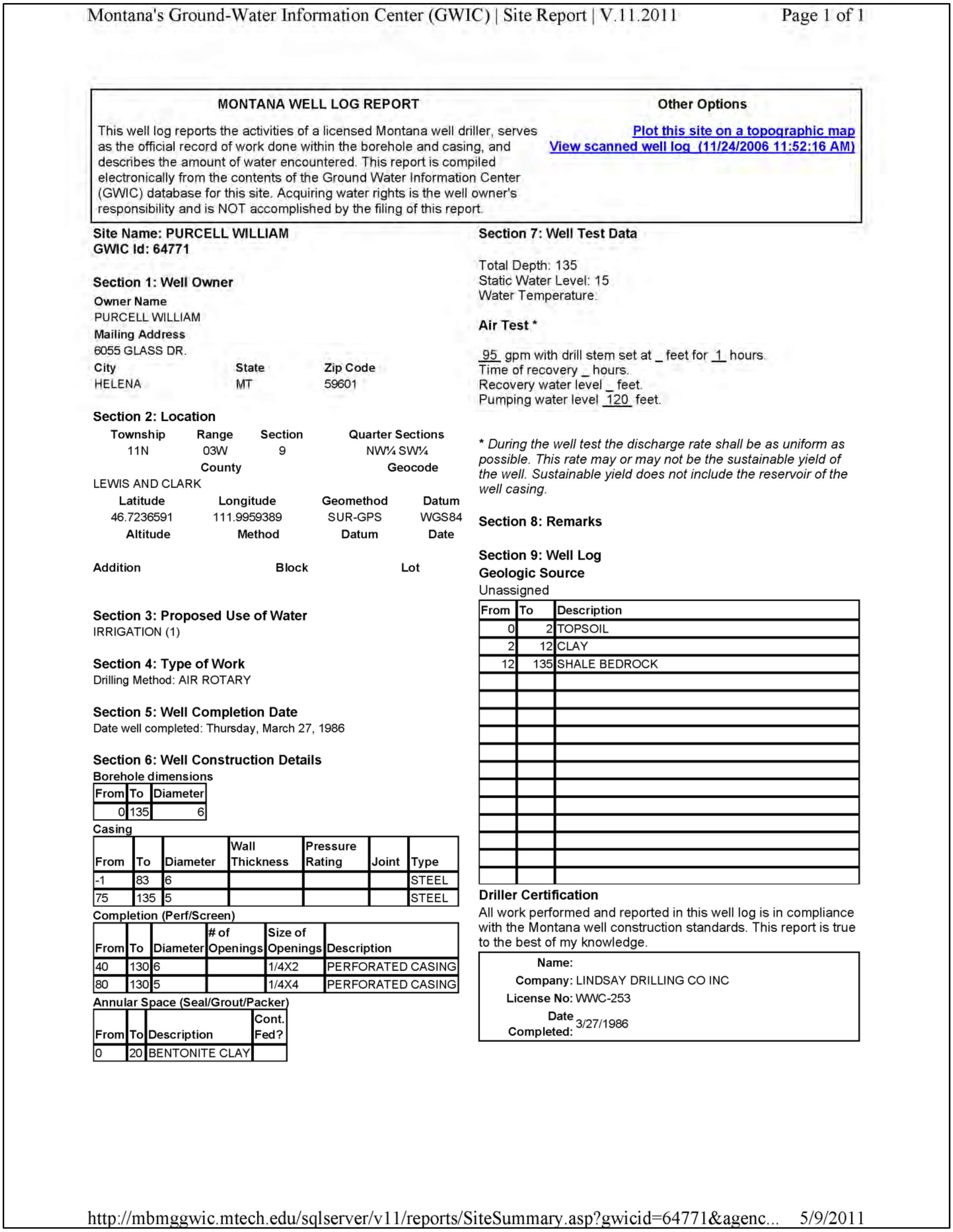
From	To	Description
0	4	TOPSOIL
4	15	CLAY AND BROKEN SHALE
15	140	HARD BLACK SHALE

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	
Company:	LINDSAY DRILLING CO INC
License No:	WWC-253
Date Completed:	1/21/1999

http://mbmggwic.mtech.edu/sqlserver/v11/reports/SiteSummary.asp?gwicid=176012&agen... 5/9/2011



MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View scanned well log (11/24/2006 11:52:16 AM)

Site Name: PURCELL WILLIAM
GWIC Id: 64771

Section 1: Well Owner

Owner Name
PURCELL WILLIAM
Mailing Address
6055 GLASS DR.

City	State	Zip Code
HELENA	MT	59601

Section 2: Location

Township	Range	Section	Quarter Sections
11N	03W	9	NW¼ SW¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7236591	111.9959389	SUR-GPS	WGS84

Altitude	Method	Datum	Date

Addition	Block	Lot

Section 3: Proposed Use of Water
IRRIGATION (1)

Section 4: Type of Work
Drilling Method: AIR ROTARY

Section 5: Well Completion Date
Date well completed: Thursday, March 27, 1986

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	135	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-1	83	6				STEEL
75	135	5				STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
40	130	6		1/4X2	PERFORATED CASING
80	130	5		1/4X4	PERFORATED CASING

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	20	BENTONITE CLAY	

Section 7: Well Test Data

Total Depth: 135
Static Water Level: 15
Water Temperature:

Air Test *

95 gpm with drill stem set at _ feet for 1 hours.
Time of recovery _ hours.
Recovery water level _ feet.
Pumping water level 120 feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log
Geologic Source
Unassigned

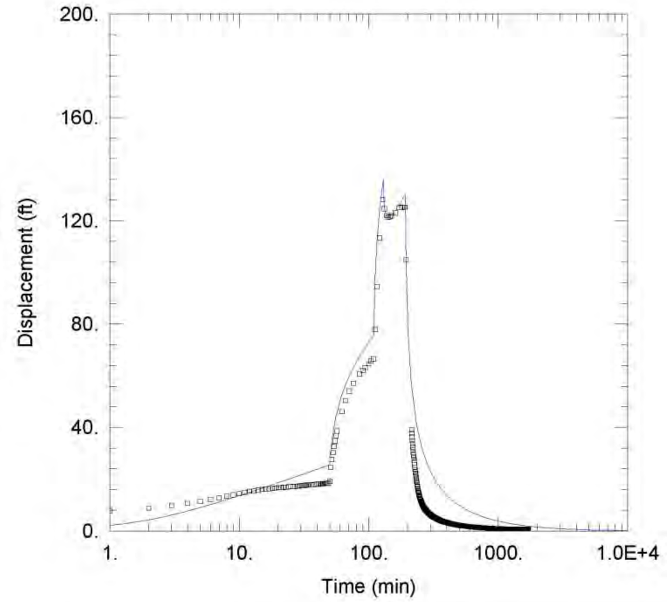
From	To	Description
0	2	TOPSOIL
2	12	CLAY
12	135	SHALE BEDROCK

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:
Company: LINDSAY DRILLING CO INC
License No: WWC-253
Date Completed: 3/27/1986

APPENDIX P-B—
RESULTS FROM
AQTESOLV
ANALYSIS
PURCELL AQUIFER TESTS



PURCELL STEP TEST

Data Set: M:\...\PS_Step2.aqt
Date: 05/27/11 Time: 09:56:54

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: PS
Test Date: 3/21/11

AQUIFER DATA

Saturated Thickness: 285. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PS	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ PS	0	0

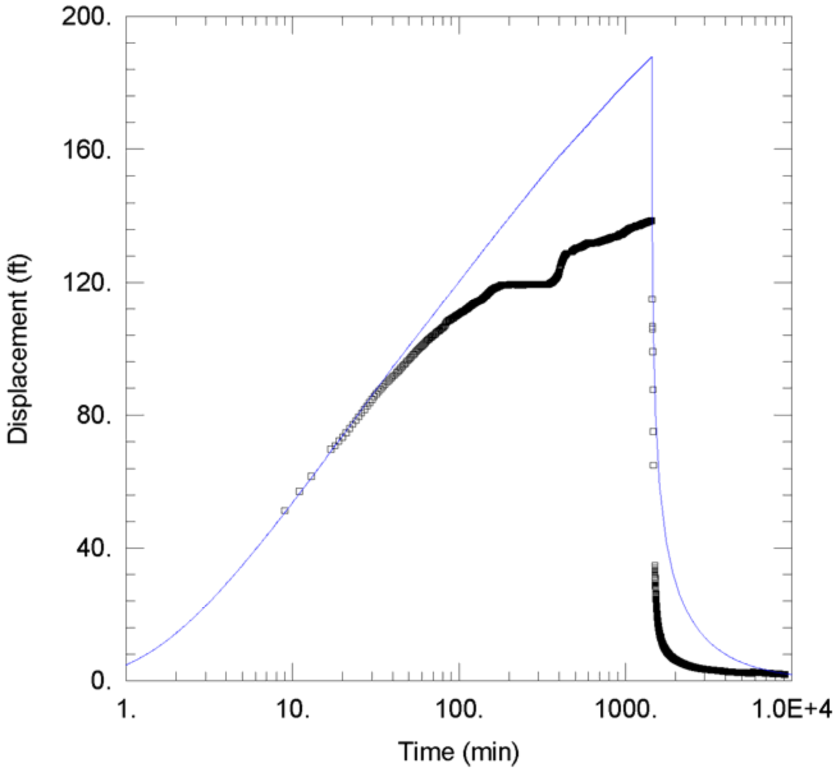
SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

$T = 70.\ \mathrm{ft}^2/\mathrm{day}$
$S = 0.27$
$Sw = 0.06397$
$C = 1.\ \mathrm{min}^2/\mathrm{ft}^5$
$P = 2.65$

Step Test Model: Jacob-Rorabaugh
$s(t) = 3.815Q + 1.Q^{2.65}$
Time (t) = 1. min Rate (Q) in cu. ft/min
W.E. = 52.29% (Q from last step)

Figure P-B1. Step test simulation using the T value determined from the Purcell constant-rate test, using the Theis method for a confined aquifer, and a partially penetrating well.



PURCELL CONSTANT RATE TEST

Data Set: M:\...\PS_CR.aqt
Date: 04/10/12 Time: 16:07:02

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: PS
Test Date: 3/24-25/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PS	0	0

Observation Wells

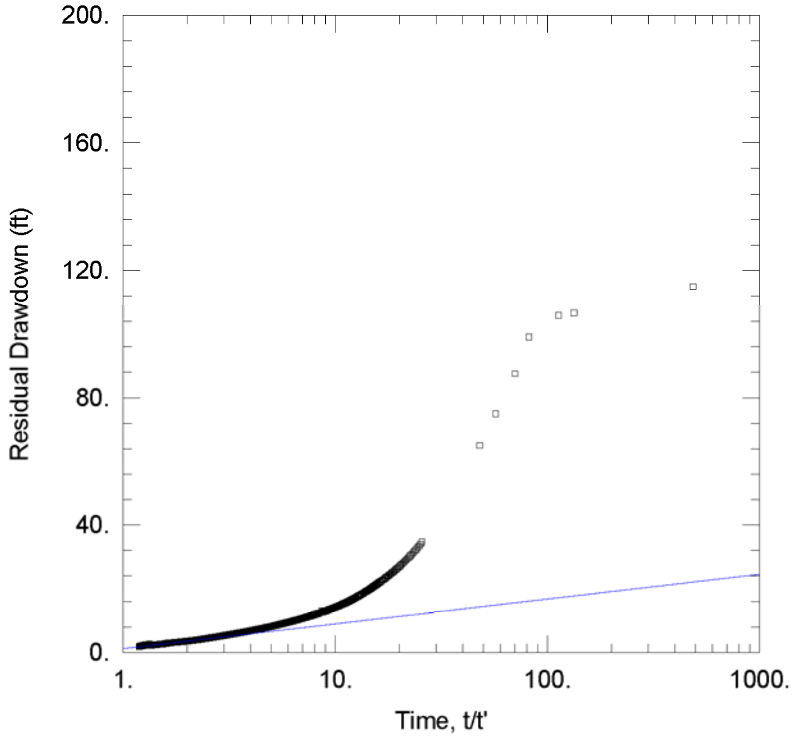
Well Name	X (ft)	Y (ft)
▫ PS	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 70. ft^2/day
Kz/Kr = 1.
S = 0.25
b = 285. ft

Figure P-B2. Purcell constant-rate test simulation of PS using the Theis method for a confined aquifer and partially penetrating well.



PURCELL CONSTANT RATE TEST

Data Set: M:\...\PS_CR.aqt
Date: 04/10/12
Time: 16:10:06

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: PS
Test Date: 3/24-25/11

AQUIFER DATA

Saturated Thickness: 285. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
PS	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ PS	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)
T = 70. ft^2/day
S/S' = 0.7

Figure P-B3. Recovery from constant-rate test simulation of PS using the Theis method for a confined aquifer and partially penetrating well.

STATE LANDS EAST AQUIFER TEST—
SPOKANE FORMATION

STATE LANDS EAST
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
April 2011

STEP TEST
AND
48-HOUR CONSTANT-RATE TEST

Background

MBMG performed a step test and a 48-h constant-rate pumping test using wells installed on State lands in the North Hills study area (fig. E1). These wells are located along the watershed divide at the top of the hills in the north-central portion of the study area. The purpose of the test was to evaluate the hydraulic conductivity and storativity of the Spokane Formation in the primary recharge area for the North Hills. The data also helped to evaluate the presence of recharge or barrier boundaries. There are no residences in the area; the closest used well is approximately 2,000 ft from the pumping well.

These tests were designed to evaluate the hydraulic properties of the Spokane Formation. A MBMG geologist was present for the installation of two wells at the State Lands East site in September 2010; cuttings were described in detail, and completion details verified. Composite cuttings samples were collected, described, and stored for every 10 ft of borehole for both wells. The well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu) by using the GWIC ID. A summary of completion details is provided in table E1 and appendix E-A.

A transducer was deployed in SLE-1 in November 2010 for long-term monitoring. Data from this transducer show that water levels in SLE-1 rose slightly over the winter (fig. E2).

Location

The test area is located in the North Hills, north of Helena, MT. The wells are located in Township 12 N., Range 3 W., Section 30, NW¼ SW¼, in Lewis and Clark County, Montana (figs. E1, E3). The altitude of the site is approximately 4,690 ft above mean sea level.

Geology

This site is located in the Spokane Formation. There are no mapped faults in the immediate vicinity of the site; however, given the fractured nature of the rock encountered during drilling, it appears that unmapped faults may be present. The Helena Valley Fault is located approximately 0.25 mi south (fig. E4).

Well Details

SLE-1 is 345 ft deep and cased with 5-in steel that was perforated between 275 and 345 ft. Due to excessive caving during drilling, steel casing needed to be driven to total depth. SLE-2 is a 350-ft-deep, 4-in PVC-cased well with screen between 280 and 350 ft.

Pretest depth to water (DTW) readings at the test site show that the groundwater elevation is 4497.57 ft-amsl at SLE-1 and 4496.19 ft-amsl at SLE-2.

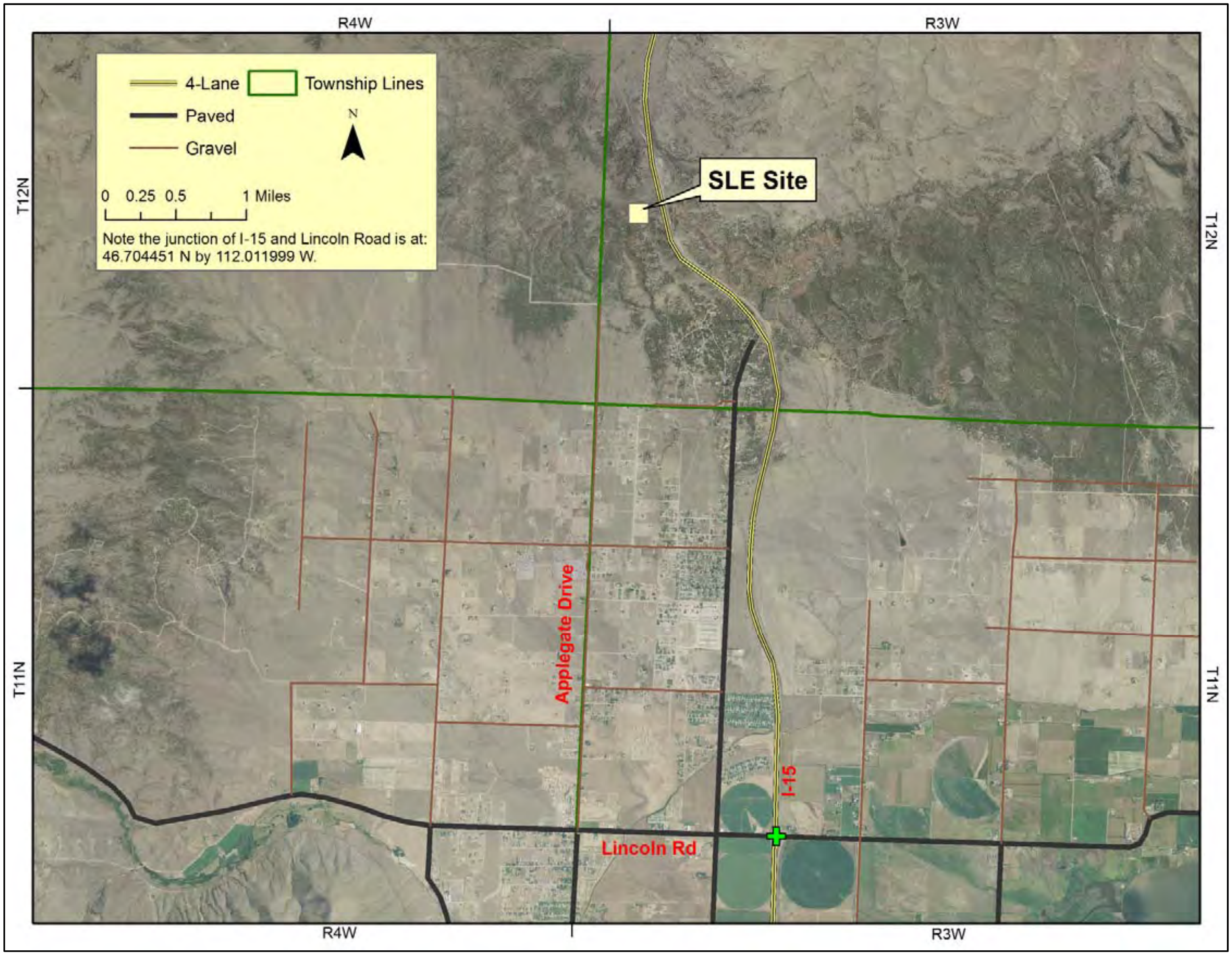


Figure E1. Location of the State Lands East Aquifer test site. The green cross located at the junction of Interstate 15 and Lincoln Road is at latitude 46.704451°N and longitude 112.011999°W.

Table E1

Well Designations, Locations, and Completion Information

State Lands East Aquifer Test—April 2011

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 4/6/11 (ft below MP)	Groundwater Elevation 4/6/11 (ft-amsl)	Distance from SLE-1 (ft)	Comments
258290	SLE-1	46.7680062	-112.0357379	4693.26	345	195.69	4497.57	---	Pumping Well
258294	SLE-2	46.7676143	-112.0359925	4694.80	350	198.61	4496.19	156	Observation Well

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

* = Horizontal Datum is NAD83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

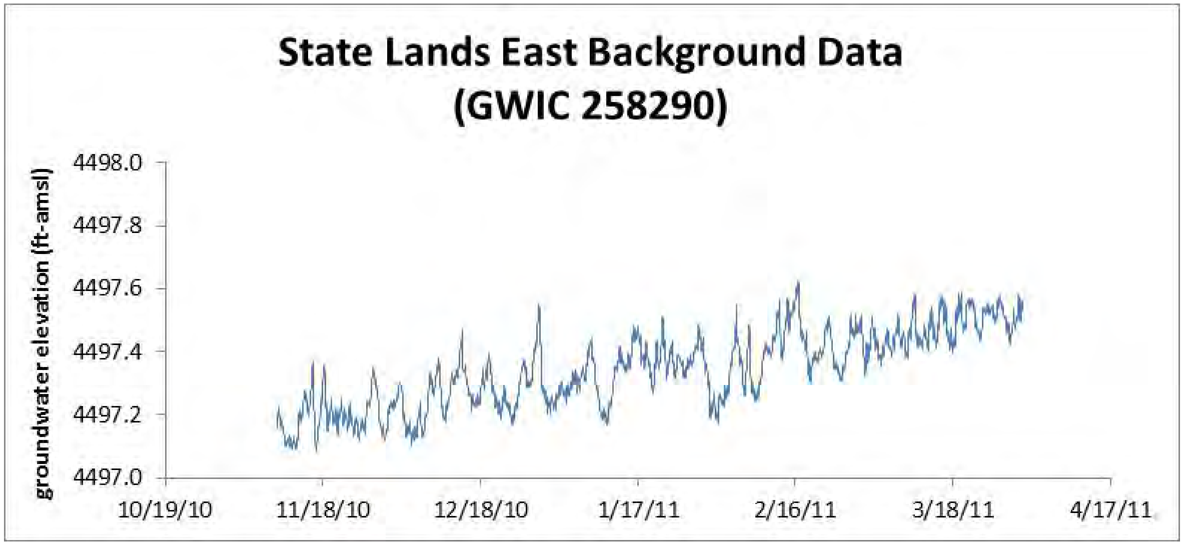


Figure E2. Background data from SLE-1 show a slight increase in water levels at the site during the winter.

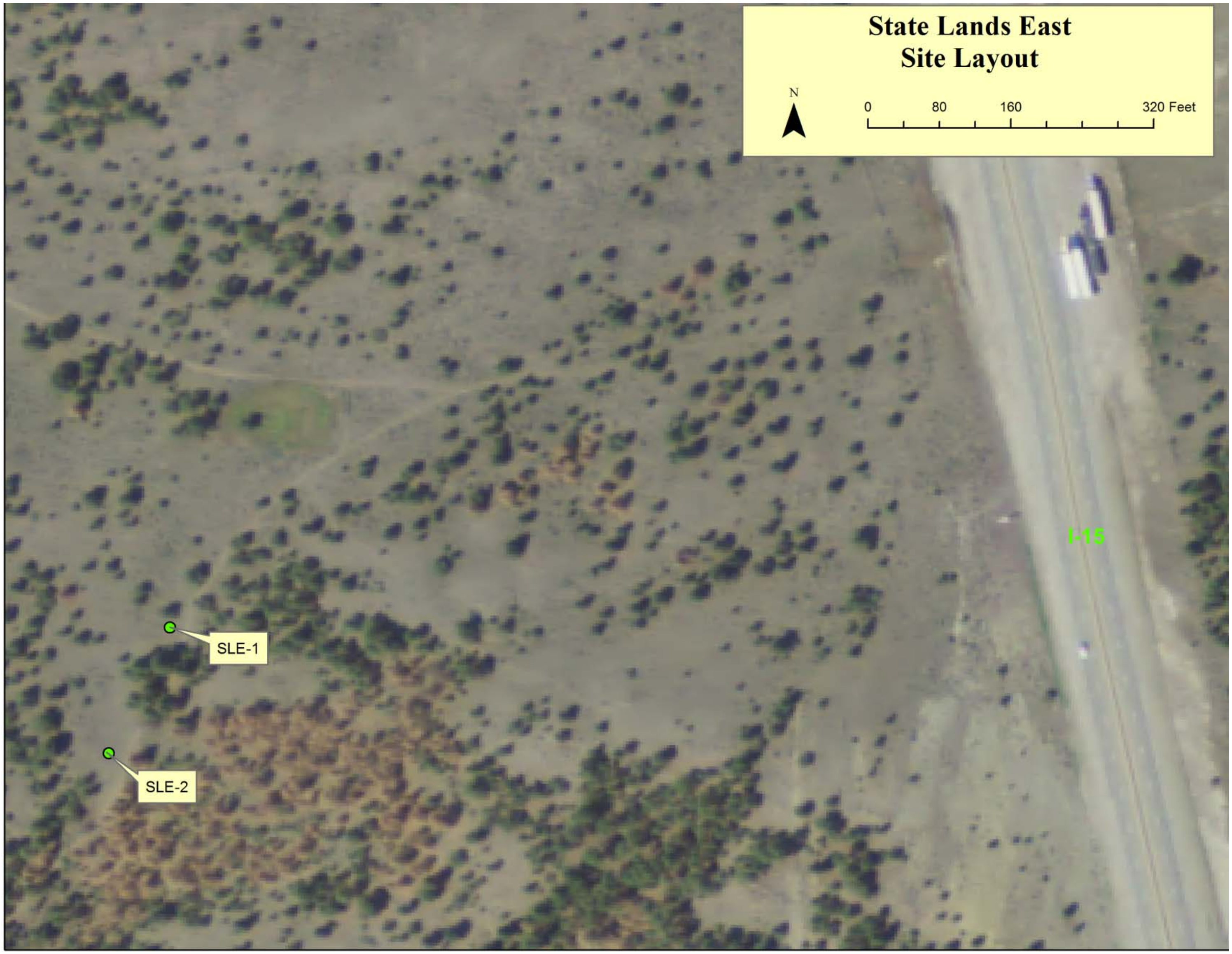


Figure E3. Site layout for the State Lands East Aquifer test.

Methodology

The pumping rate (fig. E5) was monitored throughout the test using a totalizing flow meter and an orifice bucket flow meter with a transducer in the piezometer tube. The flow meter was also checked against bucket and stopwatch measurements. When concurrent measurements were made, there was good agreement between the measured flows. Discharge was controlled using a gate valve. The discharge water was diverted approximately 200 ft northwest of the pumping well (SLE-1), and away from the observation well (SLE-2).

Non-vented pressure transducers were used to record water levels in the pumping and observation wells. The transducer in the pumping well was rated at 30 psia (35 ft), has a manufacturer-reported accuracy of ±0.1% of the rated pressure (±0.035 ft), and a resolution of ±0.01 percent of the rated pressure (0.0035 ft). The transducer in the observation well was rated for 30 ft, has a manufacturer-reported accuracy of ±0.1% of the rated pressure (±0.03 ft), and a resolution of ±0.01 percent of the rated pressure (0.003 ft). The data from these non-vented transducers were corrected for changes in barometric pressure through the use of a barologger.

Manual water-level readings were made in all wells prior to placing transducers, periodically during the test, during recovery, and prior to removing the transducers. The manual measurements were used to verify transducer response (figs. E6, E7). All water-level data are available from GWIC by using the GWIC IDs for the wells (http://mbmggwic.mtech.edu/).

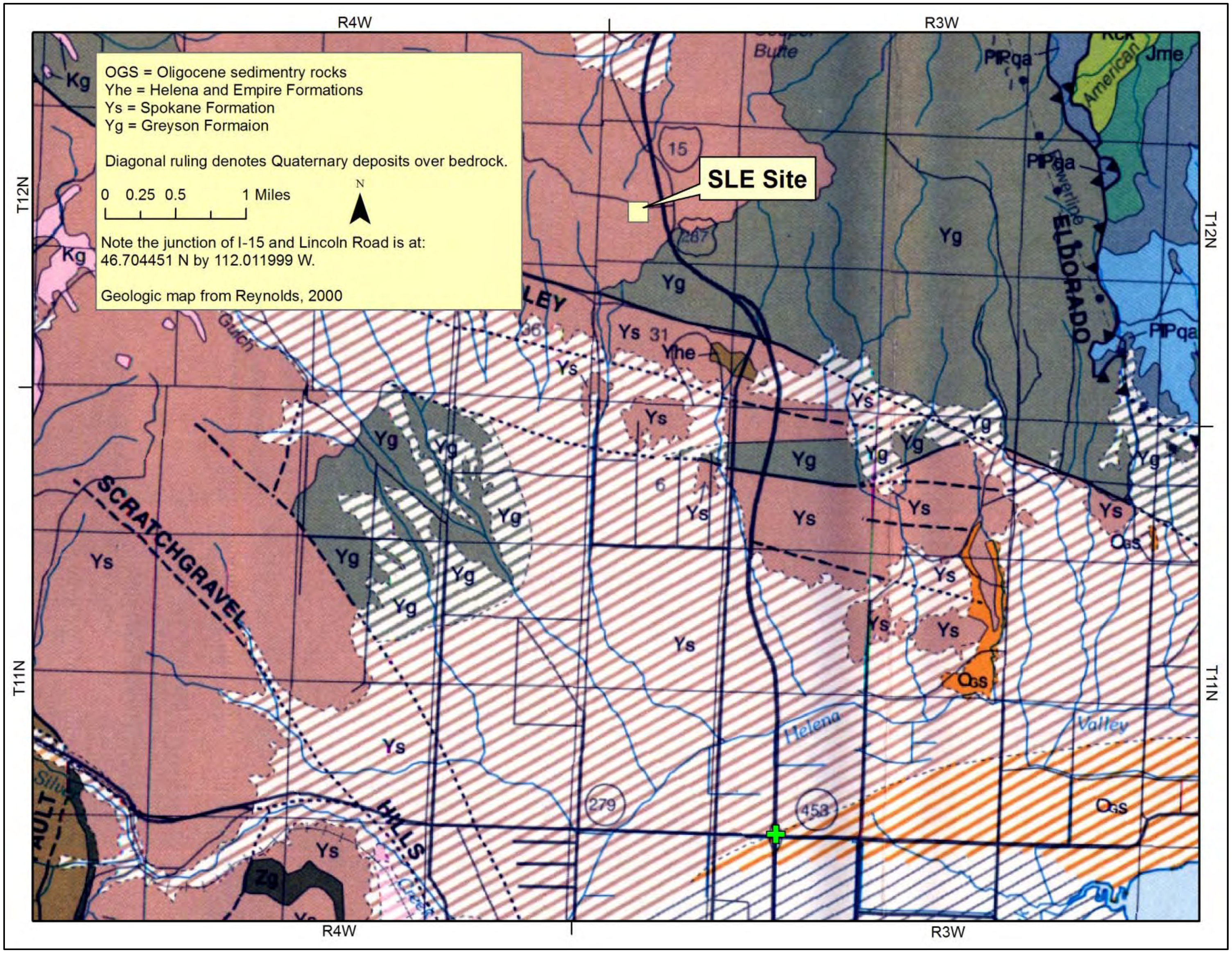


Figure E4. Geologic Map of the State Lands East Aquifer test area. Geologic map prepared by Reynolds (2000). The green cross located at the junction of Interstate 15 and Lincoln Road is at latitude 46.704451°N and longitude 112.011999°W.

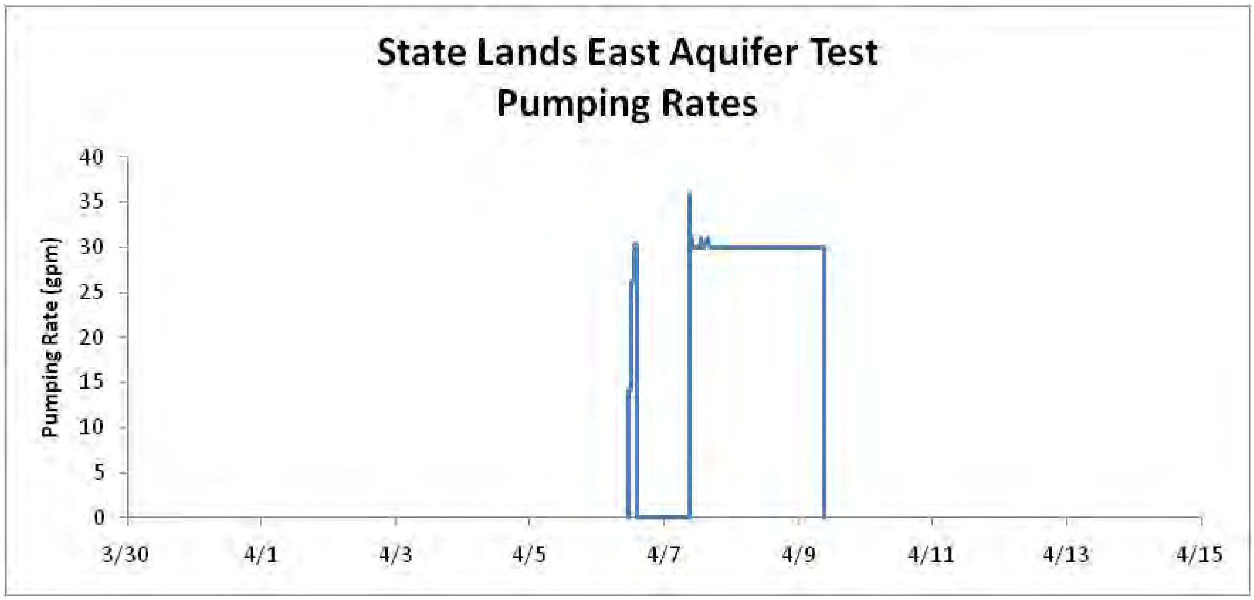


Figure E5. Pumping rates from SLE-1 during the State Lands East Aquifer test.

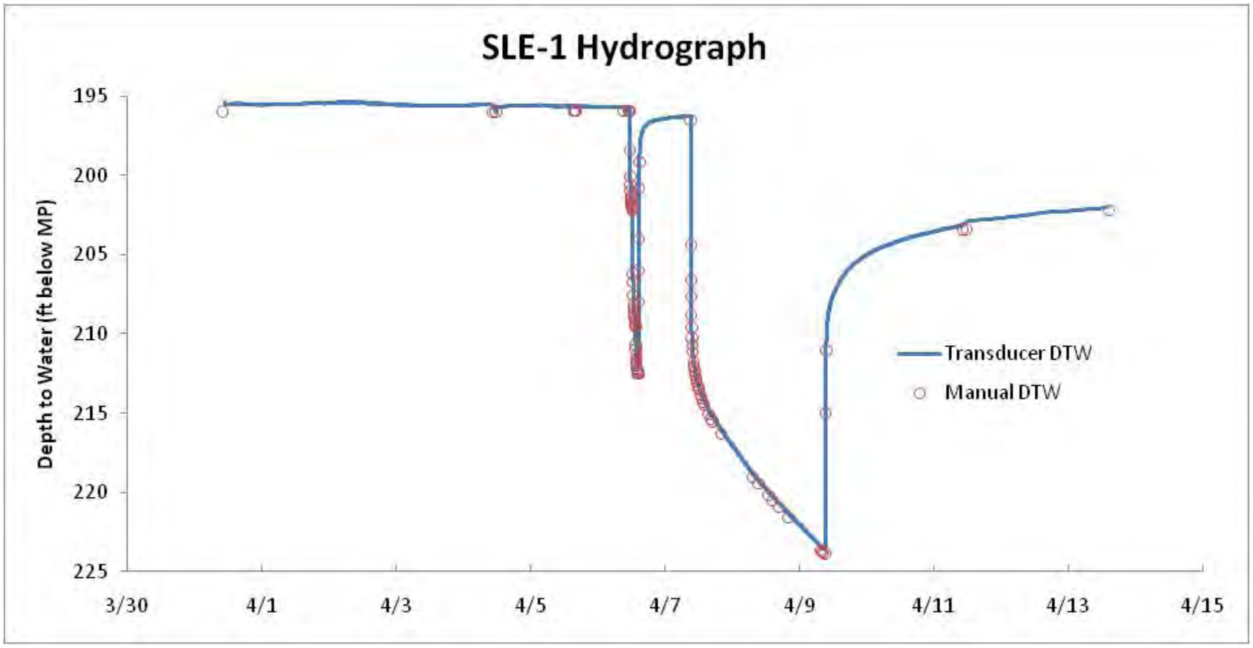


Figure E6: Depth to water readings in well SLE-1 (pumping well) during the State Lands East Aquifer test.

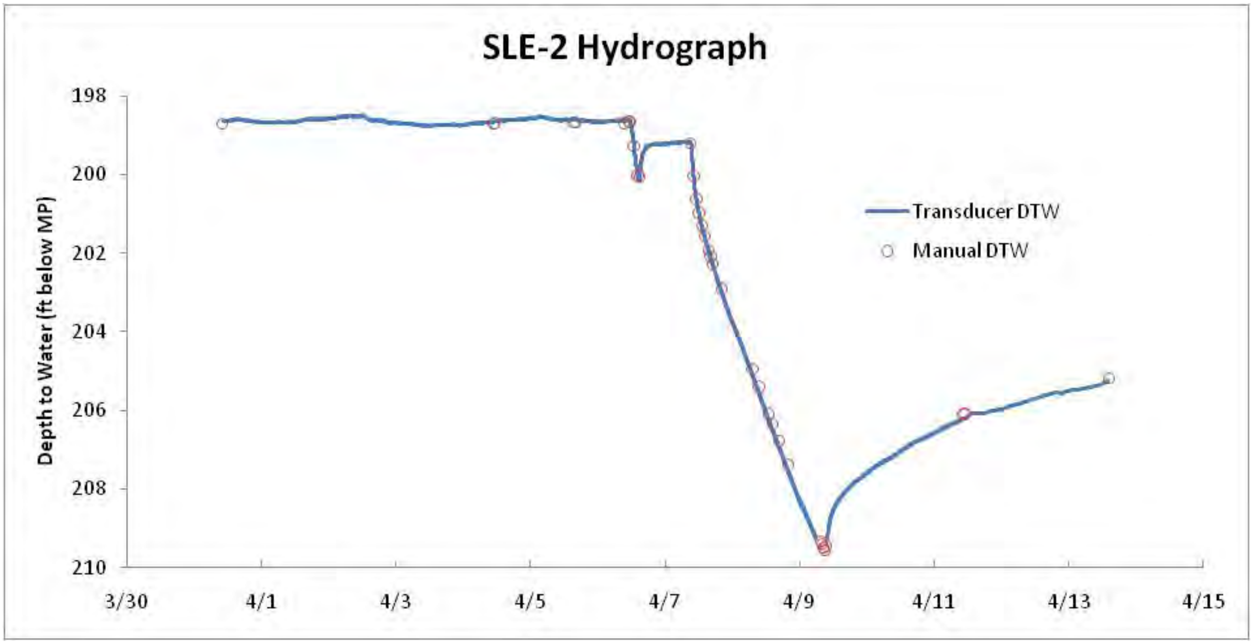


Figure E7. Depth to water readings in SLE-2 (observation well; 156 ft from SLE-1) during the State Lands East Aquifer test.

Step Test

On April 6, 2011, a step test was conducted on SLE-1 to determine an appropriate pumping rate (table E2; figs. E8, E9). Because the pump was set at 273 ft below ground, and the screen extends from the bottom up to 275 ft below ground, it was desired that the long-term pumping rate not cause water levels to drop below 270 ft (74 ft of drawdown). Analysis of the step test data suggests that the target drawdown (74 ft) would be achieved with a pumping rate of 88 gpm; however, the step test likely overestimates the sustainable yield because water levels did not fully stabilize (fig. E8). The maximum rate that pumping equipment on site could produce was 30.3 gpm, and that was determined to be a reasonable pumping rate for the constant-rate test. The weighted average discharge for the constant-rate test was 30.4 gpm, which resulted in 27 ft of drawdown (10 ft more than the step test data suggested).

Table E2
SLE-1—Step Test Summary
State Lands East Aquifer Test—April 6, 2011

Start Step	End Step	Rate (Q, gpm)	Maximum Drawdown (s, ft)	Specific Capacity (Q/s, gpm/ft)
11:25	12:25	14.3	6.28	2.28
12:25	13:25	26.2	13.59	1.93
13:25	14:25	30.3	16.53	1.83

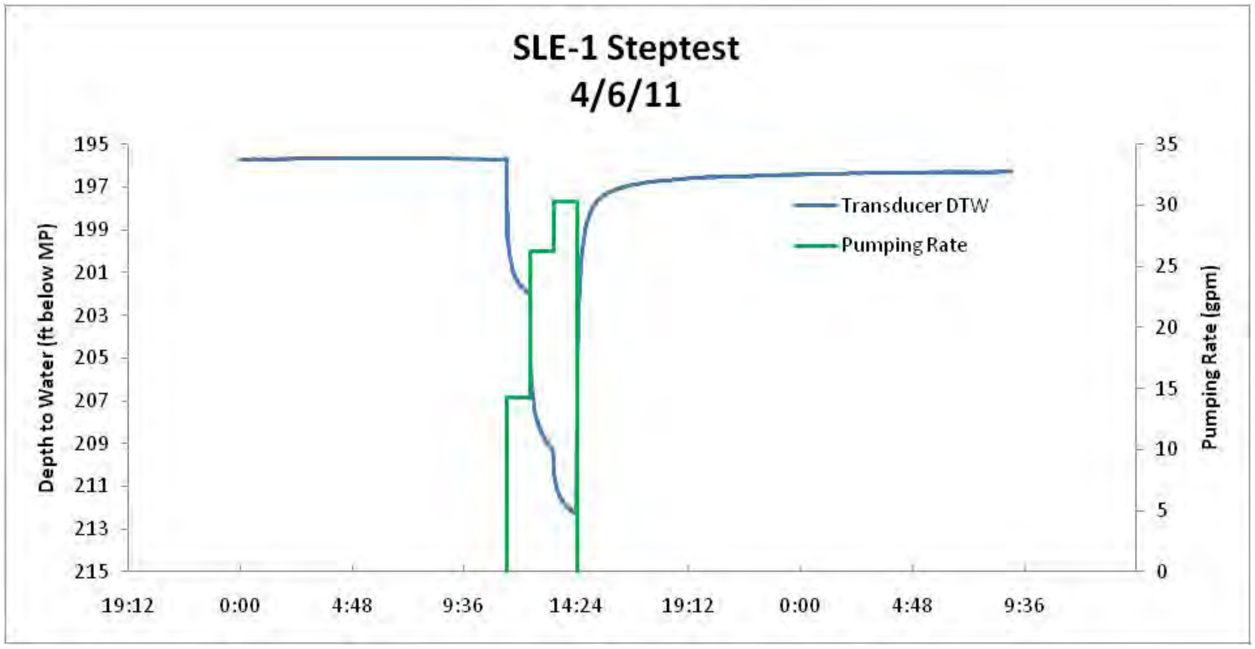


Figure E8. Depth to water in SLE-1 and pumping rates recorded during step test.

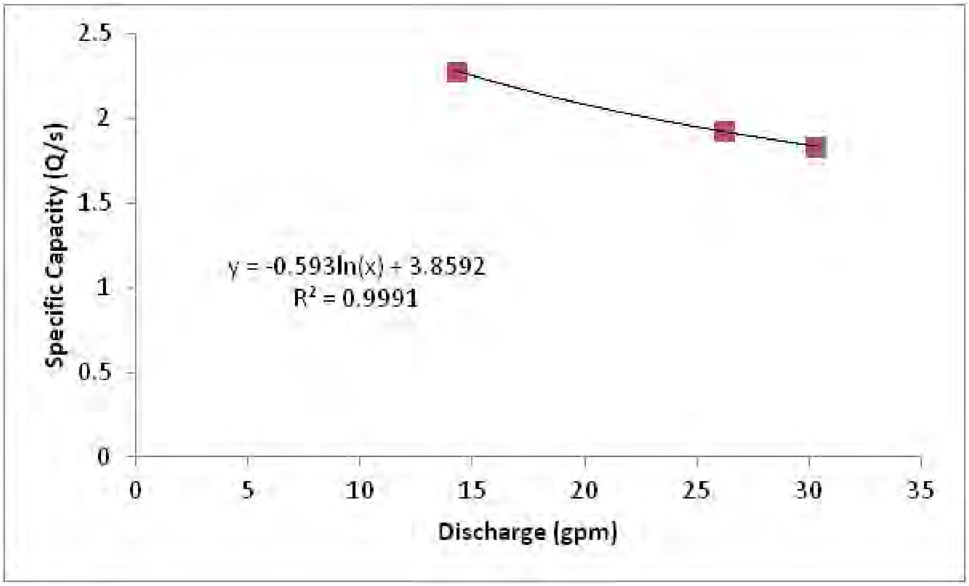


Figure E9. Specific capacity (Q/s) vs. pumping rate (Q) from the step test on SLE-1. This relationship was used to estimate the maximum pumping rate for the well.

Simulation of the step test data using AQTESOLV software was conducted (appendix E-B). The step test observations can be simulated using the aquifer properties determined during the constant-rate test. It is notable that the recovery portion of the data shows less recovery than would be predicted, indicating that a flow barrier is present. The immediate response of SLE-2 to pumping indicates that there is no hydraulic barrier between SLE-1 and SLE-2.

Constant-Rate Test Analysis

The constant-rate test started at 9:05 am on April 7, 2011, and ended at 9:05 am on April 9, for a total pumping time of 48 h. The time-weighted average pumping rate was 30.4 gpm. The maximum recorded pumping rate was 36 gpm (for a short period near the start of the test) and the minimum recorded pumping rate was 30 gpm. Thus the maximum deviation from average was 18 percent. The data were analyzed using AQTESOLV software, which allows for variable pumping rates.

The maximum recorded drawdown in well SLE-1 (pumping well) was 27.26 ft. Water levels in well SLE-1 showed a rapid initial decline, followed by a steady decline. After pumping ceased, water levels in well SLE-1 exhibited a rapid initial recovery; however, after 4.2 d, recovery was still only 79 percent. The steady decline during pumping and the slow recovery indicate that at least one barrier to flow is present in the aquifer volume impacted by the pumping. Analysis of the data collected for pumping times prior to when flow barriers were encountered resulted in a transmissivity (T) of 475 ft^2/day, which, using a thickness of 150 ft, equates to a hydraulic conductivity (K) of 3.2 ft/day.

The maximum recorded drawdown in well SLE-2 was 10.39 ft. The drawdown in SLE-2 was very steady, and again recovery after the test was much less than predicted. This slow recovery supports the likelihood that there are one or more flow barriers in this area. Analysis of data collected for pumping times prior to when flow barriers were encountered again resulted in a transmissivity of 475 ft^2/day and a storativity (S) of 0.0011.

Summary

Analysis of this aquifer test indicates that there are noticeable barriers to flow present at this site, which cause the observed drawdowns to differ from that anticipated for ideal porous media. The barriers are not between the test wells. If the early time constant-rate data and the step test data are used, the local transmissivity is approximately 475 ft^2/day; and using a saturated thickness of 150 ft, the hydraulic conductivity is 3.2 ft/day. The best estimate of storativity is 0.0011, which indicates semi-confined conditions.

References

ASTM, 2008, Standard test method (field procedure) for withdrawal and injection well tests for determining hydraulic properties of aquifer systems, D4050-96 (Reapproved 2008).

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Fetter, C.W., 1994, Applied hydrogeology, Third ed.,: New York, N.Y., Macmillan College Publishing, 691 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice Hall, 604 p.

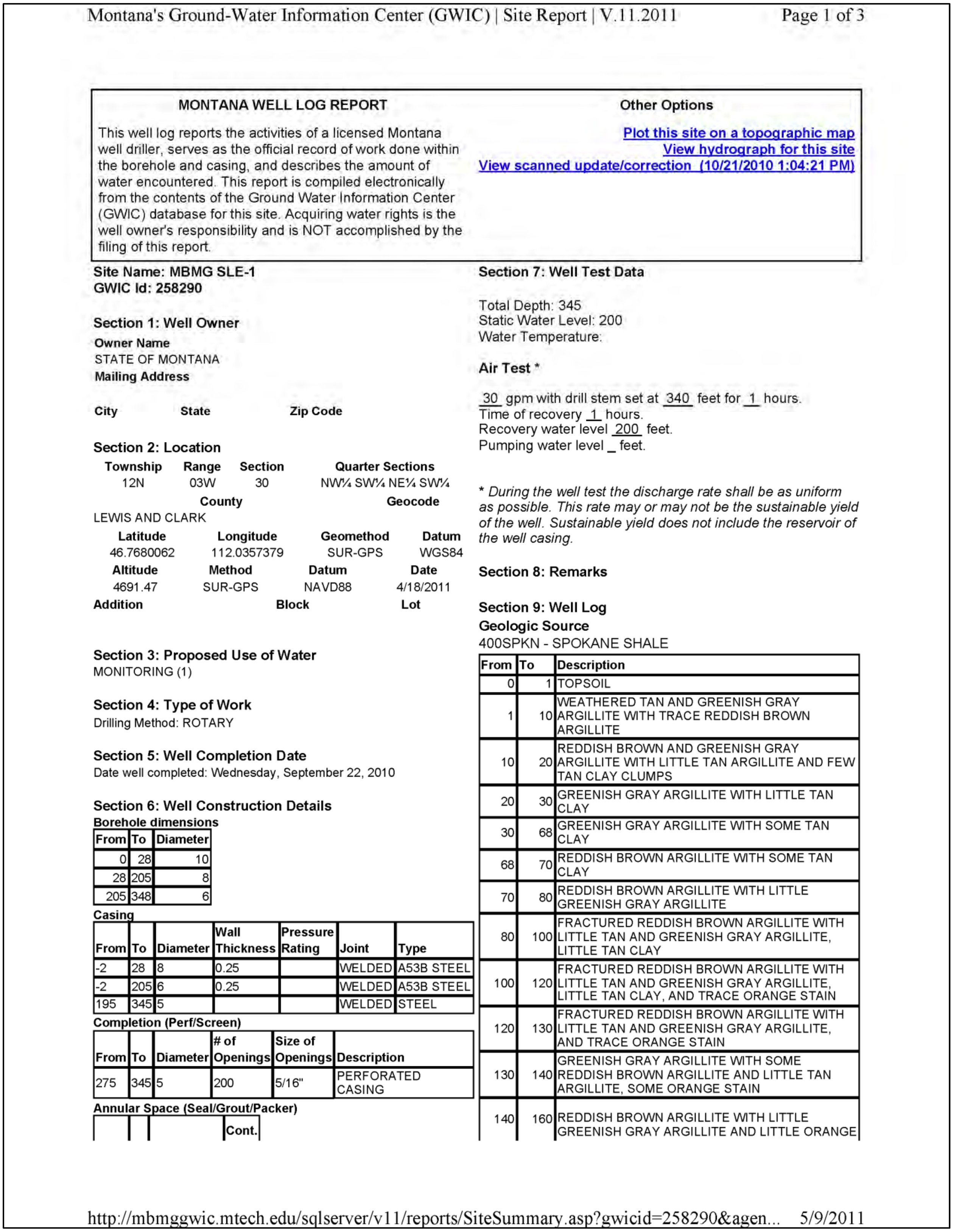
Jacob, C.E., 1950, Flow of ground-water, *in* Engineering hydraulics, Rouse, H., ed.: New York, N.Y., John Wiley Press.

Neuman, S.P., 1975, Analysis of pumping test data from anisotropic aquifers considering delayed gravity response, Water Resources Research, v. 11, no. 2, p. 329–342.

Reynolds, Mitchell W., 2000, Generalized bedrock geologic map of the Helena area, west-central Montana, *in* Thamke, J.N., 2000: Hydrology of area bedrock west-central Montana, 1993-98, USGS WRIR 00-4212.

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.

APPENDIX E-A—WELL LOGS



MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned update/correction (10/21/2010 1:04:21 PM)

Site Name: MBMG SLE-1
GWIC Id: 258290

Section 1: Well Owner

Owner Name
STATE OF MONTANA
Mailing Address

City	**State**	**Zip Code**

Section 2: Location

Township	Range	Section	Quarter Sections
12N	03W	30	NW¼ SW¼ NE¼ SW¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7680062	112.0357379	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4691.47	SUR-GPS	NAVD88	4/18/2011

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Wednesday, September 22, 2010

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	28	10
28	205	8
205	348	6

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	28	8	0.25		WELDED	A53B STEEL
-2	205	6	0.25		WELDED	A53B STEEL
195	345	5			WELDED	STEEL

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
275	345	5	200	5/16"	PERFORATED CASING

Annular Space (Seal/Grout/Packer)

			Cont.

Section 7: Well Test Data

Total Depth: 345
Static Water Level: 200
Water Temperature:

Air Test *

30 gpm with drill stem set at 340 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level 200 feet.
Pumping water level _ feet.

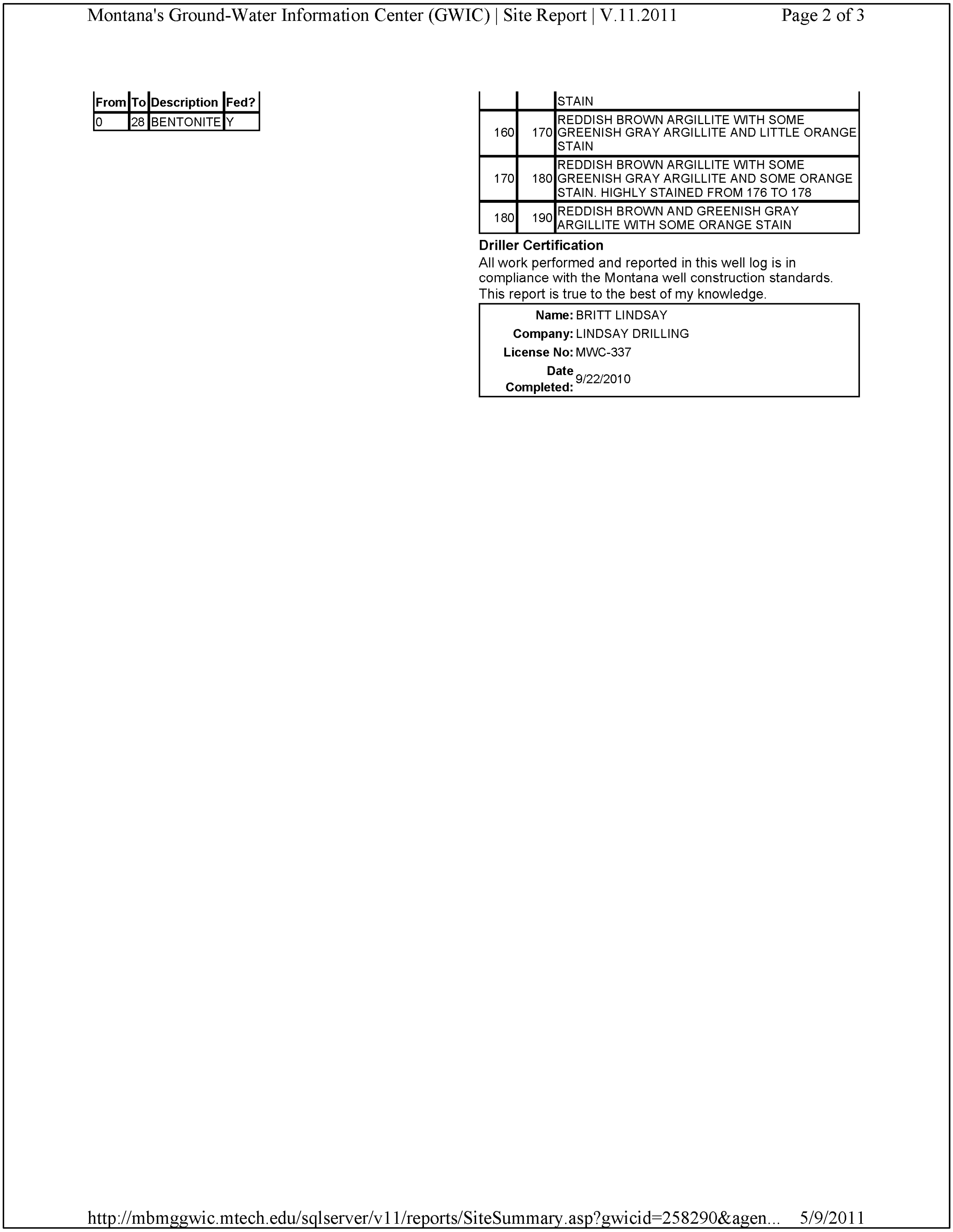
** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
400SPKN - SPOKANE SHALE

From	To	Description
0	1	TOPSOIL
1	10	WEATHERED TAN AND GREENISH GRAY ARGILLITE WITH TRACE REDDISH BROWN ARGILLITE
10	20	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH LITTLE TAN ARGILLITE AND FEW TAN CLAY CLUMPS
20	30	GREENISH GRAY ARGILLITE WITH LITTLE TAN CLAY
30	68	GREENISH GRAY ARGILLITE WITH SOME TAN CLAY
68	70	REDDISH BROWN ARGILLITE WITH SOME TAN CLAY
70	80	REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY ARGILLITE
80	100	FRACTURED REDDISH BROWN ARGILLITE WITH LITTLE TAN AND GREENISH GRAY ARGILLITE, LITTLE TAN CLAY
100	120	FRACTURED REDDISH BROWN ARGILLITE WITH LITTLE TAN AND GREENISH GRAY ARGILLITE, LITTLE TAN CLAY, AND TRACE ORANGE STAIN
120	130	FRACTURED REDDISH BROWN ARGILLITE WITH LITTLE TAN AND GREENISH GRAY ARGILLITE, AND TRACE ORANGE STAIN
130	140	GREENISH GRAY ARGILLITE WITH SOME REDDISH BROWN ARGILLITE AND LITTLE TAN ARGILLITE, SOME ORANGE STAIN
140	160	REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY ARGILLITE AND LITTLE ORANGE



From	To	Description	Fed?
0	28	BENTONITE	Y

		STAIN
160	170	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY ARGILLITE AND LITTLE ORANGE STAIN
170	180	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY ARGILLITE AND SOME ORANGE STAIN. HIGHLY STAINED FROM 176 TO 178
180	190	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN

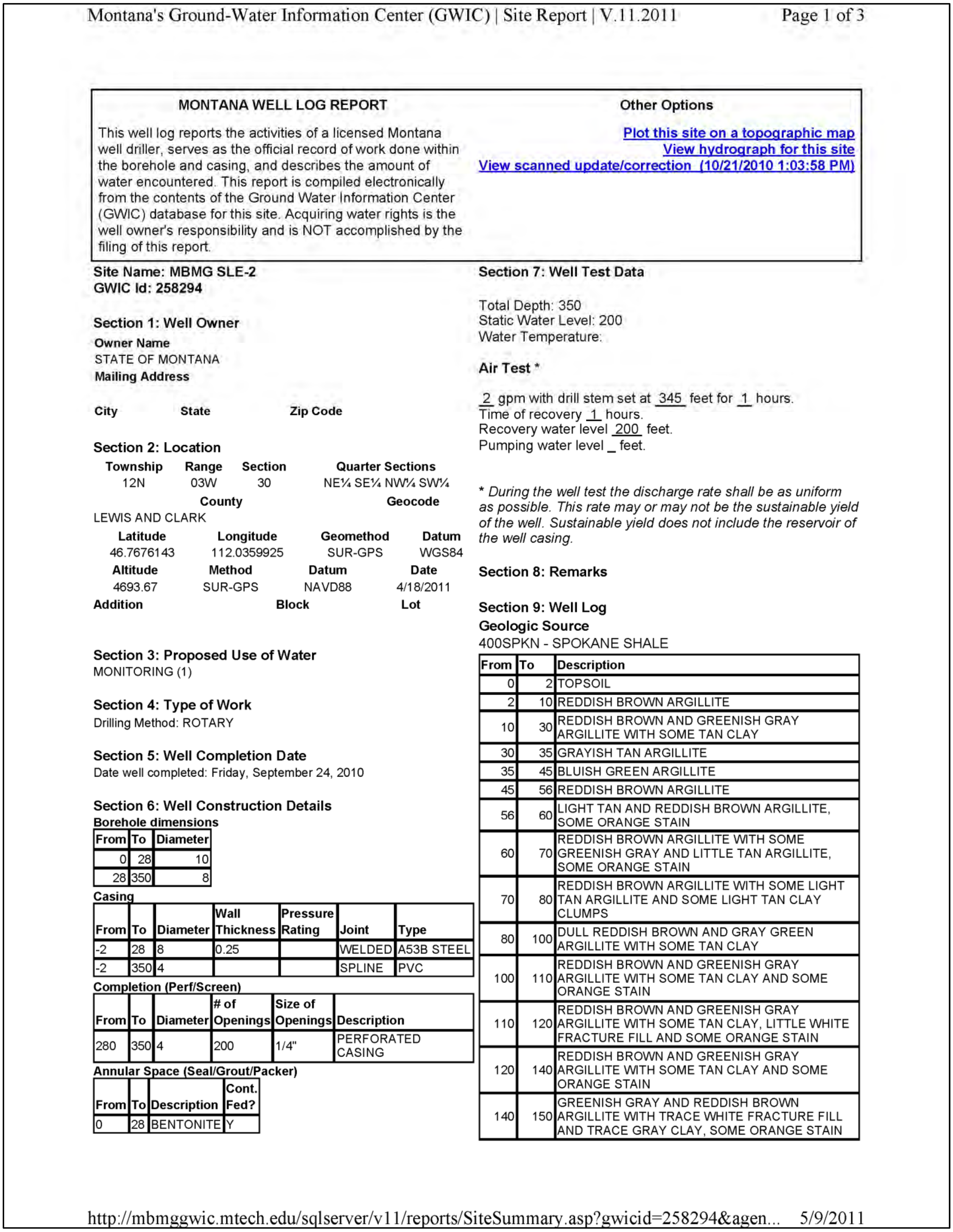
Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	BRITT LINDSAY
Company:	LINDSAY DRILLING
License No:	MWC-337
Date Completed:	9/22/2010

Site Name: MBMG SLE-1
GWIC Id: 258290
Additional Lithology Records

From	To	Description
190	200	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BRWON ARGILLITE AND LITTLE ORANGE STAIN
200	220	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN
220	234	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
234	270	REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY ARGILLITE, TRACE WHITE FRACTURE FILL AND LITTLE ORANGE STAIN
270	280	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY ARGILLITE AND SOME ORANGE STAIN
280	287	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND TRACE WHITE FRACTURE FILL
287	310	GREENISH GRAY, GRAY, AND REDDISH BROWN ARGILLITE WITH TRACE RUSTY CLAY AND ABUNDANT ORANGE STAIN (FRAC ZONE)
310	320	REDDISH BROWN ARGILLITE WITH SOM EGREENISH GRAY ARGILLITE AND SOME ORANGE STAIN
320	330	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN
330	335	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
335	348	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN (FRAC ZONE)



MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned update/correction (10/21/2010 1:03:58 PM)

Site Name: MBMG SLE-2
GWIC Id: 258294

Section 1: Well Owner

Owner Name
STATE OF MONTANA
Mailing Address

City	**State**	**Zip Code**

Section 2: Location

Township	Range	Section	Quarter Sections
12N	03W	30	NE¼ SE¼ NW¼ SW¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7676143	112.0359925	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4693.67	SUR-GPS	NAVD88	4/18/2011

Addition	Block	Lot

Section 3: Proposed Use of Water
MONITORING (1)

Section 4: Type of Work
Drilling Method: ROTARY

Section 5: Well Completion Date
Date well completed: Friday, September 24, 2010

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	28	10
28	350	8

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	28	8	0.25		WELDED	A53B STEEL
-2	350	4			SPLINE	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
280	350	4	200	1/4"	PERFORATED CASING

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	28	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 350
Static Water Level: 200
Water Temperature:

Air Test *

2 gpm with drill stem set at 345 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level 200 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

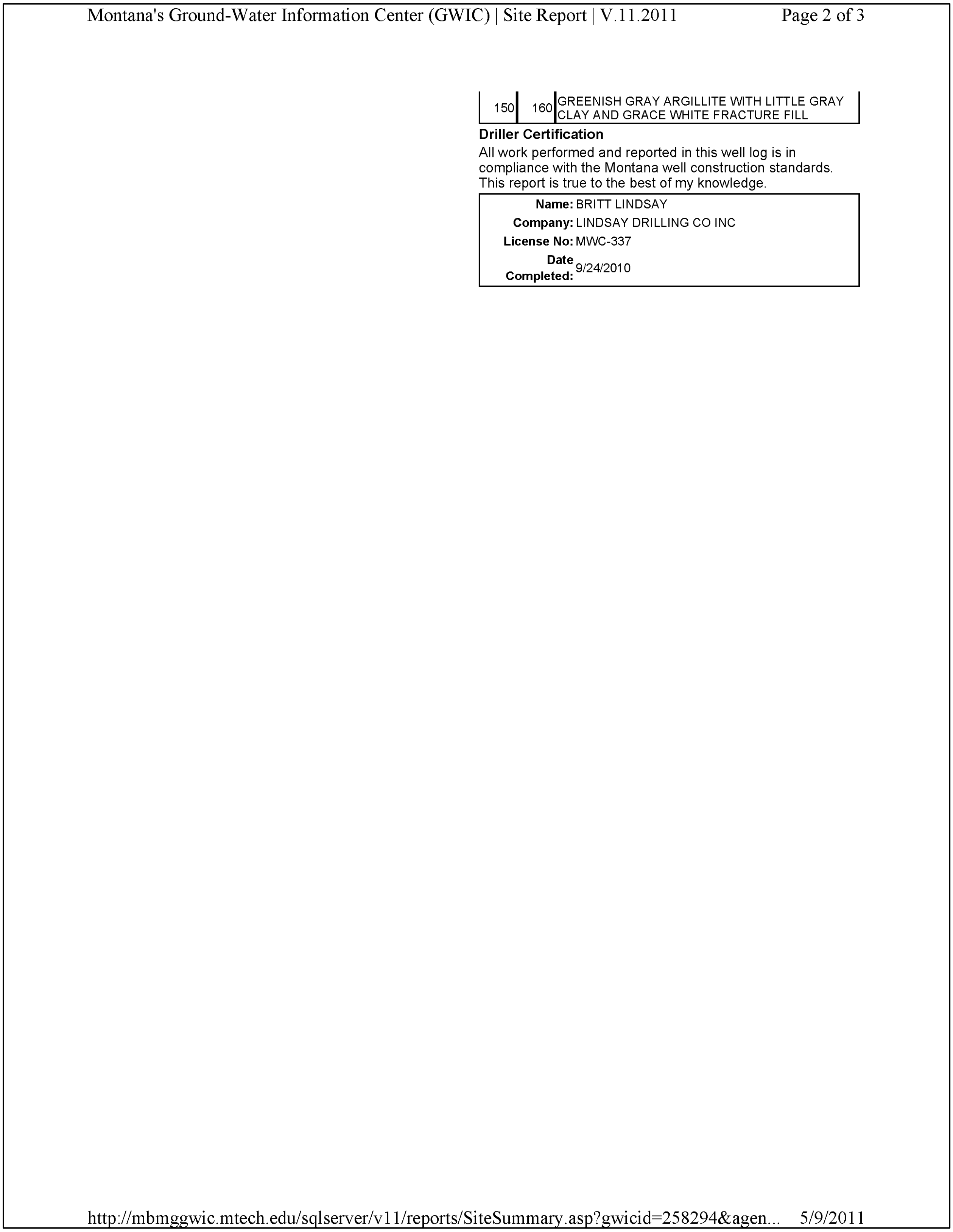
Section 8: Remarks

Section 9: Well Log

Geologic Source

400SPKN - SPOKANE SHALE

From	To	Description
0	2	TOPSOIL
2	10	REDDISH BROWN ARGILLITE
10	30	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME TAN CLAY
30	35	GRAYISH TAN ARGILLITE
35	45	BLUISH GREEN ARGILLITE
45	56	REDDISH BROWN ARGILLITE
56	60	LIGHT TAN AND REDDISH BROWN ARGILLITE, SOME ORANGE STAIN
60	70	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY AND LITTLE TAN ARGILLITE, SOME ORANGE STAIN
70	80	REDDISH BROWN ARGILLITE WITH SOME LIGHT TAN ARGILLITE AND SOME LIGHT TAN CLAY CLUMPS
80	100	DULL REDDISH BROWN AND GRAY GREEN ARGILLITE WITH SOME TAN CLAY
100	110	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME TAN CLAY AND SOME ORANGE STAIN
110	120	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME TAN CLAY, LITTLE WHITE FRACTURE FILL AND SOME ORANGE STAIN
120	140	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME TAN CLAY AND SOME ORANGE STAIN
140	150	GREENISH GRAY AND REDDISH BROWN ARGILLITE WITH TRACE WHITE FRACTURE FILL AND TRACE GRAY CLAY, SOME ORANGE STAIN



Montana's Ground-Water Information Center (GWIC) | Site Report | V.11.2011 Page 2 of 3

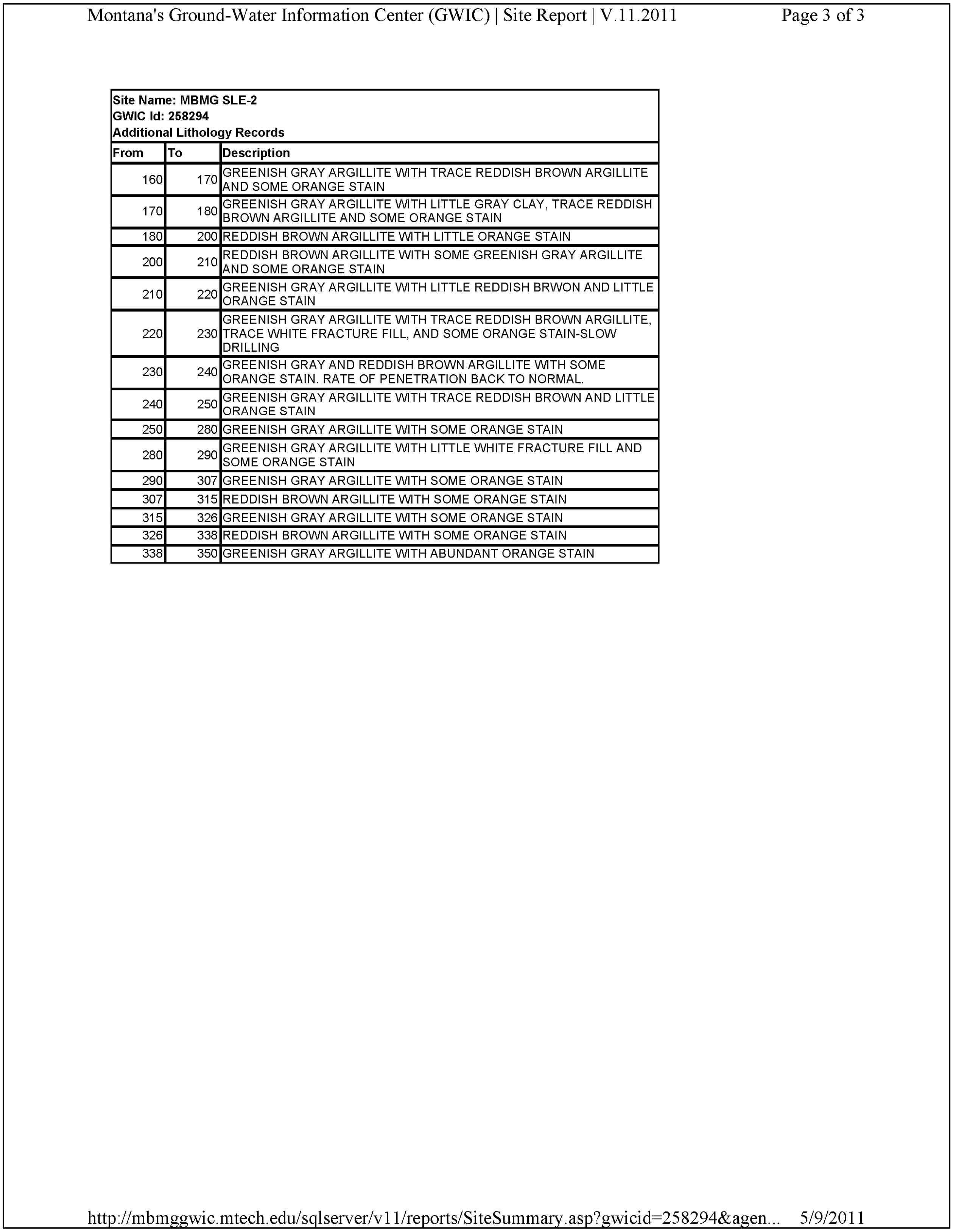
150	160	GREENISH GRAY ARGILLITE WITH LITTLE GRAY CLAY AND GRACE WHITE FRACTURE FILL

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	BRITT LINDSAY
Company:	LINDSAY DRILLING CO INC
License No:	MWC-337
Date Completed:	9/24/2010

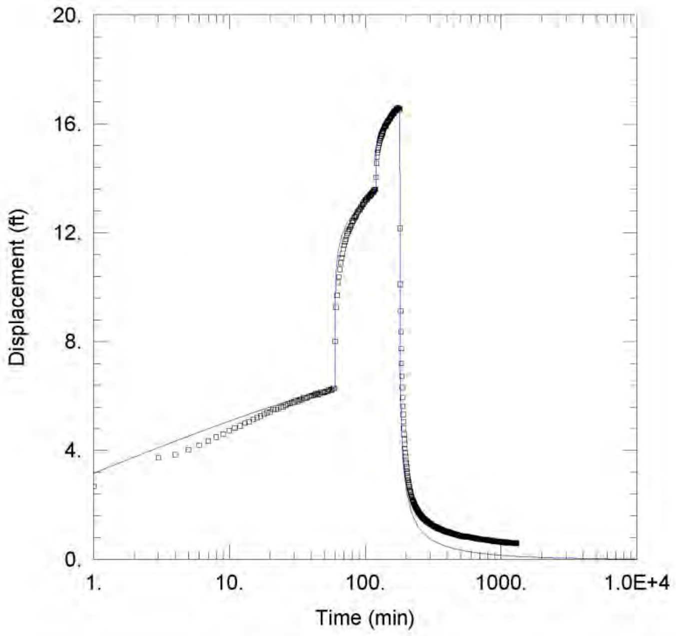
http://mbmggwic.mtech.edu/sqlserver/v11/reports/SiteSummary.asp?gwicid=258294&agen... 5/9/2011



Site Name: MBMG SLE-2
GWIC Id: 258294
Additional Lithology Records

From	To	Description
160	170	GREENISH GRAY ARGILLITE WITH TRACE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
170	180	GREENISH GRAY ARGILLITE WITH LITTLE GRAY CLAY, TRACE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
180	200	REDDISH BROWN ARGILLITE WITH LITTLE ORANGE STAIN
200	210	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY ARGILLITE AND SOME ORANGE STAIN
210	220	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BRWON AND LITTLE ORANGE STAIN
220	230	GREENISH GRAY ARGILLITE WITH TRACE REDDISH BROWN ARGILLITE, TRACE WHITE FRACTURE FILL, AND SOME ORANGE STAIN-SLOW DRILLING
230	240	GREENISH GRAY AND REDDISH BROWN ARGILLITE WITH SOME ORANGE STAIN. RATE OF PENETRATION BACK TO NORMAL.
240	250	GREENISH GRAY ARGILLITE WITH TRACE REDDISH BROWN AND LITTLE ORANGE STAIN
250	280	GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN
280	290	GREENISH GRAY ARGILLITE WITH LITTLE WHITE FRACTURE FILL AND SOME ORANGE STAIN
290	307	GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN
307	315	REDDISH BROWN ARGILLITE WITH SOME ORANGE STAIN
315	326	GREENISH GRAY ARGILLITE WITH SOME ORANGE STAIN
326	338	REDDISH BROWN ARGILLITE WITH SOME ORANGE STAIN
338	350	GREENISH GRAY ARGILLITE WITH ABUNDANT ORANGE STAIN

APPENDIX E-B—AQTESOLV ANALYSIS
STATE LANDS EAST SITE



SLE STEP TEST

Data Set: M:\...\SLE-1_Step.aqt
Date: 05/31/11
Time: 10:18:07

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

AQUIFER DATA

Saturated Thickness: 150. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ SLE-1	0	0

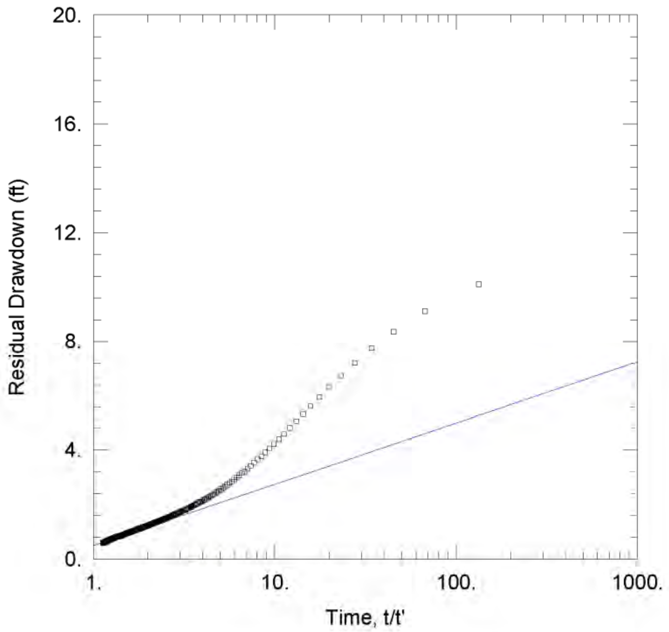
SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 475. ft^2/day
S = 0.0075
Sw = -1.005
C = 0.2198 min^2/ft^5
P = 2.1

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min
$s(t) = 1.207Q + 0.2198Q^{2.1}$
W.E. = 75.89% (Q from last step)

Figure E-B1. Step test simulation of SLE-1 (pumping well) using the T value determined from the State Lands East constant-rate test, using the Theis method.



SLE STEP TEST

Data Set: M:\...\SLE-1_Step.aqt
Date: 05/31/11 Time: 10:18:33

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

AQUIFER DATA

Saturated Thickness: 150. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells		
Well Name	X (ft)	Y (ft)
SLE-1	0	0

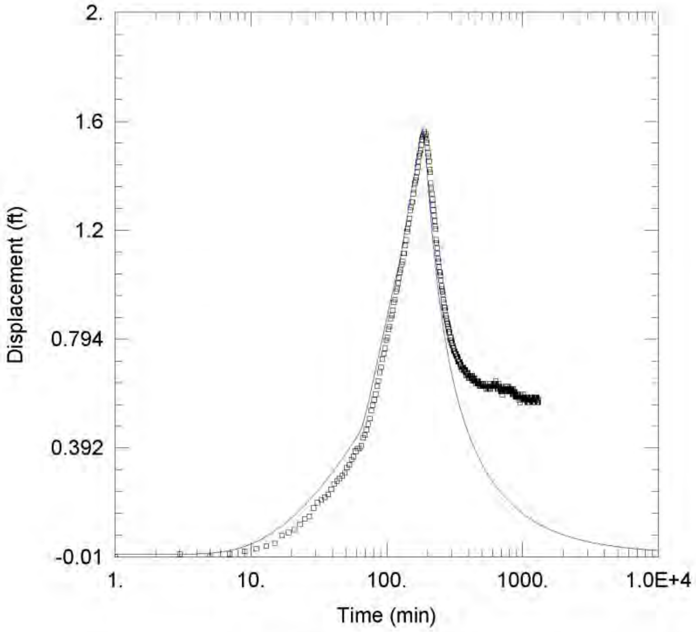
Observation Wells		
Well Name	X (ft)	Y (ft)
▫ SLE-1	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Theis (Recovery)

T = 475. ft^2/day S/S' = 0.6

Figure E-B2. Simulation of recovery in SLE-1 (pumping well) from the State Lands East step test, using the Theis recovery method.



SLE STEP TEST

Data Set: M:\...\SLE-2_Step.aqt
Date: 05/31/11 Time: 10:19:03

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

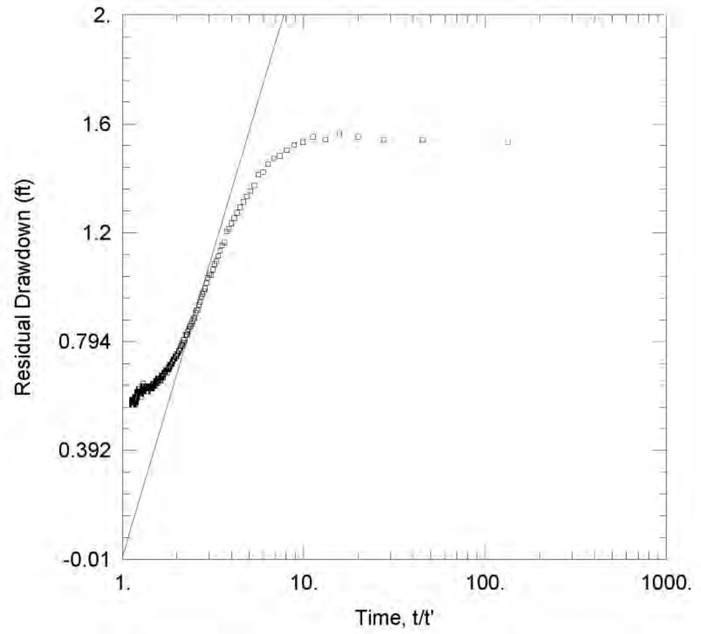
Well Name	X (ft)	Y (ft)
▫ SLE-2	0	156

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 475. ft^2/day
S = 0.001
Kz/Kr = 1.
b = 150. ft

Figure E-B3. Simulation of the State Lands East step test at observation well SLE-2, using the Theis method.



SLE STEP TEST

Data Set: M:\...\SLE-2_Step.aqt
Date: 05/31/11 Time: 10:19:27

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

AQUIFER DATA

Saturated Thickness: 150. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

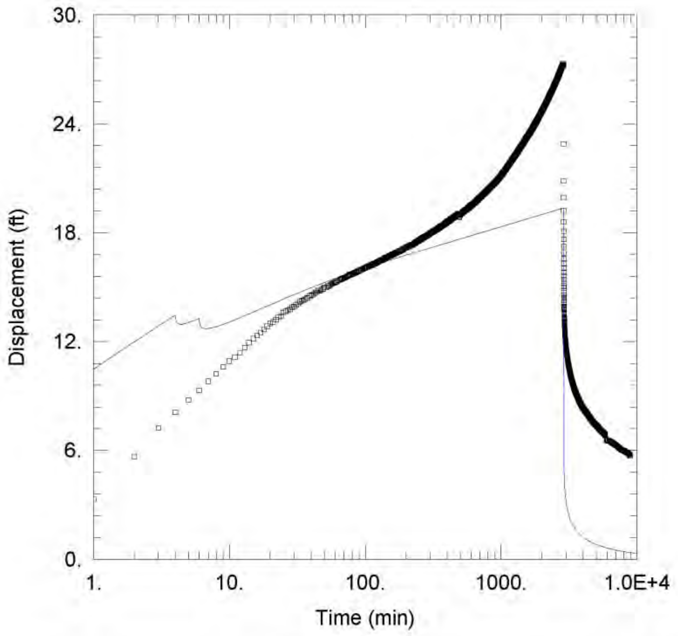
Well Name	X (ft)	Y (ft)
▫ SLE-2	0	156

SOLUTION

Aquifer Model: Confined Solution Method: Theis (Recovery)

T = 475. ft^2/day S/S' = 1.

Figure E-B4. Simulation of recovery of observation well SLE-2 from the State Lands East step test using the Theis recovery method. Note the deviation from ideal response.



SLE STEP TEST

Data Set: M:\...\SLE-1_CR.aqt
Date: 05/31/11 Time: 10:20:34

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

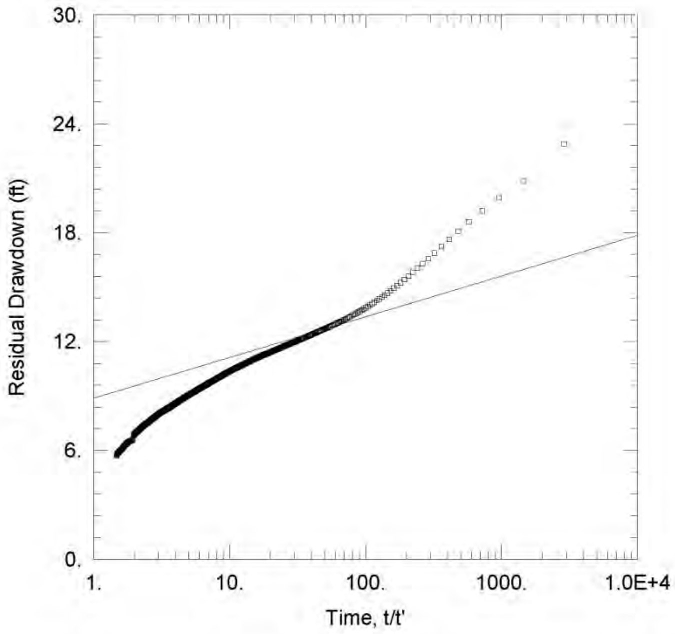
Well Name	X (ft)	Y (ft)
▫ SLE-1	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 475. ft^2/day
S = 0.0075
Kz/Kr = 1.
b = 150. ft

Figure E-B5. Simulation of the State Lands East constant-rate test at SLE-1 (pumping well), using the Theis method. Note that the late time data deviates from ideal.



SLE STEP TEST

Data Set: M:\...\SLE-1_CR.aqt
Date: 05/31/11 Time: 10:20:01

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/6/11

AQUIFER DATA

Saturated Thickness: 150. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

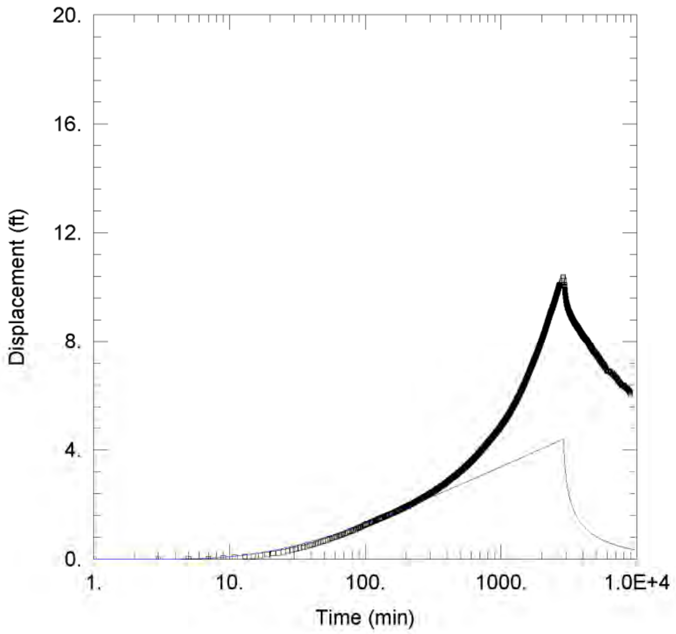
Well Name	X (ft)	Y (ft)
▫ SLE-1	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Theis (Recovery)

T = 475. ft^2/day S/S' = 0.00011

Figure E-B6. Simulation of recovery from the State Lands East constant-rate test at SLE-1 (pumping well), using the Theis recovery method.



SLE CONSTANT RATE TEST

Data Set: M:\...\SLE-2_CR.aqt
Date: 05/31/11
Time: 10:21:31

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/7/11 - 4/9/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

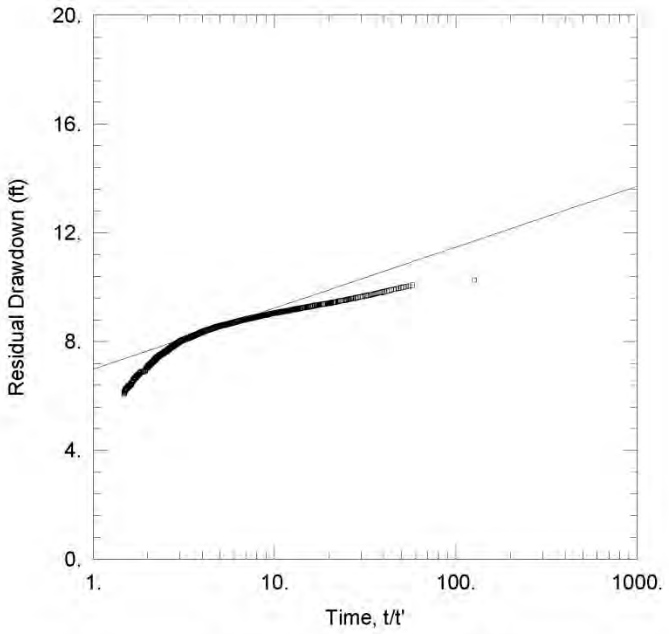
Well Name	X (ft)	Y (ft)
▫ SLE-2	0	156

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 475. ft^2/day
S = 0.001
Kz/Kr = 1.
b = 150. ft

Figure E-B7. Simulation of the State Lands East constant-rate test at observation well SLE-2, using the Theis method. Note that the late time data deviates from ideal.



SLE CONSTANT RATE TEST

Data Set: M:\...\SLE-2_CR.aqt
Date: 05/31/11
Time: 10:21:10

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLE-1
Test Date: 4/7/11 - 4/9/11

AQUIFER DATA

Saturated Thickness: 150. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLE-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
□ SLE-2	0	156

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 475. ft^2/day
S/S' = 0.00077

Figure E-B8. Simulation of recovery from the State Lands East constant-rate test at observation well SLE-1, using the Theis recovery method.

STATE LANDS WEST AQUIFER TEST—
SPOKANE FORMATION

STATE LANDS WEST
AQUIFER TEST RESULTS
NORTH HILLS PROJECT AREA
April 2011

STEP TEST
AND
48-HOUR CONSTANT-RATE TEST

Background

The following is an analysis of a step test and a 48-h constant-rate pumping test performed using wells installed on State lands in the North Hills study area. These wells are located at the top of the hills (fig. W1) in the primary recharge area in the northwest portion of the North Hills study area. The purpose of the test was to evaluate the hydraulic conductivity and storativity of the Spokane Formation. The data were also used to discover the presence of recharge or barrier boundaries. There are no residences in the area; the closest used well is approximately 1.3 mi from the pumping well.

Two wells were installed at this site in September 2010. A MBMG geologist was present for the installation of the wells; cuttings were described in detail, and completion details verified. Composite cuttings samples from each well were collected, described, and stored for every 10 ft of borehole. The well logs and all measured groundwater levels are available on GWIC (http://mbmggwic.mtech.edu) by using the GWIC IDs. A summary of completion details are provided in table W1 and appendix W-A.

A transducer was deployed in SLW-2 in November 2010 for long-term monitoring. Information from this transducer shows that groundwater altitudes increased by over 3 ft during the winter (fig. W2). The greatest rate of increase occurred during spring snowmelt.

Location

The test area is located in the North Hills, north of Helena, Montana. The wells are located in Township 12 N., Range 4 W., Section 28, SE¼ NE¼, in Lewis and Clark County, Montana (figs. W1, W3). The land surface altitude is approximately 4,670 ft above mean sea level.

Geology

This site is located in the Spokane Formation. The Helena Valley Fault (fig. W4) is mapped as trending east–west approximately 480 ft north of the site. Near-surface magnetic survey data obtained in the area (Michaletz, written commun., 2011; fig. W5) suggest that there are numerous unmapped faults in the area. Bedrock outcrops at the site are fractured, and the fractures filled with quartz veins.

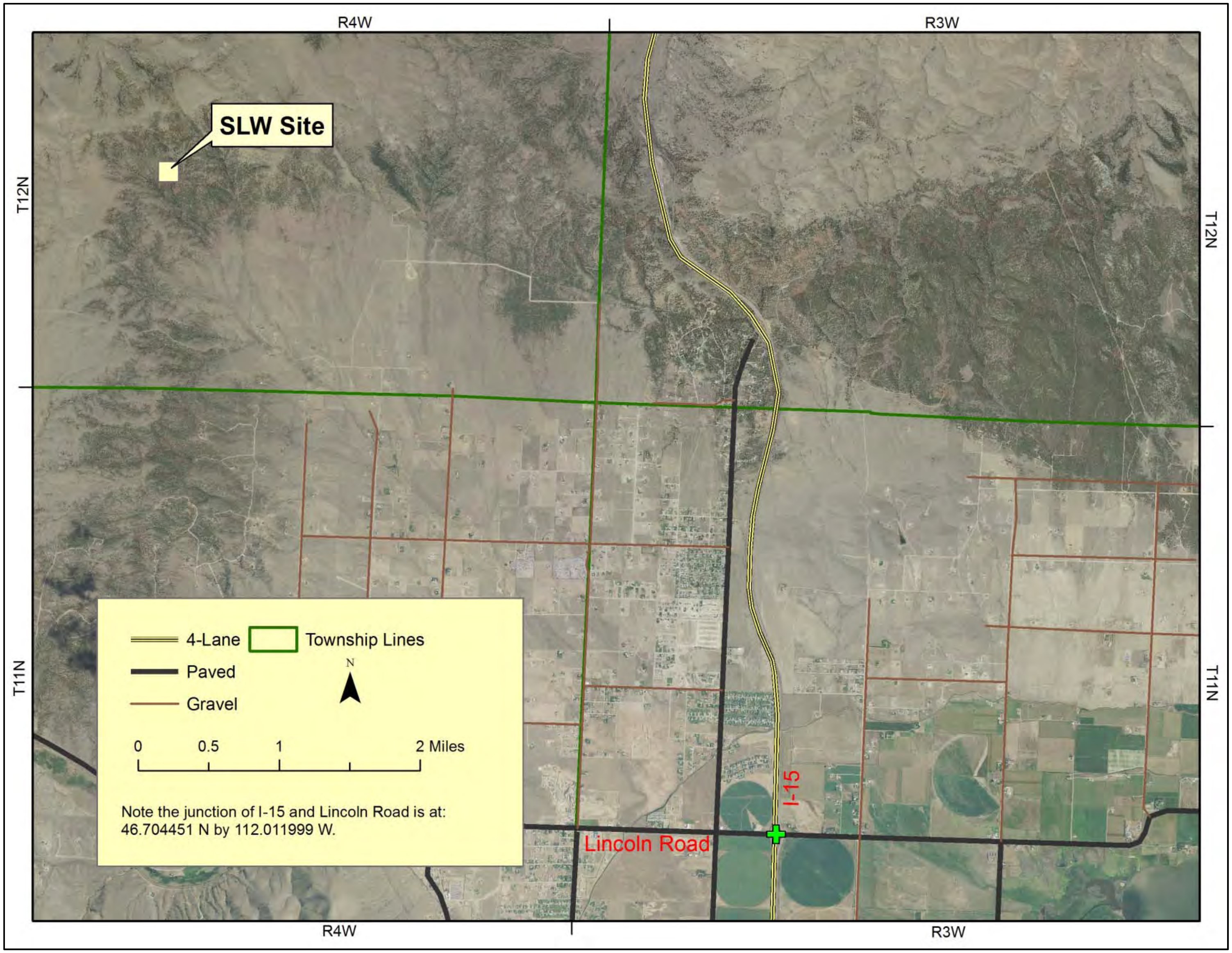


Figure W1. Location of the State Lands West Aquifer test site. The green cross located at the junction of Interstate 15 and Lincoln Road is at latitude 46.704451°N and longitude 112.011999°W.

Table W1

Well Designations, Locations, and Completion Information

State Lands West Aquifer Test—April 2011

GWIC ID	Name	Latitude*	Longitude*	Measuring Point Elevation$^+$ (ft-amsl)	Total Depth (ft below MP)	Depth to Water 4/12/11 (ft below MP)	Groundwater Elevation 4/12/11 (ft-amsl)	Distance from SLE-1 (ft)	Comments
258454	SLW-1	46.7704545	-112.1063565	4675.61	160	82.91	4592.70	—	Pumping Well
258456	SLW-2	46.7707646	-112.1060793	4672.83	160	54.71	4618.12	132	Observation Well

ft-amsl = ft above mean sea level

ft below MP = ft below measuring point

* = Horizontal Datum is NAD83

$^+$ = Vertical Datum is NAVD88

All locations and elevations determined by survey.

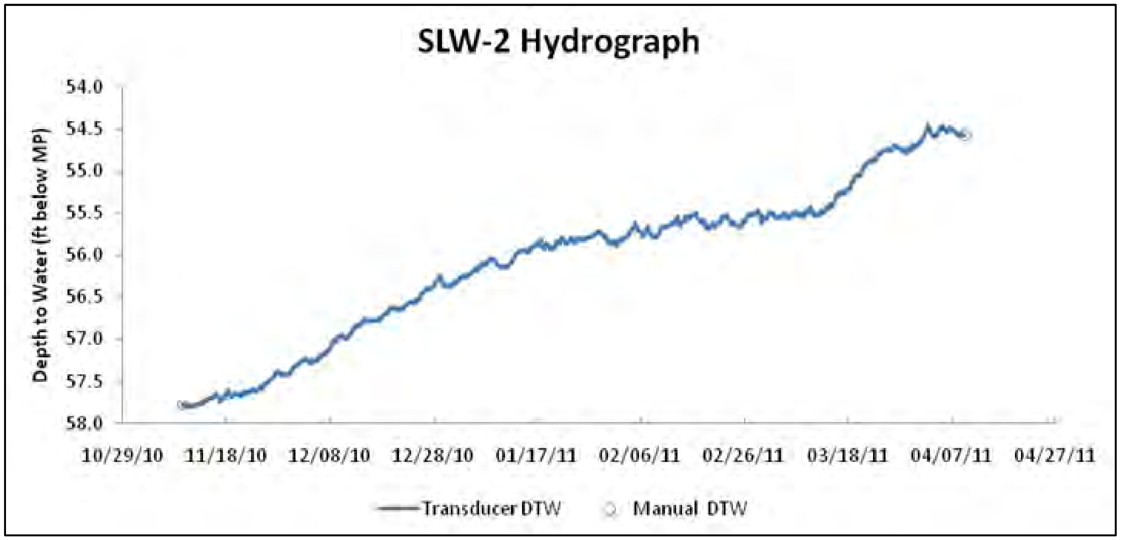


Figure W2. Hydrograph of SLW-2, November 2010 to April 2011, shows an increase in water levels of over 3 ft during the winter.

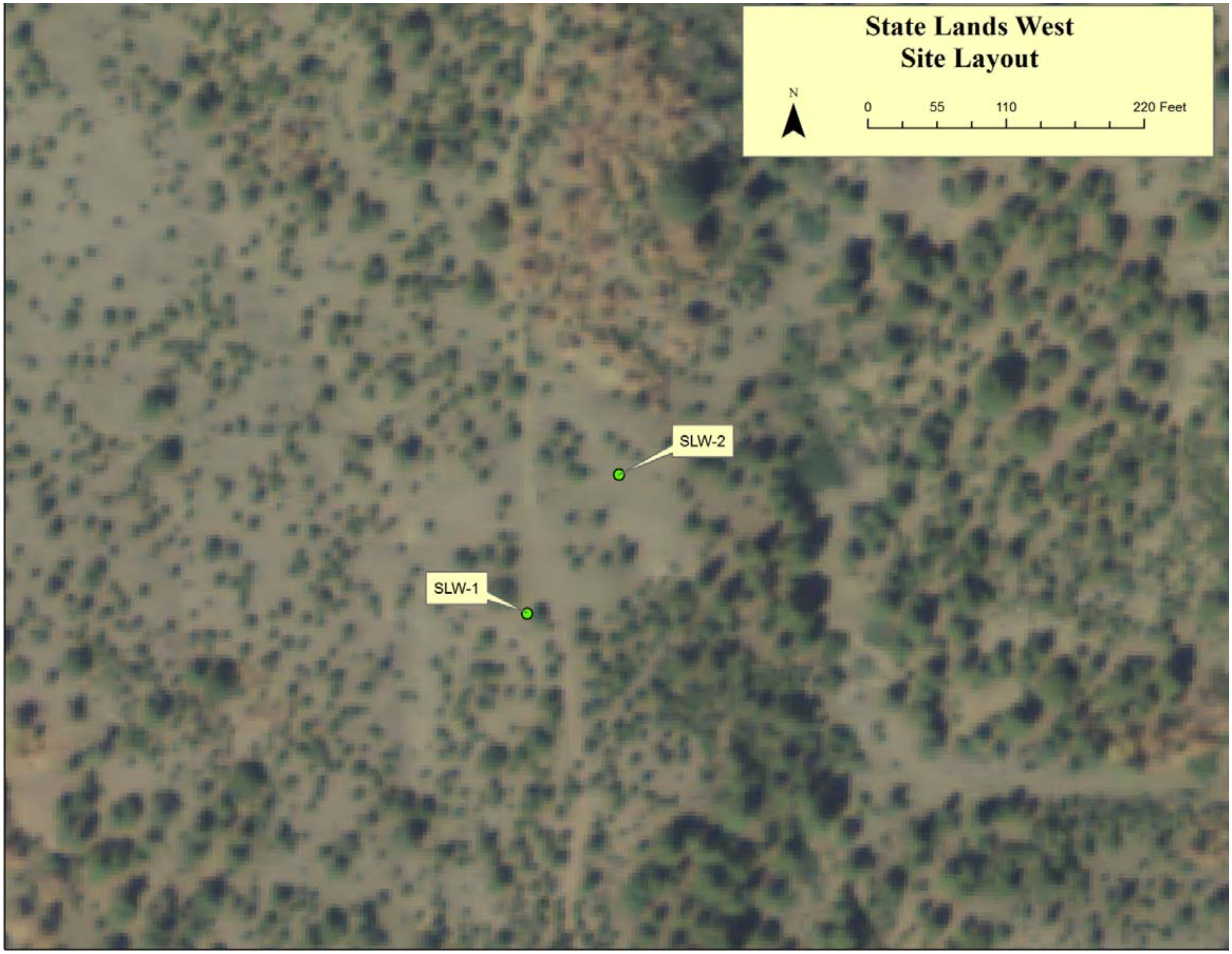


Figure W3. Site layout for the State Lands West Aquifer test. SLW-1 is at 46.7704545°N latitude by 112.1063565°W longitude.

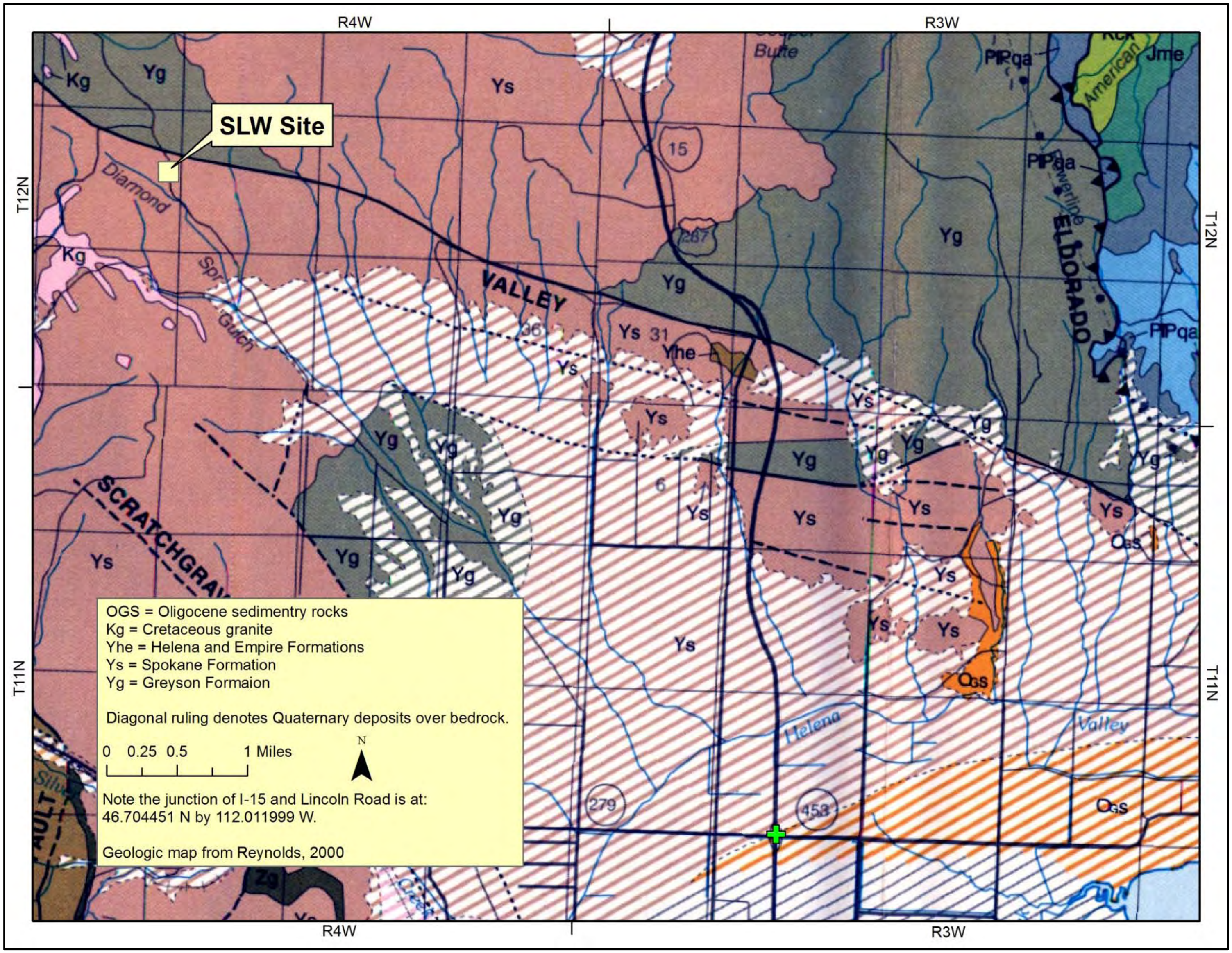


Figure W4. Bedrock geologic map of the State Lands West Aquifer test area. Geologic map prepared by Reynolds (2000). The green cross located at the junction of Interstate 15 and Lincoln Road is at latitude 46.704451°N and longitude 112.011999°W.

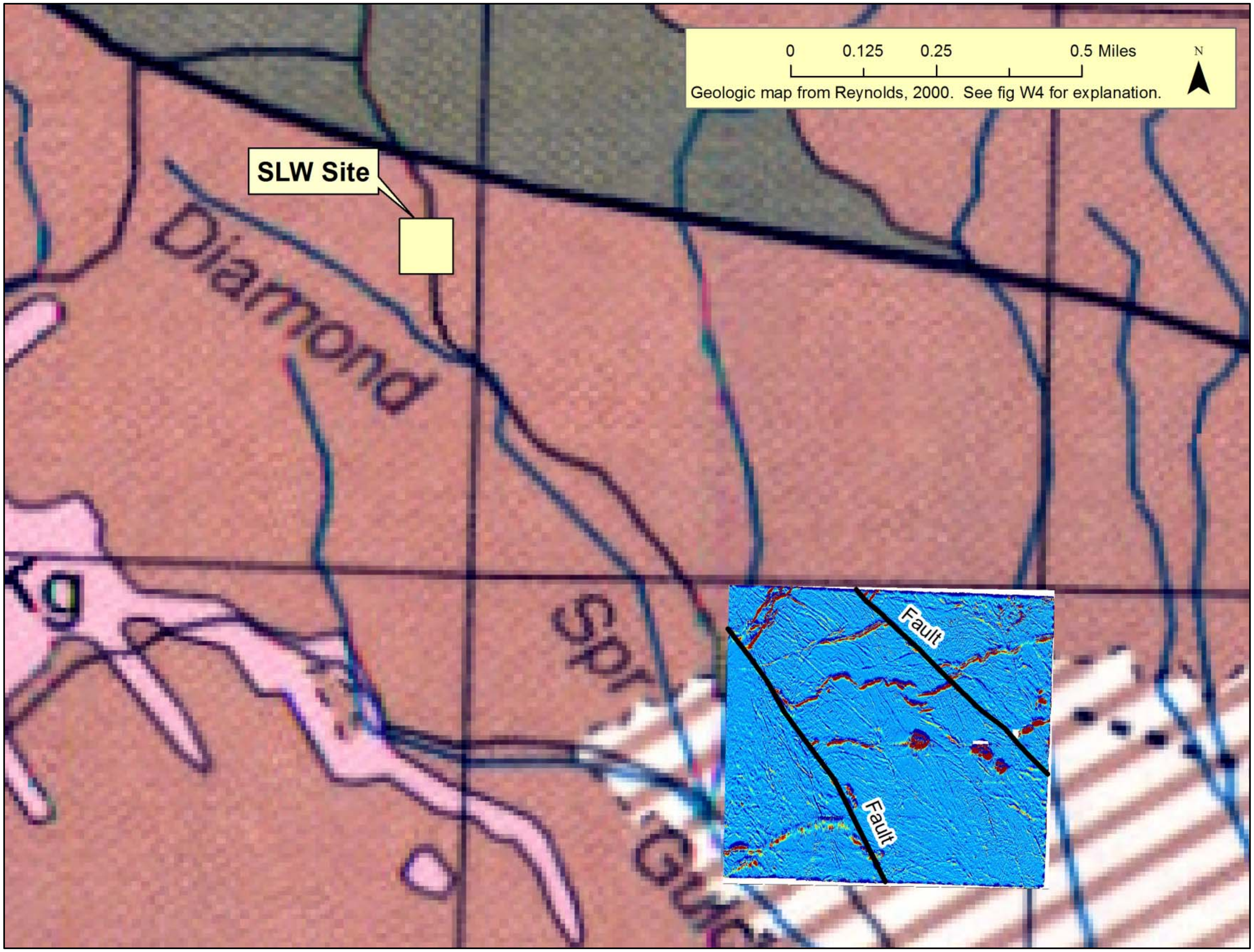


Figure W5. Results of magnetic survey by Joe Michaletz (written commun., 2011) in the NE¼ of T. 12 N., R. 4 W., Section 34. These data suggest that there are several unmapped faults in this area.

Well Details

SLW-1 and SLW-2 are both 160-ft-deep, 4-in PVC-cased wells with screen from 100 to 160 ft below land surface. Pretest depth to water (DTW) readings show that the groundwater elevation is 4592.70 ft-amsl at SLW-1 and 4618.12 ft-amsl at SLW-2 (table W1). The high gradient (0.19 ft/ft; unitless) between these wells suggests that a flow barrier is present.

Methodology

The pumping rate was monitored throughout the test using a totalizing flow meter and an orifice bucket flow meter with a transducer in the piezometer tube (fig. W6). The flow meter was checked using a bucket and stopwatch. When concurrent measurements using the flow meter and the bucket and stopwatch were made, there was good agreement in the flow rates. Discharge was controlled using a gate valve and discharge water was diverted approximately 200 ft southwest of the pumping well (SLW-1) and away from the observation well (SLW-2).

Non-vented pressure transducers were used to record water levels in both wells. The transducer used in SLW-1 (pumping well) was rated at 100 psia (200 ft), has a manufacturer-reported accuracy of ±0.1 percent of the rated pressure (±0.2 ft), and a resolution of ±0.01 percent of the rated pressure (0.02 ft). The transducer used in SLW-2 was rated for 30 ft, has a manufacturer-reported accuracy of ±0.1 percent of the rated pressure (±0.03 ft), and a resolution of ±0.01 percent of the rated pressure (0.003 ft). Data from these non-vented transducers were corrected for barometric variation.

Manual readings of water levels were made for both wells prior to placing transducers, and were made periodically during the test, during recovery, and prior to uninstalling the transducers. The manual measurements were used to verify transducer response (figs. W7, W8). All water-level data are available from GWIC by using a well's GWIC ID (http://mbmggwic.mtech.edu/).

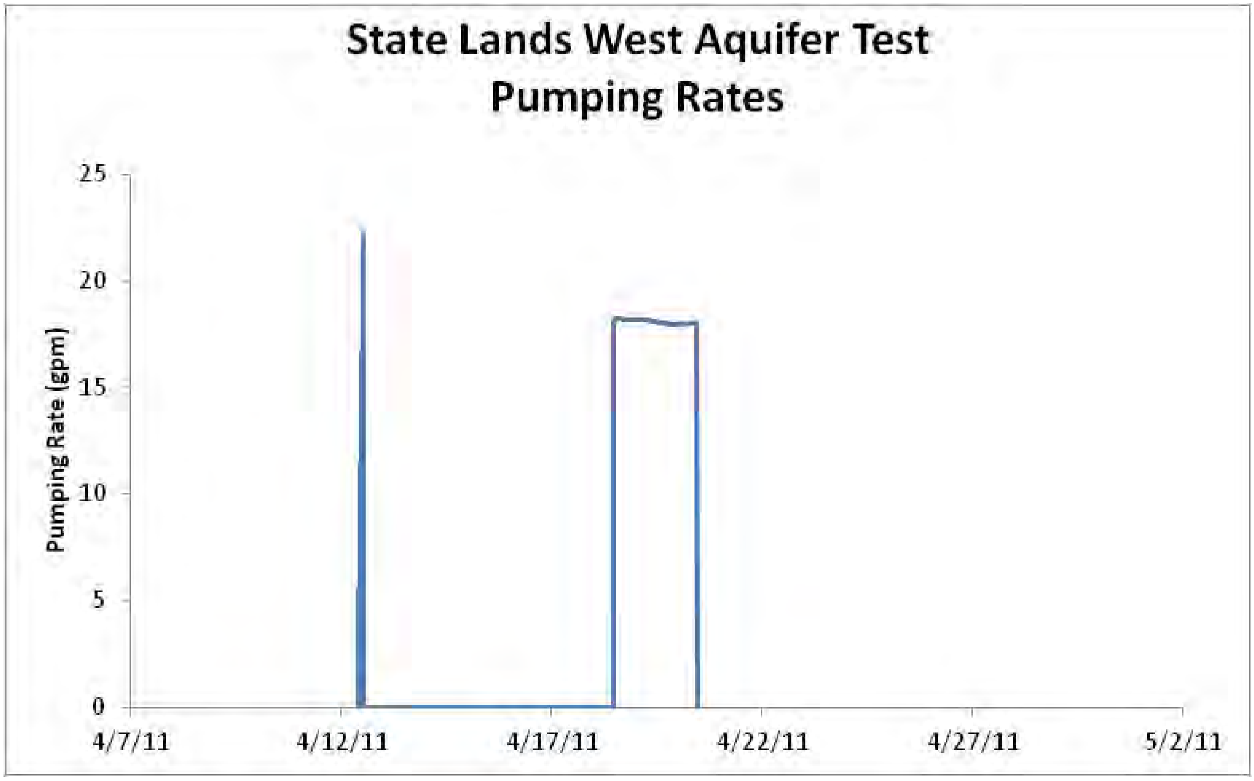


Figure W6. Pumping rates from SLW-1 during the State Lands West Aquifer test.

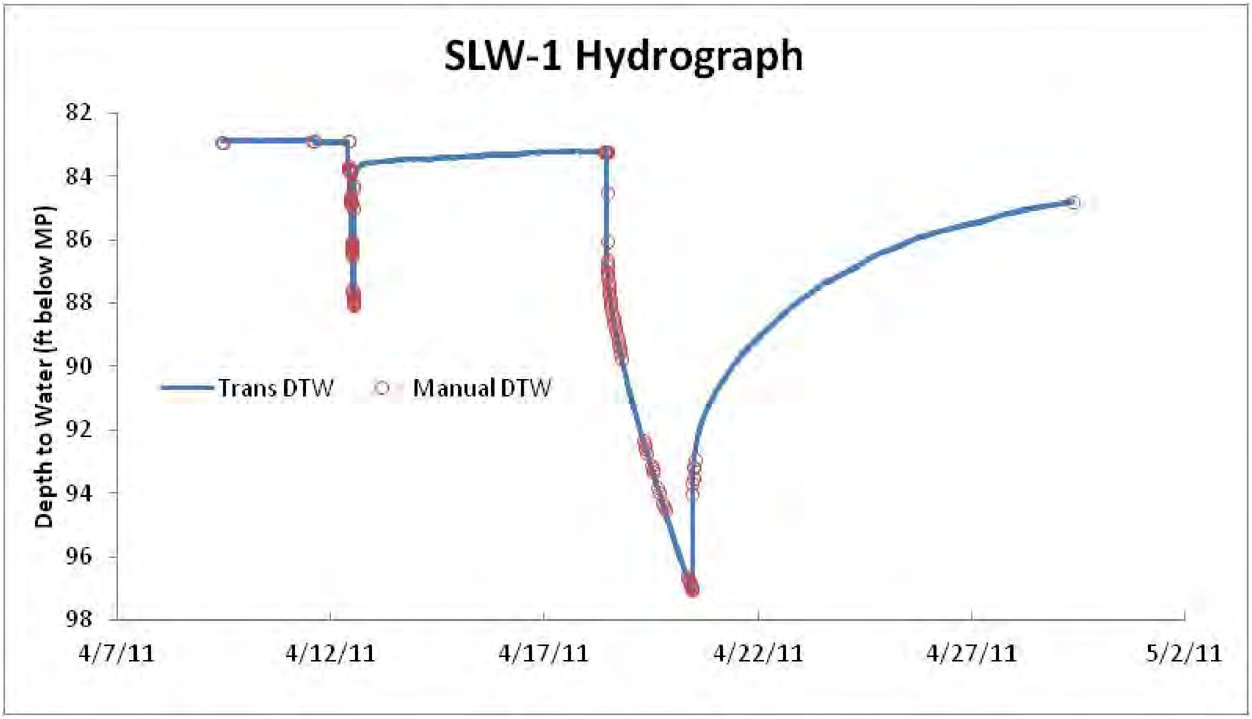


Figure W7. Depth to water readings in Well SLW-1 (pumping well) during the State Lands West Aquifer test.

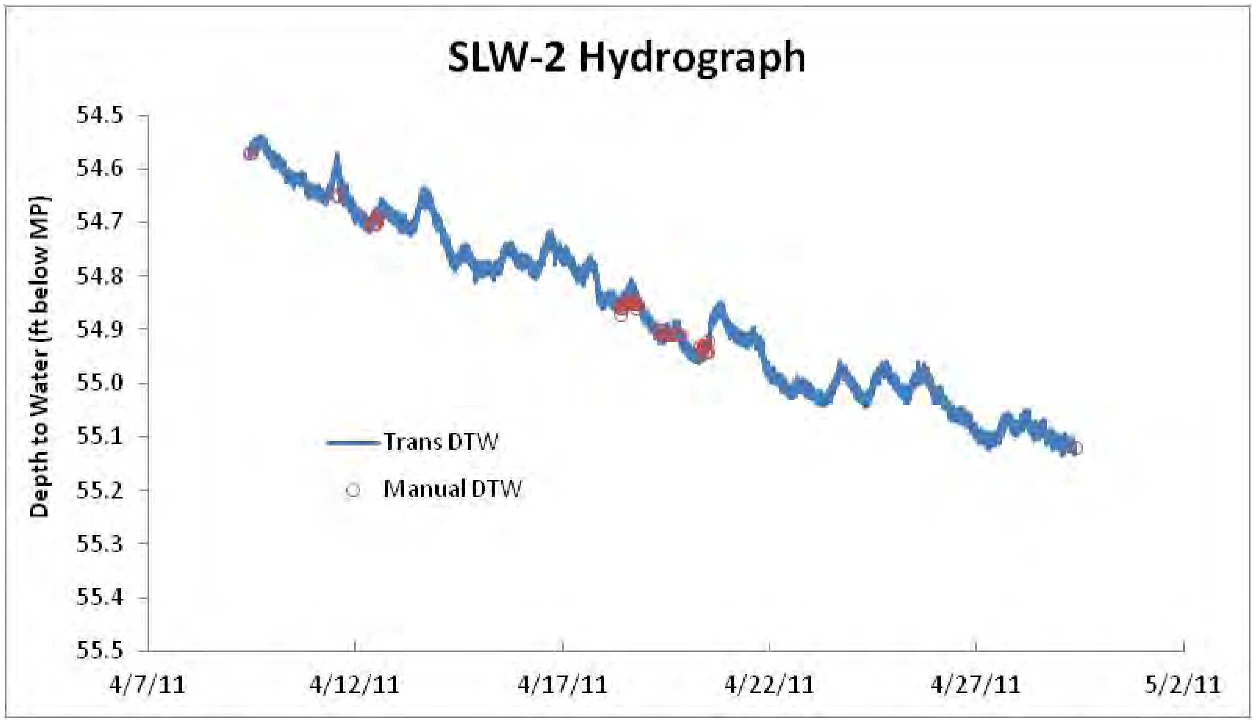


Figure W8. Depth to water readings in SLW-2 (observation well; 132 ft from SLW-1) during the State Lands West Aquifer test.

Step Test

On April 12, 2011, a step test was conducted on SLW-1 to determine an appropriate pumping rate (table W2; fig. W9). Because the pump was set at 105 ft below ground, and the screen extends from the well bottom up to 100 ft below ground, it was desired that the long-term pumping rate not cause water levels to drop below 90 ft (7 ft of drawdown). Analysis of the step test data suggests that the target drawdown would be achieved with a pumping rate of 26 gpm; however, the step test likely overestimates the sustainable yield because water levels did not stabilize during any of the steps. For this reason a discharge rate of 18 gpm was selected. The weighted average rate for the constant-rate test was 18.1 gpm, which resulted in 13.3 ft of drawdown (8.9 ft more than the step test data suggested). Although the amount of drawdown was greater than intended, the entire screened interval remained saturated at all times.

The step test observations were simulated using the aquifer properties determined during the constant-rate test using AQTESOLV software (appendix W-B). It is notable that the time for the well to recover from pumping was longer than predicted, indicating that a flow barrier is present. SLW-2 did not respond to pumping in SLW-1, indicating that there are unconnected fracture sets within the aquifer.

Table W2
SLW-1—Step Test Summary
State Lands West Aquifer Test—April 12, 2011

Start Step	End Step	Rate (Q, gpm)	Maximum Drawdown (s, ft)	Specific Capacity (Q/s, gpm/ft)
9:45	10:30	5.1	0.96	5.3
10:30	11:15	9.1	2.00	4.6
11:15	12:00	15.5	3.68	4.2
12:00	12:45	20.9	5.19	4.0

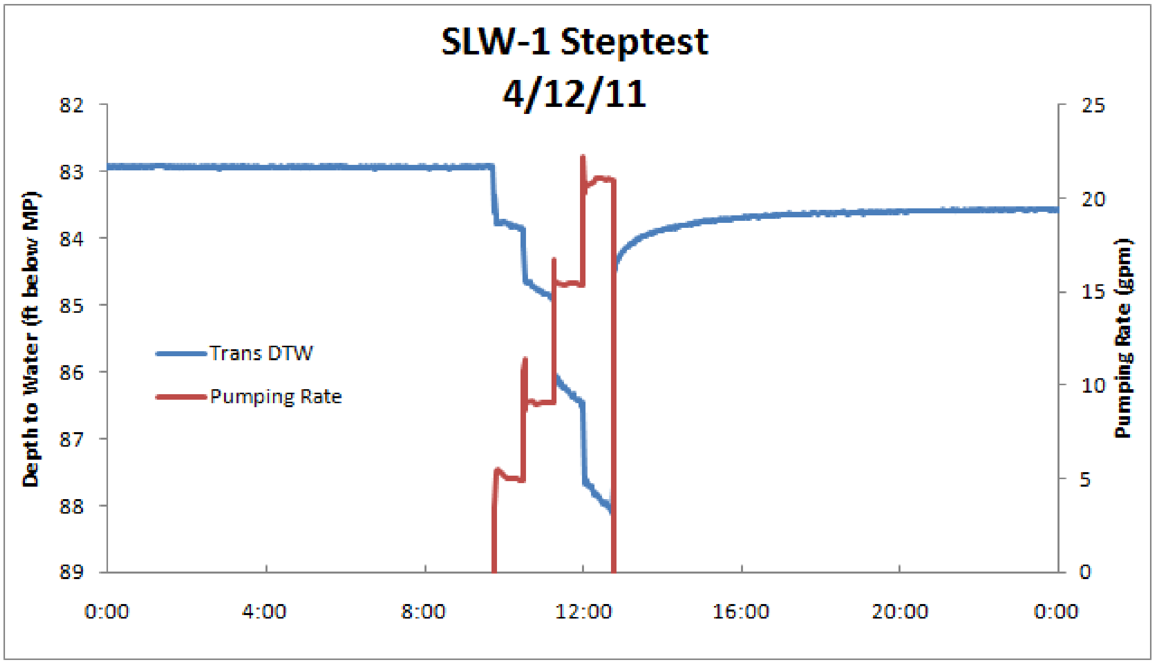


Figure W9. Depth to water in SLW-1 and pumping rates recorded during step test.

Constant-Rate Test Analysis

The constant-rate test started at 11:00 am on April 18, 2011, and ended at 11:00 am on April 20, for a total pumping time of 48 h. The time-weighted average pumping rate was 18.1 gpm. The maximum recorded pumping rate was 18.3 gpm, the minimum recorded pumping rate was 17.9 gpm, and the maximum deviation from average was 1 percent.

The maximum recorded drawdown in well SLW-1 is 13.32 ft (3.7 ft above top of screen). Water levels in well SLW-1 showed a rapid initial decline, followed by a slower but steady decline. After pumping, ceased water levels in the well initially recovered rapidly; however, 7.72 d were needed to reach 90 percent recovery (fig. W7). The steady decline during pumping, the slow recovery, and the lack of response in SLW-2 indicate that at least one barrier to flow is present. Based on data collected during the first 100 min of the constant-rate test (before there was significant deviation from idealized drawdown) transmissivity (T) is 575 ft^2/day. Using a saturated thickness of 75 ft (total depth minus static water level in SLW-1), the hydraulic conductivity (K) was 7.5 ft/day.

SLW-2 showed no response to pumping.

Summary

Analysis of this aquifer test indicates that there are barriers to flow present, and at least one barrier is located between the test wells. If the early time data (the first 100 min) and the step test data are used, estimation of local aquifer properties is possible. These data show that the transmissivity is approximately 575 ft^2/day, which equates to a hydraulic conductivity of 7.5 ft/day (saturated thickness is 75 ft).

References

ASTM, 2008, standard test method (field procedure) for withdrawal and injection well tests for determining hydraulic properties of aquifer systems, D4050-96 (Reapproved 2008).

Cooper, H.H., and Jacob, C.E., 1946, A generalized graphical method for evaluating formation constants and summarizing well-field history, Transactions, American Geophysical Union, v. 24, p. 526–534.

Fetter, C.W., 1994, Applied hydrogeology, Third Ed.: New York, N.Y., Macmillan College Publishing, 691 p.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, N.J., Prentice Hall, 604 p.

Jacob, C.E., 1950, Flow of ground-water, *in* Engineering Hydraulics, Rouse, H., ed.: New York, N.Y., John Wiley Press.

Neuman, S.P., 1975, Analysis of pumping test data from anisotropic aquifers considering delayed gravity response, Water Resources Research, v. 11, no. 2, p. 329–342.

Reynolds, Mitchell W., 2000, Generalized bedrock geologic map of the Helena area, west-central Montana, *in* Thamke, J.N., 2000, Hydrology of area bedrock west-central Montana, 1993-98, USGS WRIR 00-4212.

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.

APPENDIX W-A—WELL LOGS
STATE LANDS WEST TEST

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View scanned update/correction (10/21/2010 1:03:25 PM)

Site Name: MBMG SLW-1
GWIC Id: 258454

Section 1: Well Owner

Owner Name
STATE OF MONTANA
Mailing Address

City **State** **Zip Code**

Section 2: Location

Township	Range	Section	Quarter Sections
12N	04W	28	NW¼ SE¼ SE¼ NE¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7704545	112.1063565	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4673.32	SUR-GPS	NAVD88	4/18/2011

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Tuesday, September 28, 2010

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	28	10
28	160	8

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	28	8	0.25		WELDED	A53B STEEL
-2	158	4			SPLINE	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
100	160	4	200	1/4"	PERFORATED CASING

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	28	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 160
Static Water Level: 85
Water Temperature:

Air Test *

35 gpm with drill stem set at 150 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level 85 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
400SPKN - SPOKANE SHALE

From	To	Description
0	1	TOPSOIL
1	30	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND ABUNDANT ORANGE STAIN
30	40	TAN ARGILLITE WITH SOME REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
40	50	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND LITTLE ORANGE STAIN
50	60	REDDISH BROWN ARGILLITE WITH LITTLE TAN ARGILLITE AND LITTLE ORANGE STAIN
60	70	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND TRACE GREENISH GRAY ARGILLITE AND SOME ORANGE STAIN
70	80	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND SOME ORANGE STAIN
80	90	REDDISH BROWN AND TAN ARGILLITE WITH TRACE WHITE FRACTURE FILL (QTZ) AND SOME ORANGE STAIN
90	100	REDDISH BROWN ARGILLITE WITH LITTLE TAN ARGILLITE AND TRACE WHITE FRACTURE FILL AND SOME ORANGE STAIN
100	110	FRACTURED REDDISH BROWN ARGILLITE WITH LITTLE WHITE FRACTURE FILL AND SOME ORANGE STAIN
110	120	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND TRACE WHITE FRACTURE FILL
120	130	REDDISH BROWN ARGILLITE WITH SOME TAN ARGILLITE AND SOME ORANGE STAIN
130	140	REDDISH BROWN AND TAN ARGILLITE WITH ABUNDANT ORANGE STAIN

0	90	BENTONITE	

140	150	REDDISH BROWN ARGILLITE WITH LITTLE TAN ARGILLITE, TRACE CLAY CLUMPS AND SOME ORANGE STAIN
150	160	REDDISH BROWN AND TAN ARGILLITE WITH SOME ORANGE STAIN

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	BRITT LINDSAY
Company:	LINDSAY DRILLING
License No:	WWC-570
Date Completed:	9/28/2010

MONTANA WELL LOG REPORT

This well log reports the activities of a licensed Montana well driller, serves as the official record of work done within the borehole and casing, and describes the amount of water encountered. This report is compiled electronically from the contents of the Ground Water Information Center (GWIC) database for this site. Acquiring water rights is the well owner's responsibility and is NOT accomplished by the filing of this report.

Other Options

Plot this site on a topographic map
View hydrograph for this site
View scanned update/correction (10/21/2010 1:03:10 PM)

Site Name: MBMG SLW-2
GWIC Id: 258456

Section 1: Well Owner

Owner Name
STATE OF MONTANA
Mailing Address

City	State	Zip Code

Section 2: Location

Township	Range	Section	Quarter Sections
12N	04W	28	NW¼ SE¼ SE¼ NE¼

County	Geocode
LEWIS AND CLARK	

Latitude	Longitude	Geomethod	Datum
46.7707646	112.1060793	SUR-GPS	WGS84

Altitude	Method	Datum	Date
4670.84	SUR-GPS	NAVD88	4/18/2011

Addition	Block	Lot

Section 3: Proposed Use of Water

MONITORING (1)

Section 4: Type of Work

Drilling Method: ROTARY

Section 5: Well Completion Date

Date well completed: Thursday, September 30, 2010

Section 6: Well Construction Details

Borehole dimensions

From	To	Diameter
0	28	10
28	160	8

Casing

From	To	Diameter	Wall Thickness	Pressure Rating	Joint	Type
-2	28	8	0.25		WELDED	A53B STEEL
-2	158	4			SPLINE	PVC

Completion (Perf/Screen)

From	To	Diameter	# of Openings	Size of Openings	Description
100	160	4	200	1/4"	PERFORATED CASING

Annular Space (Seal/Grout/Packer)

From	To	Description	Cont. Fed?
0	28	BENTONITE	Y

Section 7: Well Test Data

Total Depth: 160
Static Water Level: 80
Water Temperature:

Air Test *

20 gpm with drill stem set at 150 feet for 1 hours.
Time of recovery 1 hours.
Recovery water level 80 feet.
Pumping water level _ feet.

** During the well test the discharge rate shall be as uniform as possible. This rate may or may not be the sustainable yield of the well. Sustainable yield does not include the reservoir of the well casing.*

Section 8: Remarks

Section 9: Well Log

Geologic Source
400SPKN - SPOKANE SHALE

From	To	Description
0	1	TOPSOIL
1	10	LARGE FRAGMENTS OF GREENISH GRAY AND TAN ARGILLITE, LITTLE REDDISH BROWN ARGILLITE, ABUNDANT ORANGE STAIN
10	20	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH LITTLE TAN ARGILLITE AND ABUNDANT ORANGE STAIN
20	30	REDDISH BROWN ARGILLITE WITH SOME RED CLAY
30	50	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH SOME YELLOW CLAY AND ABUNDANT ORANGE STAIN
50	60	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE, LITTLE YELLOW CLAY AND SOME ORANGE STAIN
60	70	REDDISH BROWN AND GREENISH GRAY ARGILLITE WITH LITTLE YELLOW CLAY AND SOME ORANGE STAIN
70	80	REDDISH BROWN ARGILLITE WITH SOME GREENISH GRAY AND TAN ARGILLITE; SOME ORANGE STAIN
80	90	GREENISH GRAY AND REDDISH BROWN ARGILLITE WITH SOME ORANGE STAIN
90	110	REDDISH BROWN ARGILLITE WITH LITTLE GREENISH GRAY AND SOME ORANGE STAIN
110	120	REDDISH BROWN AND TAN ARGILLITE WITH SOME YELLOW CLAY, TRACE GREENISH GRAY ARGILLITE AND ABUNDANT ORANGE STAIN
120	130	REDDISH BROWN ARGILLITE WITH LITTLE

0	90	BENTONITE	Y

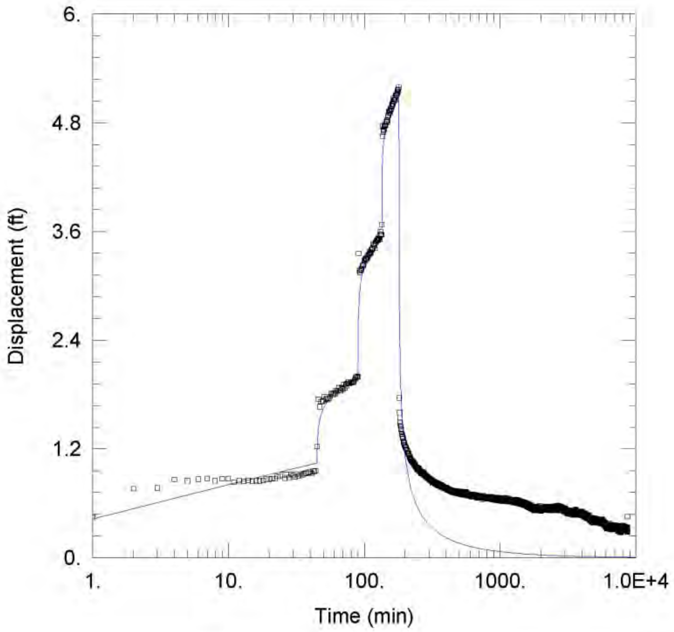
		YELLOW CLAY
130	140	GREENISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND SOME ORANGE STAIN
140	150	REDDISH BROWN ARGILLITE WITH SOME BLUISH GRAY ARGILLITE AND LITTLE ORANGE STAIN
150	160	BLUISH GRAY ARGILLITE WITH LITTLE REDDISH BROWN ARGILLITE AND LITTLE ORANGE STAIN

Driller Certification

All work performed and reported in this well log is in compliance with the Montana well construction standards. This report is true to the best of my knowledge.

Name:	BRITT LINDSAY
Company:	LINDSAY DRILLING
License No:	MWC-337
Date Completed:	9/30/2010

APPENDIX B—AQTESOLV ANALYSIS
STATE LANDS WEST TEST



SLW STEP TEST

Data Set: M:\...\SLW-1_Step.aqt
Date: 06/01/11 Time: 08:54:31

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLW-1
Test Date: 4/12/11

AQUIFER DATA

Saturated Thickness: 77. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLW-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ SLW-1	0	0

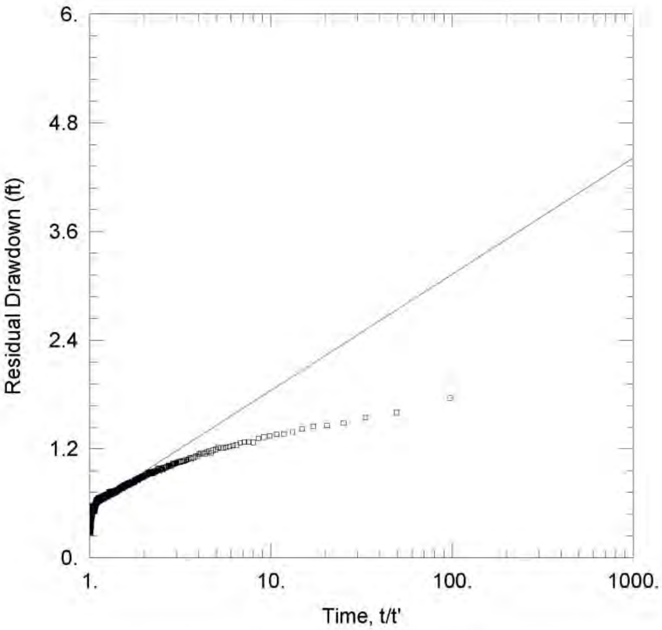
SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Step Test)

T = 575. ft^2/day
S = 0.1
Sw = 0.008878
C = 0.07815 min^2/ft^5
P = 2.

Step Test Model: Jacob-Rorabaugh
Time (t) = 1. min Rate (Q) in cu. ft/min
$s(t) = 0.5754Q + 0.07815Q^{2.}$
W.E. = 72.04% (Q from last step)

Figure W-B1. Step test simulation of SLW-1 (pumping well) using the T value determined from the State Lands West constant-rate test, using the Theis method.



SLW STEP TEST

Data Set: M:\...\SLW-1_Step.aqt
Date: 06/01/11 Time: 08:55:57

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLW-1
Test Date: 4/12/11

AQUIFER DATA

Saturated Thickness: 77. ft Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLW-1	0	0

Observation Wells

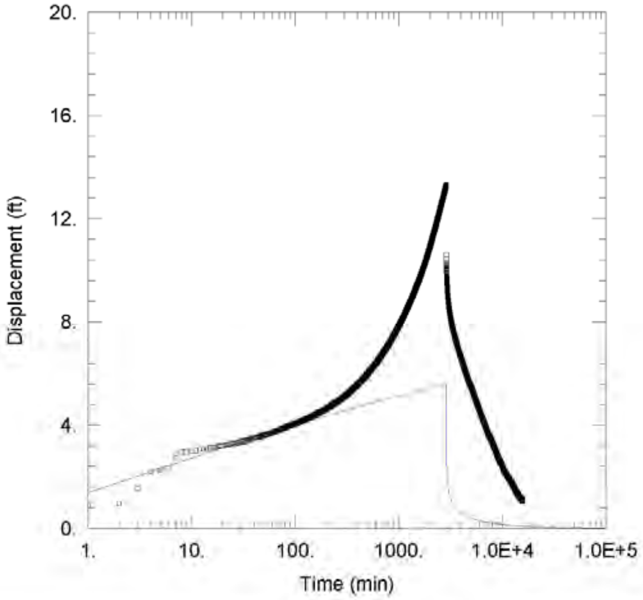
Well Name	X (ft)	Y (ft)
□ SLW-1	0	0

SOLUTION

Aquifer Model: Confined Solution Method: Theis (Recovery)

T = 575. ft^2/day S/S' = 0.3631

Figure W-B2. Simulation of recovery in SLW-1 (pumping well) from the State Lands West step test, using the Theis recovery method.



SLW CONSTANT RATE TEST

Data Set: M:\...\SLW-1_CR.aqt
Date: 06/01/11 Time: 08:59:01

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLW-1
Test Date: 4/18/11 - 4/20/11

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLW-1	0	0

Observation Wells

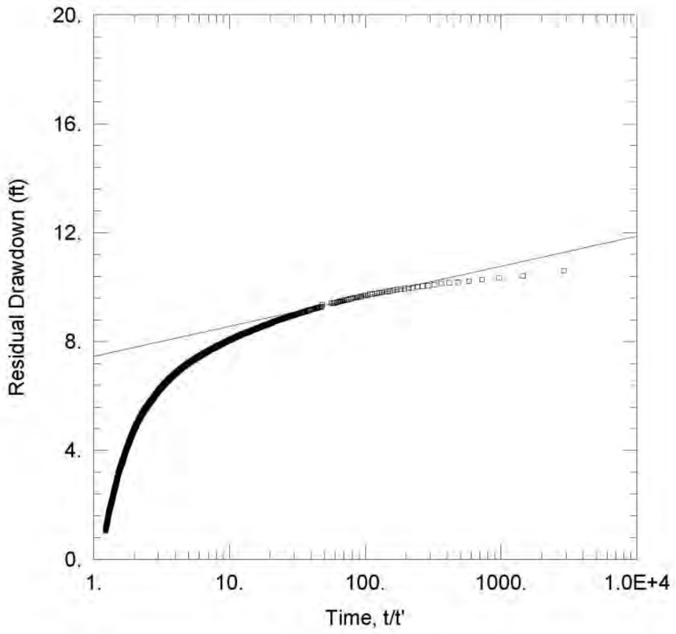
Well Name	X (ft)	Y (ft)
▫ SLW-1	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis

T = 575. ft^2/day
S = 0.1
Kz/Kr = 1.
b = 77. ft

Figure W-B3. Simulation of drawdown in SLW-1 (pumping well) from the State Lands West constant-rate test, using the Theis method. Note that the late time data (>100 min) deviate from the ideal.



SLW CONSTANT RATE TEST

Data Set: M:\...\SLW-1_CR.aqt
Date: 06/01/11 Time: 08:58:20

PROJECT INFORMATION

Company: MBMG
Client: GWIP - North Hill
Project: BWIPNH
Location: Helena, MT
Test Well: SLW-1
Test Date: 4/18/11 - 4/20/11

AQUIFER DATA

Saturated Thickness: 77. ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA

Pumping Wells

Well Name	X (ft)	Y (ft)
SLW-1	0	0

Observation Wells

Well Name	X (ft)	Y (ft)
▫ SLW-1	0	0

SOLUTION

Aquifer Model: Confined
Solution Method: Theis (Recovery)

T = 575. ft^2/day
S/S' = 1.773E-7

Figure W-B4. Simulation of recovery in SLW-1 (pumping well) from the State Lands West constant-rate test, using the Theis recovery method.

HYDROGRAPHS

Hydrographs are used to present data on groundwater levels over time. Over short time periods the timing and magnitude of changes in groundwater water levels can be evaluated. Over long time periods hydrographs can be used to assess trends.

For the North Hills groundwater investigation, the focus was on the long-term water-level trends. To test for trends in water levels, best-fit linear regression relations were developed for wells that have water-level data from 2005 and from 2010. The linear regression lines were fit to data on depth to water vs. time charts. These linear relations have the form $y = mx+b$, where y is depth to water, m is the slope in ft/d, x is time, and b is the intercept of the y-axis on January 1st, 1900. Due to this form, negative slopes represent groundwater levels that have risen, and positive values represent groundwater levels that have dropped. In table H1 the slope values have been recalculated as feet of elevation change per year, so that negative slopes indicate dropping water levels. The geographic distribution of hydrograph trends can be used to evaluate the regional or local nature of groundwater-level changes (fig. H1).

The 2005 data are from Madison (2006), and represent the most consistent dataset previously collected in the study area. Any other data for a site were used qualitatively to ensure that the resulting trend is representative of the water levels (e.g., that the seasonality of data collected does not bias the result). Historical data are from a variety of sources, including the United States Geological Survey (USGS), Lewis and Clark Water Quality Protection District, and the Montana Bureau of Mines and Geology’s (MBMG’s) Ground Water Assessment Program Monitoring Network.

Madison, J.P., 2006, Hydrogeology of the North Hills, Helena, Montana: MBMG Open-File report 544, 36 p.

Table H1
North Hills Monitoring Network - Water Level Trends, 2005 vs. 2010

GWIC ID	Site Name	2005-2010 Slope (ft/day)	Slope (ft/yr) negative values are dropping
5846	USGS Linc E	0.0002	-0.07
64649	Tralles 110	0.0037	-1.35
64686	Sing	0.0024	-0.88
64737	State	0.0043	-1.57
64774	Cole	-0.0002	0.07
65271	Garrick	0.0015	-0.55
65422	Moots 95	-0.0016	0.58
65432	Drake	-0.0039	1.42
125628	Rose	-0.0002	0.07
143645	Salsbury	0.0036	-1.31
144726	Crowley	0.0005	-0.18
148259	Jaffe	0.0028	-1.02
170202	Jacobs	0.0046	-1.68
176012	Nystrand 259	0.0007	-0.26
176012	Purcell	0.0043	-1.57
187372	Flandland	-0.0003	0.11
187850	Woehl 100	0.0043	-1.57
189417	Moots 155	-0.0014	0.51
191532	LC-NH	0.0033	-1.21
191537	LC-Linc&MT	0.0014	-0.51
195637	Collins Drive	-0.00008	0.03
196245	Forsythe	0.001	-0.37
198748	Rand	0.0006	-0.22
199992	Minkoff	0.0007	-0.26
199993	Stetzer	-0.00004	0.01
199997	Ratcliff	-0.00005	0.02
202175	Winslow	0.00005	-0.02
204043	Warren	0.00007	-0.03
206026	Brensdal	0.0037	-1.35
206393	Krei	-0.0008	0.29
206394	Parsley	0.00008	-0.03
207290	Skillman	0.0026	-0.95
211387	Foley	-0.0006	0.22
218593	Nystrand	0.0008	-0.29

Little Change (+-0.5 ft/yr)	18
Noticable Drop (0.5-1.0 ft/yr)	4
Substantial Drop (>1.0 ft/yr)	9
Noticable Rise (0.5-1.0 ft/yr)	2
Substantial Rise (>1.0 ft/yr)	1

The hydrographs summarized in this table are shown on the following pages. As noted above, linear regression lines fit to depth to water vs. time data have the form y=mx+b, where m is the slope in ft/d.

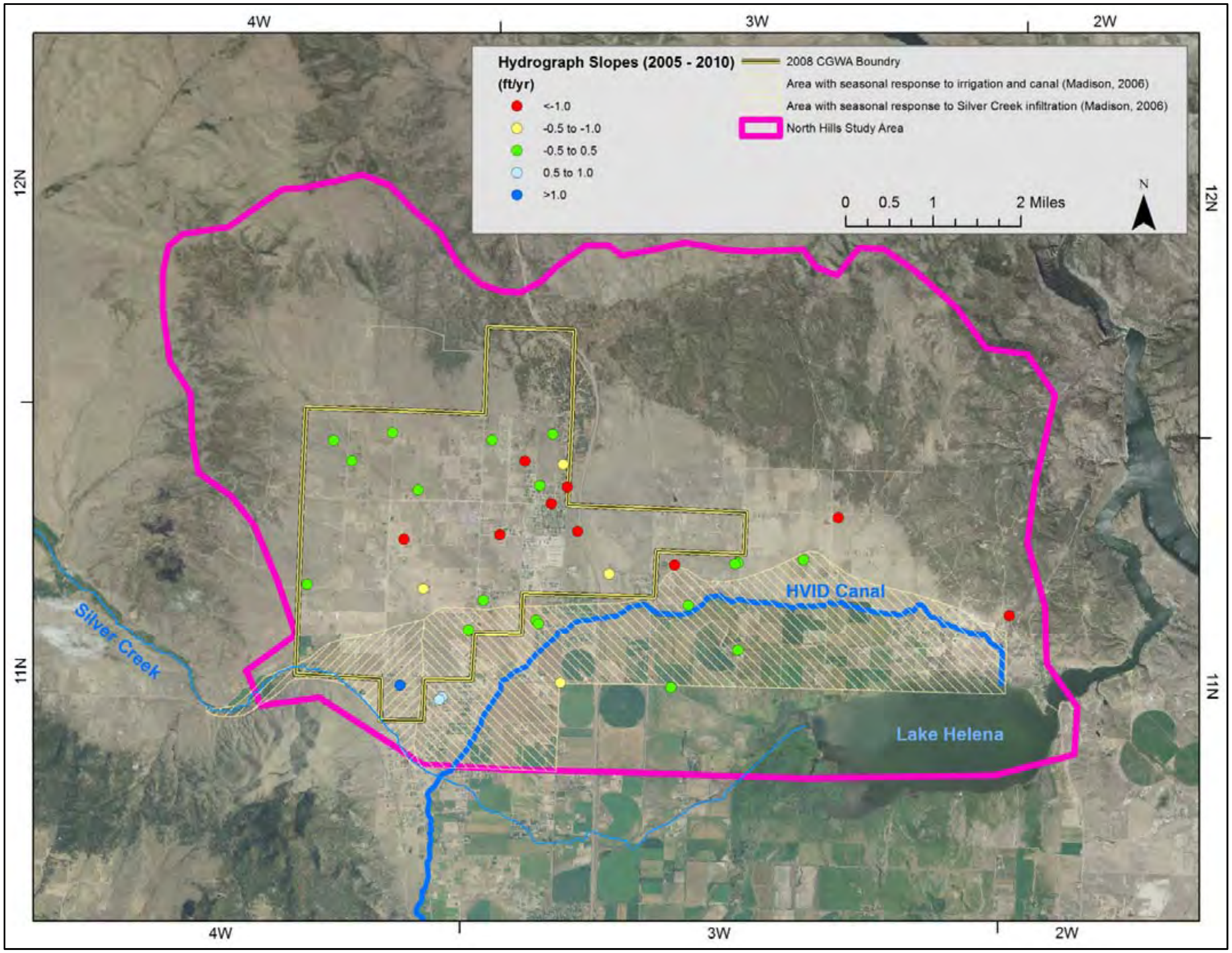
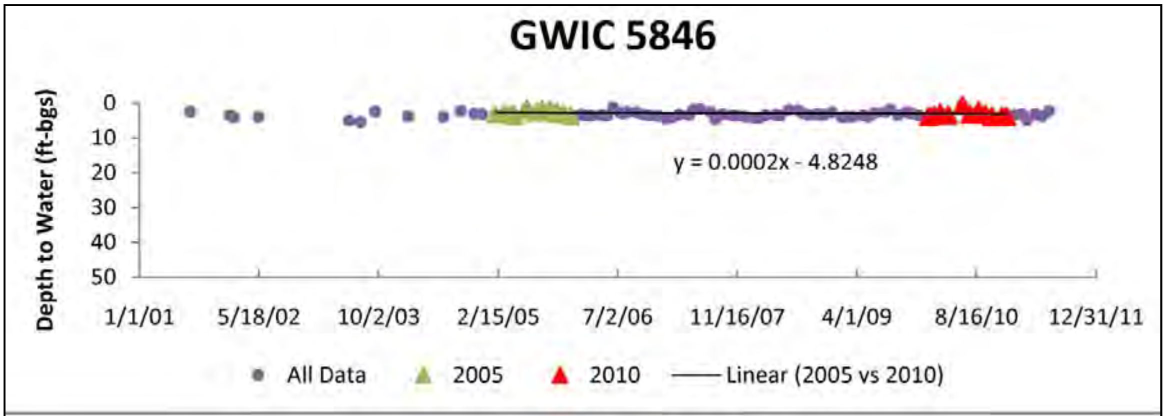
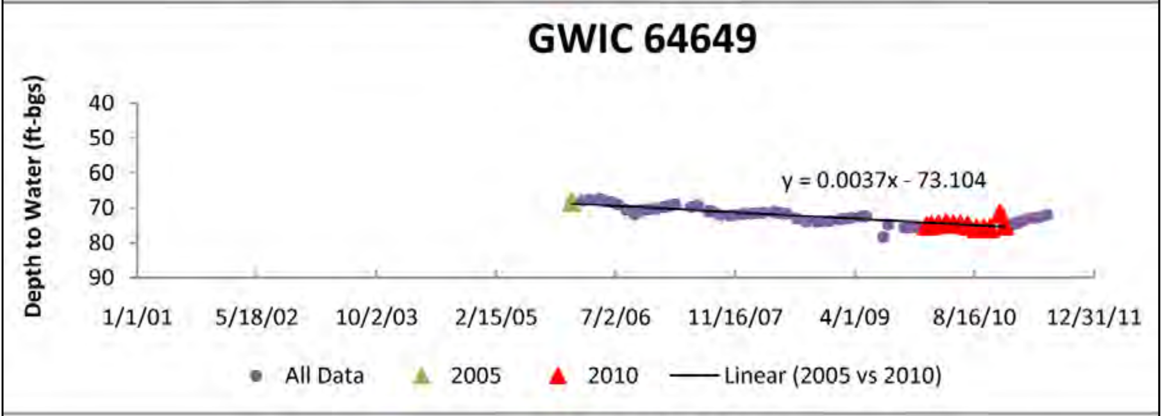
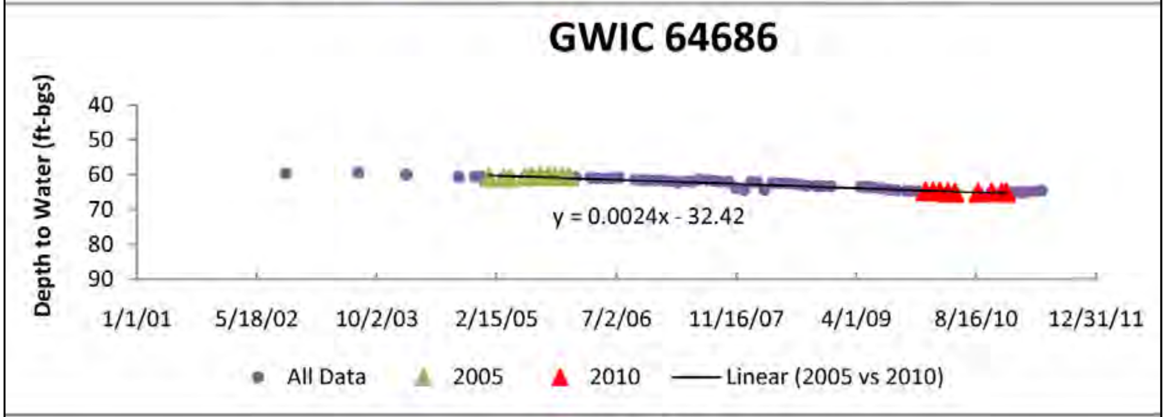
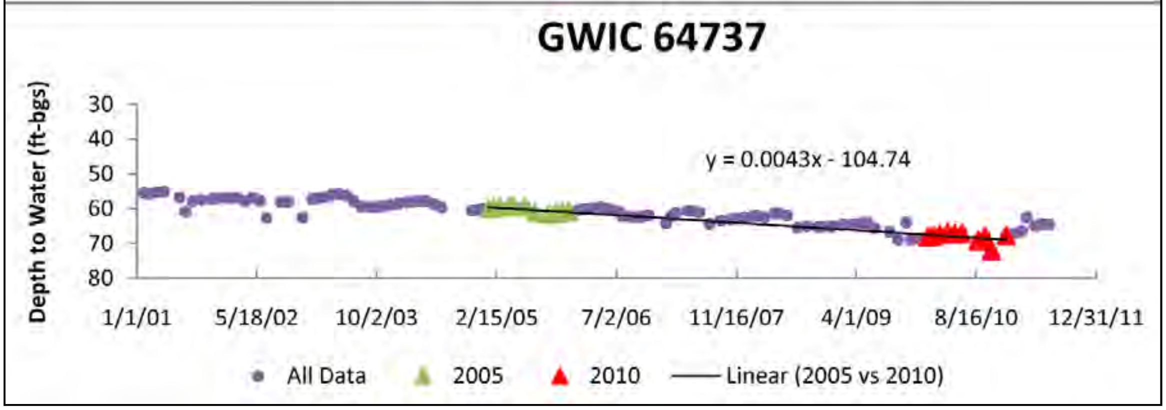


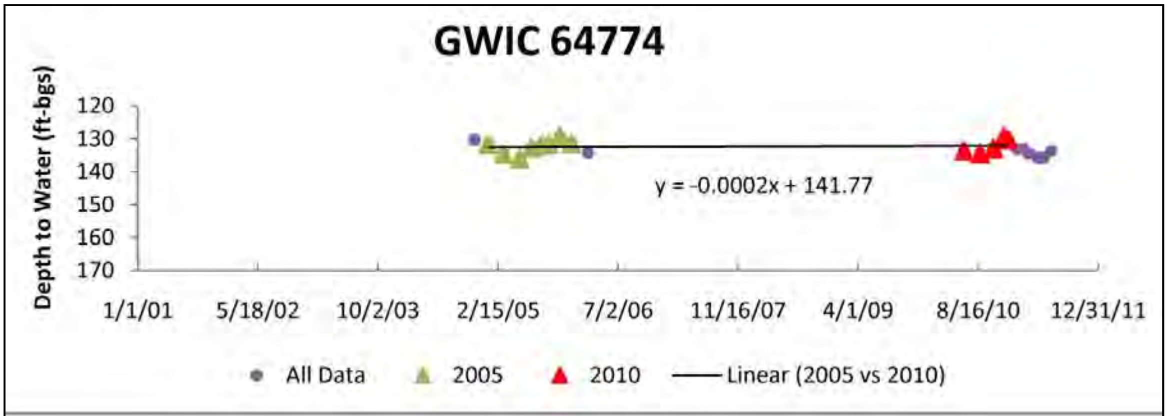
Figure H1. Hydrographs constructed from data collected in 2005 and 2010 show consistent downward trends near areas of high-density development where groundwater is obtained from Tertiary or bedrock aquifers. Isolated wells with downward trends occur in other areas where groundwater is obtained from bedrock. In areas of low-density development, areas influenced by Silver Creek and the HVID Canal, and irrigated areas, water levels are generally stable.

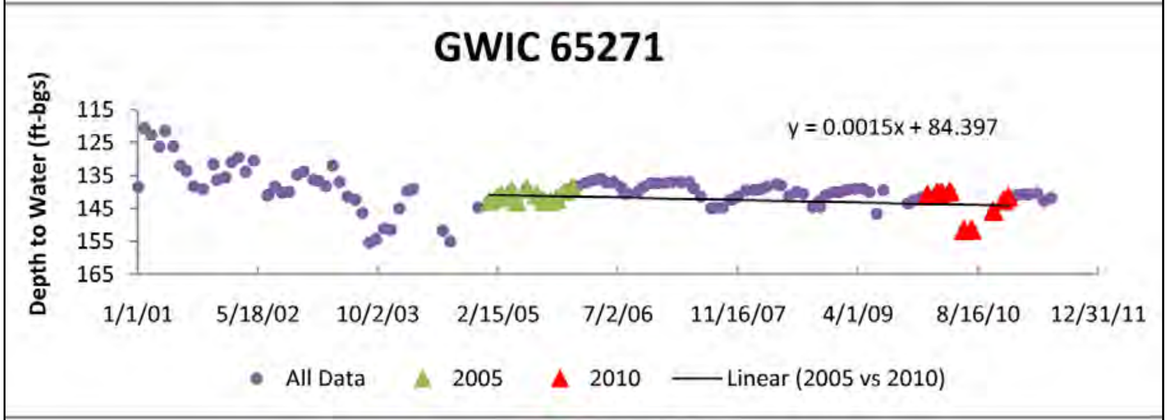

GWIC 5846
Depth to Water (ft-bgs)
0
10
20
30
40
50
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0002x - 4.8248
All Data
2005
2010
Linear (2005 vs 2010)

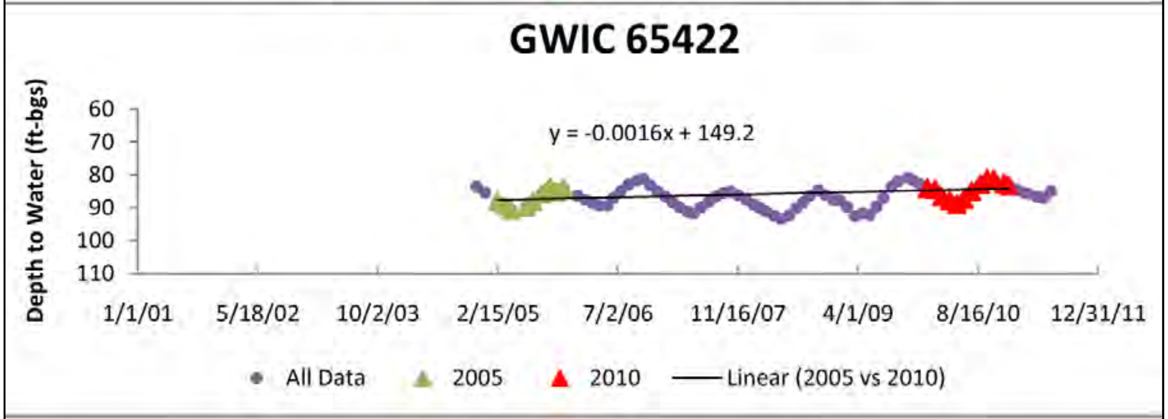

GWIC 64649
Depth to Water (ft-bgs)
40
50
60
70
80
90
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0037x - 73.104
All Data
2005
2010
Linear (2005 vs 2010)

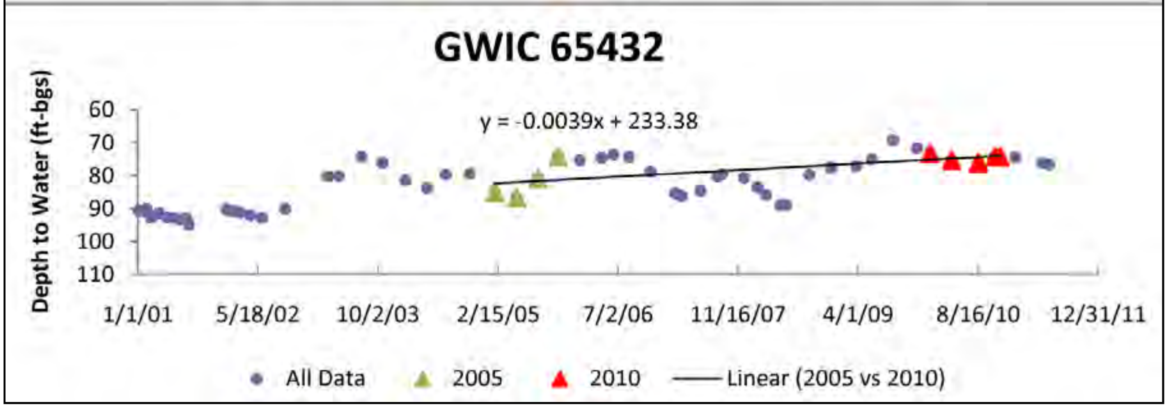

GWIC 64686
Depth to Water (ft-bgs)
40
50
60
70
80
90
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0024x - 32.42
All Data
2005
2010
Linear (2005 vs 2010)

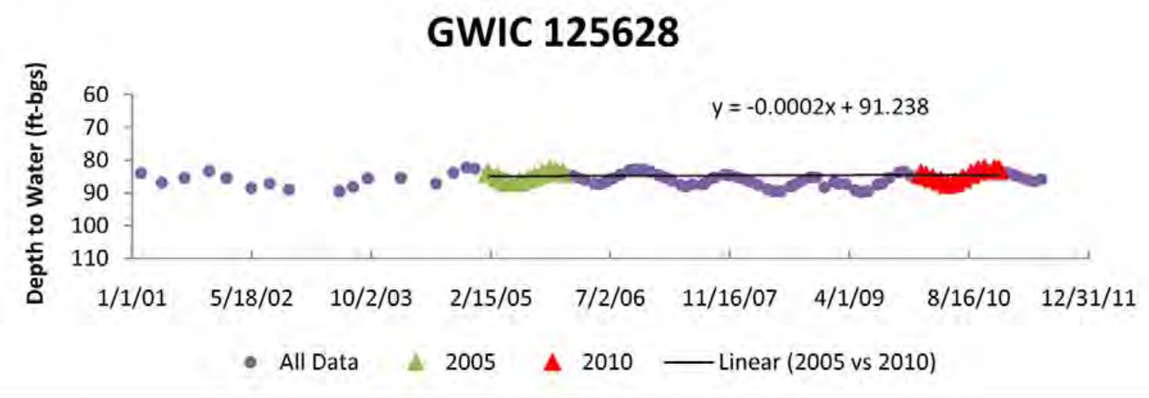

GWIC 64737
Depth to Water (ft-bgs)
30
40
50
60
70
80
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0043x - 104.74
All Data
2005
2010
Linear (2005 vs 2010)

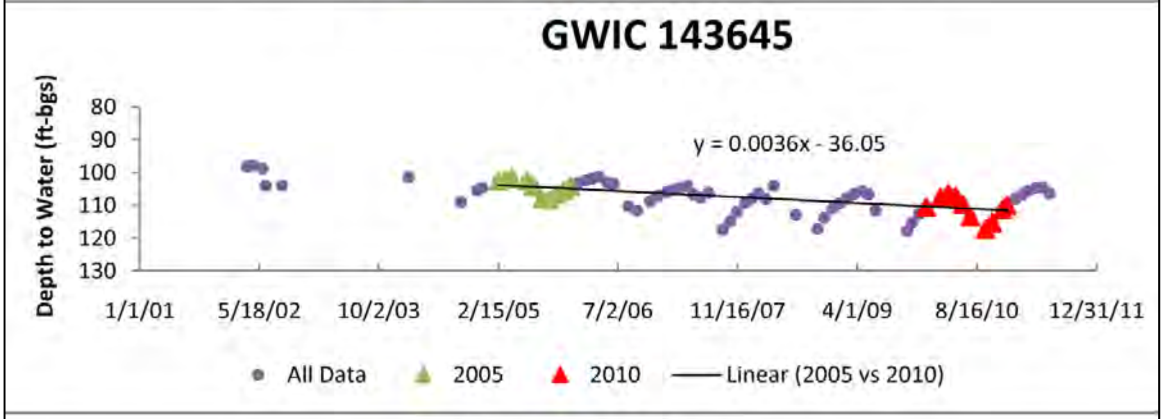

GWIC 64774
Depth to Water (ft-bgs)
120
130
140
150
160
170
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = -0.0002x + 141.77
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

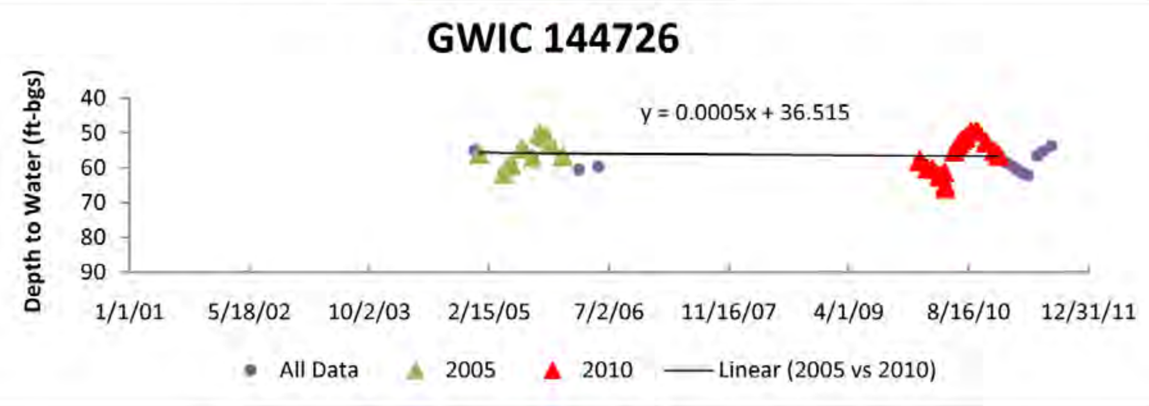

GWIC 65271
Depth to Water (ft-bgs)
115
125
135
145
155
165
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0015x + 84.397
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

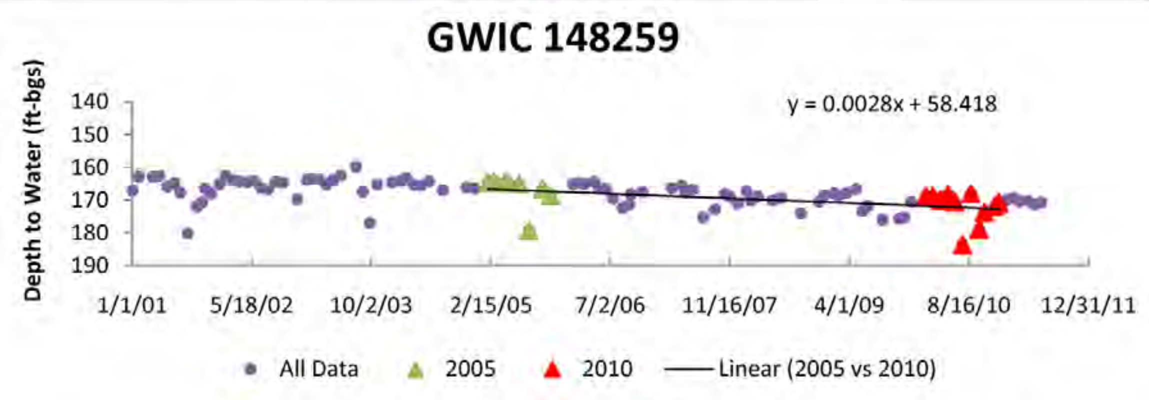

GWIC 65422
Depth to Water (ft-bgs)
60
70
80
90
100
110
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = -0.0016x + 149.2
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

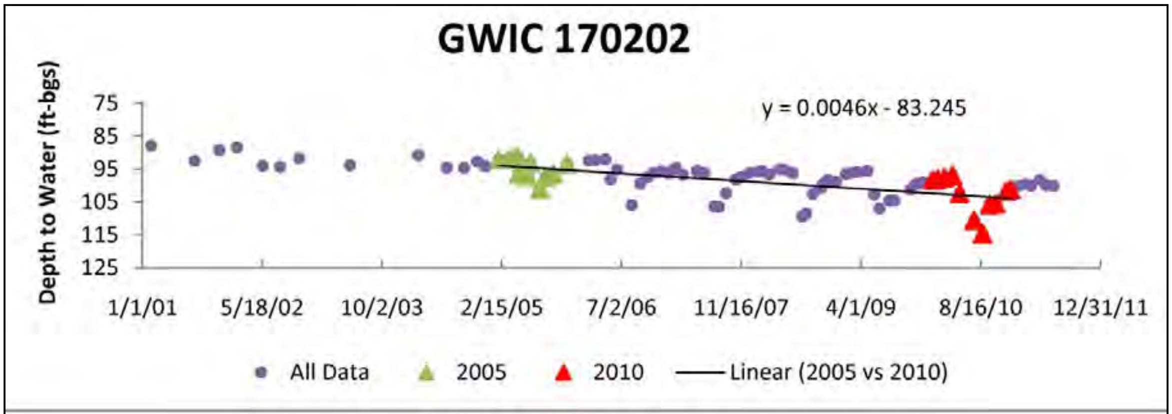

GWIC 65432
Depth to Water (ft-bgs)
60
70
80
90
100
110
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = -0.0039x + 233.38
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

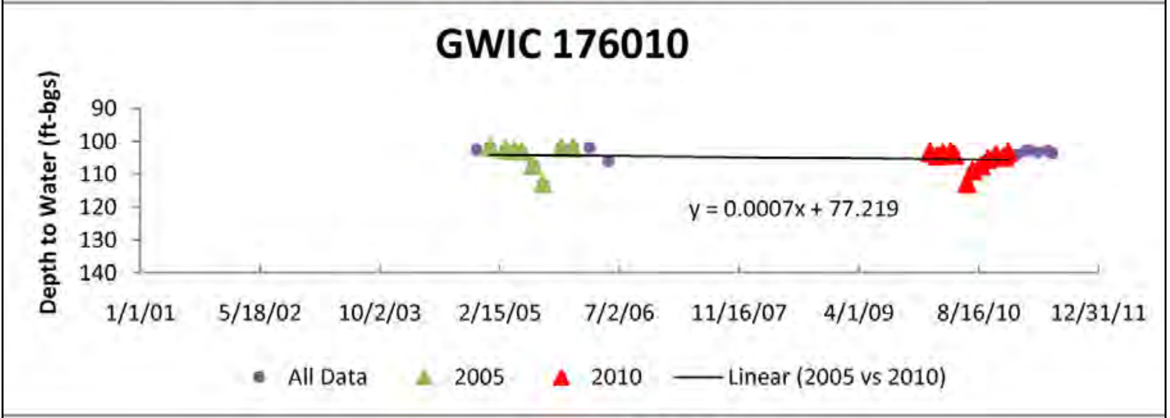

GWIC 125628

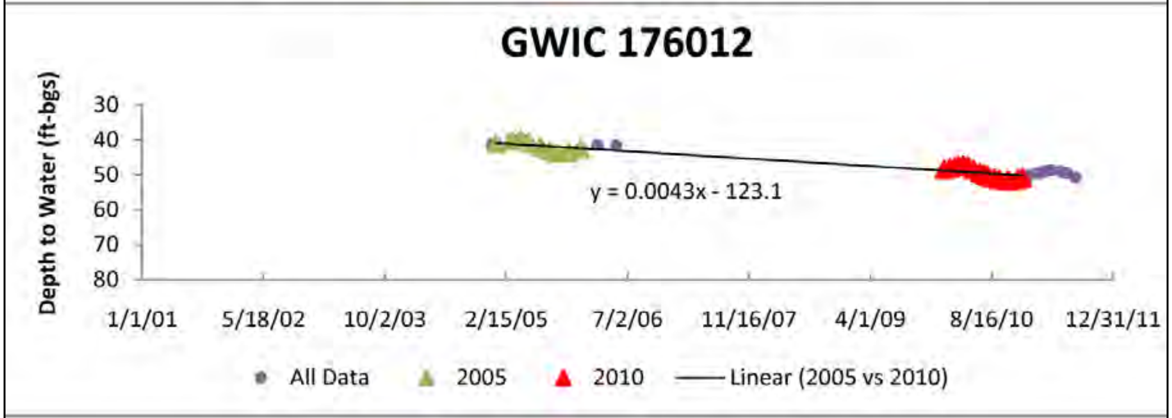

GWIC 143645

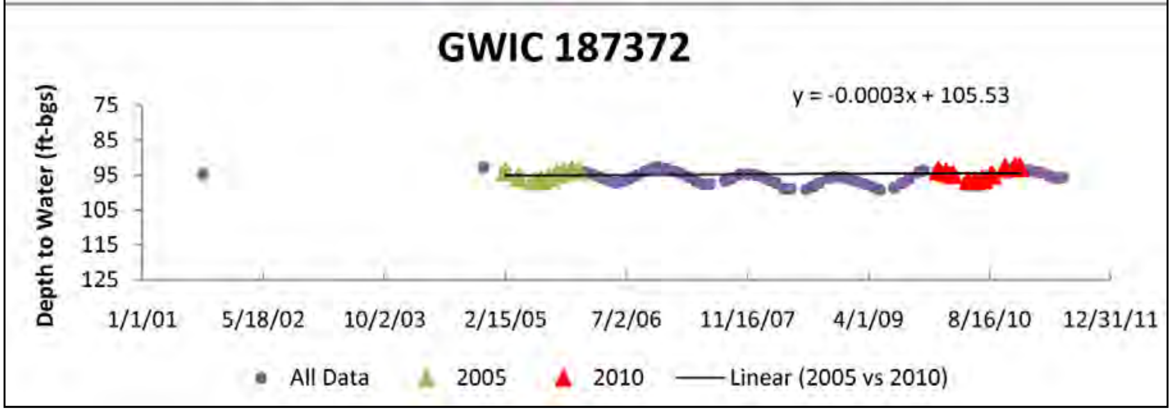

GWIC 144726

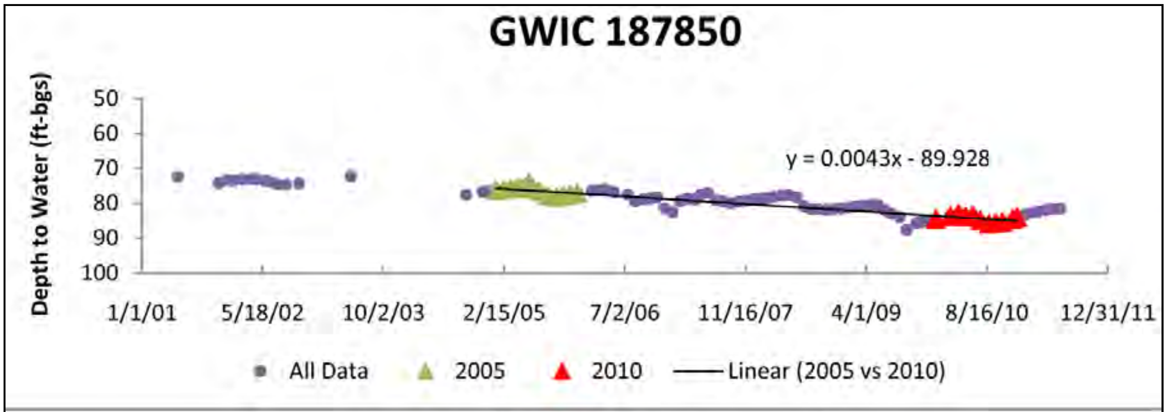

GWIC 148259

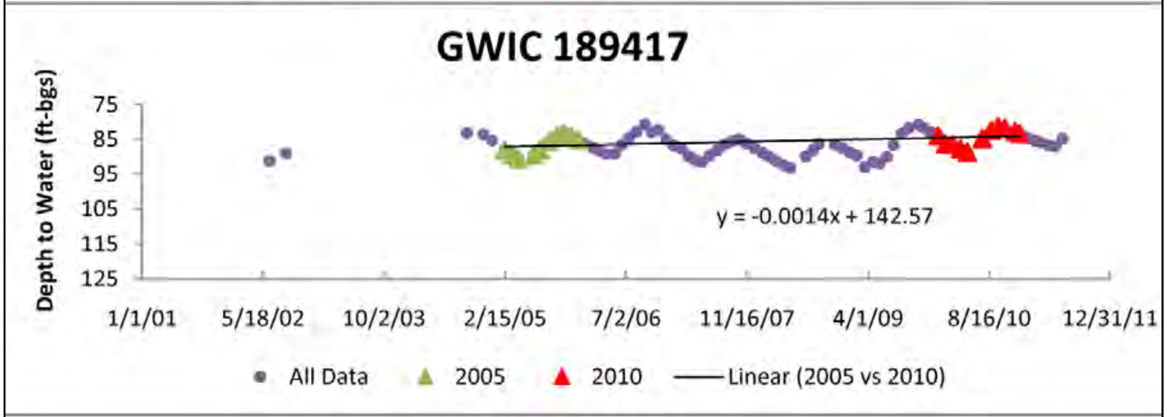

GWIC 170202
Depth to Water (ft-bgs)
75
85
95
105
115
125
y = 0.0046x - 83.245
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

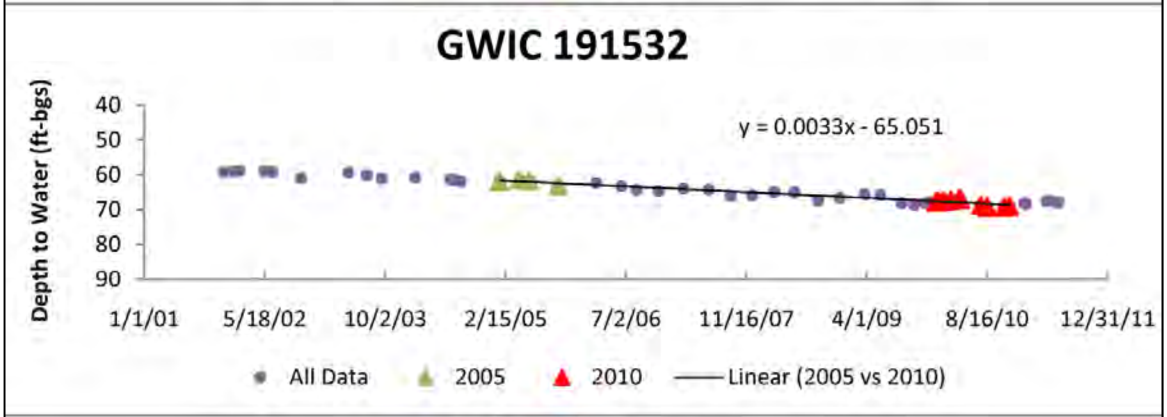

GWIC 176010
Depth to Water (ft-bgs)
90
100
110
120
130
140
y = 0.0007x + 77.219
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

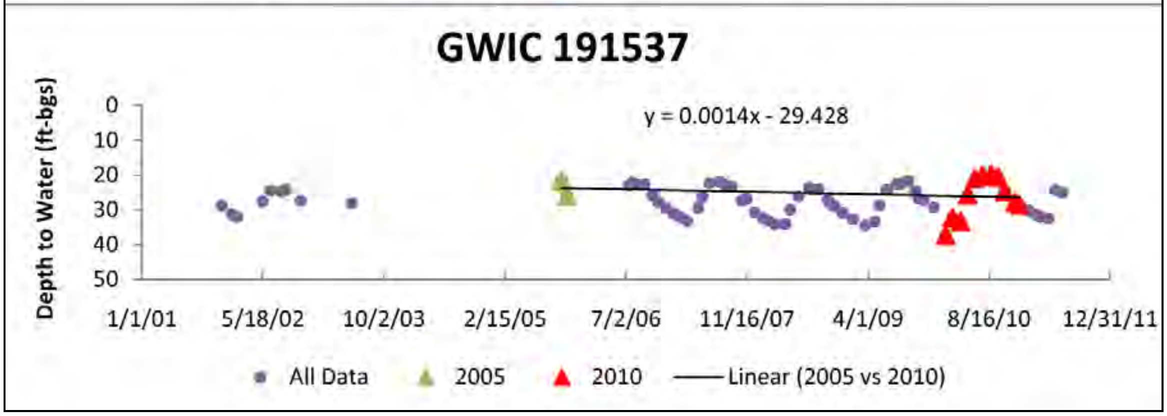

GWIC 176012
Depth to Water (ft-bgs)
30
40
50
60
70
80
y = 0.0043x - 123.1
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

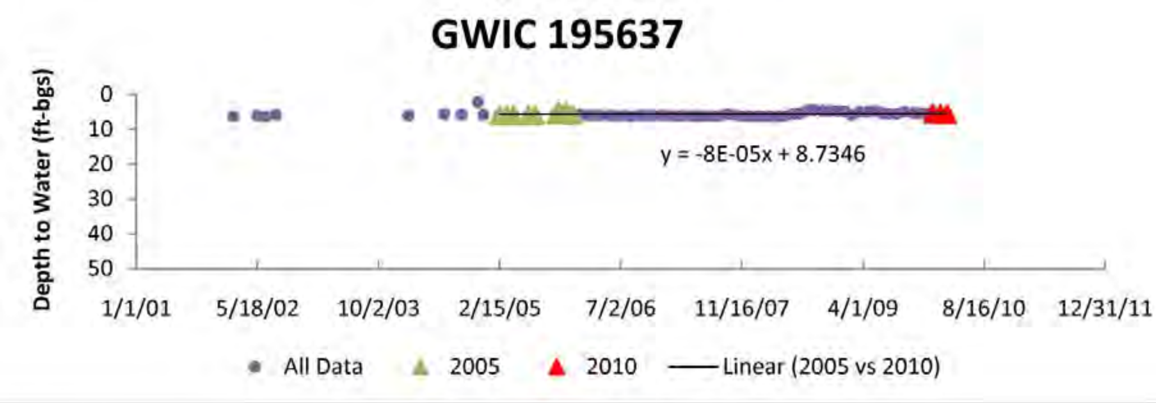

GWIC 187372
Depth to Water (ft-bgs)
75
85
95
105
115
125
y = -0.0003x + 105.53
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

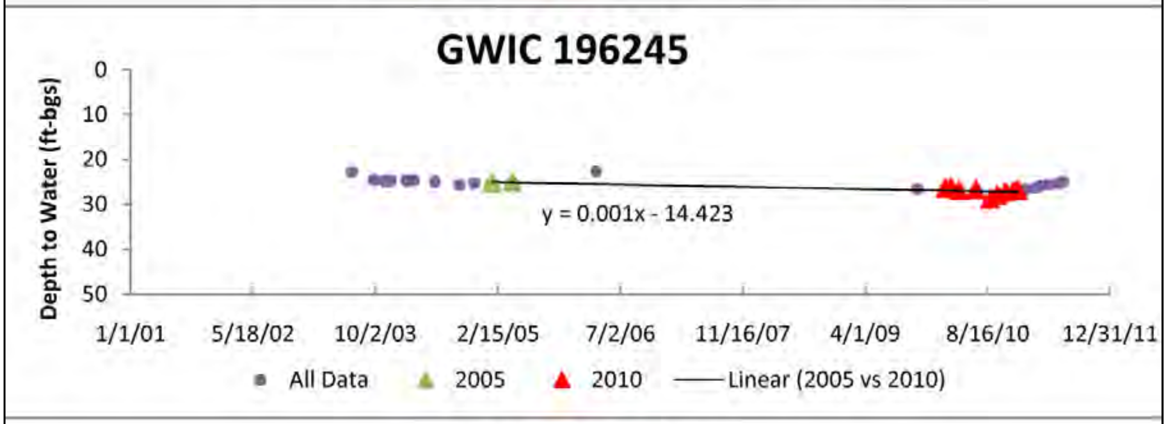

GWIC 187850
Depth to Water (ft-bgs)
50
60
70
80
90
100
y = 0.0043x - 89.928
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
—— Linear (2005 vs 2010)

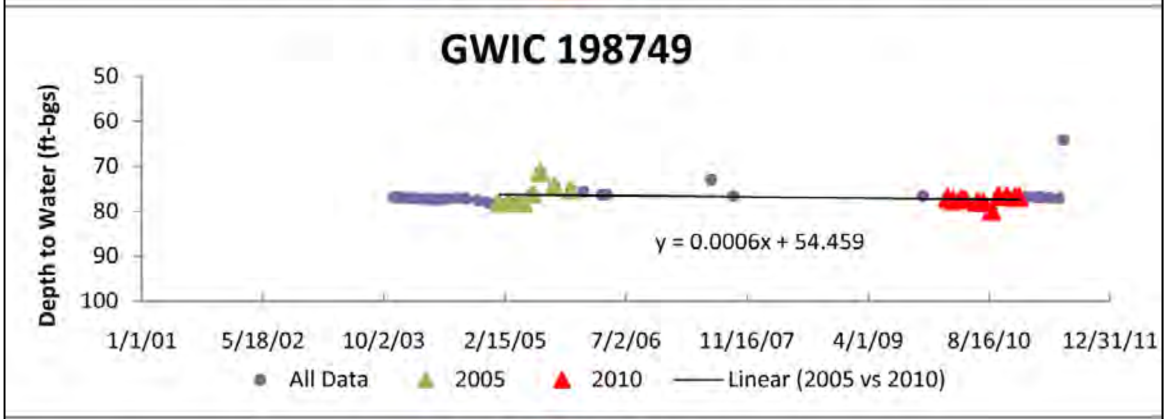

GWIC 189417
Depth to Water (ft-bgs)
75
85
95
105
115
125
y = -0.0014x + 142.57
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
—— Linear (2005 vs 2010)

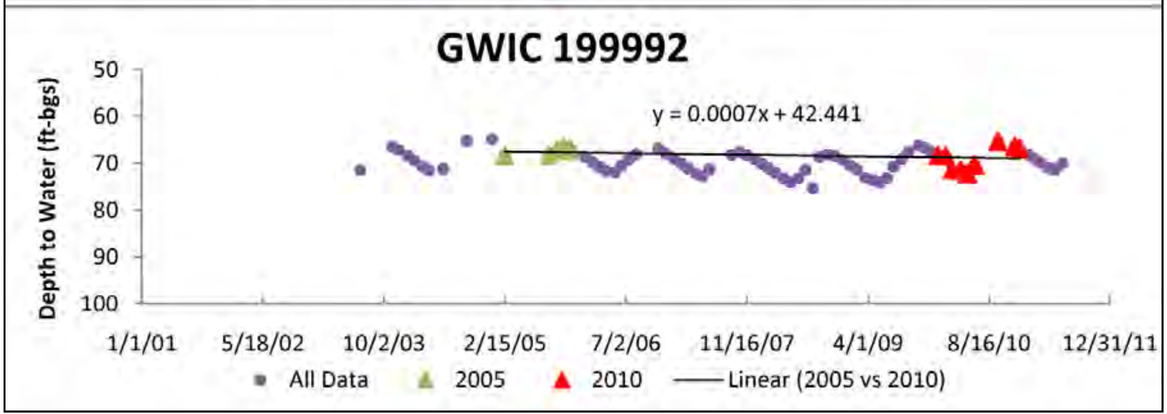

GWIC 191532
Depth to Water (ft-bgs)
40
50
60
70
80
90
y = 0.0033x - 65.051
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
—— Linear (2005 vs 2010)

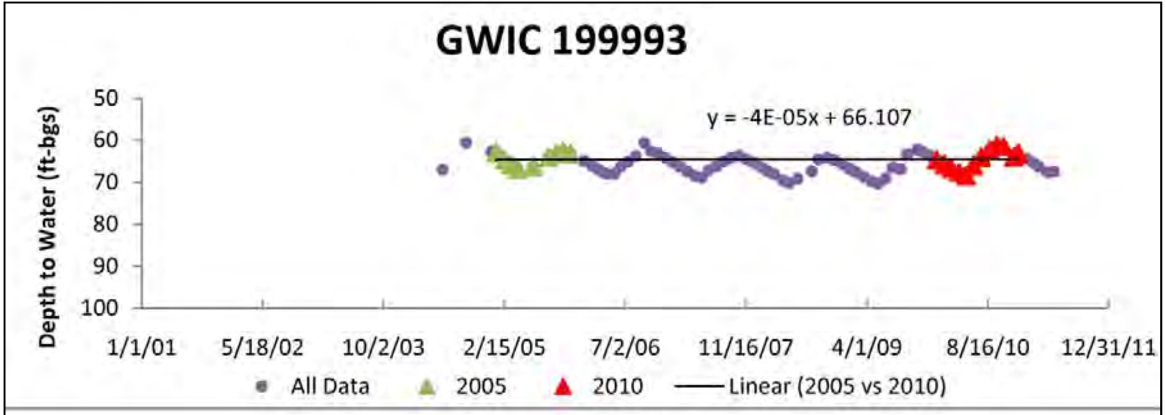

GWIC 191537
Depth to Water (ft-bgs)
0
10
20
30
40
50
y = 0.0014x - 29.428
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
—— Linear (2005 vs 2010)

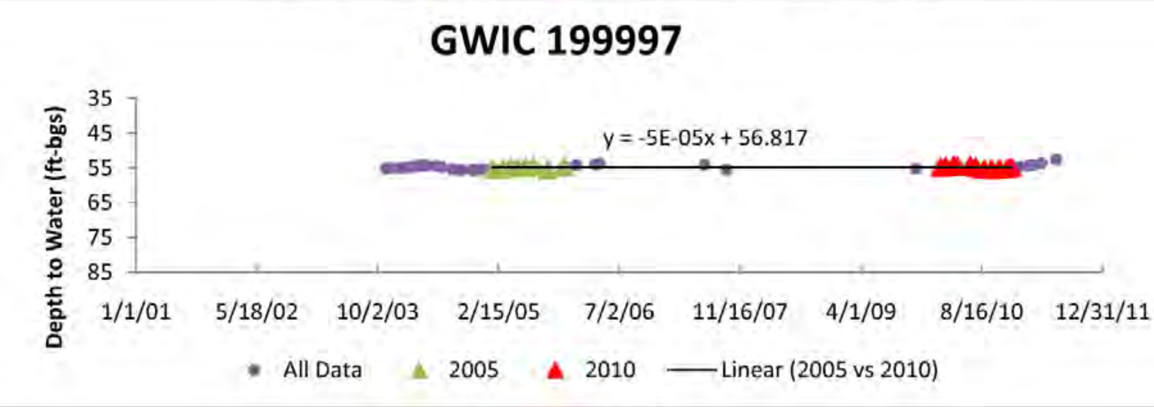

GWIC 195637
Depth to Water (ft-bgs)
0
10
20
30
40
50
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = -8E-05x + 8.7346
All Data
2005
2010
Linear (2005 vs 2010)

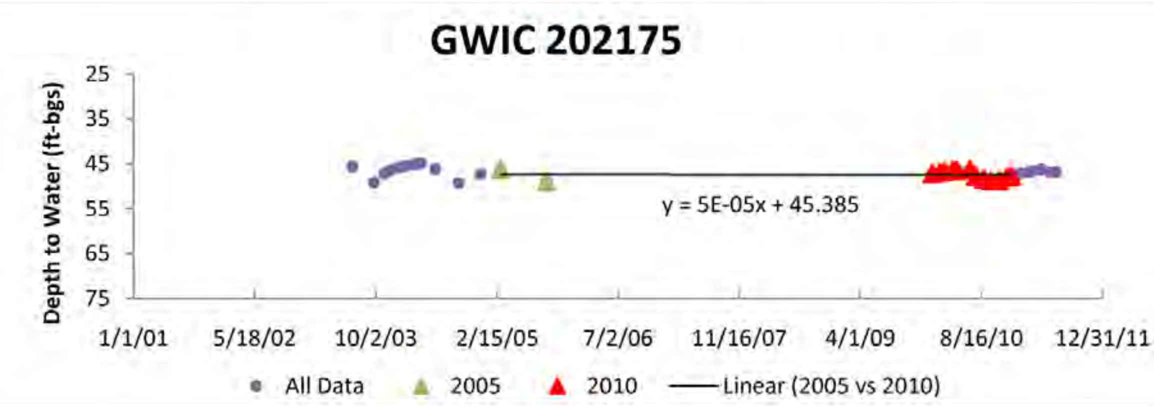

GWIC 196245
Depth to Water (ft-bgs)
0
10
20
30
40
50
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.001x - 14.423
All Data
2005
2010
Linear (2005 vs 2010)

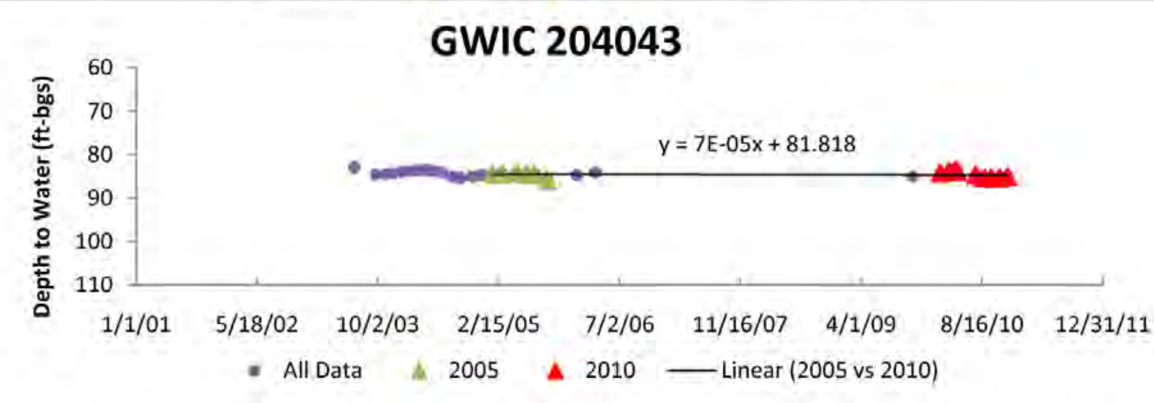

GWIC 198749
Depth to Water (ft-bgs)
50
60
70
80
90
100
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0006x + 54.459
All Data
2005
2010
Linear (2005 vs 2010)

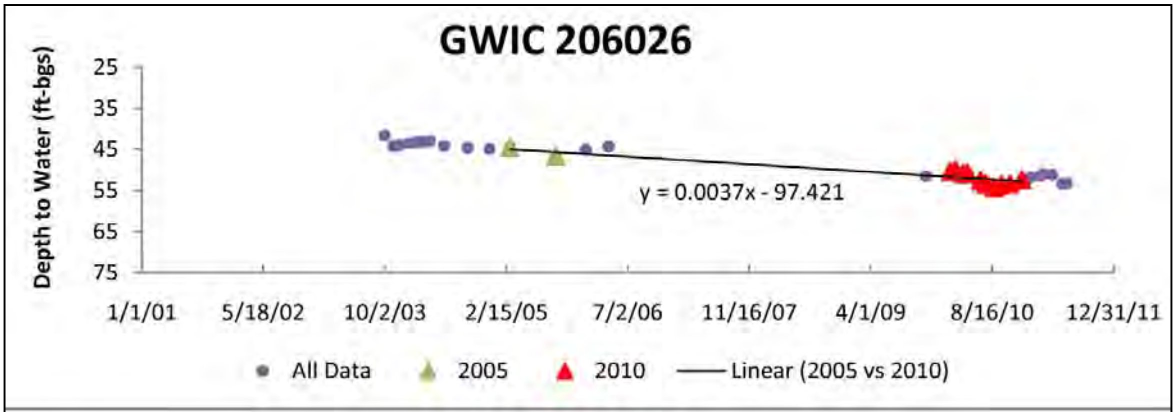

GWIC 199992
Depth to Water (ft-bgs)
50
60
70
80
90
100
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
y = 0.0007x + 42.441
All Data
2005
2010
Linear (2005 vs 2010)

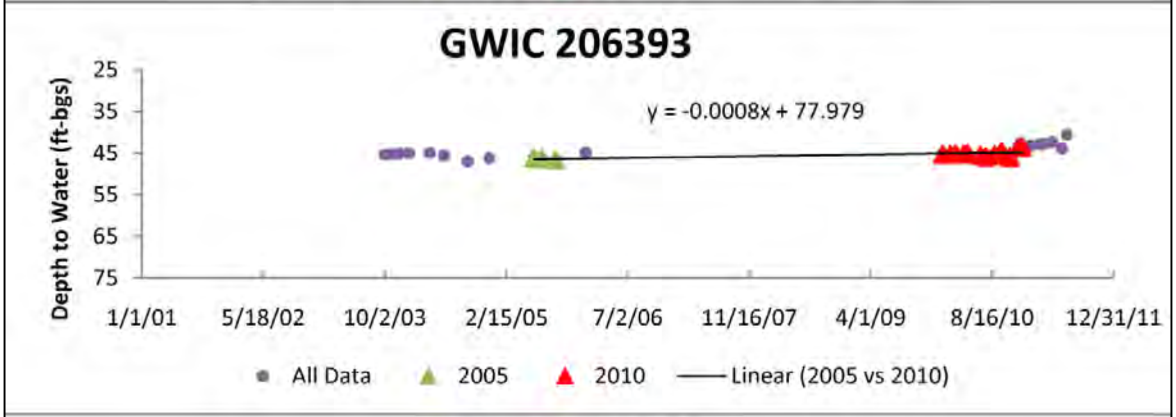

GWIC 199993
Depth to Water (ft-bgs)
50
60
70
80
90
100
y = -4E-05x + 66.107
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
All Data
2005
2010
Linear (2005 vs 2010)

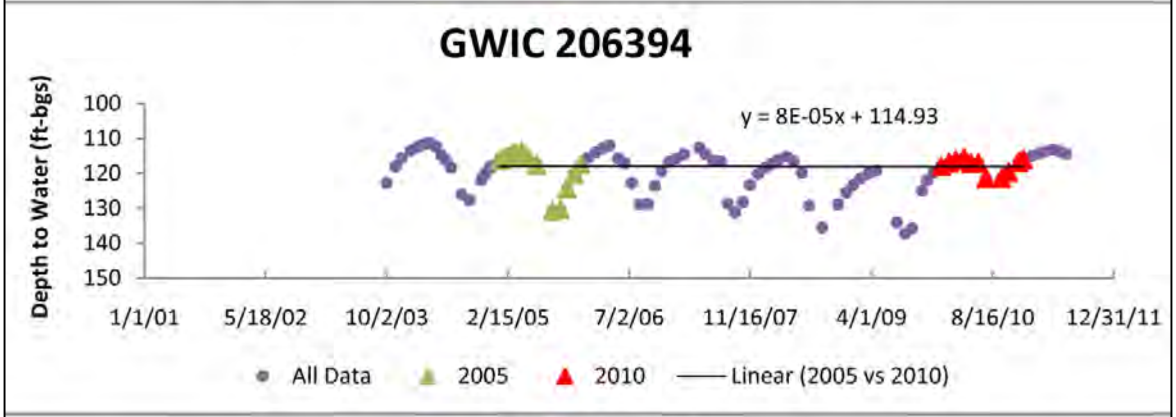

GWIC 199997
Depth to Water (ft-bgs)
35
45
55
65
75
85
y = -5E-05x + 56.817
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
All Data
2005
2010
Linear (2005 vs 2010)

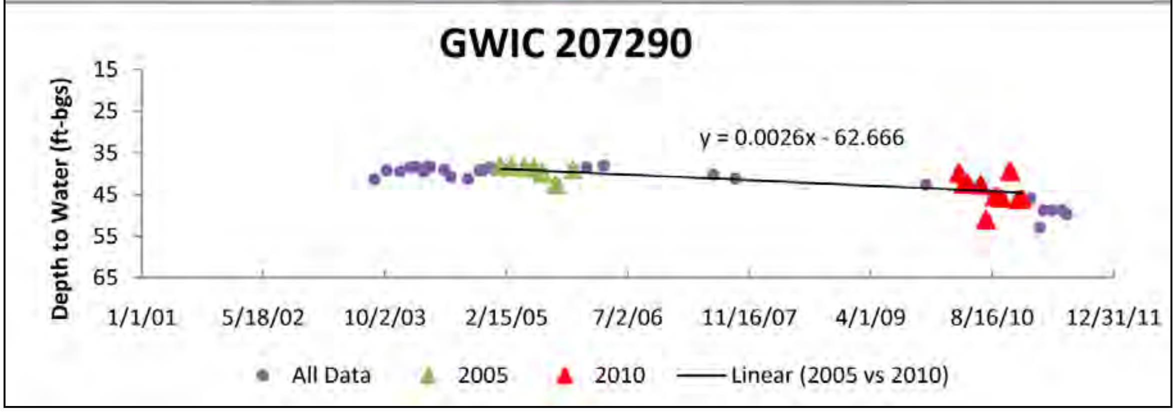

GWIC 202175
Depth to Water (ft-bgs)
25
35
45
55
65
75
y = 5E-05x + 45.385
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
All Data
2005
2010
Linear (2005 vs 2010)

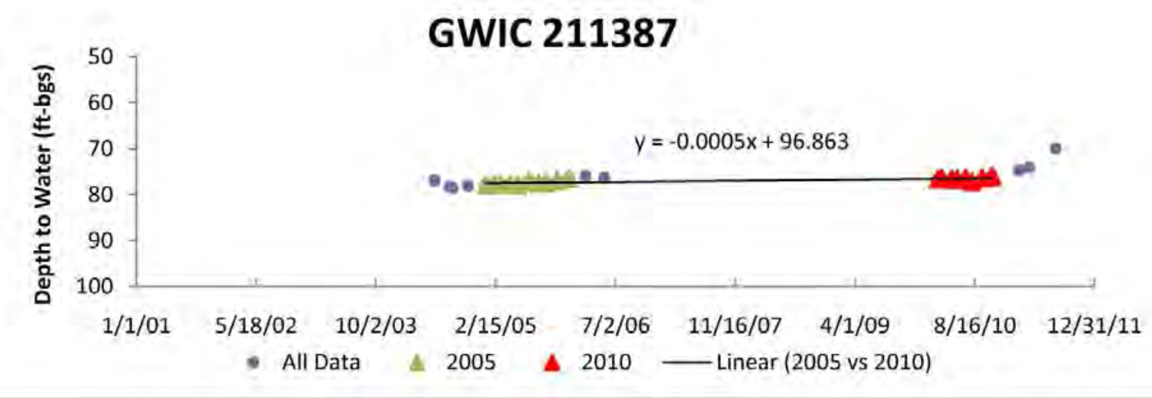

GWIC 204043
Depth to Water (ft-bgs)
60
70
80
90
100
110
y = 7E-05x + 81.818
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
All Data
2005
2010
Linear (2005 vs 2010)

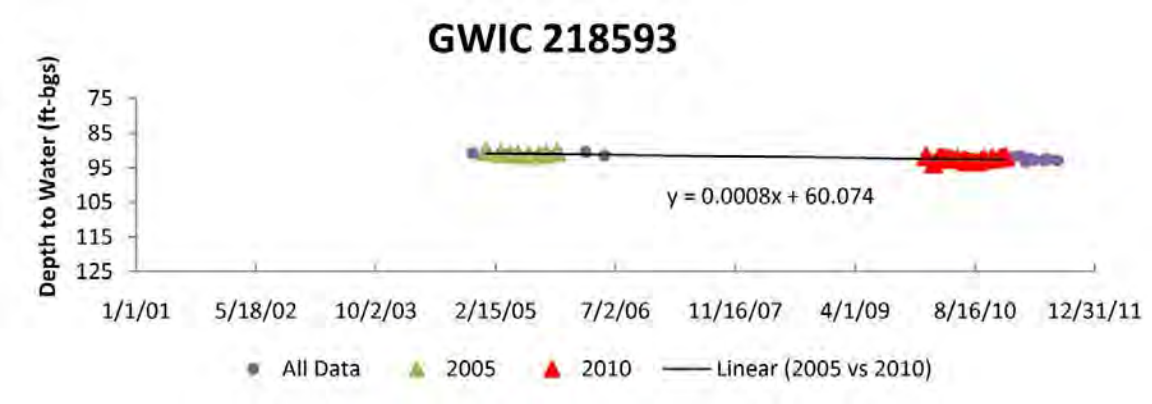

GWIC 206026
Depth to Water (ft-bgs)
25
35
45
55
65
75
y = 0.0037x - 97.421
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)


GWIC 206393
Depth to Water (ft-bgs)
25
35
45
55
65
75
y = -0.0008x + 77.979
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)


GWIC 206394
Depth to Water (ft-bgs)
100
110
120
130
140
150
y = 8E-05x + 114.93
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)


GWIC 207290
Depth to Water (ft-bgs)
15
25
35
45
55
65
y = 0.0026x - 62.666
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)


GWIC 211387
Depth to Water (ft-bgs)
50
60
70
80
90
100
y = -0.0005x + 96.863
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)


GWIC 218593
Depth to Water (ft-bgs)
75
85
95
105
115
125
y = 0.0008x + 60.074
1/1/01
5/18/02
10/2/03
2/15/05
7/2/06
11/16/07
4/1/09
8/16/10
12/31/11
● All Data
▲ 2005
▲ 2010
— Linear (2005 vs 2010)

COMPARISON OF HYDROGRAPHS TO PRECIPITATION

Standardized Precipitation Index

McKee and others (1993) at the Colorado Climate Center developed the Standardized Precipitation Index (SPI) to provide a comparison between observed departures from average precipitation and other parts of the hydrologic system. Different parts of the hydrologic system (i.e., surface water vs. groundwater) respond to departures from average precipitation on different time scales. Consequently, SPI values are typically calculated for a selection of time scales.

Madison (2006) notes that direction of groundwater-level change in the North Hills area often corresponds to the 30-month SPI. The National Weather Service's cooperative weather station at the Helena airport (Coop number 244055; Helena WSO) was used for these calculations. The 30-month SPI was posted quarterly (fig. SDI-1). The average 30-month SPI for 2005 was -0.33, and in 2010 the average 30-month SPI was -0.65. Thus groundwater levels would be expected to be somewhat lower in 2010; however, both values are within the range considered to be "near normal" (-0.75 to 0.75; WRCC, 2013). For this reason the best-fit linear regression relations used in the Hydrographs section would be expected to be flat or show a weak downward trend if the 30-month SPI were the dominate signal.

The water-level hydrographs for a number of wells in the North Hills (GWIC IDs 206393, 206394, 218593, 144726, 199992, 199993, 125628, 191537, 187372, 189417, 65422, and 65432) show little or no long-term trend; however, these wells do deviate upward and downward with the 30-month SPI. A few wells that are influenced by recharge from Silver Creek (GWIC IDs 189417, 65422, 65432) show an upward trend from 2005 to 2010, with shorter-term deviations reflecting the 30-month SPI. Some wells (GWIC IDs 195637, 257064, 5846, and 5854) have little or no long-term trend and do not respond to the 30-month SPI. These wells are in irrigated areas, where annual recharge overwhelms the 30-month SPI. Water-level trends in other wells (GWIC IDs 170202, 64649, 64640, 143645, 191532, 64737, 207290, 176012, 148259, 206026, and 65271) are consistently downward while the 30-month SPI signal is absent, weak, or overwhelmed by a different stress signal. Given that the downward-trending wells that do not track with the 30-month SPI are clustered near the area of densest development (fig. SPI-2) or are pumped wells, and short-term water levels fall as local pumping rates increase, it is likely that this other stress signal is pumping.

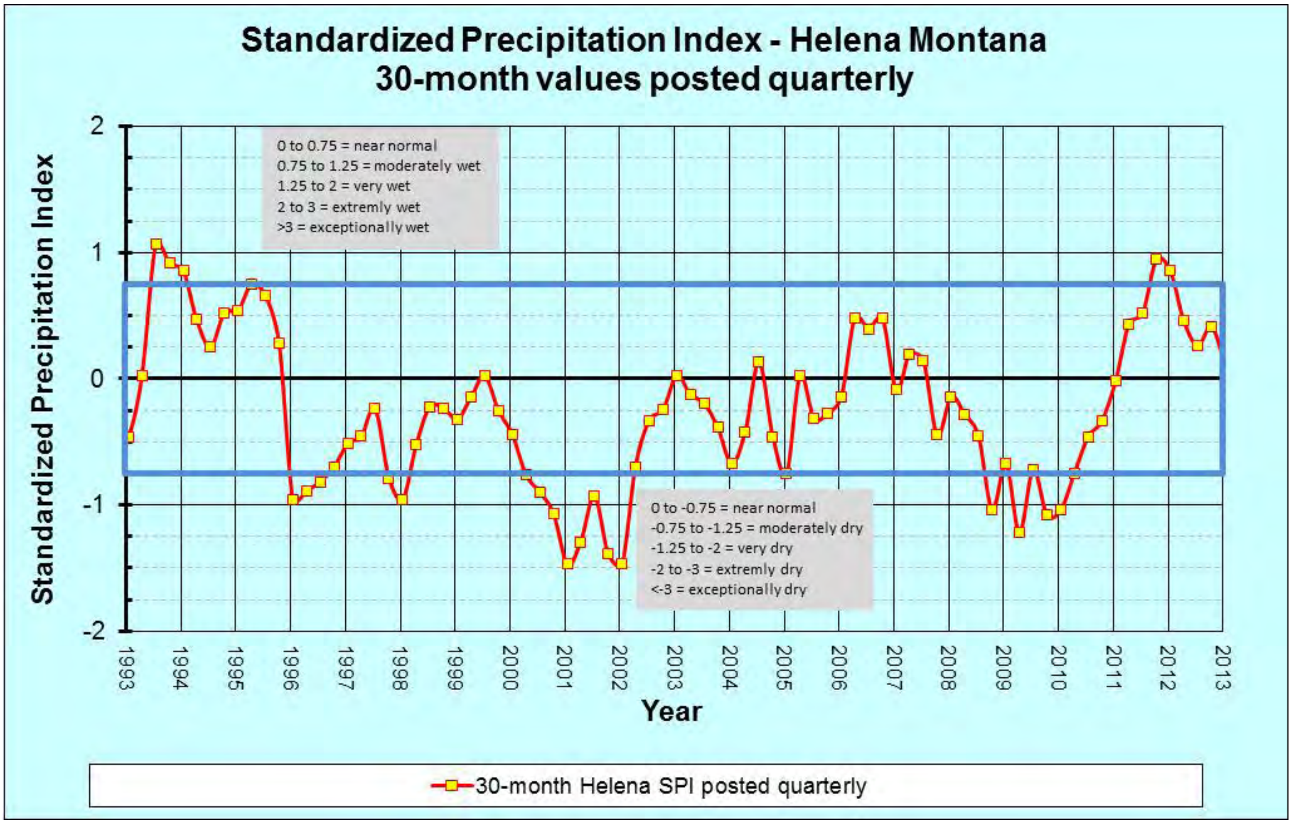


Figure SDI-1. The standardized precipitation index (SDI) was calculated for the Helena area using data from the cooperative weather station at the Helena airport (Coop number 244055; Helena WSO).

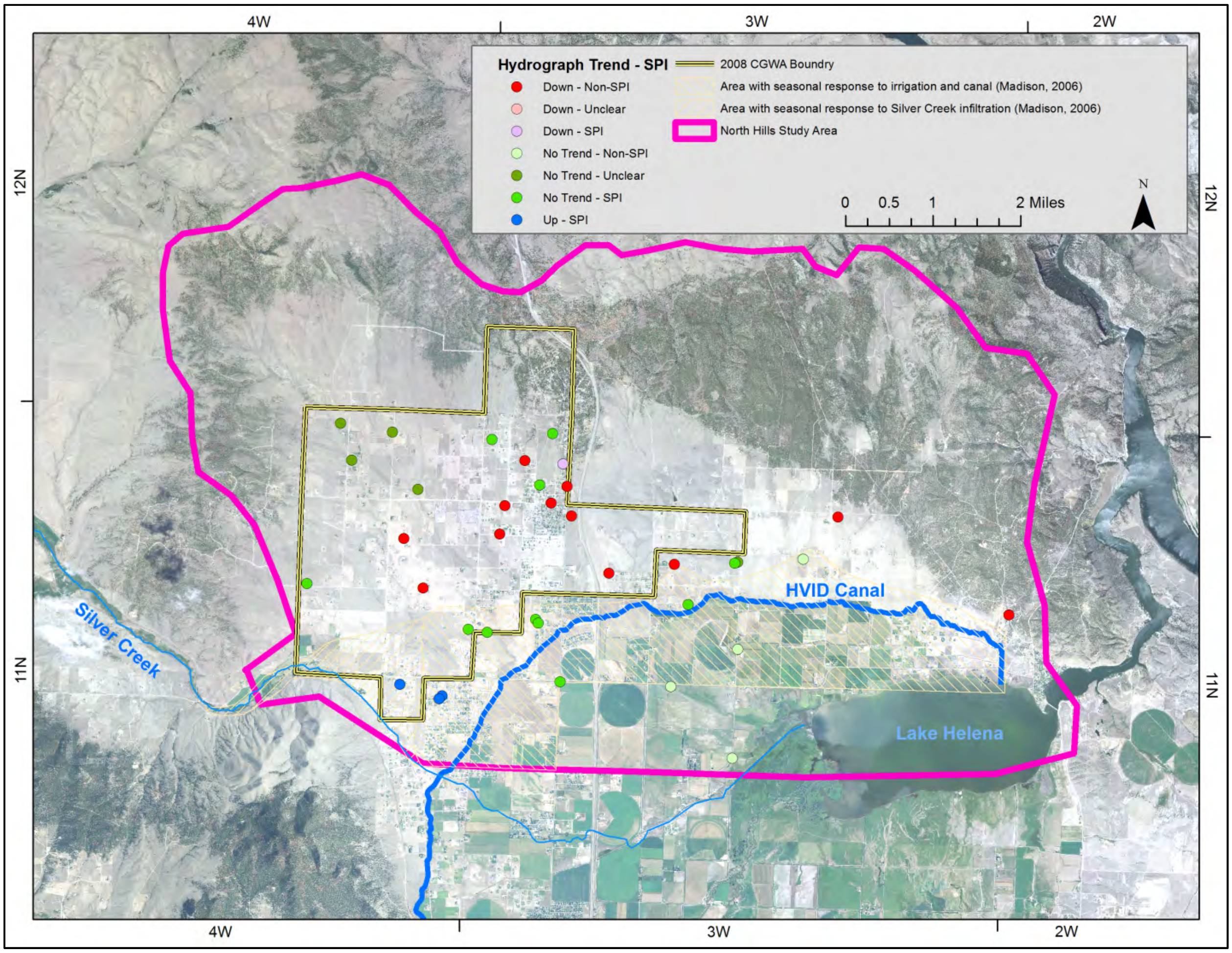


Figure SDI-2. Hydrographs show upward, downward, or no trend between 2005 and 2010. Water levels in some wells deviate with the 30-month SPI, while for other wells the 30-month SPI signal is absent, weak, or overwhelmed ("Non-SPI"). For other wells there is insufficient data to clearly determine if variations are related to the 30-month SPI. Wells with downward trends that do not deviate with the 30-month SPI are in the areas of densest development, or are pumping wells, and water levels drop during times of increased pumping, indicating that the dominant driver for water levels in these wells is pumping. Wells with no trend that do not deviate with the 30-month SPI are in irrigated areas, indicating that the dominant driver for water levels in these wells is related to irrigation.

References

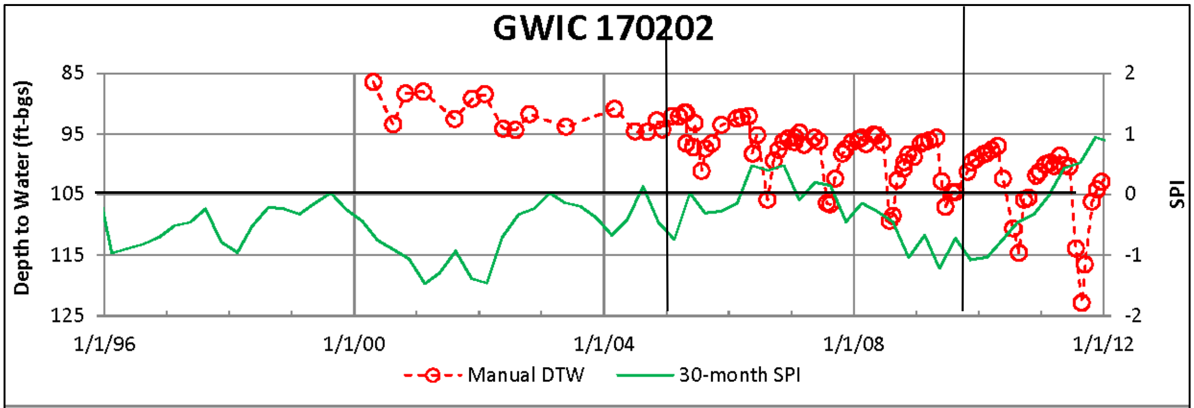
Guttman, N.B., 1999, Accepting the standardized precipitation index: A calculation algorithm: Journal of the American Water Resources Association, v. 35, no. 2, p. 311–322.

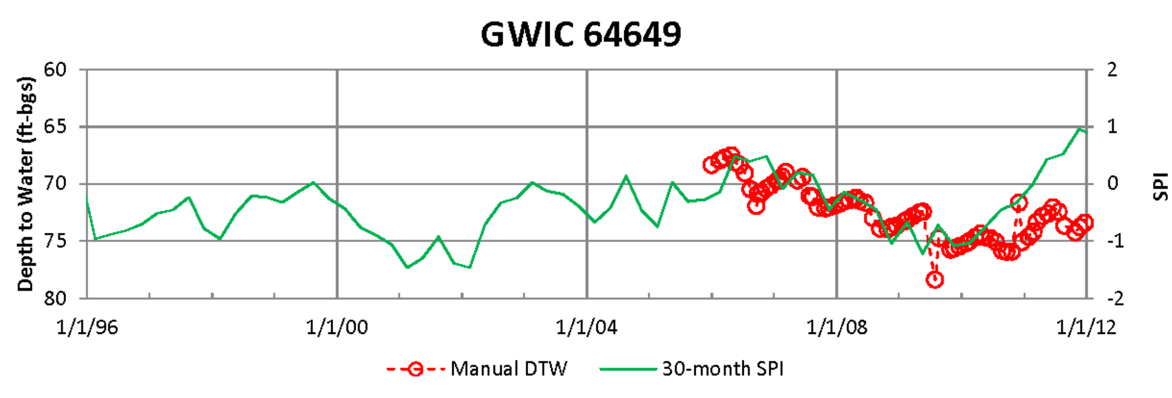
Madison, J.P., 2006, Hydrogeology of the North Hills, Helena, Montana: MBMG Open-File Report 544, 36 p.

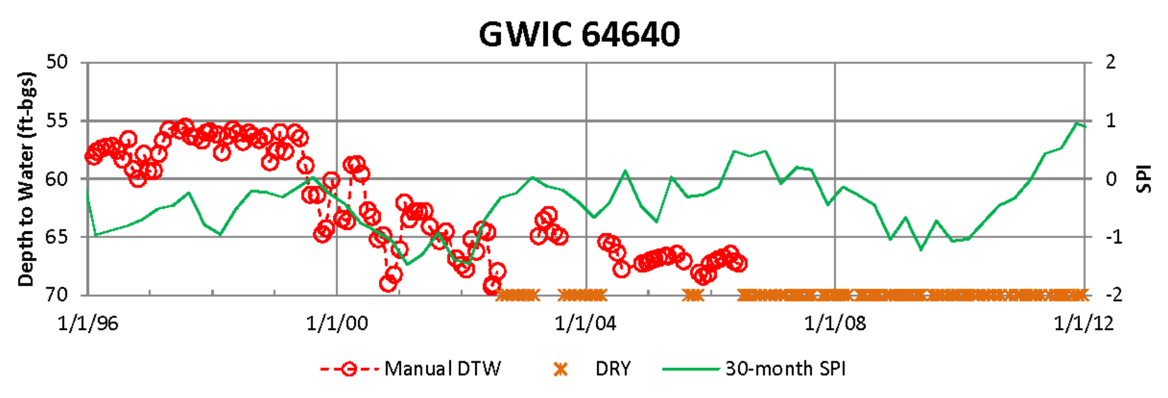
McKee, T.B., Doeskin, N.J., and Kleist, J., 1993, The relationship of drought frequency and duration to time scales: Proceedings of the 8th Conference on Applied Climatology, January 17–22, 1993, American Meteorology Society, Boston, Mass., p. 179–184.

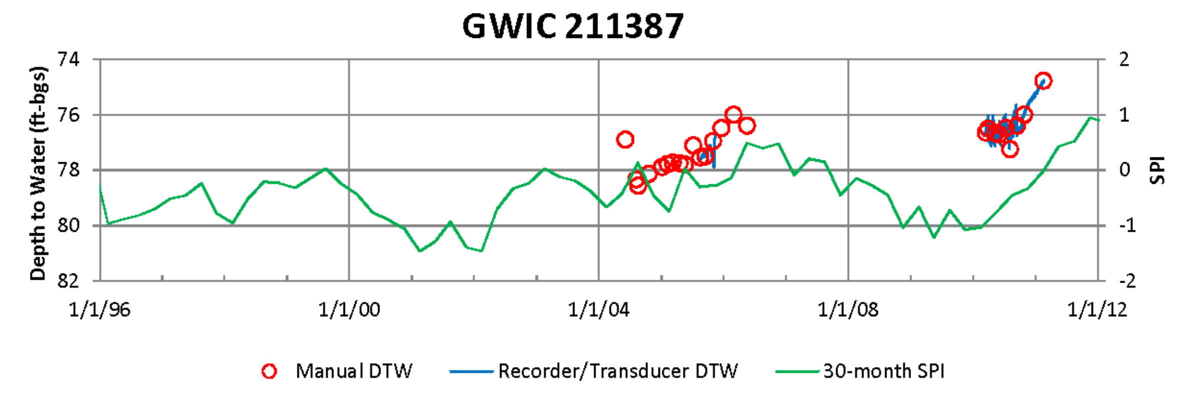
McKee, T.B., Doeskin, N.J., and Kleist, J., 1995, Drought monitoring with multiple time scales: Proceedings of the 9th Conference on Applied Climatology, January 15–20, 1995, American Meteorology Society, Boston, Mass., p. 223–236.

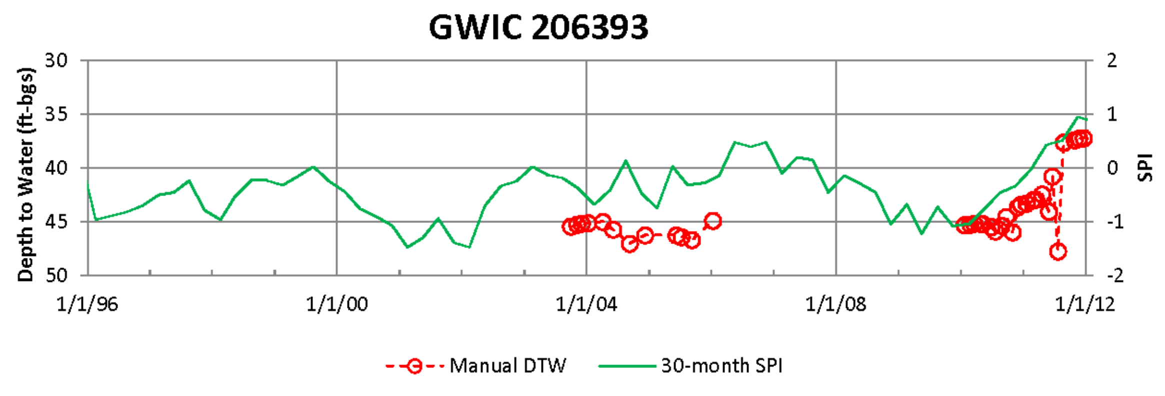
Western Regional Climate Center, 2013, 30-month Standardized Precipitation Index through the end of December 2013: http://www.wrcc.dri.edu/cgi-bin/spiFmap.pl?spi30 [Accessed January 22, 2014].

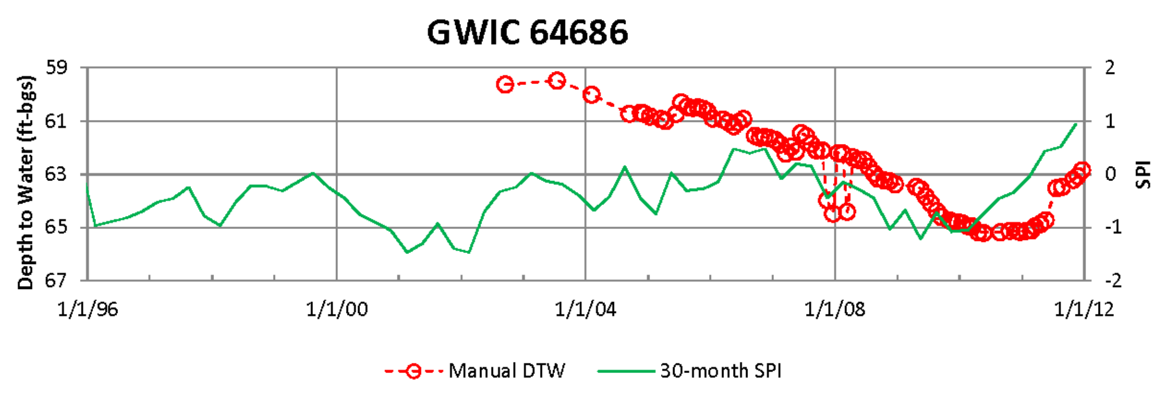

GWIC 170202
Depth to Water (ft-bgs)
85
95
105
115
125
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

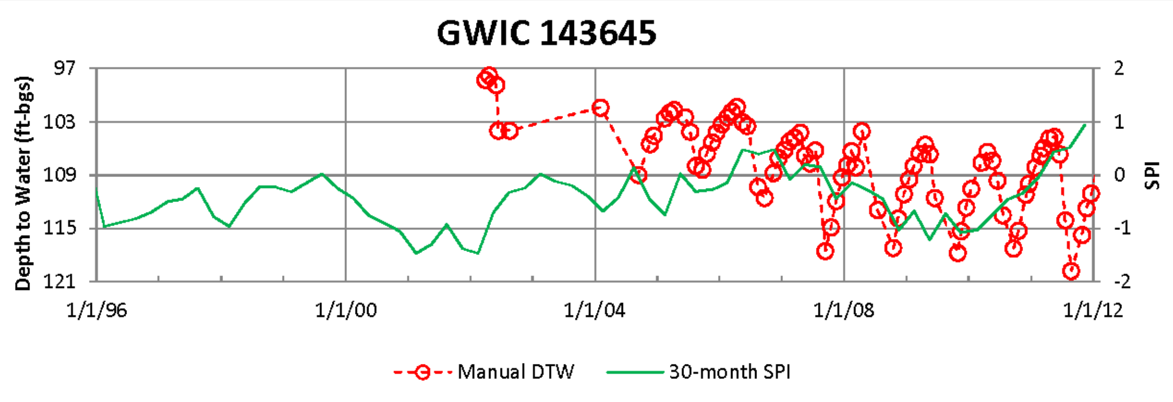

GWIC 64649
Depth to Water (ft-bgs)
60
65
70
75
80
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

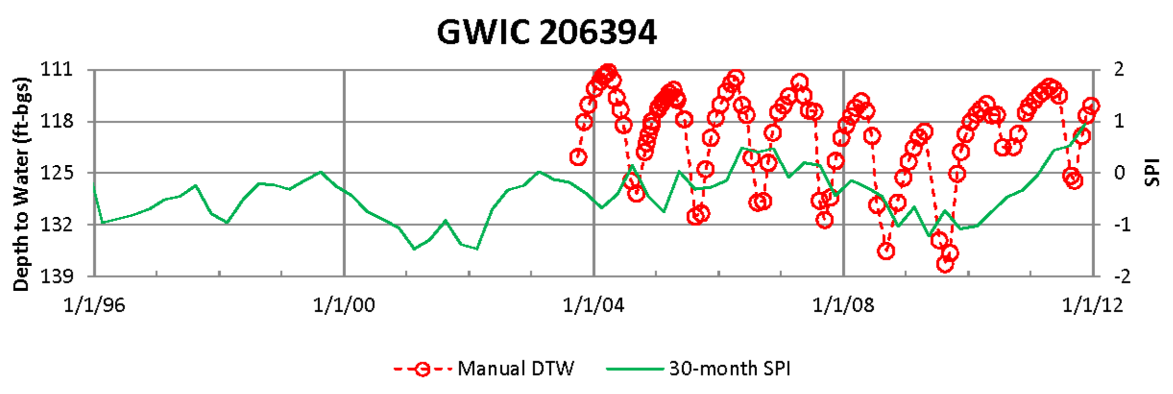

GWIC 64640
Depth to Water (ft-bgs)
50
55
60
65
70
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
DRY
30-month SPI

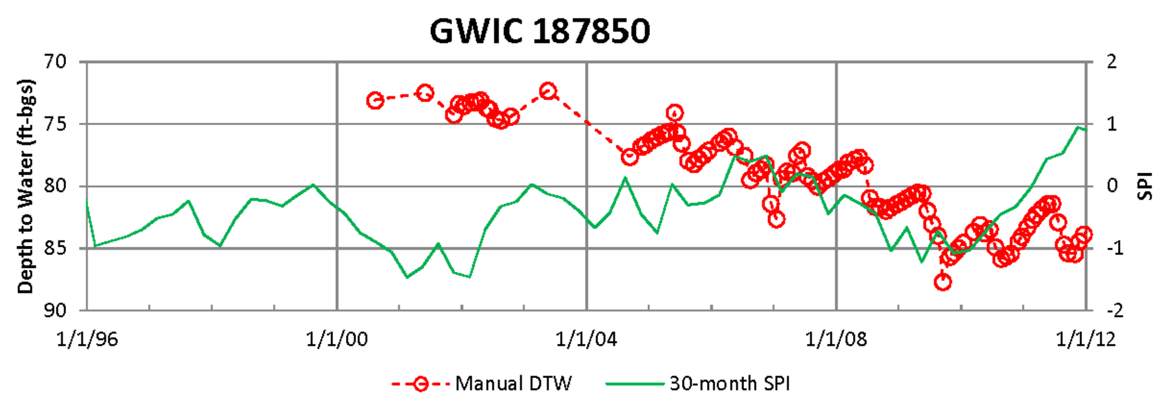

GWIC 211387
Depth to Water (ft-bgs)
74
76
78
80
82
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
Recorder/Transducer DTW
30-month SPI

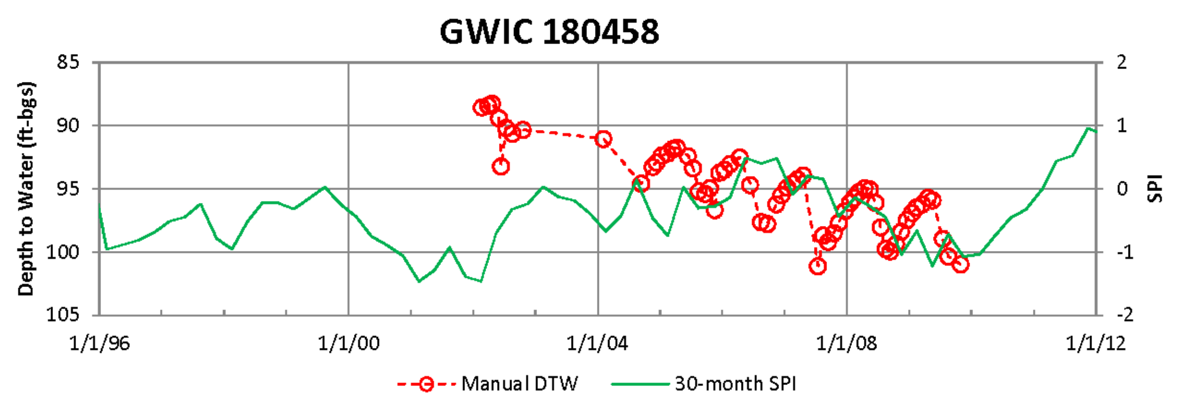

GWIC 206393
Depth to Water (ft-bgs)
30
35
40
45
50
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

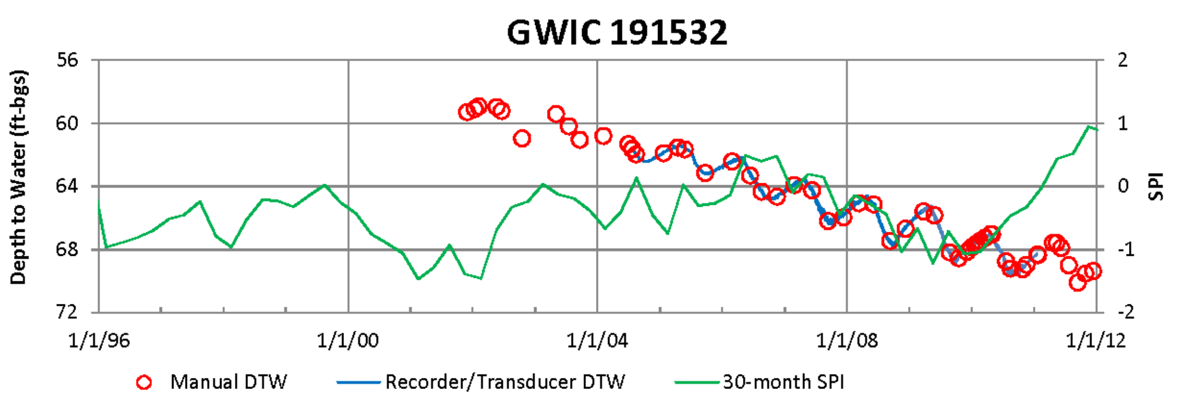

GWIC 64686
Depth to Water (ft-bgs)
59
61
63
65
67
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

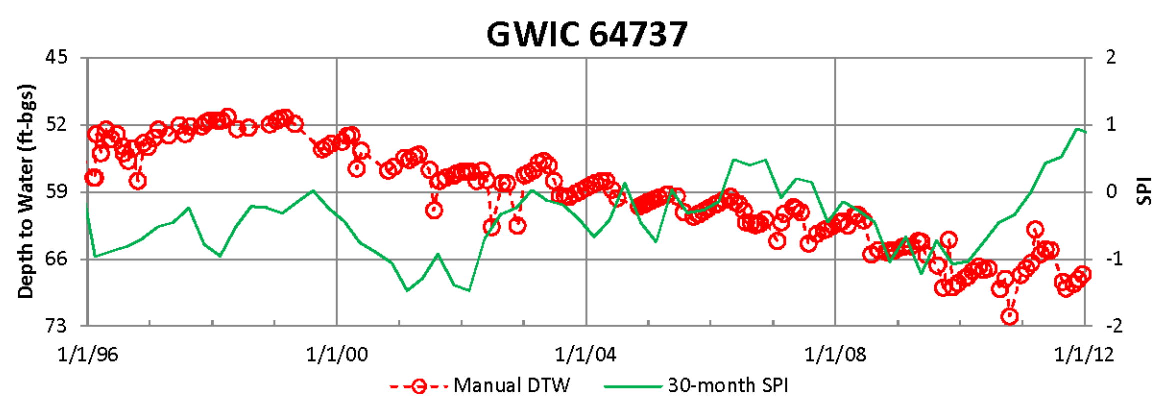

GWIC 143645
Depth to Water (ft-bgs)
97
103
109
115
121
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

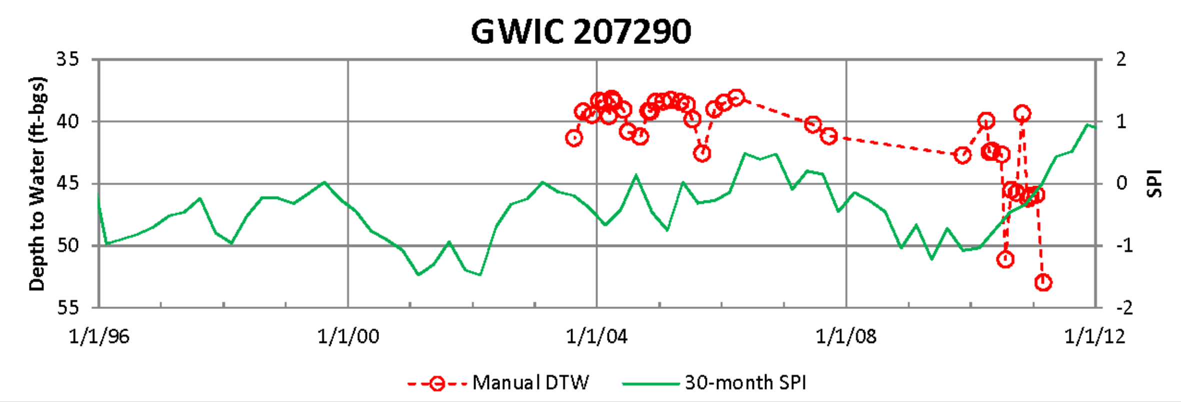

GWIC 206394
Depth to Water (ft-bgs)
111
118
125
132
139
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

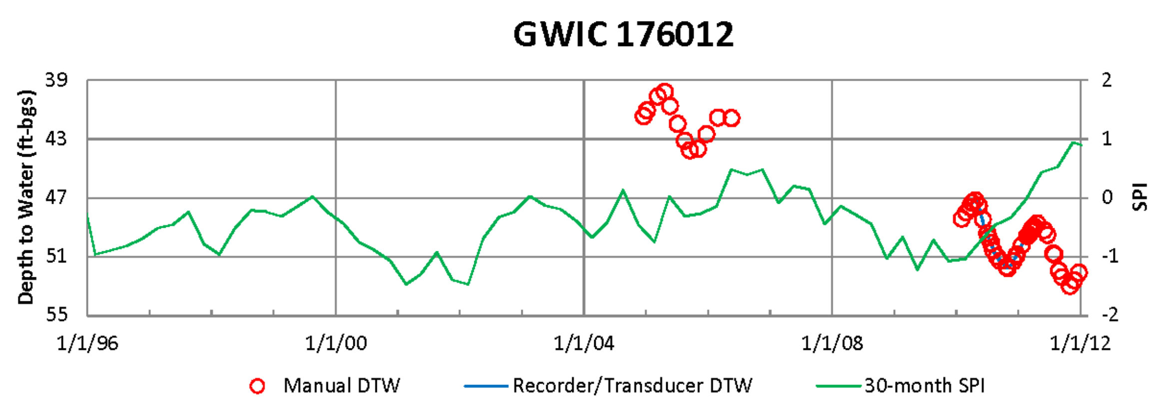

GWIC 187850
Depth to Water (ft-bgs)
70
75
80
85
90
2
1
0
-1
-2
SPI
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

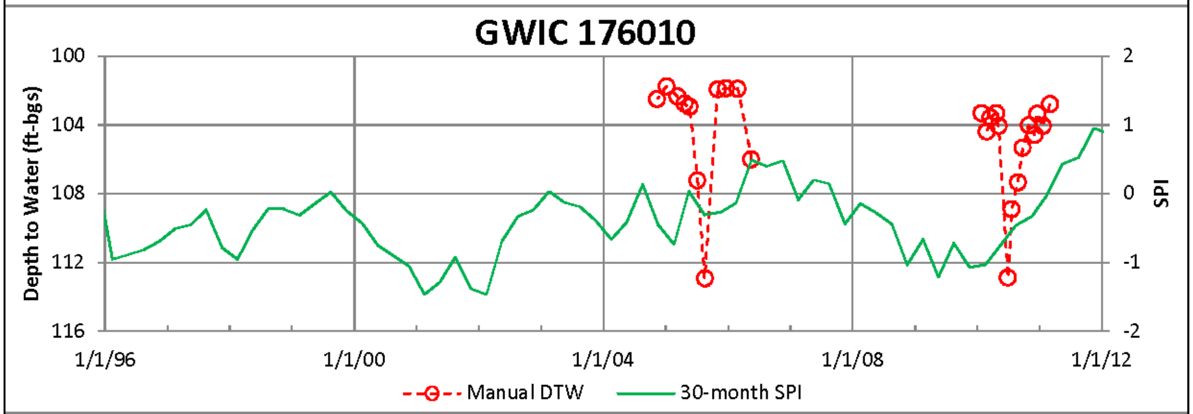

GWIC 180458
Depth to Water (ft-bgs)
85
90
95
100
105
2
1
0
-1
-2
SPI
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

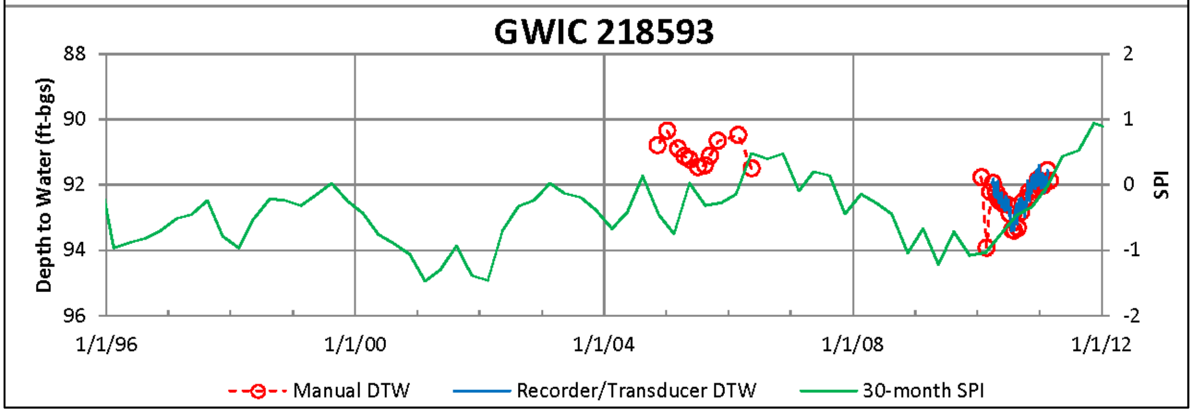

GWIC 191532
Depth to Water (ft-bgs)
56
60
64
68
72
2
1
0
-1
-2
SPI
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
Recorder/Transducer DTW
30-month SPI

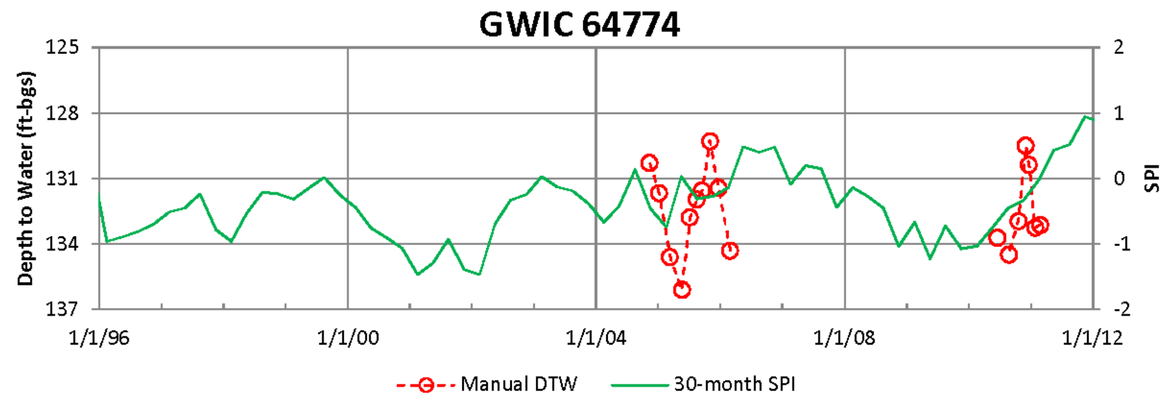

GWIC 64737
Depth to Water (ft-bgs)
45
52
59
66
73
2
1
0
-1
-2
SPI
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

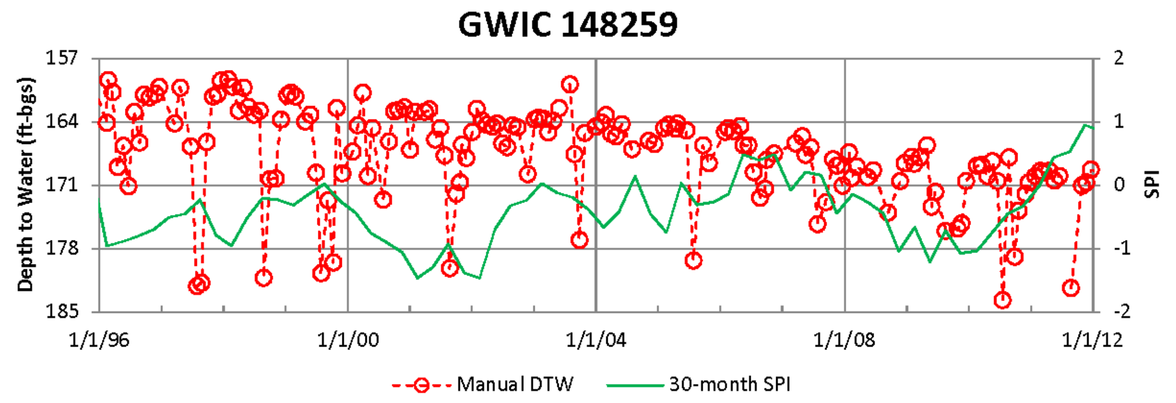

GWIC 207290

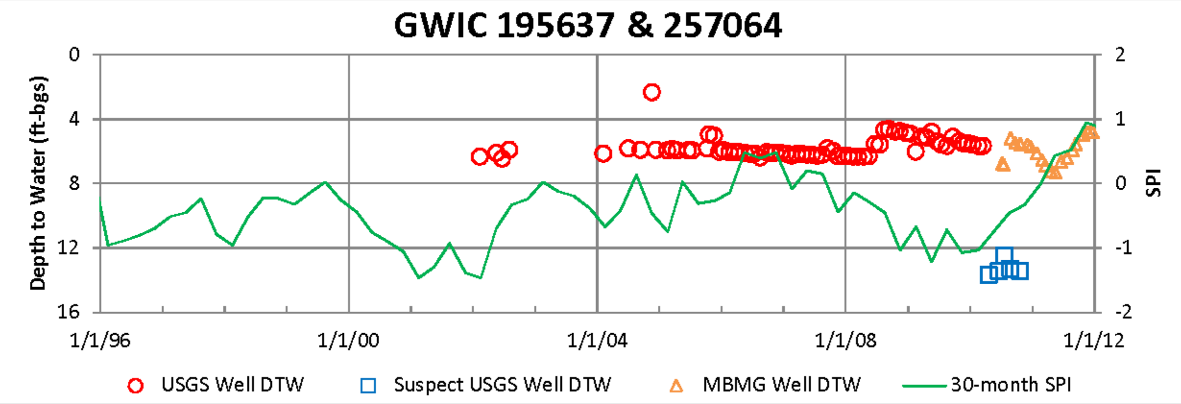

GWIC 176012

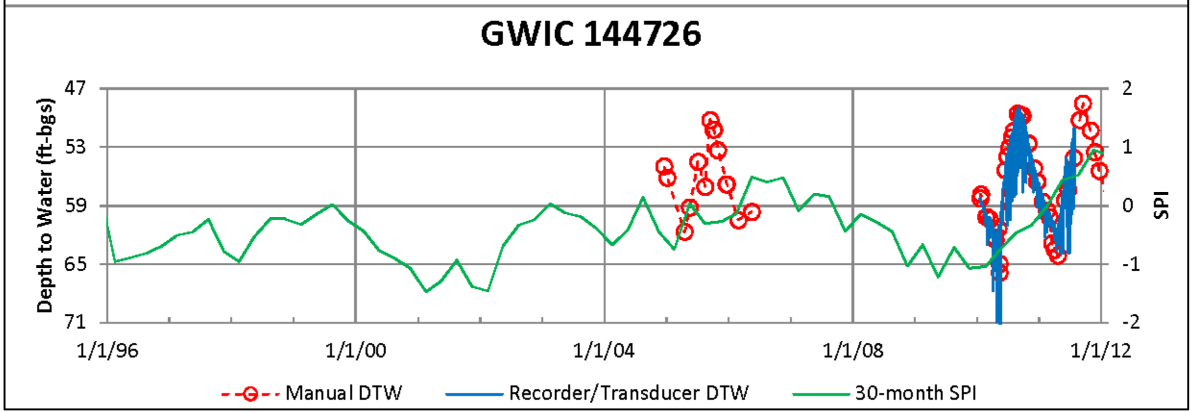

GWIC 176010

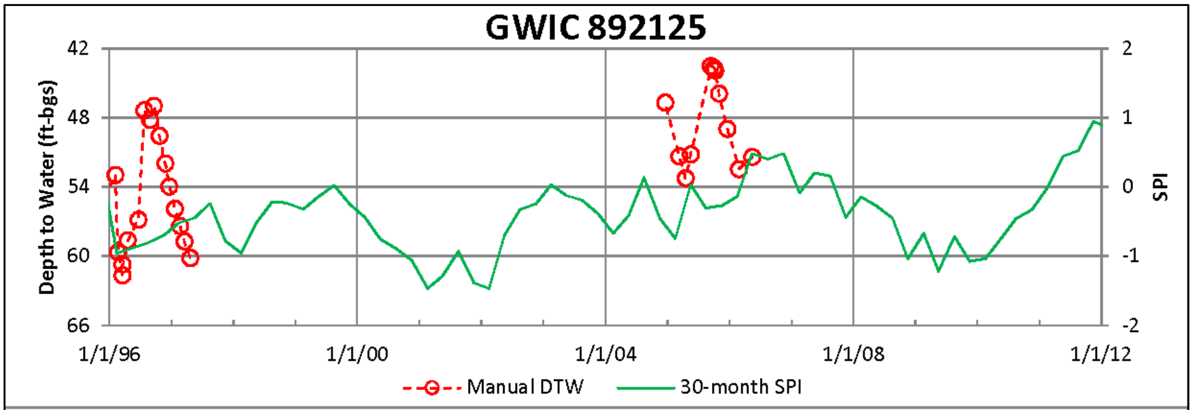

GWIC 218593

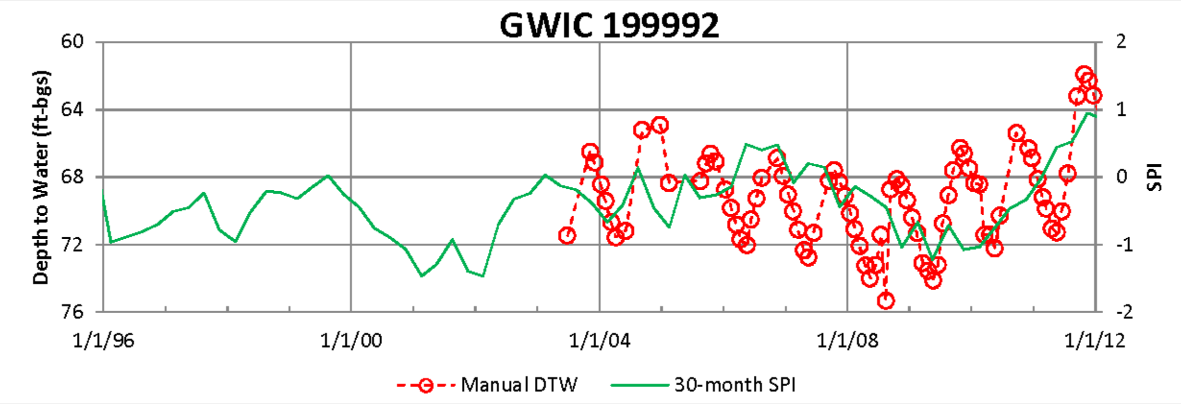

GWIC 64774

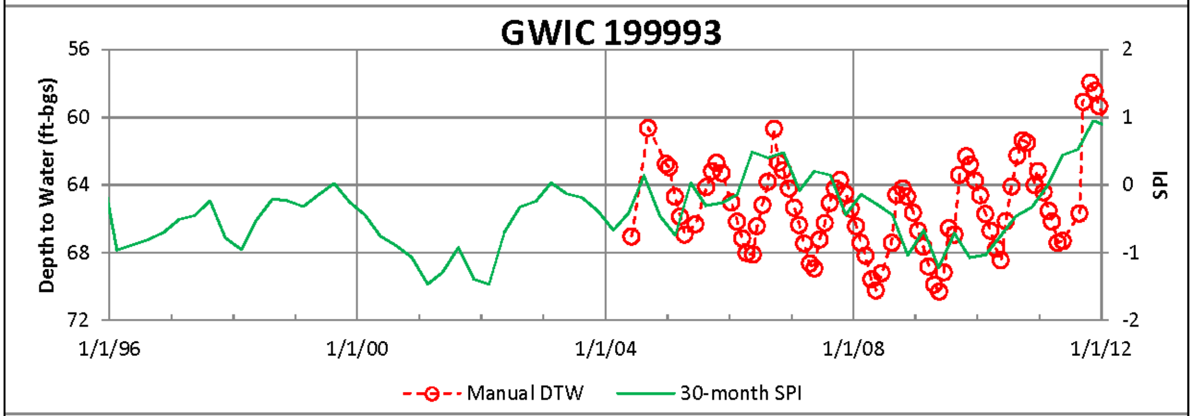

GWIC 148259

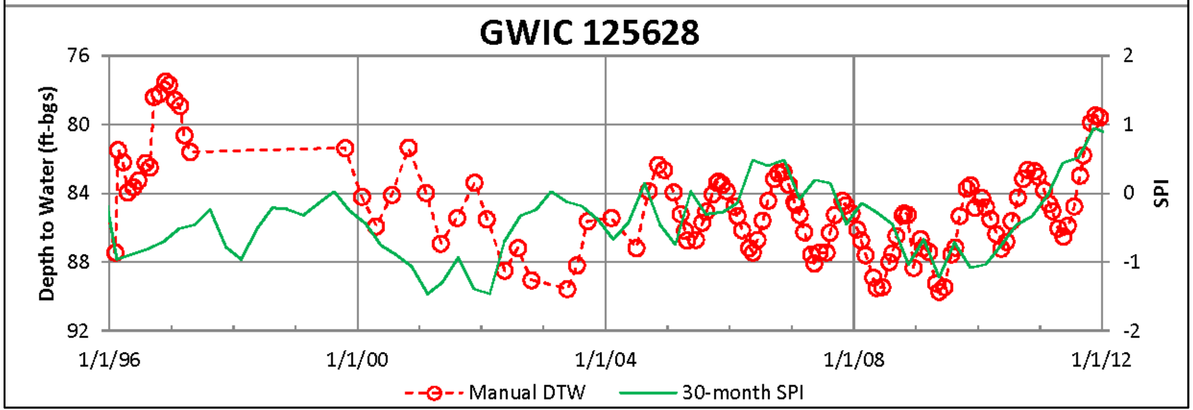

GWIC 195637 & 257064

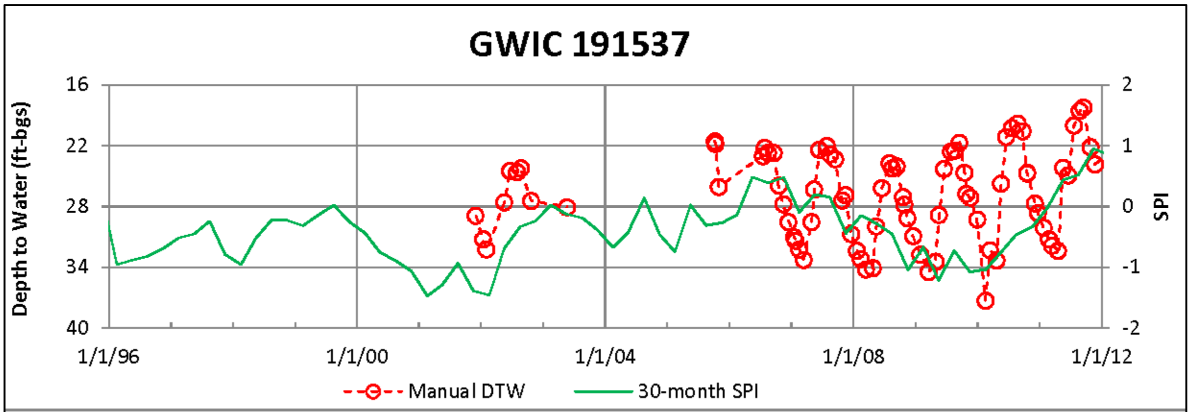

GWIC 144726

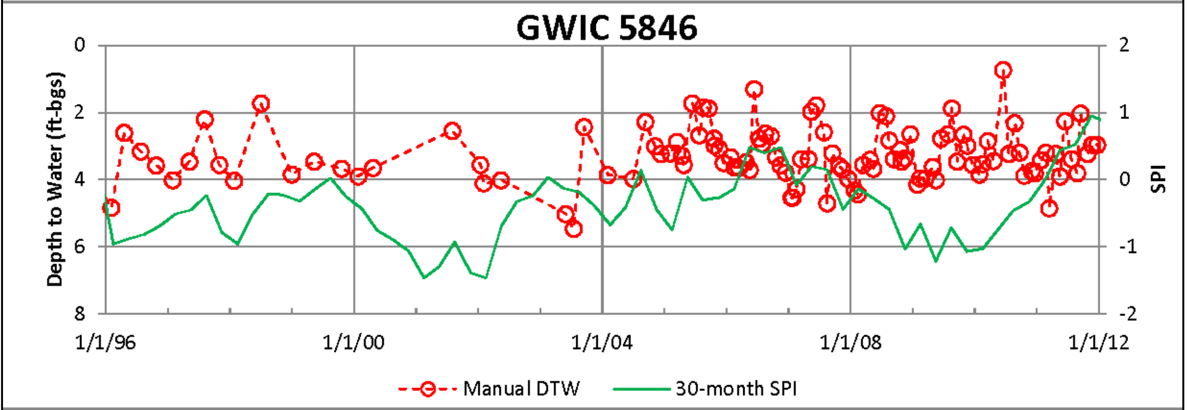

GWIC 892125

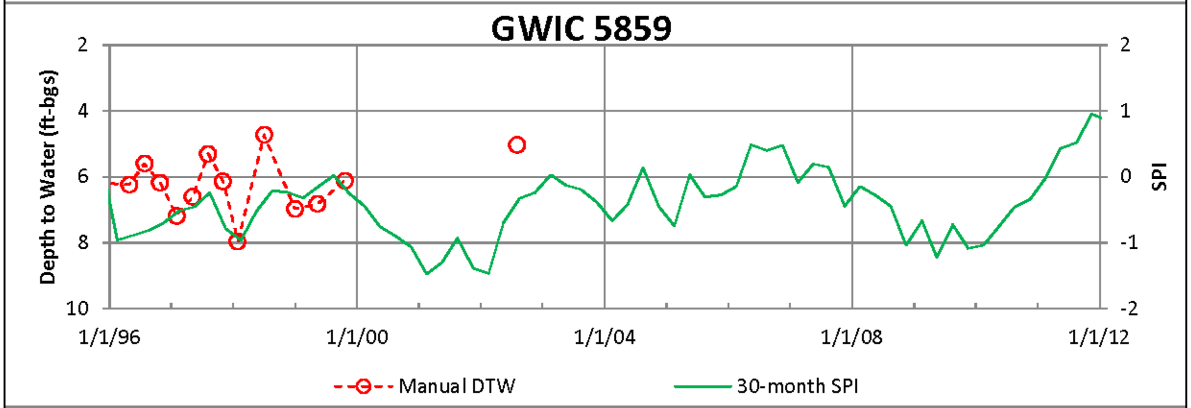

GWIC 199992

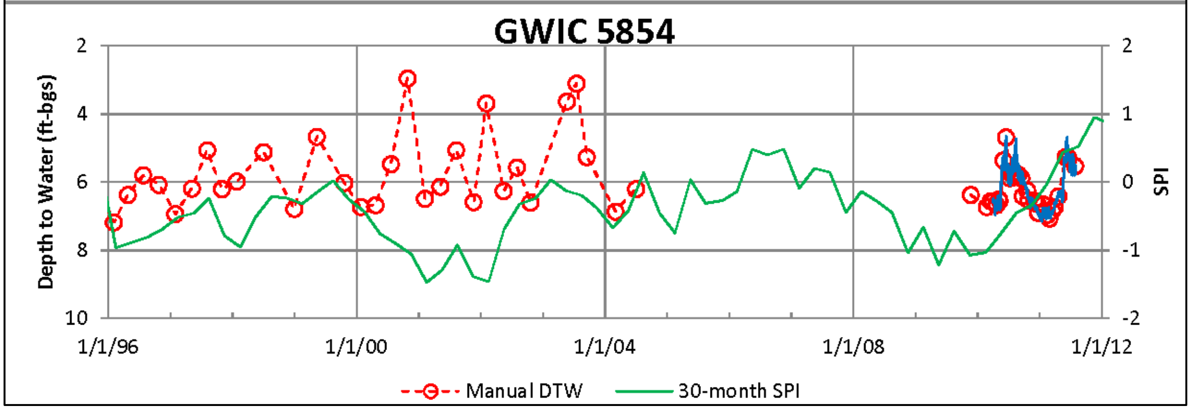

GWIC 199993

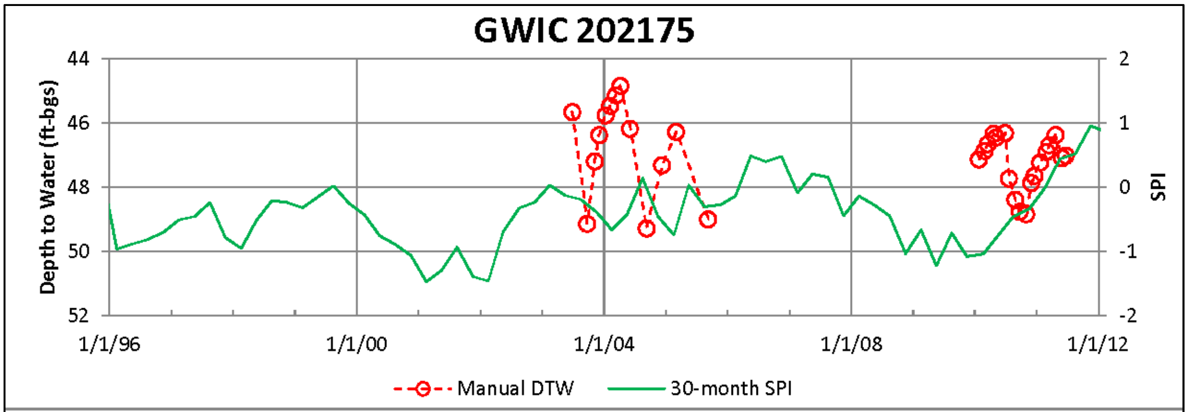

GWIC 125628

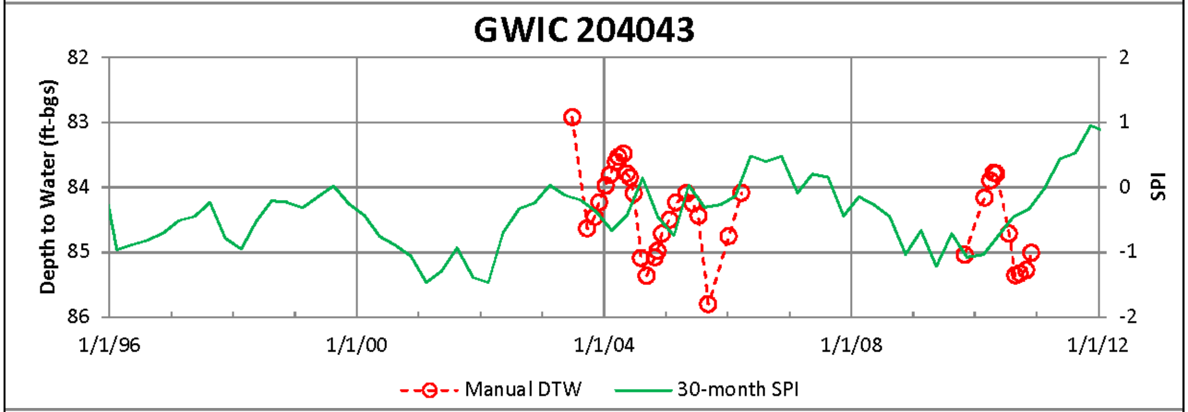

GWIC 191537
Depth to Water (ft-bgs)
16
22
28
34
40
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

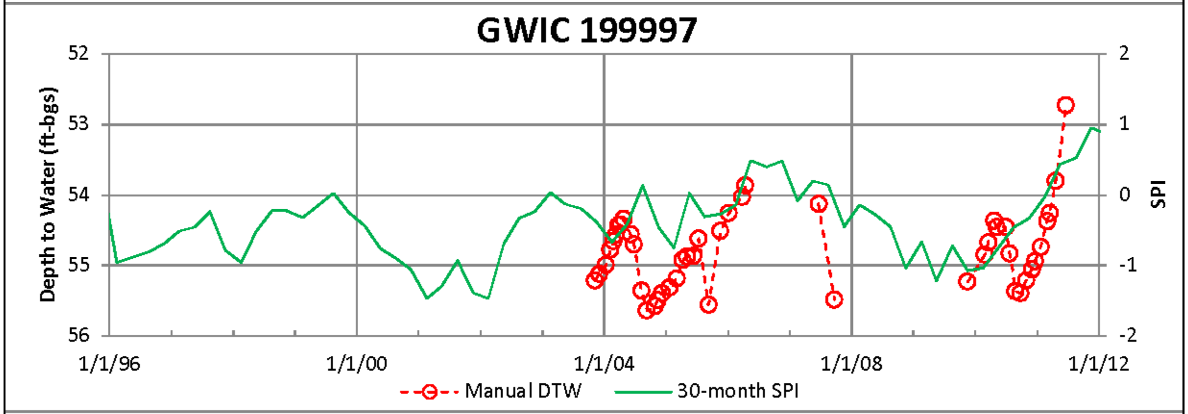

GWIC 5846
Depth to Water (ft-bgs)
0
2
4
6
8
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

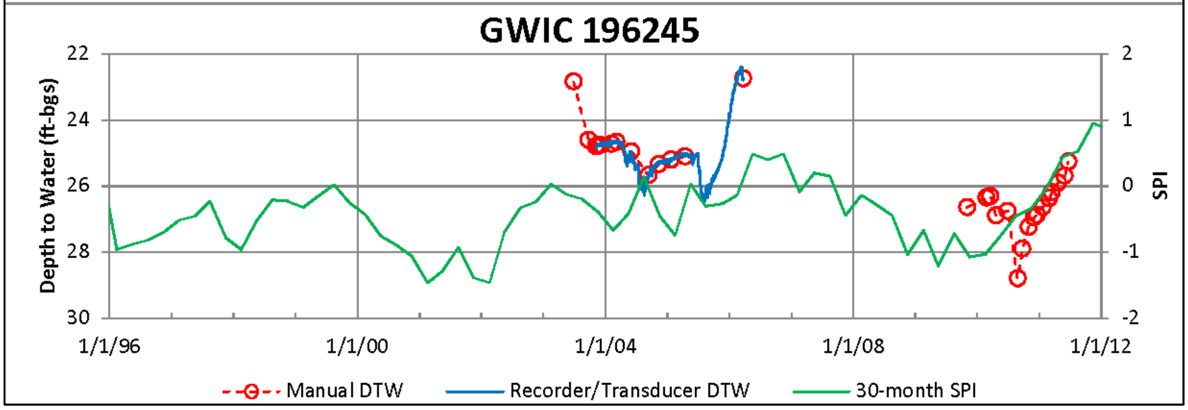

GWIC 5859
Depth to Water (ft-bgs)
2
4
6
8
10
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

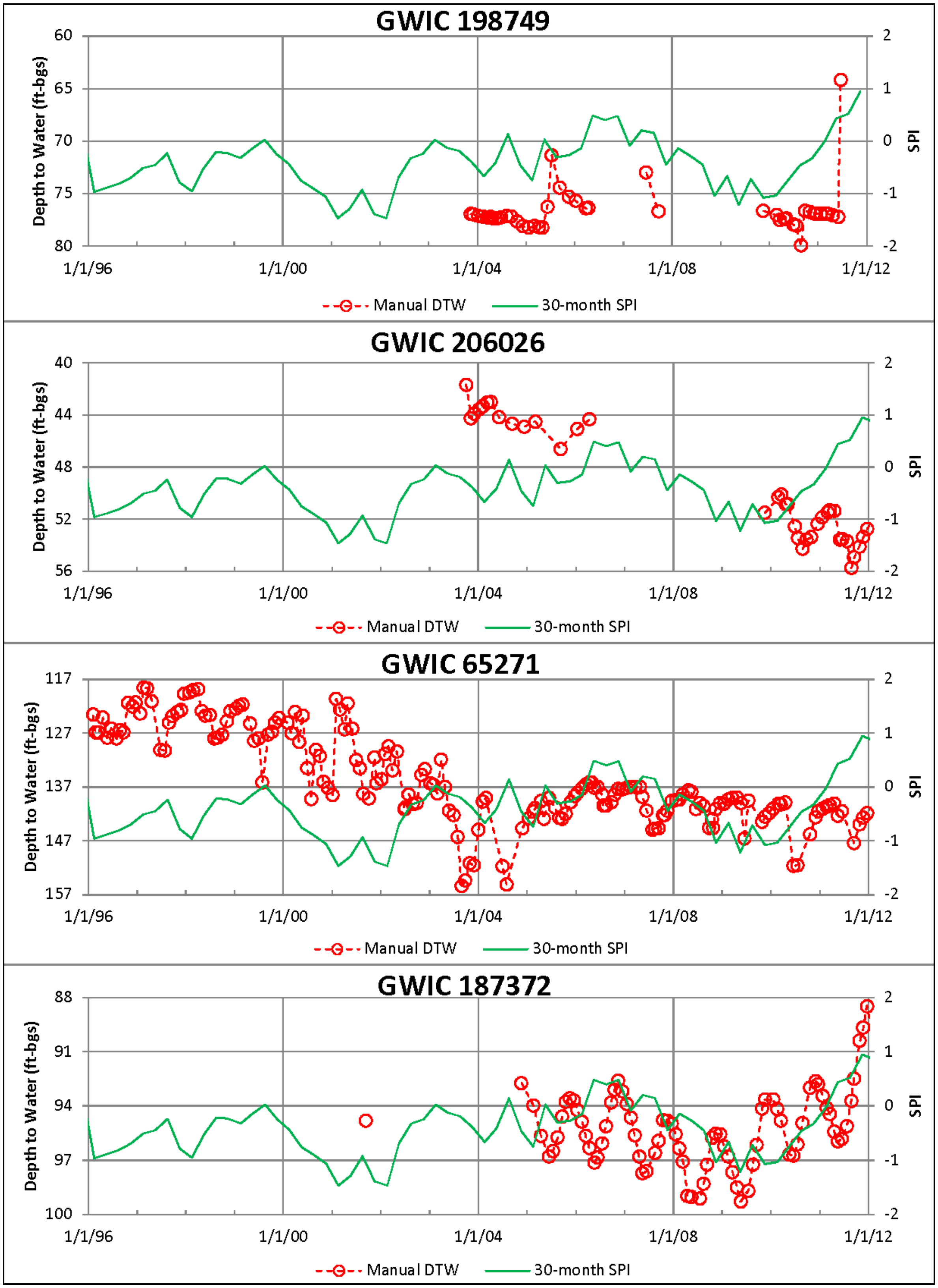

GWIC 5854
Depth to Water (ft-bgs)
2
4
6
8
10
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

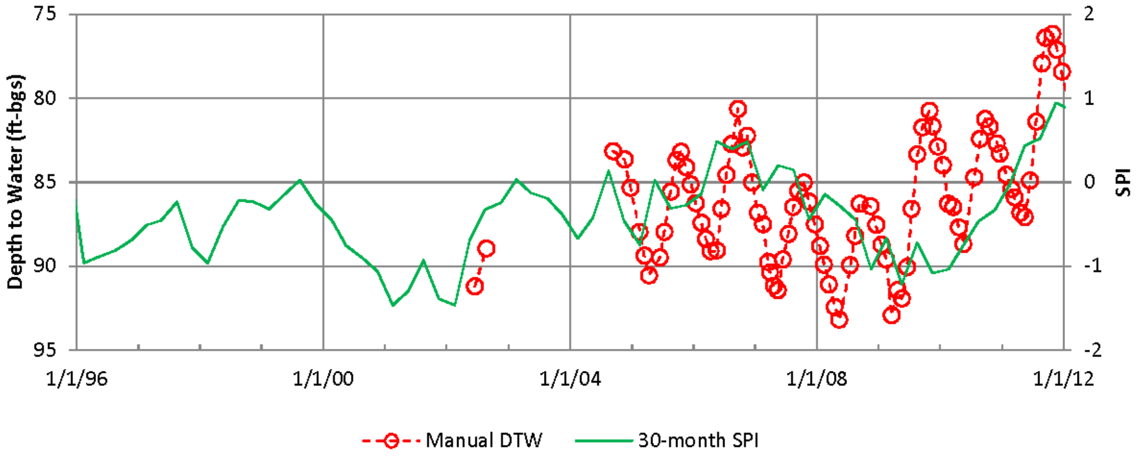

GWIC 202175
Depth to Water (ft-bgs)
44
46
48
50
52
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI


GWIC 204043
Depth to Water (ft-bgs)
82
83
84
85
86
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI

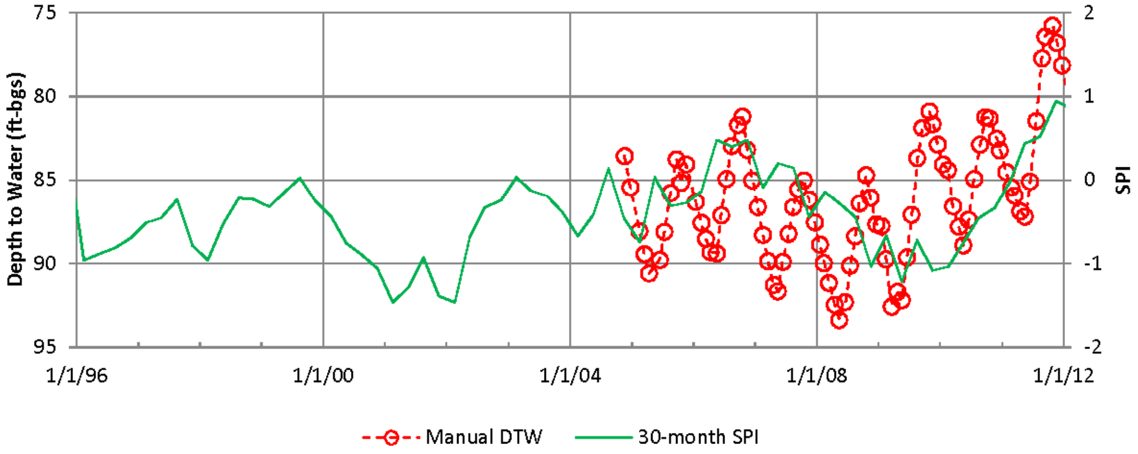

GWIC 199997
Depth to Water (ft-bgs)
52
53
54
55
56
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI


GWIC 196245
Depth to Water (ft-bgs)
22
24
26
28
30
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
Recorder/Transducer DTW
30-month SPI

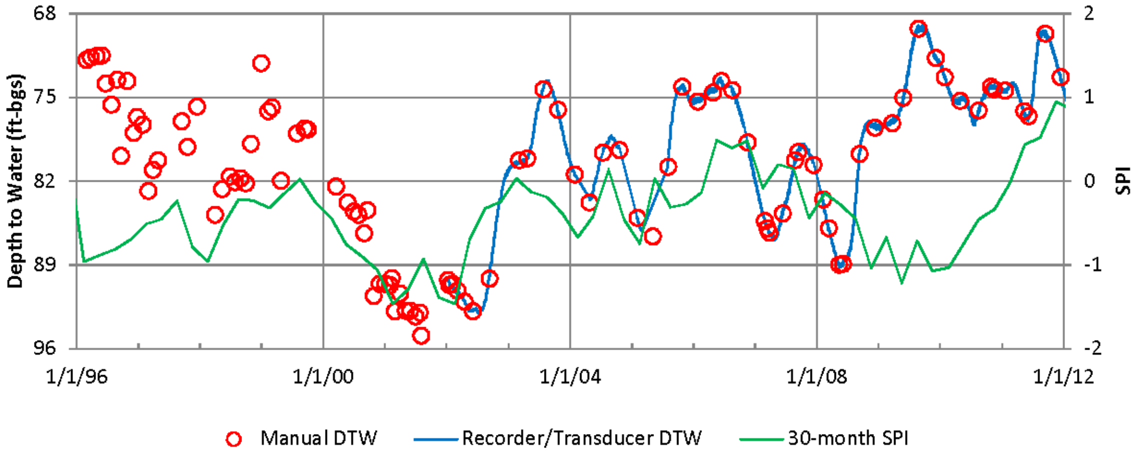

GWIC 198749
Depth to Water (ft-bgs)
60
65
70
75
80
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI
GWIC 206026
Depth to Water (ft-bgs)
40
44
48
52
56
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI
GWIC 65271
Depth to Water (ft-bgs)
117
127
137
147
157
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI
GWIC 187372
Depth to Water (ft-bgs)
88
91
94
97
100
SPI
2
1
0
-1
-2
1/1/96
1/1/00
1/1/04
1/1/08
1/1/12
Manual DTW
30-month SPI



GWIC 189417



GWIC 65422



GWIC 65432

POTENTIOMETRIC SURFACE MAPS

A potentiometric surface is an imaginary surface representing the total head of groundwater, and is defined at any point on the surface as the height at which water will stabilize in a well. A potentiometric surface map shows this surface as a contour map. Flow lines run perpendicular to potentiometric contours (Fetter, 1994, p. 114–115).

For the North Hills project, potentiometric surface maps were developed for selected months. For most of the monthly data sets, the potentiometric contours were drawn using interpolation software, and were not further refined (referred to as raw contours on the following maps). For October 2010 (the first event for which all monitoring wells were available), the raw contours were further refined, based on topography, surface-water features, data from outside the study area, and previous work.

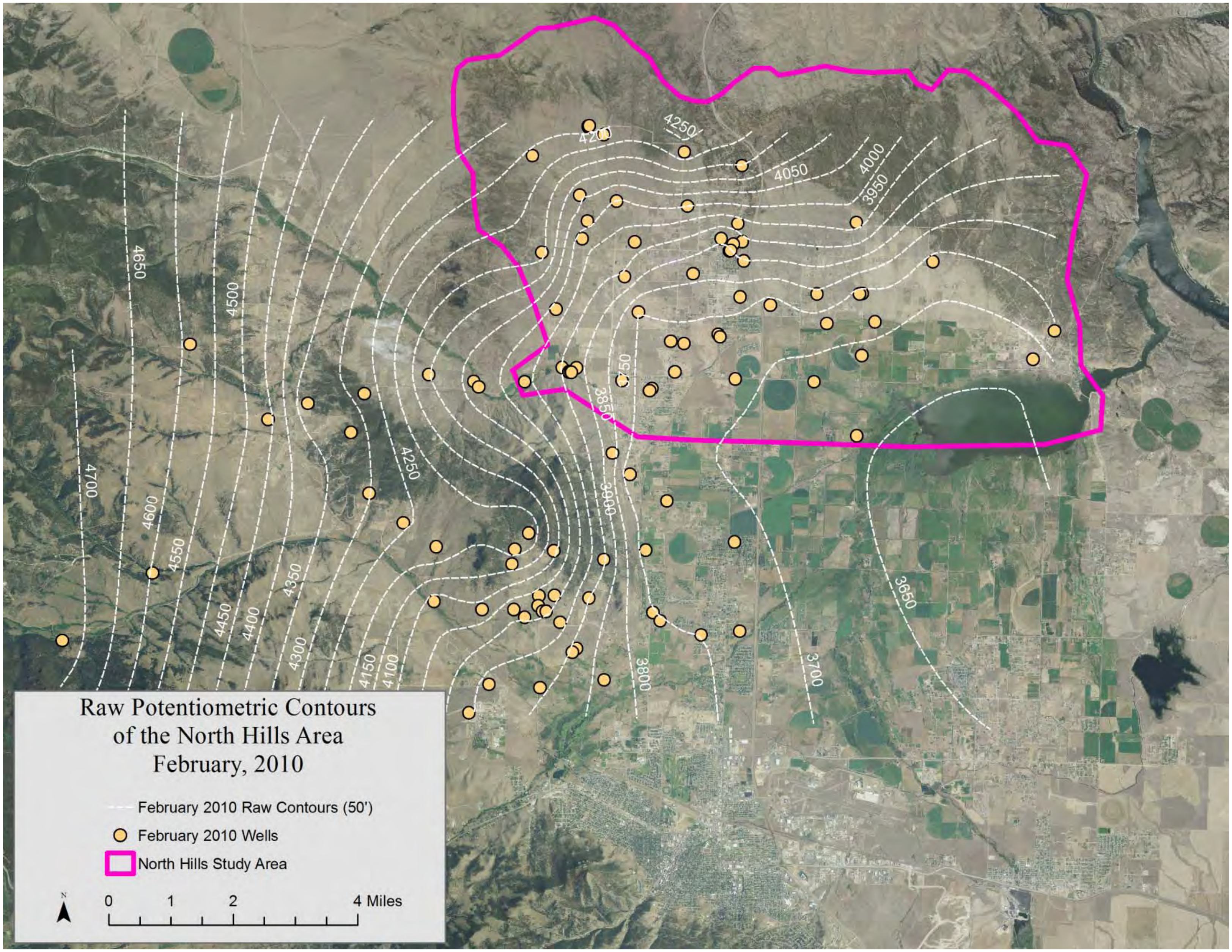
Comparison of the contour maps shows that there is little variation in the overall shape of the potentiometric surface by season. The shape of the current surface is comparable to previous potentiometric surface maps in areas where the new maps overlap historic maps (Lorenz and Swenson, 1951; Briar and Madison, 1992).

The potentiometric surface in the study area is generally a subdued reflection of the topography. Groundwater-level altitudes are high at upland locations. Upland locations receive more precipitation and fractured bedrock is at the surface or under a thin layer of soil, so most groundwater recharge occurs in these areas. The bedrock underlying upland areas also has a low permeability (modeled as <6.4 ft/d based on aquifer tests, flow barriers, and observed water levels), which limits the flow of groundwater. All of the flow in the North Hills is towards Lake Helena.

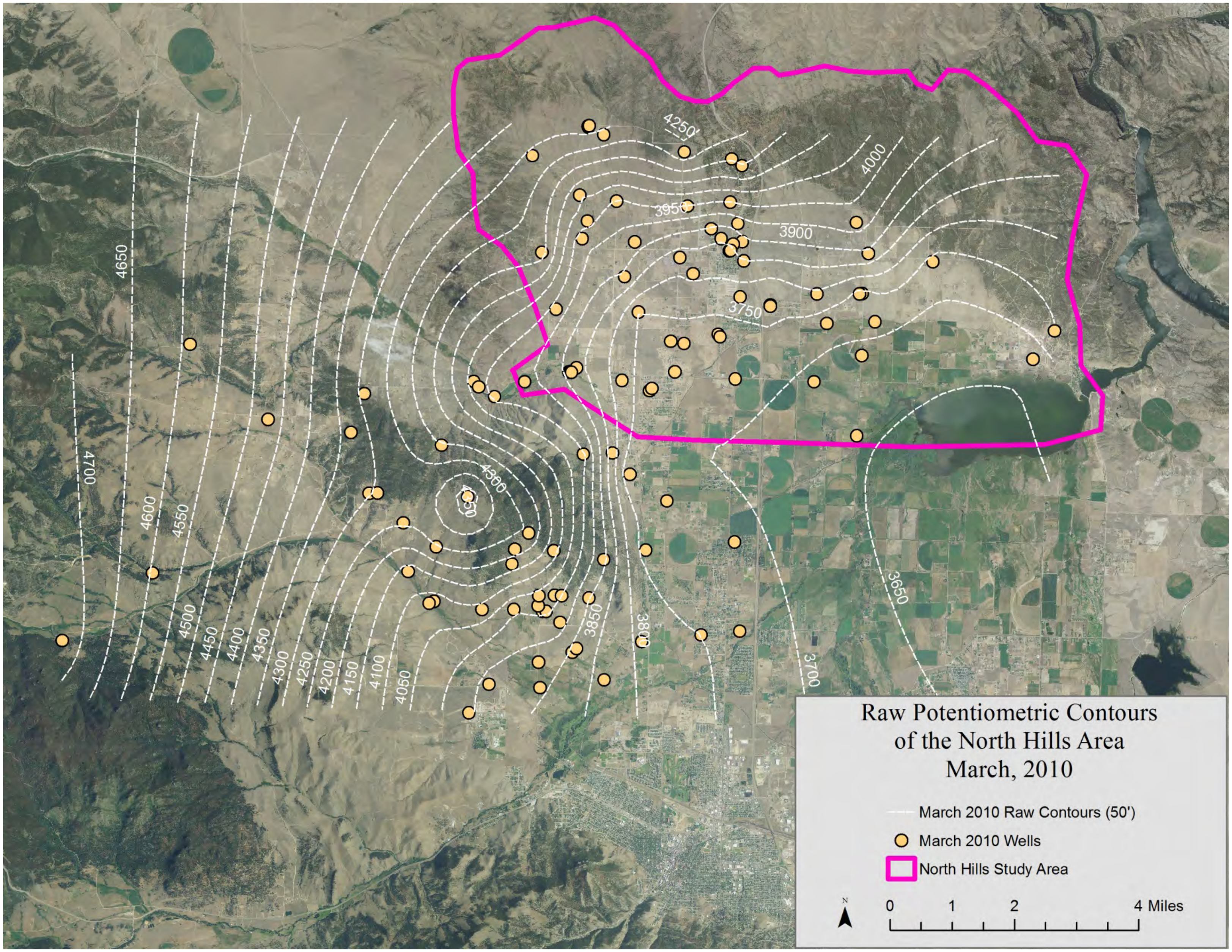
Briar, D.W., and Madison, J.P., 1992, Hydrogeology of the Helena valley-fill aquifer system, west-central Montana: U.S. Geological Survey Water Resources Investigations Report 92-4023, 92 p.

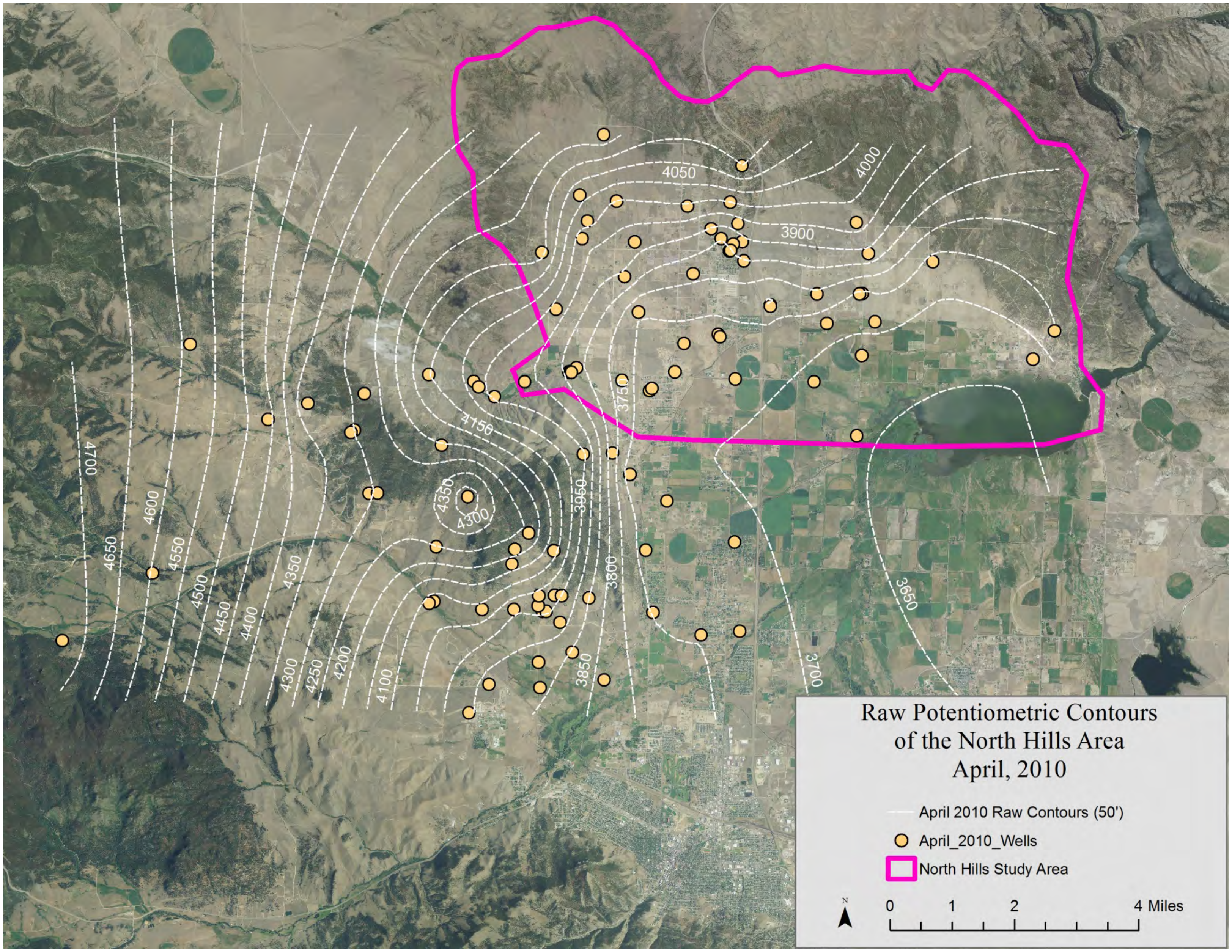
Fetter, C.W., 1994, Applied hydrogeology (3d ed.): New York, N.Y., MacMillan College Publishing, 691 p.

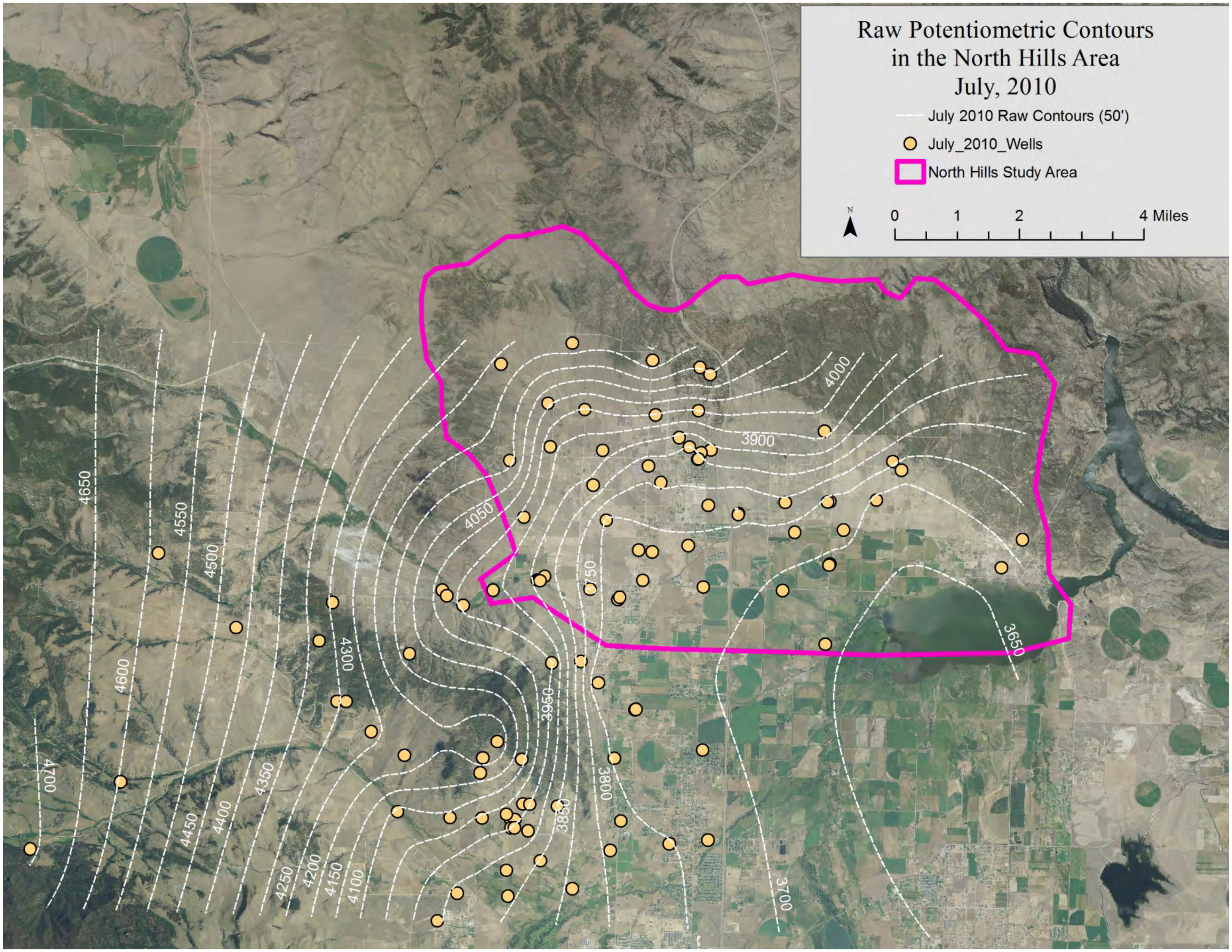
Lorenz, H.W., and Swenson, F.A., 1951, Geology and ground-water resources of the Helena Valley, Montana, with a section on the chemical quality of the water by H.A. Swenson: U.S. Geological Survey Circular 83, 68 p.

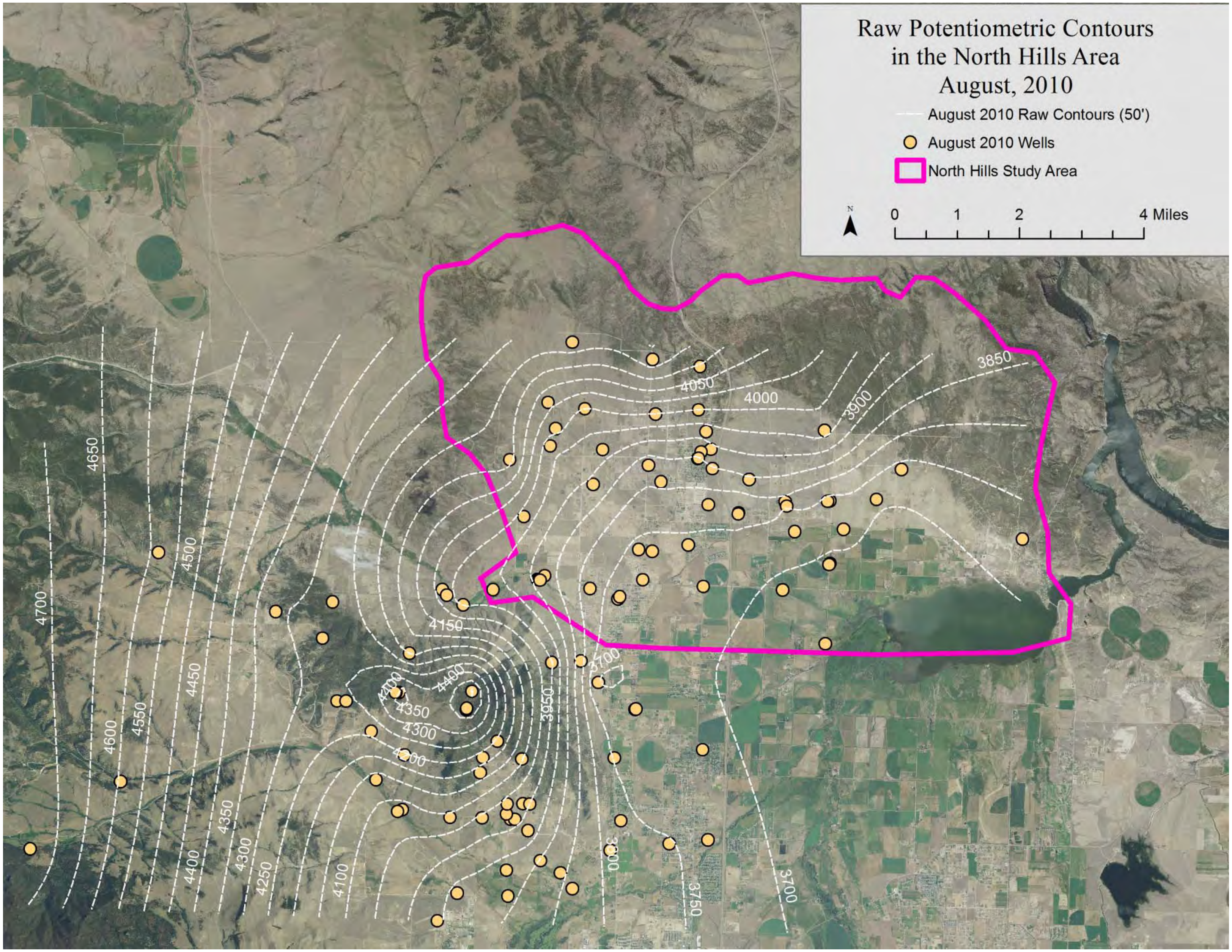


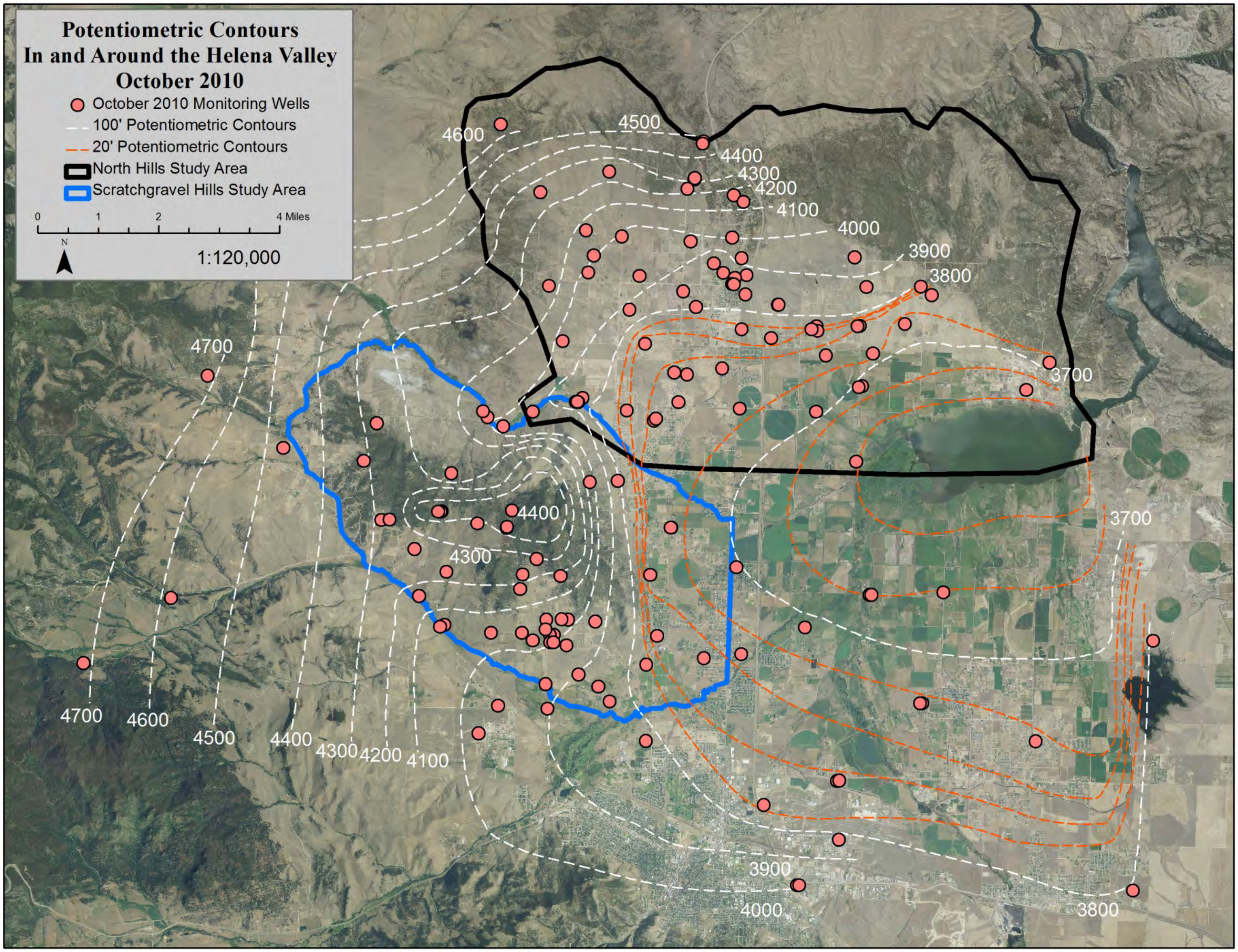
Raw Potentiometric Contours of the North Hills Area February, 2010

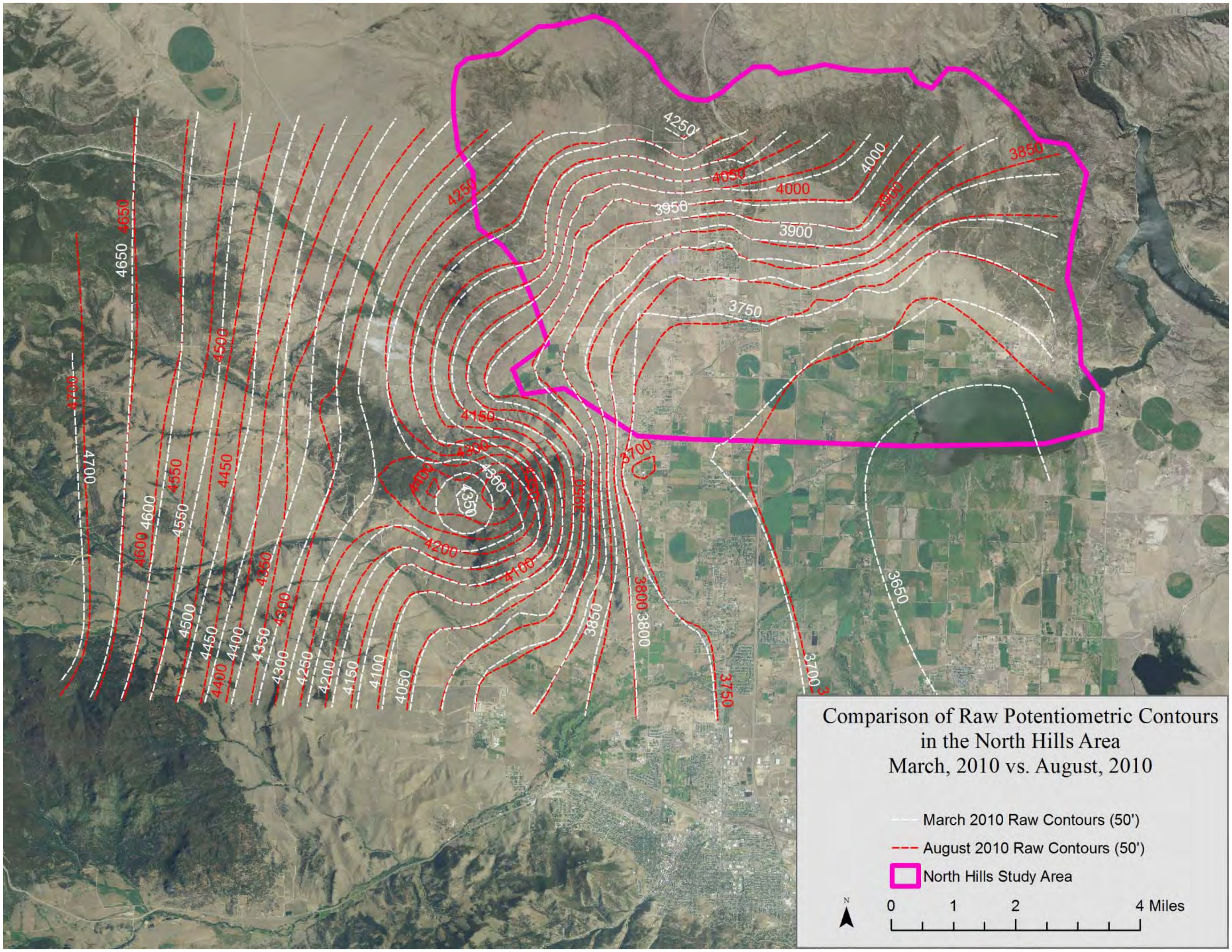

Raw Potentiometric Contours
of the North Hills Area
March, 2010
March 2010 Raw Contours (50')
March 2010 Wells
North Hills Study Area
N
0
1
2
4 Miles
4250'
4000
3950
3900
3750
4650
4700
4600
4550
4300
4350
3850
3800
3700
3650
4500
4450
4400
4350
4300
4250
4200
4150
4100
4050


Raw Potentiometric Contours
of the North Hills Area
April, 2010
April 2010 Raw Contours (50')
● April_2010_Wells
▭ North Hills Study Area
N
0
1
2
4 Miles
4050
4000
3900
3750
4150
4350
4300
3950
3800
3850
3700
3650
4700
4600
4650
4550
4500
4450
4400
4350
4300
4250
4200
4100

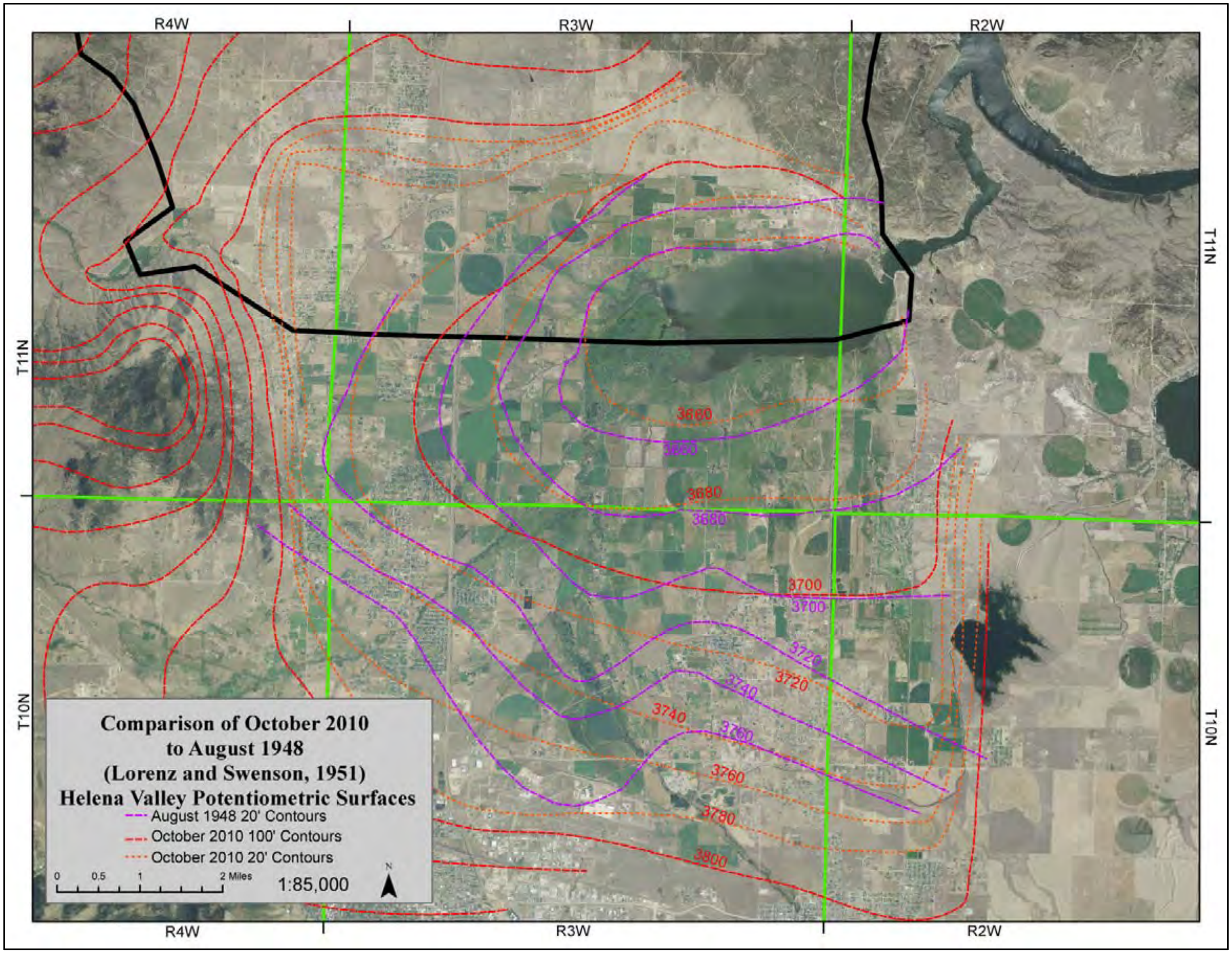

Raw Potentiometric Contours
in the North Hills Area
July, 2010
July 2010 Raw Contours (50')
July_2010_Wells
North Hills Study Area
N
0
1
2
4 Miles
4700
4650
4600
4550
4500
4450
4400
4350
4300
4250
4200
4150
4100
4050
4000
3950
3900
3850
3800
3750
3700
3650

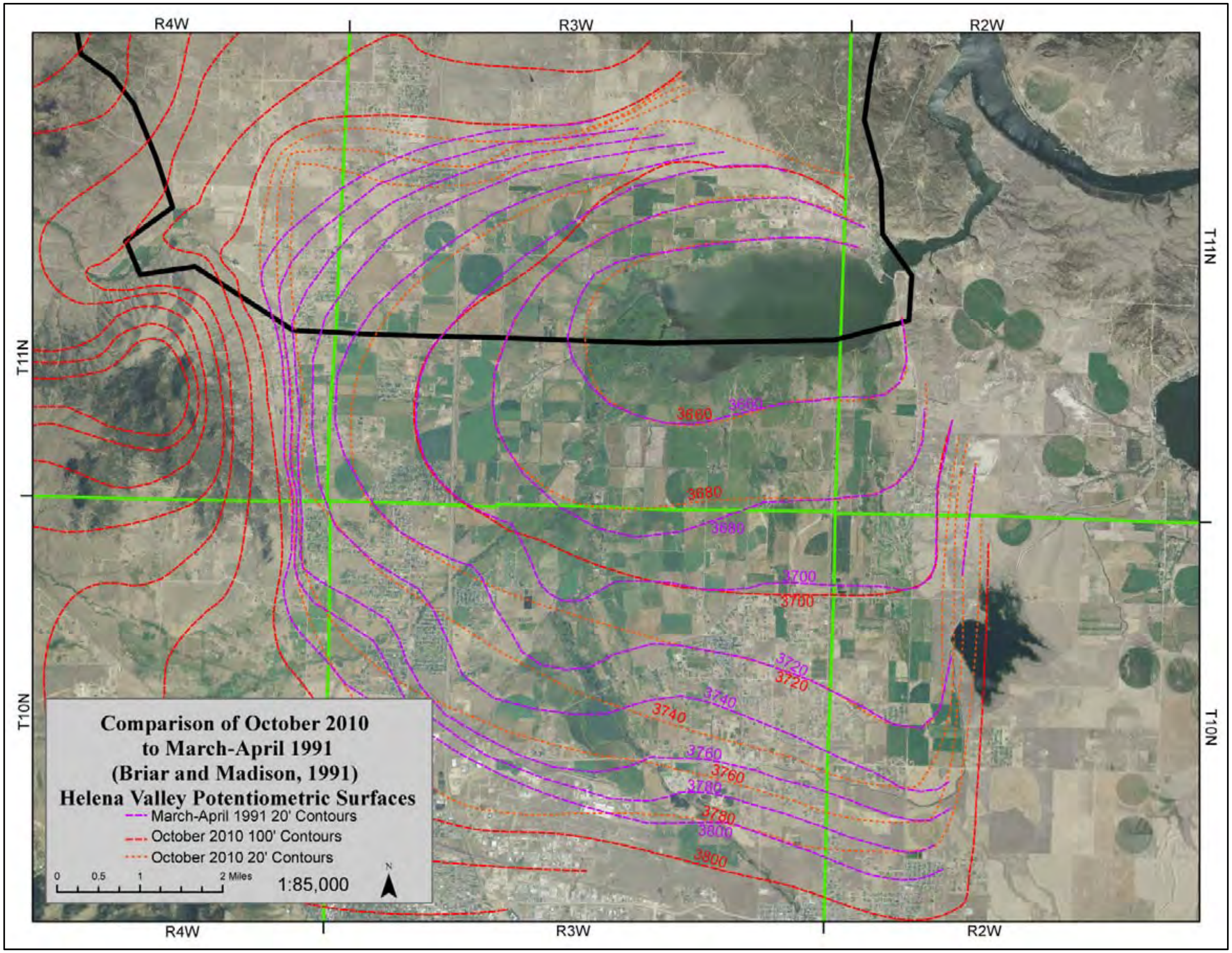

Raw Potentiometric Contours
in the North Hills Area
August, 2010
August 2010 Raw Contours (50')
August 2010 Wells
North Hills Study Area
N
0
1
2
4 Miles
4700
4650
4600
4550
4500
4450
4400
4350
4300
4250
4100
4150
4400
4400
4350
4300
4200
3950
3700
3800
3750
3700
4050
4000
3900
3850


Potentiometric Contours
In and Around the Helena Valley
October 2010
● October 2010 Monitoring Wells
100' Potentiometric Contours
20' Potentiometric Contours
North Hills Study Area
Scratchgravel Hills Study Area
0
1
2
4 Miles
N
1:120,000
4600
4500
4400
4300
4200
4100
4000
3900
3800
3700
4700
4400
4300
3700
4700
4600
4500
4400
4300
4200
4100
3900
4000
3800



Comparison of Raw Potentiometric Contours in the North Hills Area March, 2010 vs. August, 2010


R4W
R3W
R2W
T11N
T11N
T10N
T10N
3660
3660
3680
3680
3700
3700
3720
3720
3740
3740
3760
3760
3780
3800
Comparison of October 2010
to August 1948
(Lorenz and Swenson, 1951)
Helena Valley Potentiometric Surfaces
August 1948 20' Contours
October 2010 100' Contours
October 2010 20' Contours
0
0.5
1
2 Miles
1:85,000
N
R4W
R3W
R2W


R4W
R3W
R2W
T11N
T10N
3660
3680
3700
3720
3740
3760
3780
3800
Comparison of October 2010
to March-April 1991
(Briar and Madison, 1991)
Helena Valley Potentiometric Surfaces
March-April 1991 20' Contours
October 2010 100' Contours
October 2010 20' Contours
0 0.5 1 2 Miles
1:85,000
N

GROUNDWATER/SURFACE-WATER INTERACTIONS

The direction water flows between surface-water bodies and groundwater at any time is determined by the relative elevations of the surface water-body surface and the unconfined groundwater table at that time (Winter and others, 1998; Rosenberry and others, 2008). The timing of water-level changes can also be used qualitatively to assess how direct the connection is. Comparison of groundwater and surface-water temperature changes (e.g., diurnal variations) can also be used to assess the direction and magnitude of flow (Constantz and others, 2008). The overall change in streamflow can also indicate gains or losses; however, knowledge of all flow into or out of the stream between the measurement locations (e.g., tributary inputs or irrigation withdrawals) is needed for this technique to be used quantitatively.

For this study four wells were installed at three sites along Silver Creek (southwest portion of the study area; map below). These wells were completed in permeable zones near the top of the saturated zone. Groundwater levels and temperatures were continuously recorded at the wells. Stage and temperature were continuously recorded in the streams. GWIC IDs for the sites are included in the table below.

All three sites on Silver Creek showed that stream surface elevations were typically higher than groundwater elevations; however, at the upstream and downstream sites groundwater and surface-water elevations were similar during the spring of 2011, which was a particularly high-flow period. These water levels indicate that except for during extended flood events, the stream loses to the underlying groundwater. During floods, the available storage in the aquifer becomes fully saturated and there is little flux between surface and groundwater. The generally losing nature of this stream is qualitatively supported by comparison of flows at the three sites, which shows that flow generally diminished downstream (the observations were complicated due to irrigation activities). The general water-level change pattern was also closely related at all three sites. At the most downstream site, variations in groundwater levels caused by changes in stream stage were observed in wells with depths of up to 465 ft.

At all three of these sites, noticeable diurnal variations in stream temperature were recorded; however, changes in groundwater temperature were muted. Given the clear difference in elevations, it appears that the wells were completed too far below the stream to provide a high-resolution thermal response to surface-water infiltration (i.e., the unsaturated zone is too thick and/or the wells were completed too far below the water table). It is notable that the shallow (12 ft deep) monitoring well at the lower site (SC-2) showed greater seasonal temperature variation and more short-term temperature variations than the deeper well (22 ft deep). Also, both shallow monitoring wells showed more temperature variation than the deep wells (97 and 465 ft deep).

Table GS-1. Scratchgravel Hills Surface-Water/Groundwater Evaluation Sites Data Sources

Site	Staff Gauge GWIC ID	Piezometer GWIC IDs	GWIC IDs for Nearby Water Wells
Silver Creek SC-1	254994	254216	—
Silver Creek SC-2	255001	254227, 254237	65316, 237167
Silver Creek SC-3	254993	254242	—

References

Constantz, J.E., Niswonger, R.G., and Stewart, A.E., 2008, Analysis of temperature gradients to determine stream exchanges with ground water, *in* Field techniques for estimating water fluxes between surface water and ground water, Rosenberry, D.O., and LaBaugh, J.W., eds.: USGS Techniques and Methods 4-D2, 128 p.

Rosenberry, D.O., LaBaugh, J.W., and Hunt, R.J., 2008, Use of monitoring wells, portable piezometers, and meters to quantify flow between surface water and ground water, *in* Field techniques for estimating water fluxes between surface water and ground water, Rosenberry, D.O., and LaBaugh, J.W., eds.: USGS Techniques and Methods 4-D2, 128 p.

Winter, T.C., Harvey, J.W., Franke, O.L., and Alley, W.M., 1998, Ground water and surface water, a single resource: U.S. Geological Survey Circular 1139, 79 p.

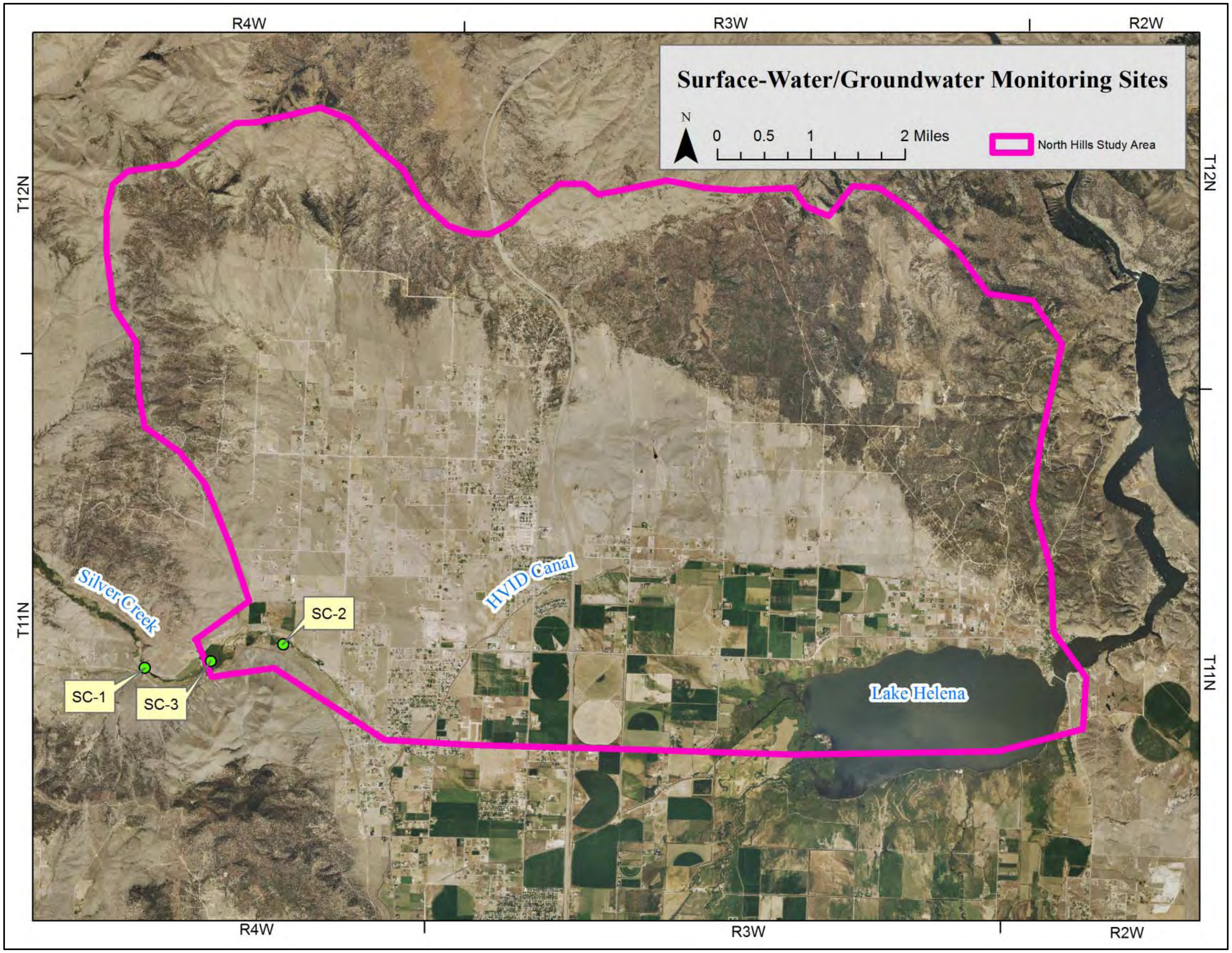
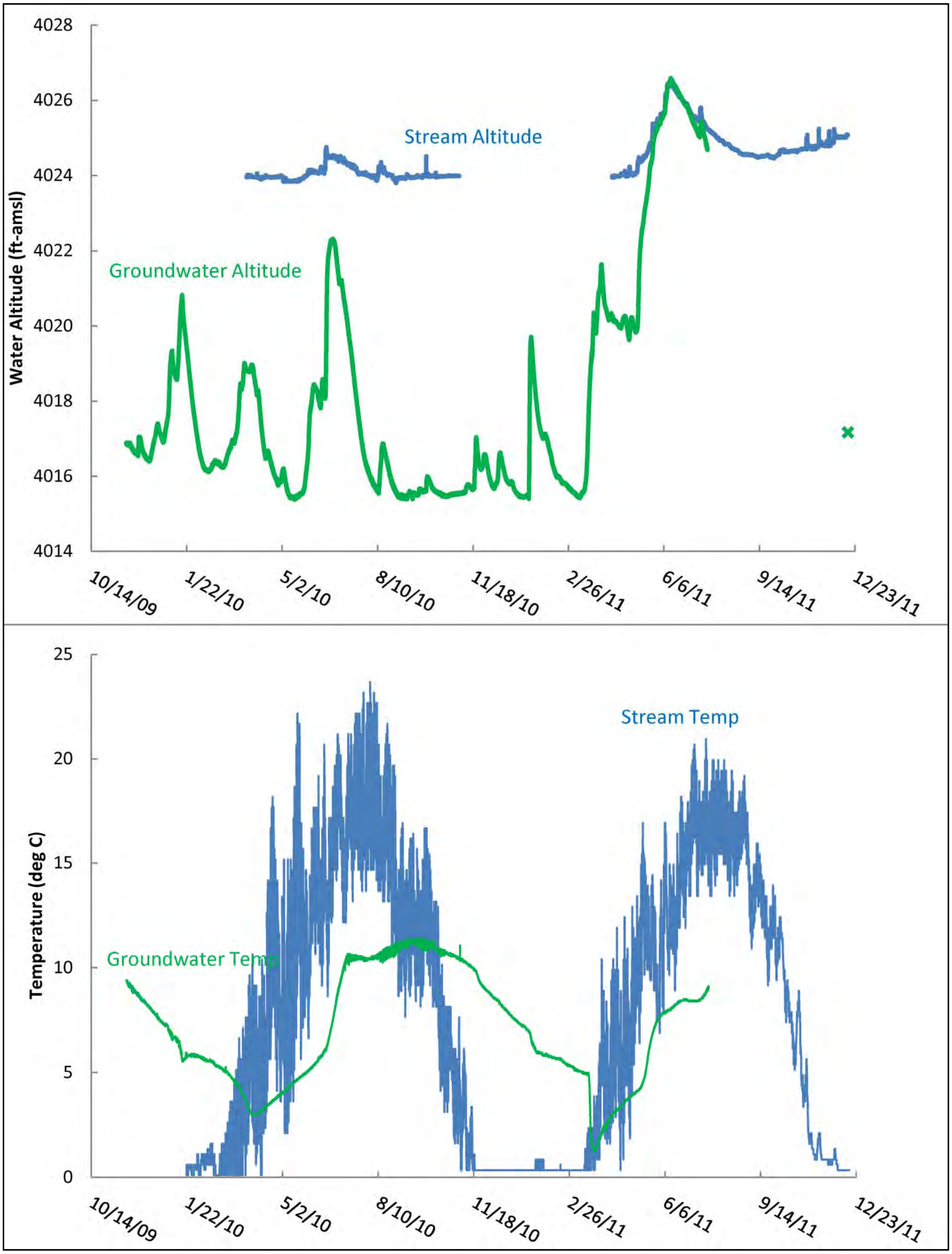
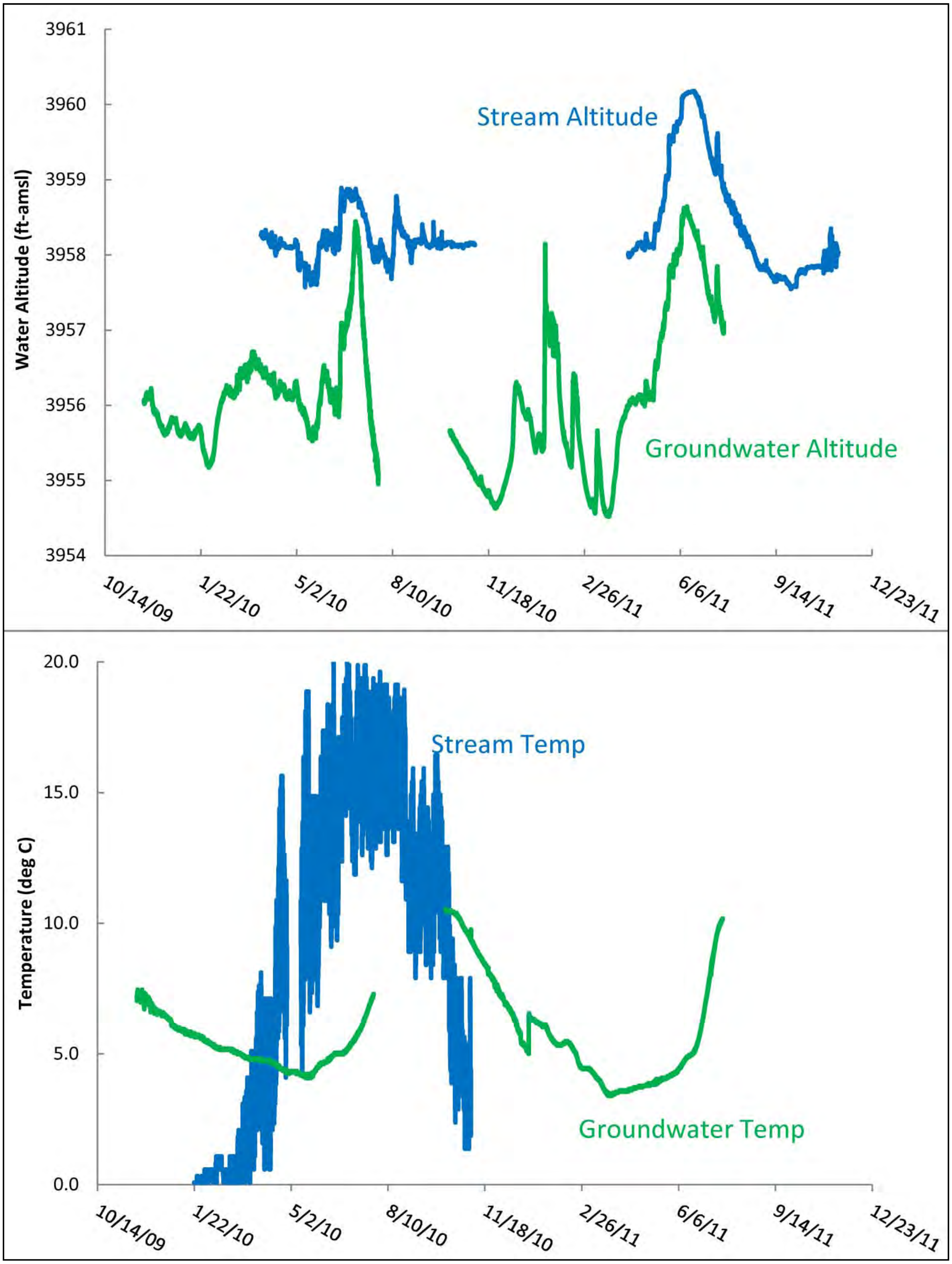


Figure GS-1. Locations of the surface-water/groundwater monitoring sites.

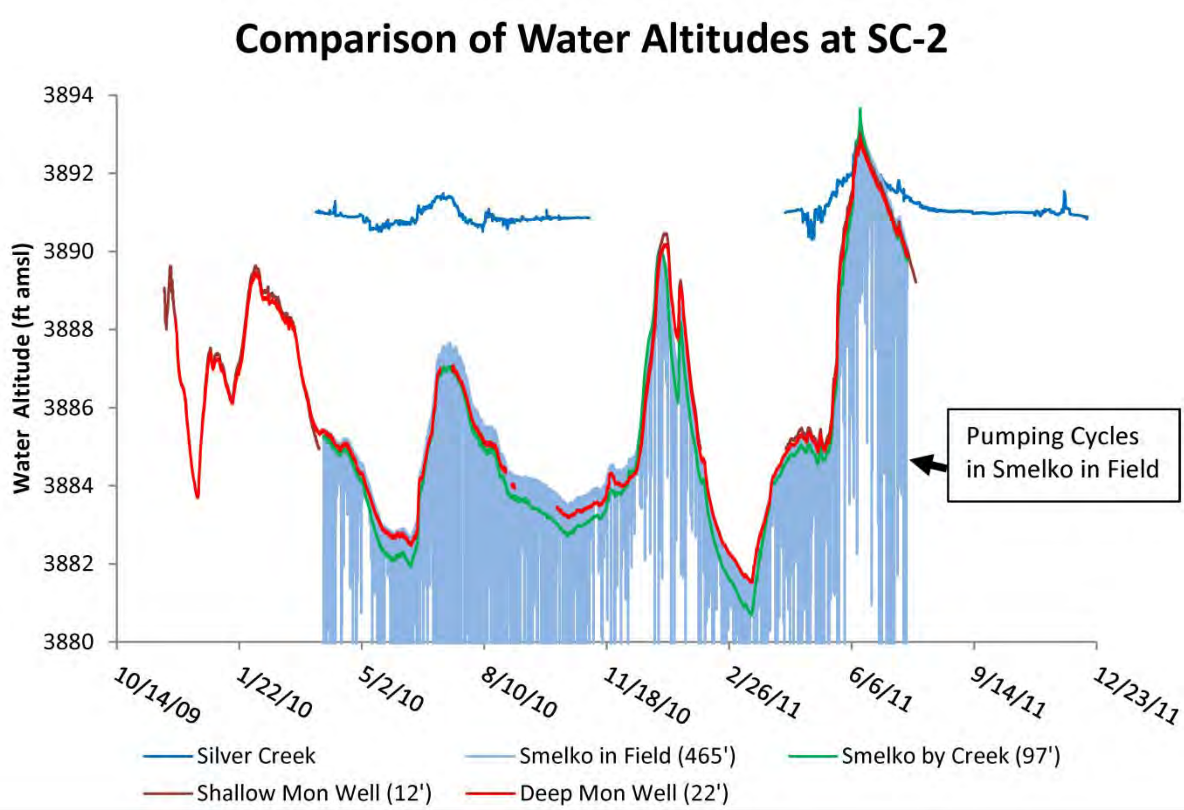
Upper Silver Creek Site (SC-1)

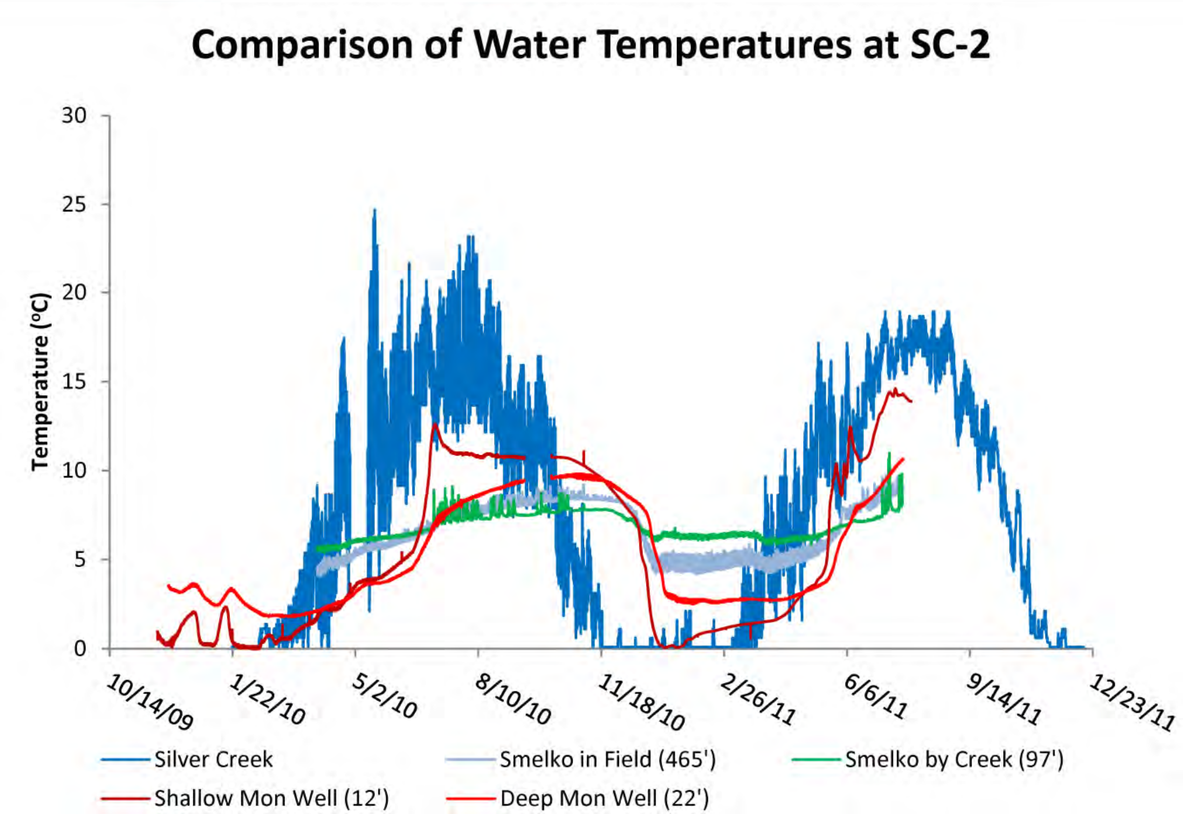


Middle Silver Creek Site (SC-3)

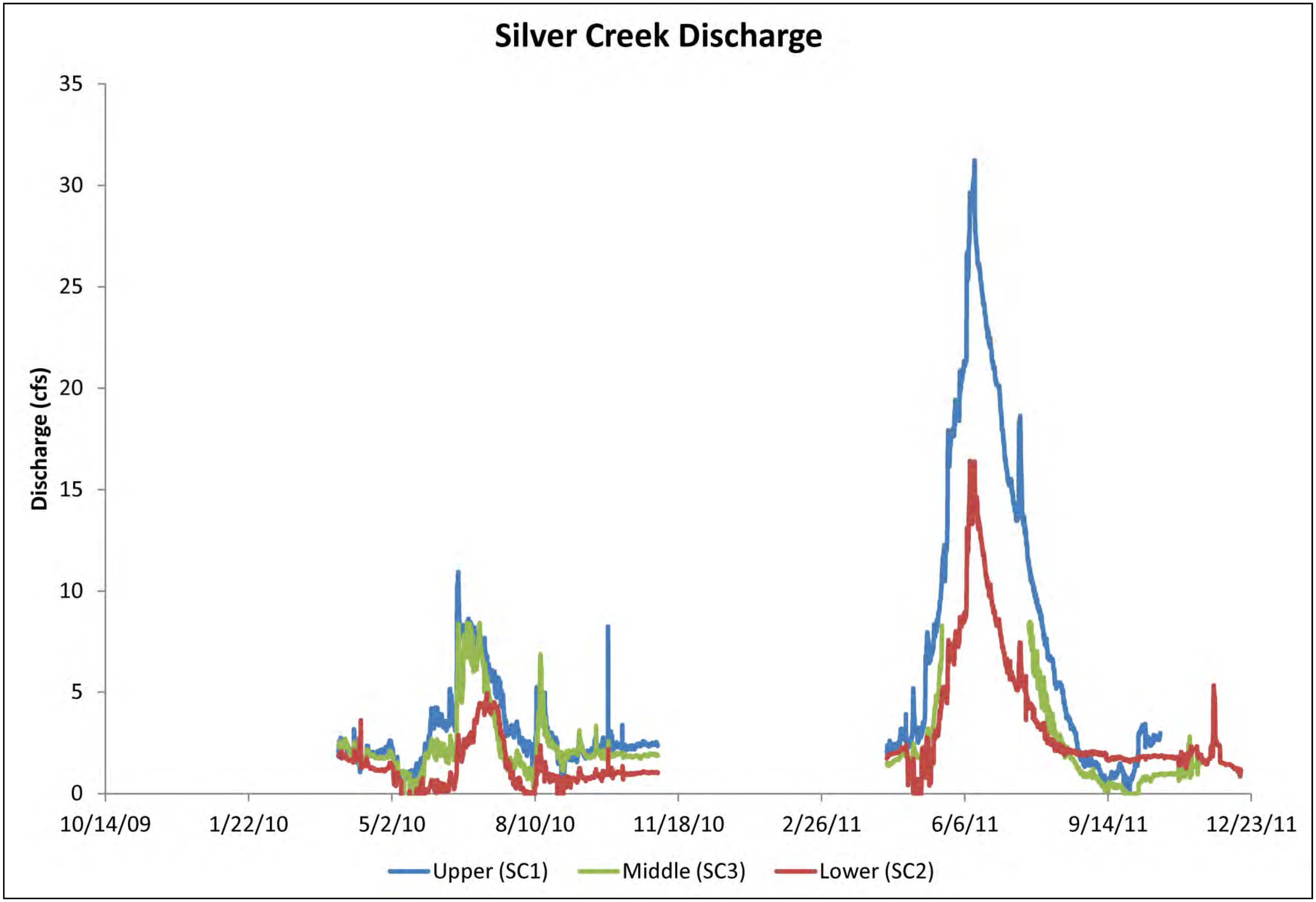


Lower Silver Creek Site (SC-2)





Comparison of discharge at Silver Creek sites.



GROUNDWATER BUDGET ANALYSIS

North Hills Study Area

GROUNDWATER BUDGET ANALYSIS
NORTH HILLS PROJECT AREA
LEWIS AND CLARK COUNTY

Background

The North Hills study area is located approximately 8 mi north of Helena, Montana, on the northern edge of the Helena Valley (fig. WB-1). In recent years there has been increasing subdivision in this area. Analysis of aerial photographs and GIS data indicates that the number of North Hills area residences increased from 1,077 to 2,150 between 1995 and 2009. Many of the new homes use individual water wells (exempt wells) and individual septic systems. Residents are concerned about the long-term capability of area aquifers to supply water and the potential for contamination of these aquifers by septic effluent.

This report provides a detailed evaluation of the groundwater budget for the North Hills study area that can help define the area's conceptual groundwater model and provide information against which a numerical groundwater model can be evaluated.

While these calculations are useful in determining a reasonable range of values, they inherently have a high degree of uncertainty and should be treated as first-order estimates.

The budget is based on the mass balance equation:

$$\text{Input} = \text{Output} \pm \text{Changes in storage.}$$

It is important to note that local water budgets can be out of equilibrium even if the overall study area budget is balanced. Local imbalances can result in localized changes in groundwater levels. To evaluate this aspect, the North Hills study area was subdivided into four sub-areas (fig. WB-2). Sub-Area 1 lies east to west along the southern boundary of the North Hills study and is the area Madison (2006) identified as being influenced by Silver Creek and the Helena Valley Irrigation Canal. Sub-Area 2 is the upland area, north of Sub-Area 1, but generally west of the interstate. Sub-Area 3 is the upland area north of Sub-Area 1, but generally east of the interstate. Sub-Area 4 is a small upland area southwest of Sub-Area 1. The southern edge of Sub-Area 1 is parallel to a groundwater flow line, so it acts as a no-flow boundary. The juncture between Sub-Areas 2 and 3 also parallels a groundwater flow line and is a no-flow boundary. The northern and western edges of Sub-Area 2, and the northern and eastern edges of Sub-Area 3, are along surface-water divides that are also believed to be groundwater divides. As such, these are no-flow boundaries. The northeast corner of the study area is east of the surface-water divide and groundwater in this area likely flows toward the Missouri River (Hauser Lake). As such this northeastern area is not addressed in the budget.

Sub-Areas 1 through 4 cover 10,236; 12,572; 10,051; and 249 acres, respectively. Counts based on 2009 aerial imagery show that residences in Sub-Areas 1 through 4, respectively, numbered 874; 991; 277; and 8. Thus, the average acres per home ranged from 11.7 in Sub-Area 1 to 44.3 in Sub-Area 3.

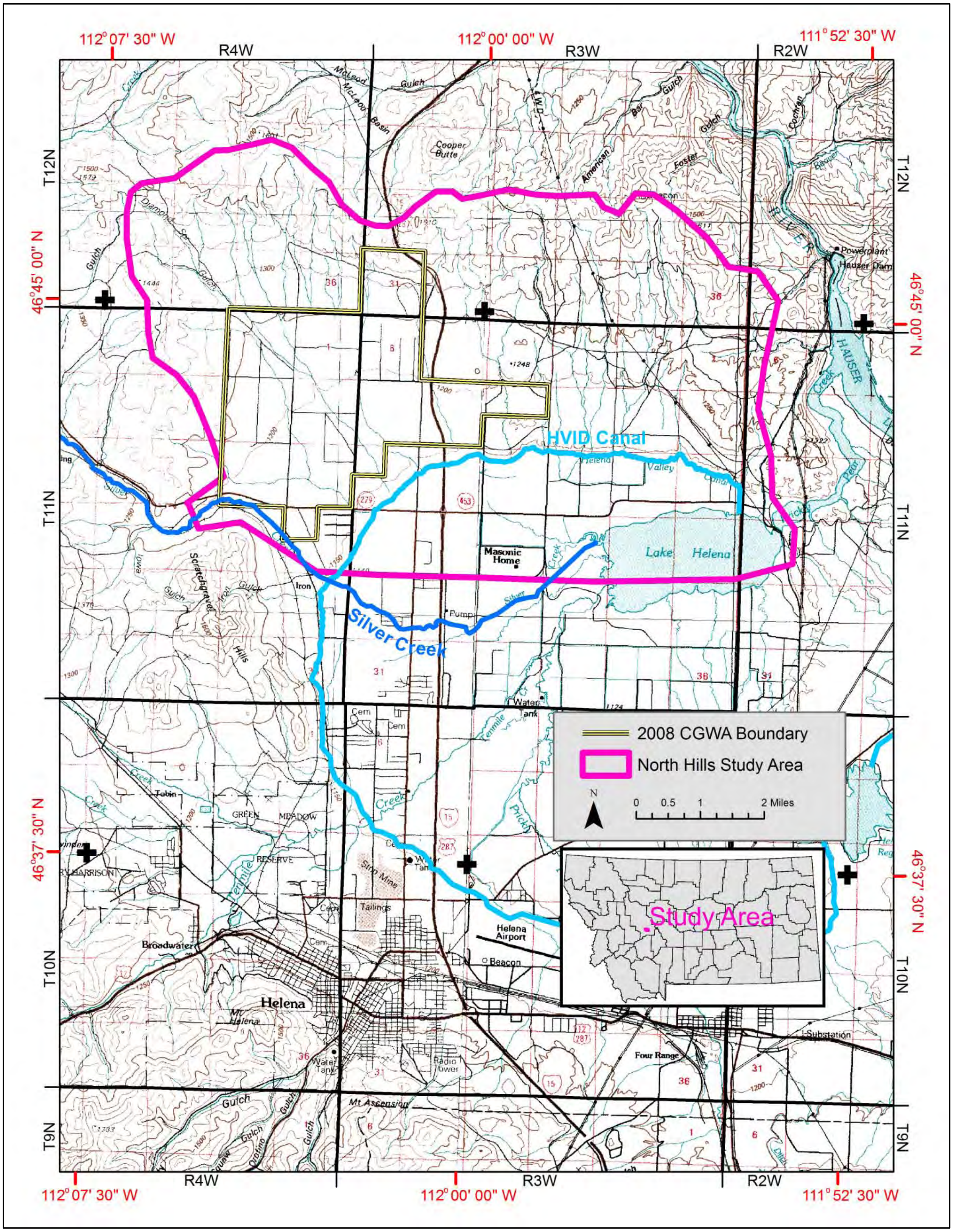


Figure WB-1. Location of the North Hills study area. Black crosses show the intersections of the 7.5' latitude and longitude divisions shown on the edges of the map.

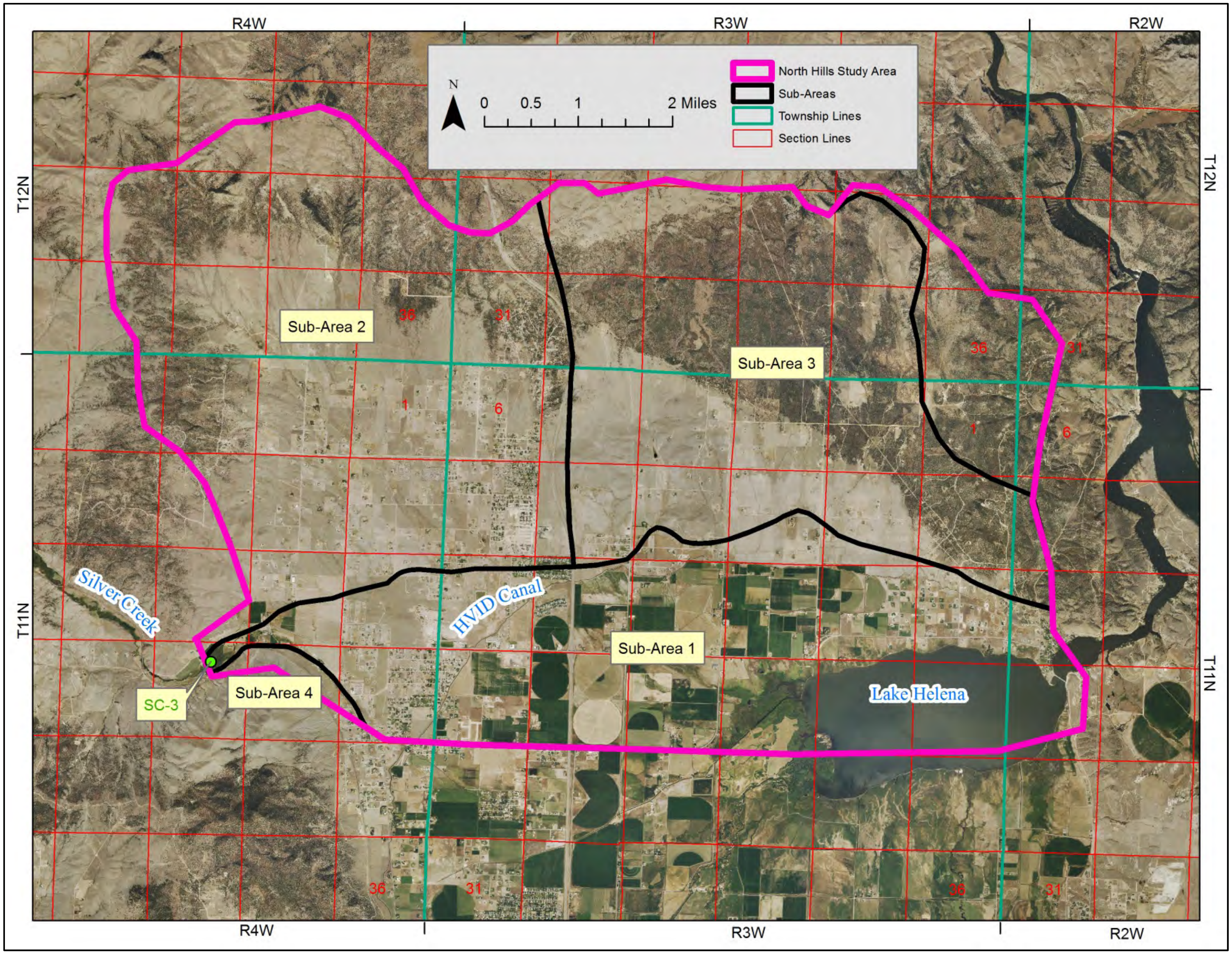


Figure WB-2. Local water budgets were constructed for four Sub-Areas within the North Hills study area.

Sub-Area 1

Following the general form of the equation above but expanding the input and output terms to include their various components, the groundwater budget for Sub-Area 1 can be written as:

$$SC_{al}\_IN + A2\_IN + A3\_IN + A4\_IN + D\_INF + SC\_INF + IC\_INF + IR\_INF = WL\_OUT + SD\_OUT + LH\_OUT \pm \Delta S,$$

where:

SC_{al}_IN, inflow from Silver Creek alluvium at SC3;
A2_IN, groundwater inflow from Sub-Area 2;
A3_IN, groundwater inflow from Sub-Area 3;
A4_IN, groundwater inflow from Sub-Area 4;
D_INF, diffuse infiltration (non-irrigated areas);
SC_INF, Silver Creek infiltration;
IC_INF, irrigation canal infiltration;
IR_INF, irrigation recharge (irrigated areas);
WL_OUT, withdrawals from wells;
SD_OUT, groundwater flow to streams and drains;
LH_OUT, groundwater flow to Lake Helena; and
ΔS, changes in storage.

Sub-Area 1 Inputs

Inflow

Inflow is groundwater that enters from outside the Sub-Area, coming from the alluvium of Silver Creek as well as from all other sub-areas. These flows can be calculated using Darcy's Law (Darcy, 1856; Fetter, 1994, pg. 142), which is:

$$Q = -KA\frac{dh}{dl},$$

where:

Q, inflow (ft^3/d; 1 ft^3/d = 0.0084 acre-ft/yr);
K, hydraulic conductivity (ft/d);
A, cross-sectional area of the boundary (ft^2); and
dh/dl, slope of the potentiometric surface (dimensionless; ft/ft).

For the Silver Creek alluvium (SC_{al}_IN), inflow was calculated at the western edge of Sub-Area 1. Based on water levels in piezometers adjacent to Silver Creek (wells 254242 and 254216, 1/11/2010 at 12:00), the slope of the potentiometric surface is 0.0122 (ft/ft; unitless). Aquifer tests indicate that hydraulic conductivity (K) is between 31 and 57 ft/d with an average of 44 ft/d (see aquifer test section of this report). A well log (GWIC 65631) records the alluvial thickness as 32 ft and reports a static water level of 15 ft below ground surface, giving a saturated thickness of 17 ft at the deepest point. Geologic mapping (Reynolds, 2000) shows the alluvium to be approximately 1,000 ft wide at the western boundary. If it is assumed that the alluvial deposit is V-shaped in cross section, the saturated cross-sectional area (A) is 4,522 ft^2. Using the average K of 44 ft/d, groundwater inflow from the Silver Creek alluvium is about 20 acre-ft/yr. The maximum and minimum hydraulic conductivities of 30 and 60 ft/d produce probable inflows between 14 and 28 acre-ft/yr (table WB-1).

Inflow to Sub-Area 1 from Sub-Area 2 (A2_IN) was calculated along their common boundary. Because the slope of the potentiometric surface varies along the boundary, the calculation was done in three segments. Hydraulic conductivities based on aquifer tests conducted in the argillite bedrock aquifers of the North Hills have a geometric mean of 3.6 ft/d and range from 0.1 to 37.8 ft/d (P. Faber, written commun., 2006, 2010). Hydraulic conductivities determined from aquifer tests conducted for this study ranged from 0.24 to 3.0 ft/d, and tests across faults show that they impede flow. Considering all factors, a hydraulic conductivity of 2.5 ft/d appears to be the best estimate for bulk conductivity in the argillite bedrock. The probable range of K is likely between 1 and 5 ft/d. Very few wells in this area extend deeper than 400 ft, and typically the rocks become less permeable with depth, so a saturated thickness of 400 ft was used for flow in argillite bedrock.

The first segment along the Sub-Area 1–Sub-Area 2 (A1-A2_1) boundary extends from the western edge of the study area, to the eastern edge of section 14 (T. 11 N., R. 4 W.; 8,830 ft). Water-level data from October 2010 (based on measurements in GWIC wells 198749 and 246101) show that the potentiometric surface slope perpendicular to this segment is 0.023. Given these values, it is calculated that groundwater inflow from Sub-Area 2 along this first segment is about 1,700 acre-ft/yr. Using the range of K values from 1 to 5 ft/d results in a probable range of inflow from 680 to 3,410 acre-ft/yr.

The second segment along the Sub-Area 1–Sub-Area 2 boundary (A1-A2_2) extends from the eastern edge of section 14 (T. 11 N., R. 4 W.) to the center of section 18 (T. 11 N., R. 3 W.; 8,530 ft). The gradient across A1-A2_2 was 0.0020 in October 2010 (based on measurements in GWIC wells 65271 and 187372). Assuming the same K values as above, the inflow was approximately 140 acre-ft/yr, and the probable range was from 60 to 290 acre-ft/yr.

Table WB-1

Sub-Area 1 Water Budget
Calculated Values in Acre-Feet per Year

INPUTS

	Best Estimate		Probable Budget		Adjusted to Zero
	acre-ft/yr	percent	Minimum	Maximum	
Silver Creek Alluvium Inflow	20.4	0.1	13.9	27.8	19.6
Inflow from Sub-Area 2	2,103	15.2	841	4,206	2,023
Inflow from Sub-Area 3	2,291	16.6	916	4,581	2,203
Inflow from Sub-Area 4	1,252	9.0	834	1,669	1,204
Silver Creek Infiltration	974	7.0	876	1,071	936
Canal Leakage	2,598	18.8	2,339	2,858	2,499
Irrigation Recharge	4,598	33.2	4,138	5,057	4,421
TOTAL IN	13,835	100	9,958	19,470	13,305

OUTPUTS

	Best Estimate		Probable Range		Adjusted to Zero
	acre-ft/yr	percent	Minimum	Maximum	
Discharge to Drains	3,004	23.5	2,704	3,304	3,129
Discharge to Lake Helena	9,346	73.2	8,411	10,280	9,733
Well Withdrawals	426	3.3	392	490	444
TOTAL OUT	12,776	100	11,506	14,074	13,305

Segment three of the Sub-Area 1–Sub-Area 2 boundary (A1-A2_3) extends from the center of section 18 (T. 11 N., R. 3 W.) to the eastern edge of Sub-Area 2 (4,800 ft length). The gradient across A1-A2_3 was 0.0064 in October 2010 (based on measurements in GWIC wells 64755 and 199993). Assuming the same K values as above, the inflow was approximately 260 acre-ft/yr, and the probable range was from 100 to 520 acre-ft/yr.

Thus, total groundwater inflow to Sub-Area 1 from Sub-Area 2 (A2_IN) was approximately 2,100 acre-ft/yr. The probable range was from 840 to 4,210 acre-ft/yr (table WB-1).

Groundwater inflow to Sub-Area 1 from Sub-Area 3 (A3_IN) was treated similarly to flow entering from Sub-Area 2. The first segment along the Sub-Area 1–Sub-Area 3 (A1-A3_1) boundary extends from the western edge of Sub-Area 3 to 1,725 ft west of the eastern edge of section 9 (T. 11 N., R. 3 W.; 7,110 ft). Water-level data from October 2010 (based on measurement in GWIC wells 257065 and 144726) indicate that the hydraulic gradient in this segment was 0.0048. Assuming the same hydraulic conductivities as previously, the inflow was approximately 290 acre-ft/yr, and the probable range was from 120 to 570 acre-ft/yr.

The second segment of the Sub-Area 3–Sub-Area 1 boundary (A1-A3_2) extends from 1,725 ft west of the eastern edge of section 9 (T. 11 N., R. 3 W.) to the eastern edge of section 11 (T. 11 N., R. 3 W.; 12,455 ft). The gradient across A1-A3_2 was 0.0038 in October 2010 (based on measurements in GWIC wells 218593 and 64798). Assuming the same K values as above, the inflow was approximately 400 acre-ft/yr, and the probable range was from 160 to 790 acre-ft/yr.

The third segment of the Sub-Area 3–Sub-Area 1 boundary (A1-A3_3) extends from the eastern edge of section 11 (T. 11 N., R. 3 W.) to the eastern edge of the study area (8,045 ft). The gradient across A1-A2_3 was 0.024 in October 2010 (based on measurements in GWIC wells 170202 and 252831). Assuming the same K values as above, the inflow was approximately 1,610 acre-ft/yr, and the probable range was from 640 to 3,220 acre-ft/yr.

The total groundwater inflow to Sub-Area 1 from Sub-Area 3 (A3_IN) was approximately 2,290 acre-ft/yr. The probable range was from 920 to 4,580 acre-ft/yr (table WB-1).

The inflow to Sub-Area 1 from Sub-Area 4 (A4_IN) can be calculated similarly; however, the bedrock in this area is granite that aquifer tests show to be less permeable than the argillite. A reasonable hydraulic conductivity based on the tests is 0.75 ft/d, and ranges from 0.5 to 1 ft/d. Considering the geometry of this area relative to flow lines, the segment length was calculated where flow lines from the boundary intersect the 4,000-foot above mean sea level (amsl) potentiometric contour. The cross-sectional length along the 4,000-ft contour is 6,550 ft. The gradient across the contour in October, 2010 was 0.076 (based on measurements in GWIC wells 65536 and 254703). Using a saturated thickness of 400 ft, inflow of across the boundary was approximately 1,250 acre-ft/yr. The calculated probable range of inflow was between 830 and 1,670 acre-ft/yr.

Diffuse Infiltration

Diffuse infiltration occurs throughout the study area at times when the amount of water received via precipitation is in excess of the combined rates of evapotranspiration (ET) and runoff. Monitoring of ephemeral streams and drainages shows that there is little if any runoff in most years. As such, diffuse infiltration can be approximated by the amount of precipitation less ET. ET includes that portion of precipitation that evaporates, sublimates, is transpired by plants, or is trapped by under-saturated soil in the root zone. Because all of this water eventually leaves the study area as water vapor, it is accounted for in a single ET term. Potential ET is equal to “the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation” (Thornthwaite, 1944). As is noted by Fetter (1994) “[b]ecause there is often not sufficient water available from soil moisture, the term actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions." That there is often not sufficient water from soil moisture is particularly true for arid and semi-arid areas. The North Hills study area is semi-arid. While potential ET values can be readily estimated, actual ET values are more difficult to determine.

Briar and Madison (1992) note that the actual ET for pasture grasses in this area is approximately 11–16 in of water per year. Precipitation in Sub-Area 1 averages 9.7 in per year (fig. WB-3), which indicates that there is very little infiltration in non-irrigated areas in most years. Rare high-intensity precipitation events may cause there to be infiltration to groundwater; however, this amount would be volumetrically small on a long-term basis.

The actual evapotranspiration for the North Hills has been estimated for this study by researchers at the University of Idaho using "Mapping EvapoTranspiration at high Resolution with Internalized Calibration" (METRIC) remote sensing techniques (fig. WB-4). According to the project report (Trezza and others, written commun., 2011), "[t]he METRIC procedure utilizes the visible, near-infrared, and thermal infrared energy spectrum bands from Landsat satellite images and weather data to calculate ET on a pixel by pixel basis. Energy is partitioned into net incoming radiation (both solar and thermal), ground-heat flux, sensible-heat flux to the air and latent-heat flux. The latent-heat flux is calculated as the residual of the energy balance and represents the energy consumed by ET." A more detailed description of METRIC is provided in Allen and others (2007a,b; 2010).

For non-irrigated areas in Sub-Area 1, METRIC estimates ET to be essentially equal to precipitation, which matches well with previous assessments (Briar and Madison, 1992; Madison, 2006). Thus diffuse infiltration is not a significant factor in the non-irrigated areas of Sub-Area 1.

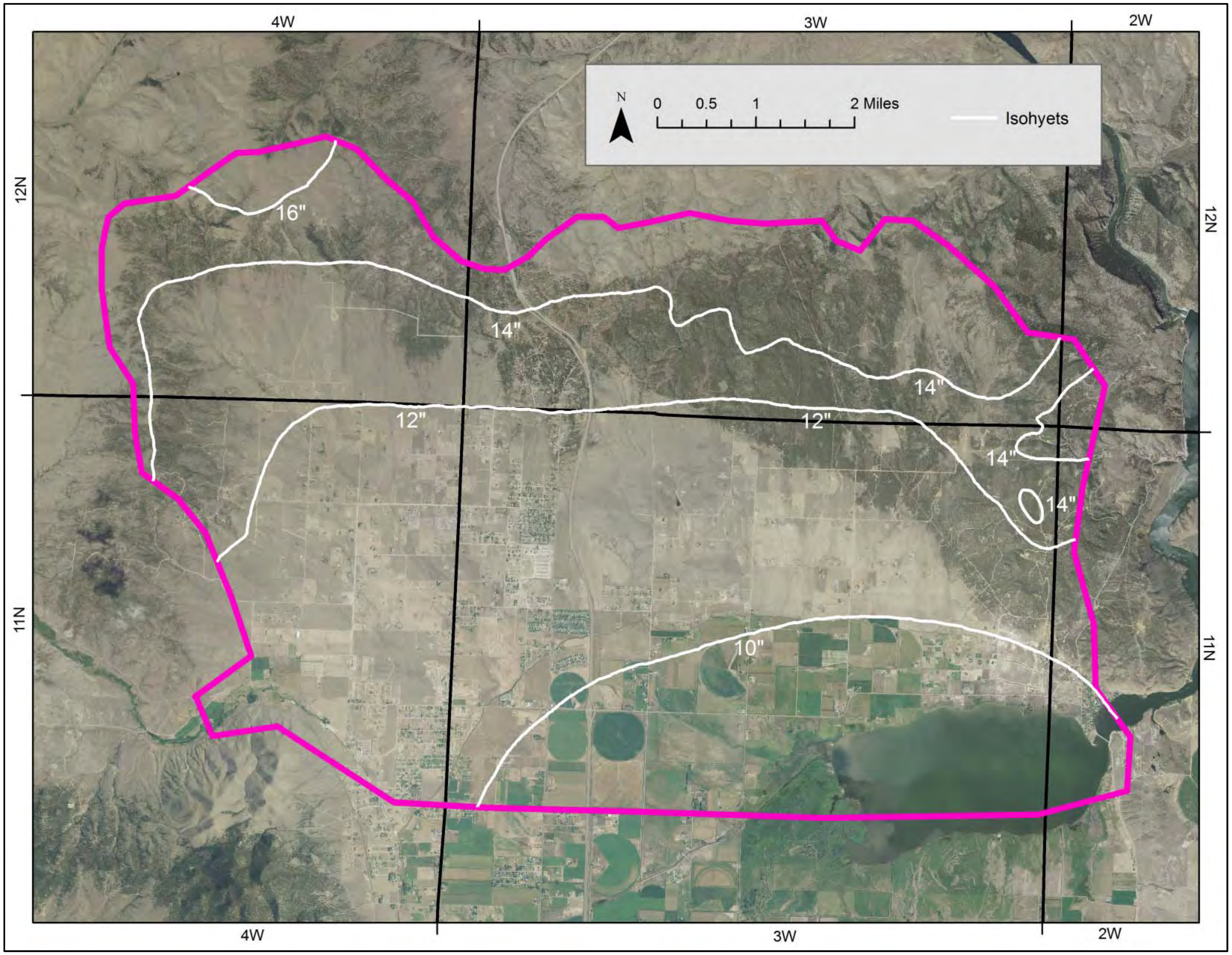


Figure WB-3. Precipitation isohyets (in) in the North Hills study area. Data prepared by Snowcap Hydrology (P. Farnes, written commun., 2010).

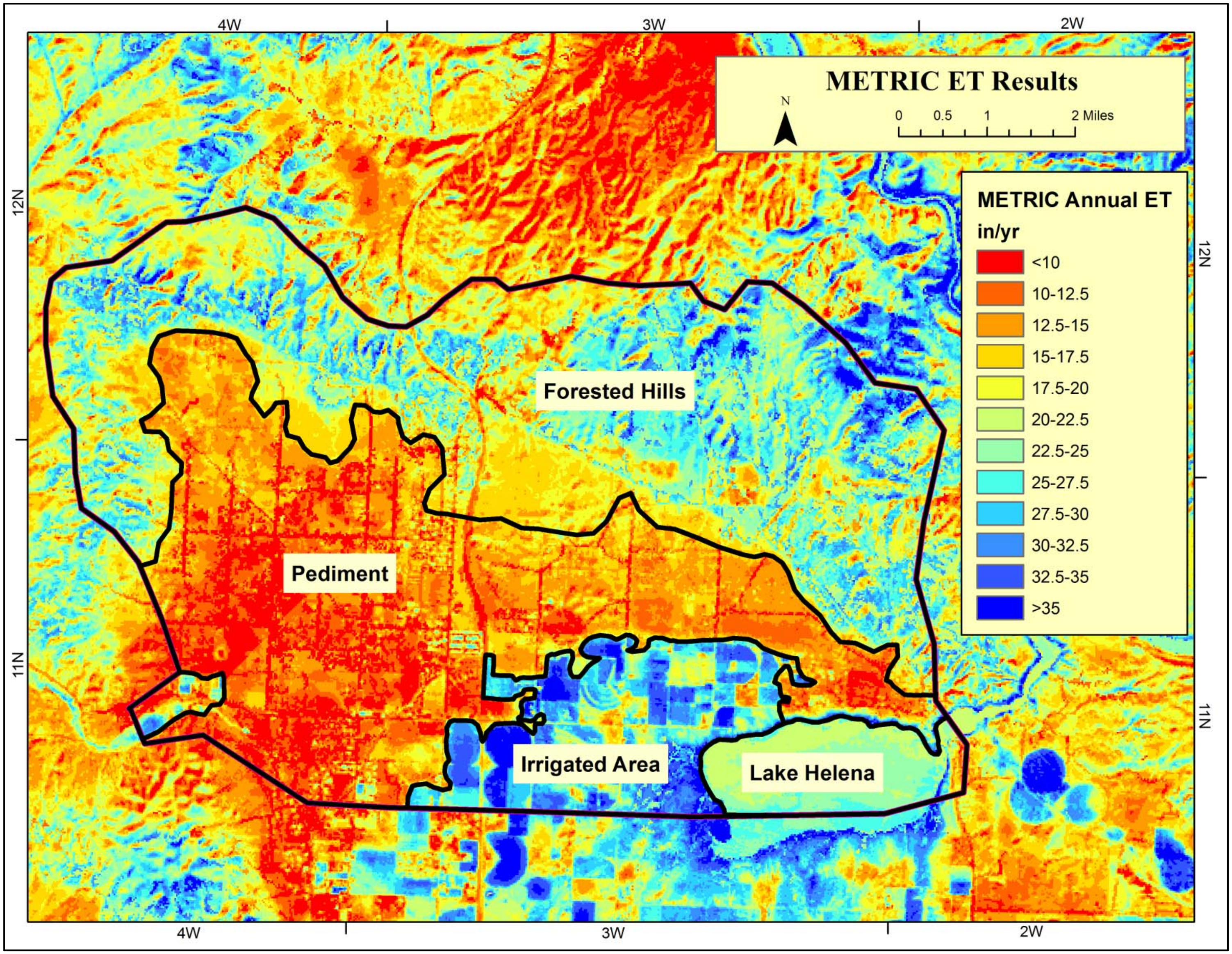


Figure WB-4. Results of the METRIC ET analysis (Trezza and others, written commun., 2011).

Silver Creek Infiltration

Silver Creek is the only stream that regularly enters the study area. Silver Creek loses flow and is typically dry prior to reaching Green Meadow Drive. Discharge measurements for Silver Creek at stream gauge SC3 (western boundary of Sub-Area 1; fig. WB-2) during 2010 (3/25/2010 to 11/3/2010) were used to estimate average annual infiltration from Silver Creek.

Continuous measurements of discharge in Silver Creek at SC-3 were obtained from stage recordings converted to flow based on a rating curve derived from flow measurements made approximately every 2 weeks (fig. WB-5). From these measurements, the flow between April and October 2010 was 962 acre-ft.

Continuous measurements of discharge in Silver Creek at SC-3 were determined from stage recordings and a rating curve developed from bi-weekly flow measurements (fig. WB-5). From these measurements, total monthly flow volumes for April–October 2010 were calculated to be 960 acre-ft. Tenmile Creek, based on the 1908–1998 period of record, flowed an average of 17,540 acre-ft during the April–October period (data from the United States Geological Survey (USGS) database; http://wy-mt.water.usgs.gov/; site 06063000). Thus, flow in Silver Creek during April–October 2010 was 5.5% of the average flow in Tenmile Creek for the same period. Assuming that this relationship holds for other times of the year, mean monthly Silver Creek discharge values for November–March 2010 period were estimated. Combining the estimated values with observations results in a total flow of 1,080 acre-ft/yr in 2010 (fig. WB-6).

It must also be considered if the April–October 2010 period was climatologically “average” and usable for calculating a long-term average annual input from Silver Creek. Weather data from the Helena Regional Airport indicate that 2010 precipitation from April to October was 111% of normal; thus it would be expected that flow in Silver Creek would be about 11% greater than normal. Using this relationship, the values can be recalculated, and converted to a best estimate average annual inflow of 970 acre-ft. Given the uncertainties, the range of probable values is likely ±10%, or 870 to 1,070 acre-ft/yr. For this calculation, it is assumed that all of the Silver Creek flow passing station SC3 infiltrates to groundwater.

Irrigation Canal Infiltration

The Helena Valley Irrigation District (HVID) canal runs through Sub-Area 1 (fig. WB-2), entering in the southwest portion of the area, and eventually discharges any remaining water into Lake Helena. Several laterals run off of the main canal and route water to fields. Neither the canal nor laterals are lined. Briar and Madison (1992) evaluated infiltration from irrigation canals, and concluded that the main canal loses an average of about 0.63 cubic feet per second (cfs) per mile, and the laterals lose about 0.21 cfs/mile. This water recharges the groundwater system.

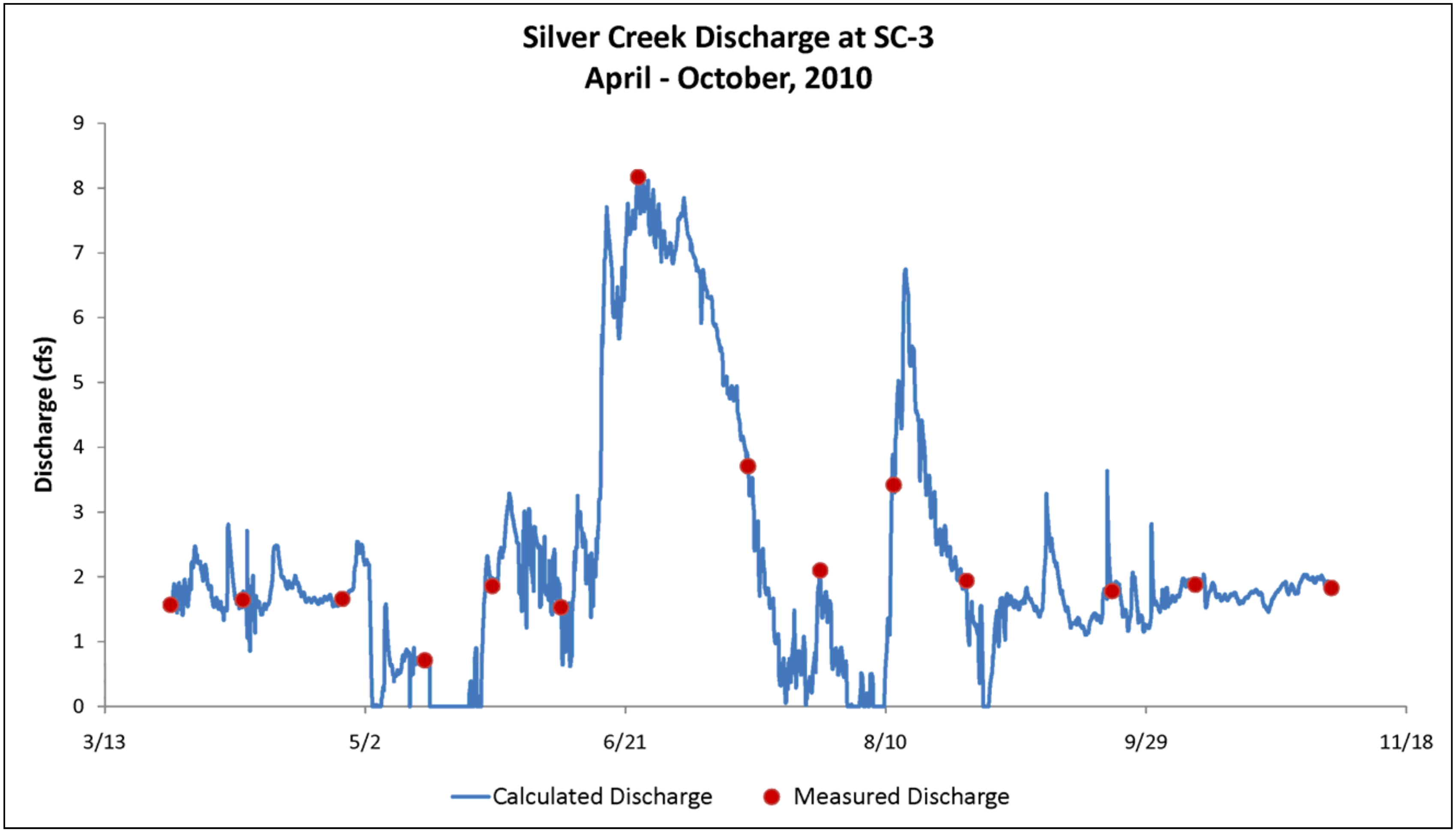


Figure WB-5. Discharge measurements on Silver Creek at SC-3 (western edge of study area).

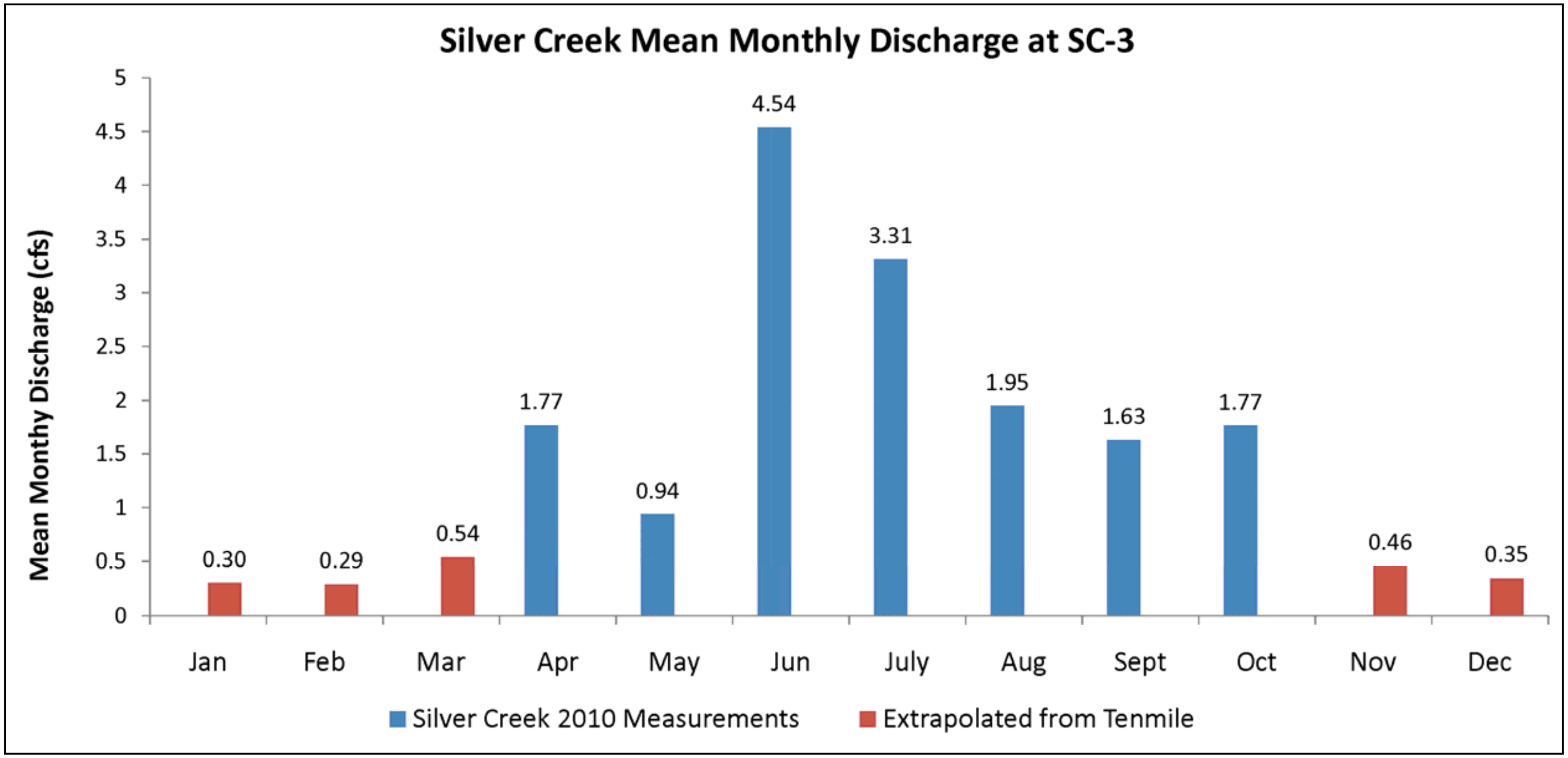


Figure WB-6. Mean monthly discharge values for Silver Creek at SC-3 during 2010. January–March and November–December discharges are extrapolated from observed relationships between Silver Creek discharge and flow in Tenmile Creek.

To determine the amount of irrigation canal infiltration in Sub-Area 1, detailed maps of the irrigation infrastructure obtained from the Helena Valley Irrigation District (written commun., 2009) were loaded into a Geographic Information System (GIS), and the HVID canal, laterals, and drains were digitized. This analysis showed that 8.2 mi of the HVID canal and 12.4 mi of laterals are within Sub-Area 1. Multiplying the canal type lengths with leakage rates shows that about 7.8 cfs is lost from these structures while they are used from April 15 to October 1. Monitoring in the main canal shows that the average flow into the study area is approximately 85 cfs, so this loss represents approximately 9% of the water in the irrigation system. Using this information, the best estimate of annual infiltration is 2,600 acre-ft/yr. Given the uncertainties in these calculations, the range of probable values is ±10%, or 2,340 to 2,860 acre-ft/yr (table WB-1).

Irrigation Recharge

Water is diverted from the HVID canal and its laterals and is applied to fields. Briar and Madison (1992) estimated that about 1.5 ft/yr (18 in/yr) of water is applied per unit area to the fields in excess of the crop demand. This excess water flows through the root zone to recharge groundwater. The application of excess water is a standard practice since some excess water is needed to prevent the buildup of salts in the root zone and to minimize plant stress (USDA, 1954). GIS data from the Montana Department of Revenue (DOR, 2010) show that 3,065 acres are irrigated within Sub-Area 1. The best estimate of irrigation recharge to groundwater is 4,600 acre-ft/yr. Given the uncertainties in these calculations, the range of probable values is ±10%, or 4,140 to 5,060 acre-ft/yr (table WB-1).

Sub-Area 1 Outputs

The possibility of subsurface groundwater flow out of Sub-Area 1 was considered; however, it is likely negligible. The only place that subsurface flow could leave the Sub-Area would be through alluvium underneath the Lake Helena Causeway; however, because Lake Helena and Hauser Lake are controlled by Hauser Dam, the gradient between the two water bodies is negligible. Surface water flow direction through the causeway gates depends on Hauser Dam operations, but regardless of direction, gradients are not large enough to invoke significant groundwater flow under the causeway. All other Sub-Area 1 boundaries are where water enters the area, or fall along no-flow boundaries (parallel to potentiometric flow lines or groundwater divides). All groundwater that leaves Sub-Area 1 does so as surface water flow through the causeway, as evaporation from Lake Helena, or as withdrawals through wells (WL_OUT). Groundwater flow into Lake Helena is either from groundwater discharge to streams and drains that flow into Lake Helena (SD_OUT), or from direct inflow through the bottom of Lake Helena (LH_OUT) (Briar and Madison, 1992).

Because almost all water leaves the study area as surface flow out of Lake Helena, it is important to evaluate the probable range of Lake Helena discharge through the causeway. Flow measurements at the causeway are complicated by periods of reversed flow depending on the operation of Hauser Dam. An additional complication relative to estimating groundwater discharge from the study area is that flow at the causeway includes contributions from sources other than the North Hills study area.

USGS measurements obtained during November 1990 using a pair of water-level recorders (one on each side of the causeway), recording every 15 min, show that the monthly average flow was 102 cfs (J.P. Madison, written commun., 2010). Daily average flows ranged from 21 to 169 cfs. Briar and Madison (1992) also reported an outflow of 148 cfs on October 25, 1990. Six other USGS measurements collected during January to June 1990 range from 72.4 to 431 cfs (NWIS; http://waterdata.usgs.gov/nwis/; downloaded 5/12/2011; USGS 06064500).

Ten measurements of flow at the Lake Helena Causeway were conducted during this study during May through September 2010. These measurements ranged from 167 to 828 cfs.

Based on the available data, average monthly flows were calculated and used to estimate a total annual downstream flow through the causeway of about 160,400 acre-ft/yr. Given the uncertainties in these calculations, the range of probable values is ±10%, which results in a range from 144,300 to 176,400 acre-ft/yr.

Surface-water inflow into Lake Helena can be estimated from USGS measurements during May 1997 through September 1998 at a gauge on Tenmile Creek located just above its confluence with Prickly Pear Creek (fig. WB-1; USGS 06064150). The average flow is 57 cfs. Data from USGS monitoring (seven measurements in 1988; three measurements in 1995) on Prickly Pear Creek just above the Tenmile Creek confluence (fig. WB-1; USGS 463939111582801) provide an average flow of 50 cfs. Thus about 107 cfs of flow to Lake Helena on average can be attributed to these streams. This equates to about 78,000 acre-ft/yr. Some of the water measured at these gauges comes from groundwater flow into streams and drains.

Briar and Madison (1992) calculated the groundwater flow through the bottom of Lake Helena in two ways. A calculation using Darcy's Law resulted in an estimate of 53,000 acre-ft/yr flowing into Lake Helena. Also, a synoptic flow measuring event where all surface water inflows and outflows were measured on October 25, 1990, suggested an inflow of approximately 50,000 acre-ft/yr from groundwater.

Briar and Madison (1992) also show that total groundwater flow into Lake Helena was about 86,220 acre-ft/yr, which includes flow through the bottom of Lake Helena, and groundwater discharge to streams and drains (36,190 acre-ft). It is estimated that about a third of this groundwater discharge to streams and drains is to Tenmile and Prickly Pear Creeks (about 12,060 acre-ft/yr).

The outflow from the Lake Helena causeway is created by a combination of groundwater inflow through the bottom of the lake (~50,000 acre-ft/yr), inflow from Tenmile and Prickly Pear Creeks (~78,000 acre-ft/yr), and groundwater discharge to other streams and drains which then flows as surface water into Lake Helena (~24,000 acre-ft/yr). Combining these sources results in a total inflow of about 152,000 acre-ft/yr. This inflow value is well within the range of estimated outflows (144,300 to 176,400 acre-ft/yr), and is reasonably close to the best estimate (~160,000 acre-ft/yr).

Well Withdrawals

Various estimates of the amount of water used per residence appear in table WB-2 and appendix WB-A. For this study, the most reliable information available is from the Townview subdivision, where monthly water-use data from 1991 through 2009 are available (figs. WB-7, WB-8, WB-9; B. Thompson, written commun., 2010). Consumptive use is that water that is removed from the groundwater and not returned by septic systems. A comparison of consumptive use estimates provided by several different sources is provided in table WB-2. Although the best consumptive use estimate is 435 gpd/residence, the sources suggest that consumptive use ranges from 400 to 500 gpd/residence. Aerial photographs taken in 2009 show that at that time 874 homes were within Sub-Area 1. Multiplying the estimated consumptive use per residence by the number of residences produces an estimated consumptive withdrawal by wells of about 430 acre-ft/yr, with the probable range being from 390 to 490 acre-ft/yr. The seasonality of use was also calculated (figs. WB-10, WB-11). Detailed tables for each Sub-Area are included in appendix WB-A.

Surface-Water Flow to Lake Helena

The drains near Lake Helena are fed by groundwater. These provide the only surface-water flow out of Sub-Area 1. Measurements of the drains show that discharge is approximately 0.98 acre-ft/yr per acre drained. When this rate was applied to all irrigated acres in Sub-Area 1 (3,065 acres), the discharge from groundwater to drains is about 3,000 acre-ft/yr. Given the uncertainties in these calculations, the range of probable discharge is ±10%, or 2,700 to 3,300 acre-ft/yr.

Groundwater Flow to Lake Helena

Most sub-surface flow out of Sub-Area 1 is directly to Lake Helena. As discussed above, groundwater inflow to Lake Helena, as estimated by Briar and Madison (1992), appears to be approximately 50,000 acre-ft/yr.

Much of the water that flows into Lake Helena through its bottom is derived from irrigated land supported by the HVID canal. The total acreage supported by the canal is approximately 38,600 acres, of which about 7,200 are in Sub-Area 1. Thus it is estimated that about 19 percent of the flow through the base of Lake Helena is derived from Sub-Area 1 (9,300 acre-ft/yr). Given the uncertainties in these calculations, the range of probable values is ±10%, or 8,400 to 10,300 acre-ft/yr.

Sub-Area 1 Changes in Groundwater Storage

It can be seen from hydrographs (fig. WB-12) that there are no noticeable trends in groundwater levels in Sub-Area 1. While there are seasonal variations, there is no net change. Because hydrographs representative of the Sub Area show no change, the net annual change in groundwater storage is negligible, and for the purposes of the water budget analysis, can be assumed to be zero.

Sub-Area 1 Summary

A summary of all input and output values for Sub-Area 1 is shown in table WB-1.

The best estimates show a 7.6% excess between inputs and outputs. This difference can be removed by applying an adjustment to these values based on the percentage of input or output represented by each value. The result is the adjusted to zero value on table WB-1; this results in all values being within the probable range.

Overall Sub-Area 1 transmits about 13,300 acre-ft of water per year as groundwater. Therefore, annual consumptive use from wells accounts for about 440 acre-ft or 3.3% of the total flow.

Table WB-2
Comparison of Calculated Consumptive Water Use per Home

Source	Delivered (gpd/residence)	Septic Return (gpd/residence)	Consumptive Use (gpd/residence)
EPA, 2008	400	NR	NR
DNRC, 1986	312	NR	NR
Madison, 2006	464	162	302
DNRC	629	152	477
Townview Subdivision	572	164	408
Combined Ranchview and Skyview Subdivisions	607	188	420
Northstar Subdivision	506	NA	506
Average	499	167	423
Average (Excluding EPA; DNRC, 1986; Madison; and Northstar)	603	168	435

NR = Not Reported

NA = Not Applicable

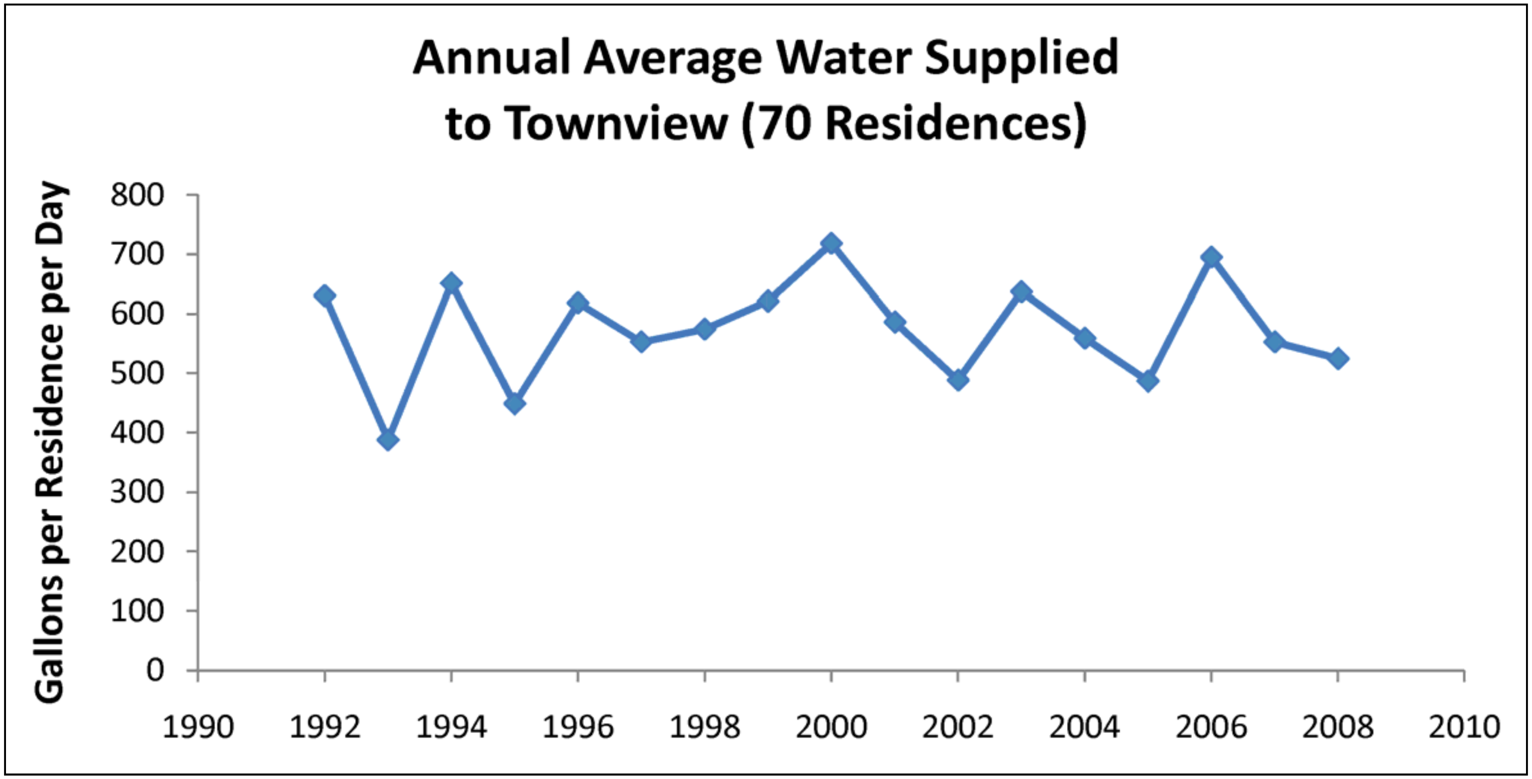


Figure WB-7. Average amount of water delivered to each home in the Townview Subdivision, by year.

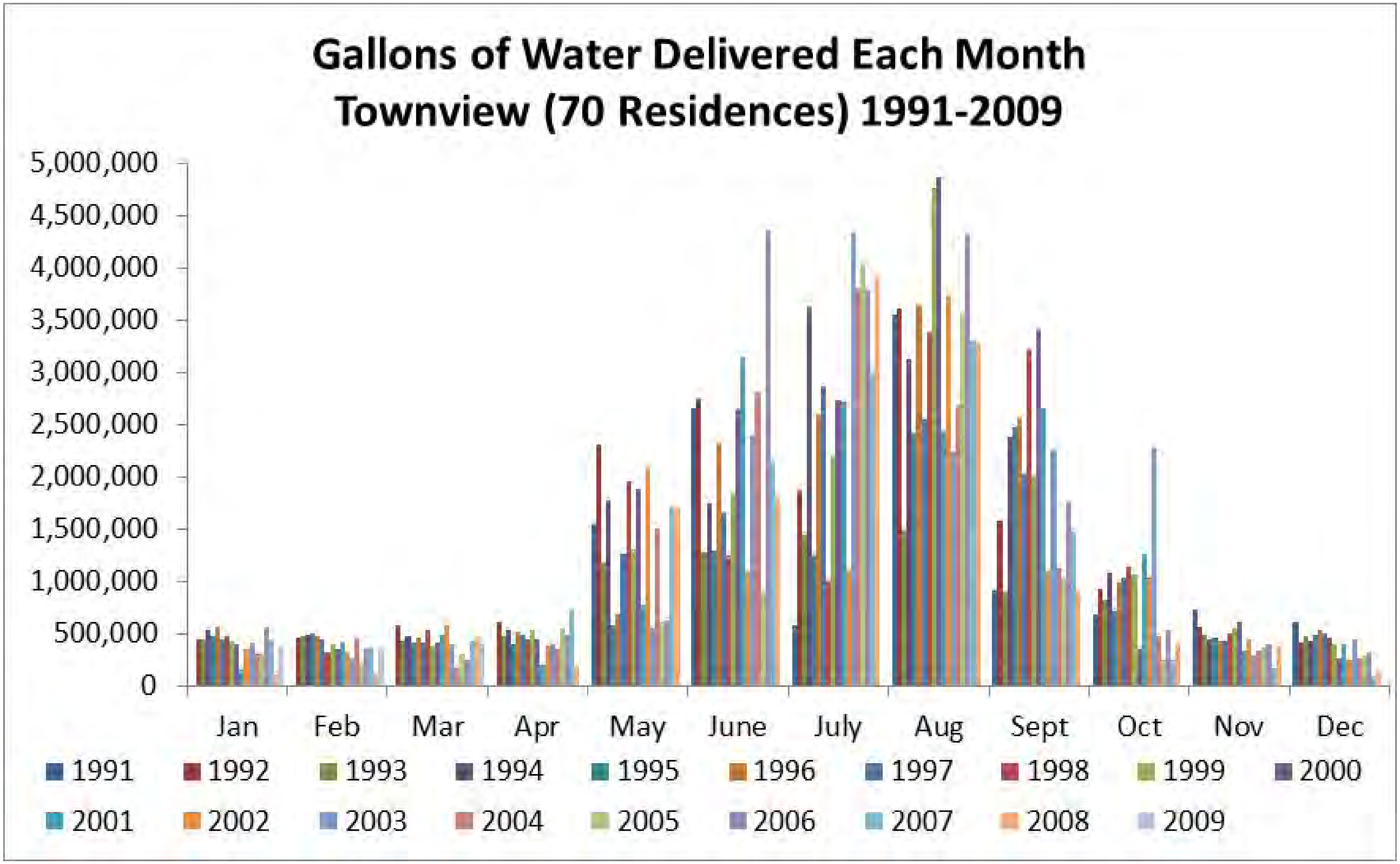


Figure WB-8. Water delivered to homes in the Townview Subdivision by month, 1991–2009.

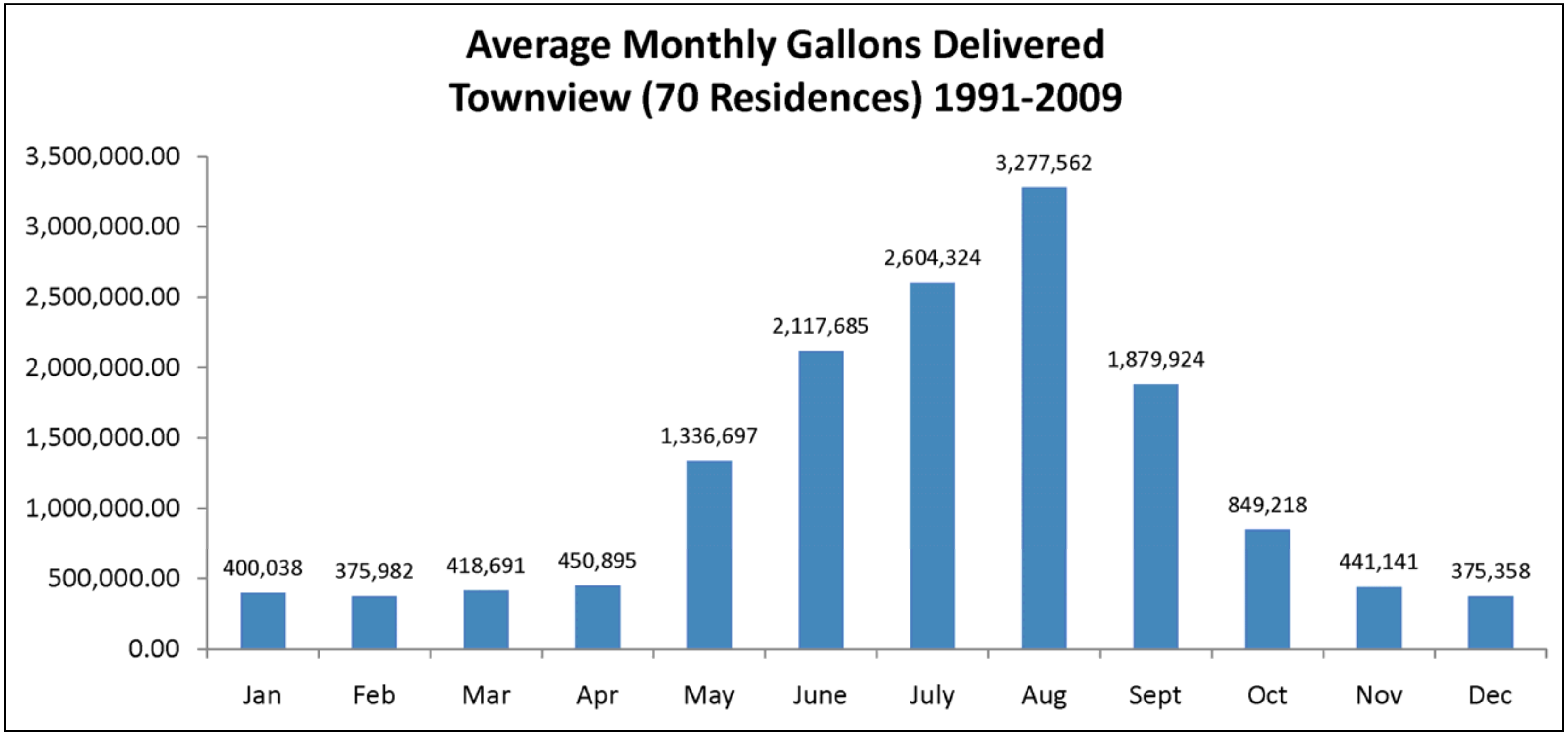


Figure WB-9. Average monthly water delivered to 70 homes in the Townview Subdivision.

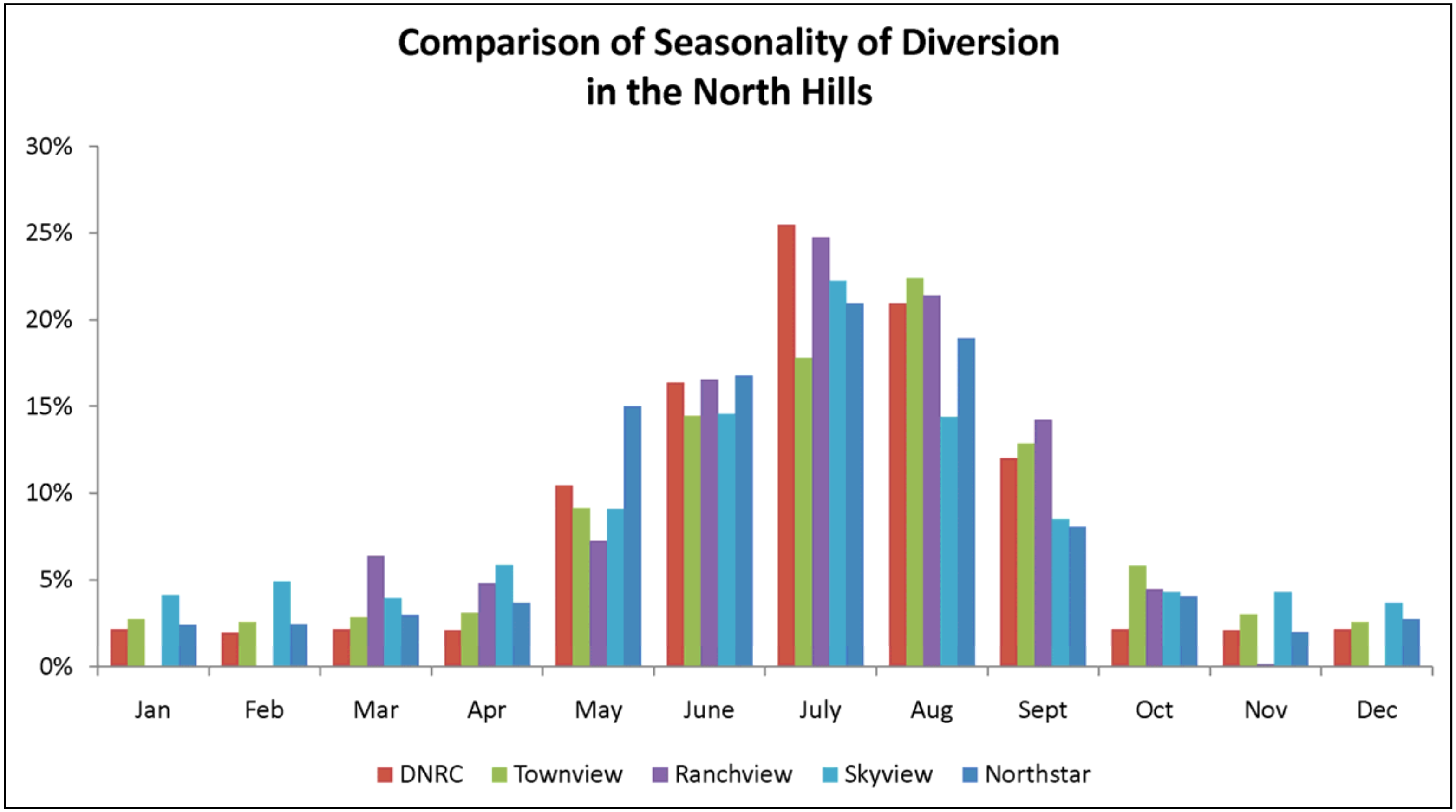


Figure WB-10. Comparison of the seasonal distribution of consumptive use of water in the North Hills, using empirical data from different subdivisions, and theoretical values from DNRC.

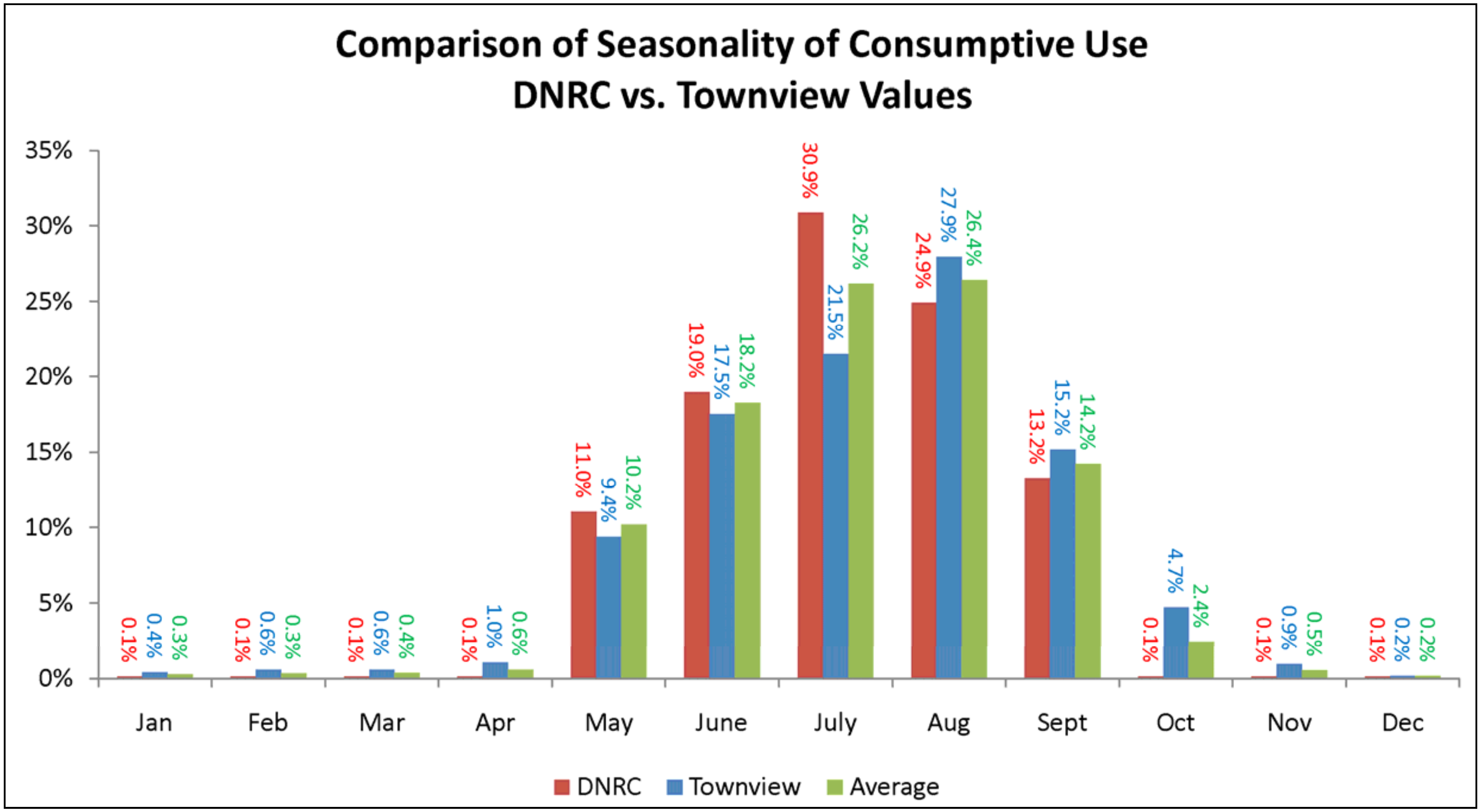


Figure WB-11. Comparison of seasonality of consumptive use in the North Hills. Theoretical values from DNRC compared to 19 years of empirical data from Townview Subdivision.

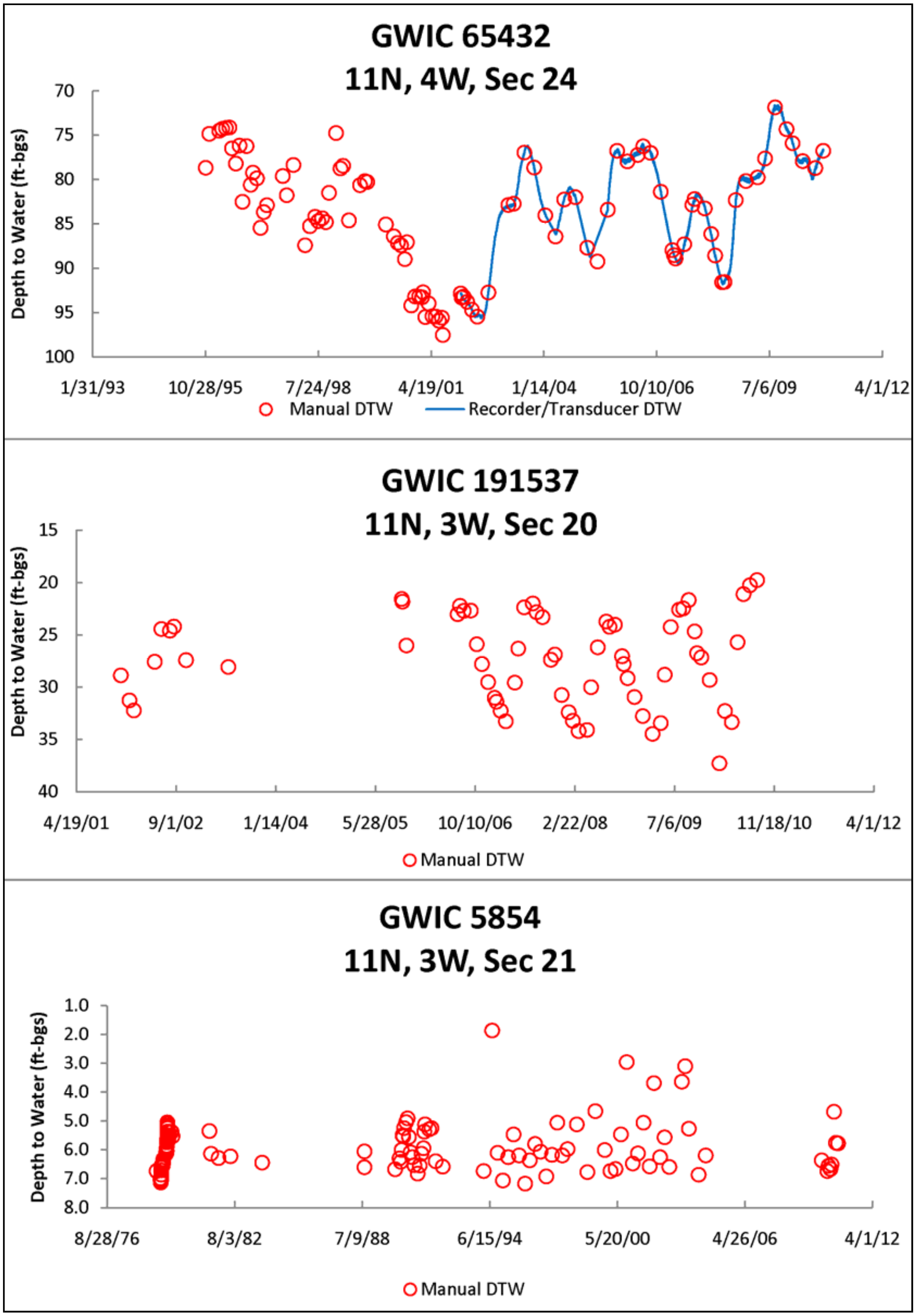


Figure WB-12. Hydrographs from Sub-Area 1 respond to short-term pumping and climatic patterns, but there are no long-term trends.

Sub-Area 2

The water budgets for Sub-Areas 2–4 are substantially simpler than for Sub-Area 1. The water budget for Sub-Area 2 can be written as:

$$D\_INF = WL\_OUT + A1\_OUT \pm \Delta S,$$

where:

D_INF, diffuse infiltration;
WL_OUT, withdrawals from wells;
A1_OUT, outflow to Sub-Area 1 (same as A2_IN for Sub-Area 1); and
ΔS, changes in storage.

Sub-Area 2 Inputs

Diffuse infiltration from precipitation is the only Sub-Area 2 input because all other Sub-Area boundaries are either no-flow (groundwater divides and flow lines) or outflow. Monitoring of surface drainages in this area shows that annually there is little if any runoff. Diffuse infiltration will then equal precipitation less ET.

On the non-irrigated pediment the METRIC estimated ET is essentially equal to precipitation, which matches well with previous assessments (Briar and Madison, 1992; Madison, 2006). The METRIC-calculated ET values for the forested hills are significantly higher than precipitation. Precipitation in this area averages 15 in. Because the precipitation data are believed to have less potential for errors, alternative methods were used to estimate ET in the forested area. Other workers have noted this problem with METRIC ET values outside of agricultural areas (Alves and others, 2000; Gowda and others, 2008; Allen and others, 2013). Thiros and others (1996) estimated that in alluvial basins in Utah receiving 8–16 in of precipitation, 1–25 percent infiltrates. Anthoni and others (1999) measured ET in a Ponderosa Pine stand in a semi-arid environment in central Oregon at 1.6 mm per day in the summer. This equates to approximately 11.6 in/yr (April–October, assuming April and October are at half the summer rate), leaving 3.4 in for infiltration. The USGS has also noted that recharge in Montana ranges from “less than 1 in/yr in parts of the eastern plains to several inches in parts of the western mountains” (USGS, 1985). Numerical modeling also provides a constraint on how much recharge is occurring. In the model, hydraulic conductivities for the argillite bedrock are on the low end of the range considered to be reasonable when 3 to 4 in of recharge is applied in the hills. Lower recharge values would require lower hydrologic conductivity values to reproduce observed water levels, which would cause the hydrologic conductivity values to be outside the range considered to be reasonable. Given these factors, it is estimated that infiltration is equal to approximately 25 percent of precipitation (3.75 in/yr on average) in the forested hills. The remainder (11.25 in/yr on average) is lost to ET.

Diffuse infiltration only needs to be calculated in the forested hill area because ET and precipitation are essentially equal on the pediment. Given that the average precipitation in the forested hills is approximately 15 in, and 25 percent is assumed to recharge groundwater, the total groundwater recharge in this area is about 3.75 in. Given that the total area of the forested hills in Sub-Area 2 is 6,227 acres, the calculated recharge is 1,950 acre-ft/yr. The uncertainty associated with this calculation is ±20%, which results in a probable range from 1,560 to 2,340 acre-ft/yr.

Sub-Area 2 Outputs

Well Withdrawals

2009 aerial photographs show 991 homes in Sub-Area 2, so the net groundwater withdrawn by wells account s for approximately 480 acre-ft/yr, and the probable range is from 444 to 560 acre-ft/yr.

Outflow to Sub-Area 1

Using the corrected to zero value from table WB-1, the calculated outflow from Sub-Area 2 to Sub-Area 1 is about 2,020 acre-ft/yr. The likely range is from 1,820 to 2,220 acre-ft/yr (±10%).

Sub-Area 2 Summary

Using the best estimate values discussed above, there appears to be a budget deficit of about 80 acre-ft/yr (3% of outputs) in Sub-Area 2 (table WB-3).

Hydrographs from wells located in the northern and western portions of Sub-Area 2 show no changes in storage (fig. WB-13); however, in the southeastern part of the Sub-Area where there is relatively intense development, hydrographs show downward trends (fig. WB-14) consistent with a probable water budget deficit.

Total outflow for Sub-Area 2 is about 2,500 acre-ft of water per year. As such, consumptive use from wells accounts for about 19 percent of the total outflow (480 acre-ft/yr).

Table WB-3
Sub-Area 2 Water Budget
Calculated Values in Acre-Feet per Year

INPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Diffuse Infiltration	1,946	100	1,557	2,335
OUTPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Well Withdrawals	483	19.3	444	555
Outflow to Sub-Area 1	2,023	80.7	1,820	2,225
TOTAL OUT	2,506	100.0	2,264	2,780

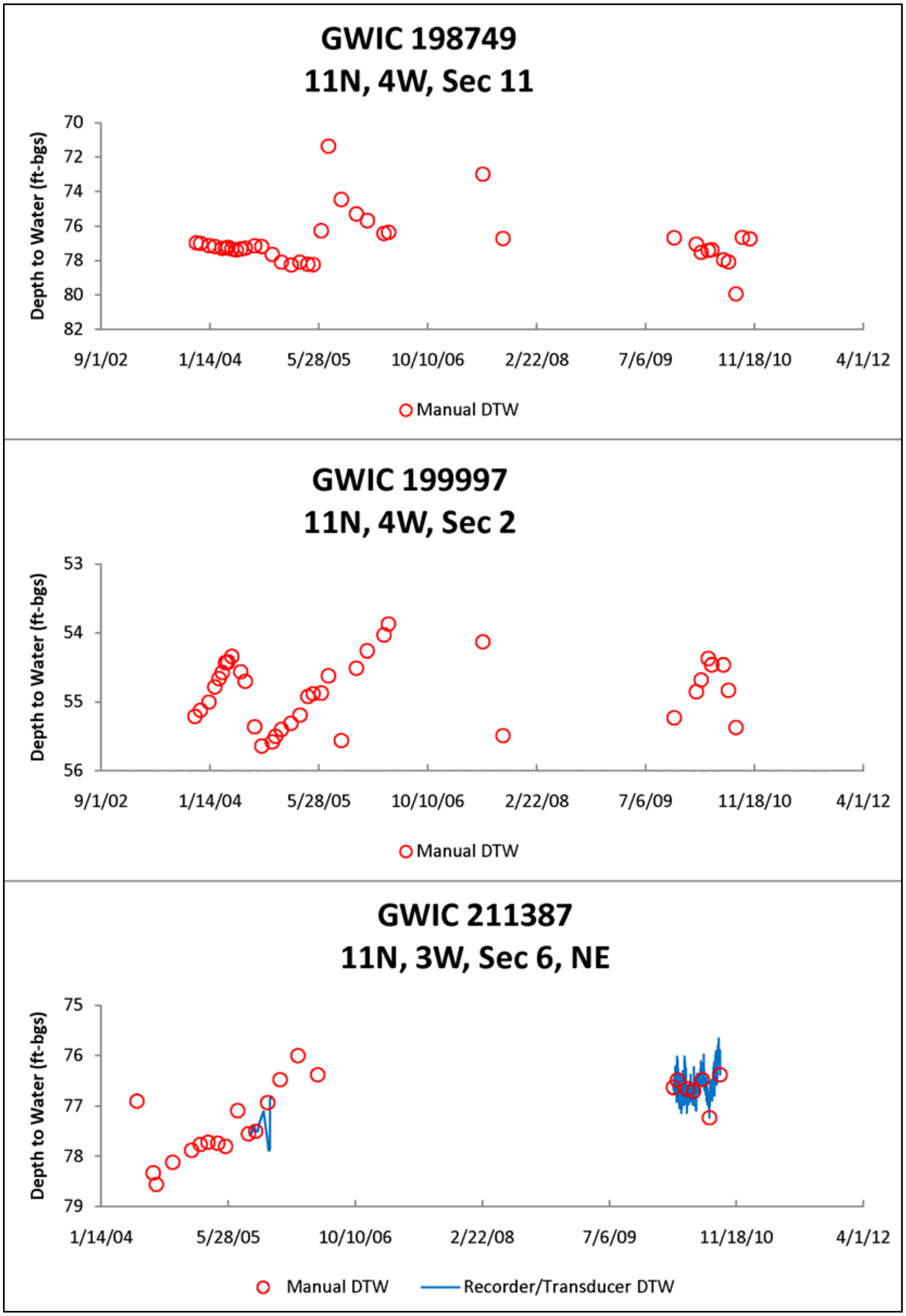


Figure WB-13. Hydrographs with no trend in the western and northern portions of Sub-Area 2.

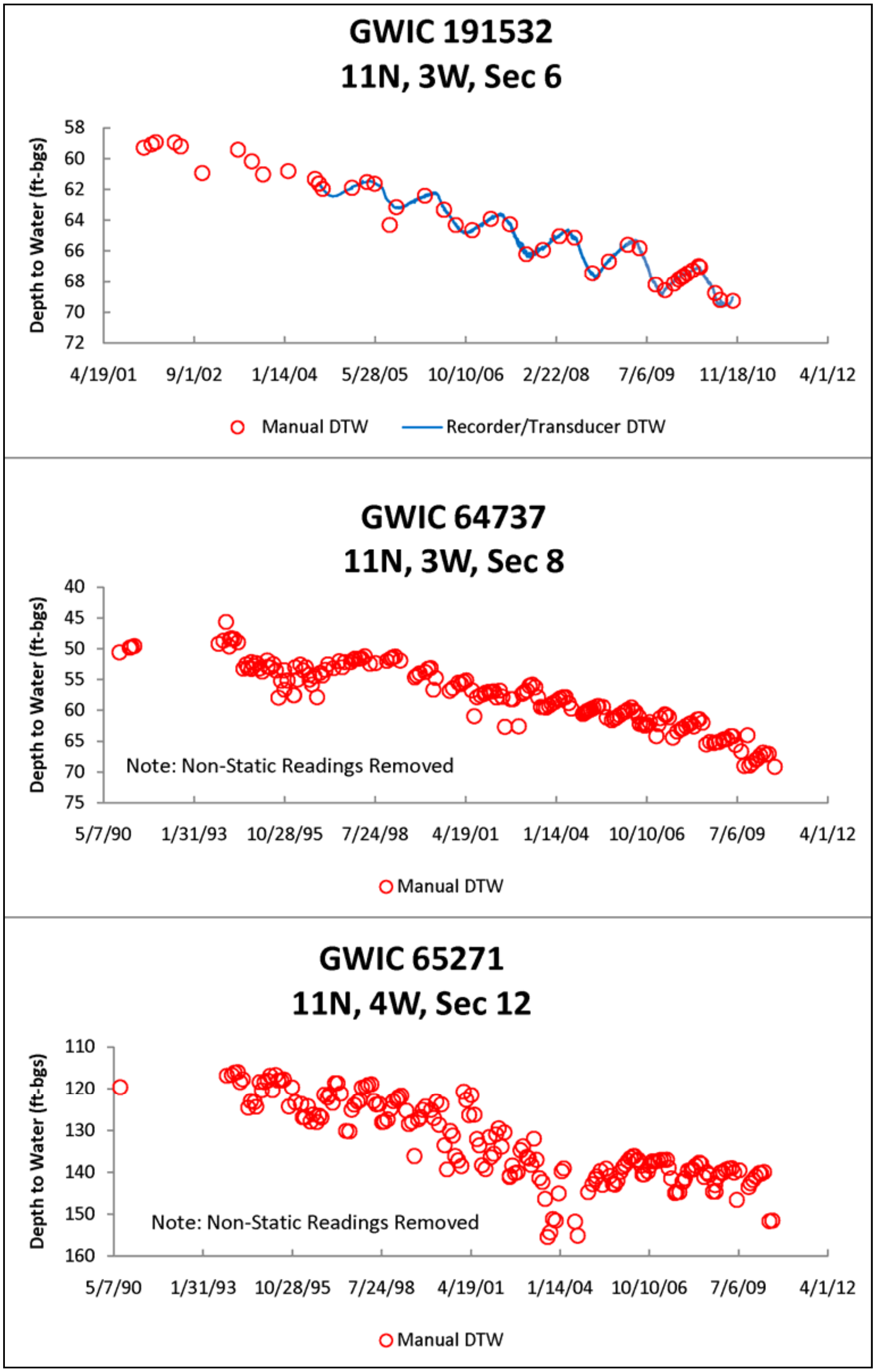


Figure WB-14. Falling hydrographs in the southeastern portion of Sub-Area 2.

Sub-Area 3

The water budget for Sub-Area 3 is similar to that for Sub-Area 2; however, there are fewer homes. The water budget for Sub-Area 3 can be written as:

$$D\_INF = WL\_OUT + A1\_OUT \pm \Delta S,$$

where:

D_INF, diffuse infiltration;
WL_OUT, withdrawals from wells;
A1_OUT, outflow to Sub-Area 1 (same as A3_IN for Sub-Area 1); and
ΔS, changes in storage.

Sub-Area 3 Inputs

Diffuse infiltration is the only source of recharge water in this area, because there are no-flow boundaries (groundwater divides and flow lines) on three sides and an outflow boundary on the fourth side. Monitoring of surface drainages in this area shows that there is little if any annual runoff, so diffuse infiltration is equal to precipitation, less ET.

Similar to Sub-Area 2, METRIC data show that on the pediment precipitation and ET are equal. Assuming 3.75 in of infiltration in the hills (7,789 acres within Sub-Area 3), the area receives about 2,430 acre-ft/yr of recharge with a probable range from 2,190 to 2,680 acre-ft/yr.

Sub-Area 3 Outputs

Well Withdrawals

2009 air photos show 277 homes in Sub-Area 3. Using a rate of 435 gpd per home as in Sub-Area 1, groundwater withdrawn by wells is approximately 135 acre-ft/yr, and the probable range is from 120 to 160 acre-ft/yr.

Outflow to Sub-Area 1

The calculated outflow from Sub-Area 3 to Sub-Area 1, assuming a K equal to 2.5 ft/d, is about 2,290 acre-ft/yr with a probable range between 915 and 4,580 acre-ft/yr. Assuming no change in groundwater storage in Sub-Area 1 during the period covered by the water budget, outflow from Sub-Area 3 to Sub-Area 1 should be about 2,200 acre-ft/yr in order to balance the water budget for Sub-Area 1.

Sub-Area 3 Summary

Using the best estimate values discussed above, there is an estimated excess of 96 acre-ft/yr in Sub-Area 3 (table WB-4), which, considering the errors in all the factors, shows that the Sub-Area is essentially in balance.

Total outflow for Sub-Area 3 is about 2,400 acre-ft/yr. As such, consumptive use through wells accounts for about 5.6 percent of the total outflow (135 acre-ft/yr).

Table WB-4
Sub-Area 3 Water Budget
Calculated Values in Acre-Feet per Year

INPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Diffuse Infiltration	2,434	100	2,191	2,678
OUTPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Well Withdrawals	135	5.8	124	155
Outflow to Sub-Area 1	2,203	94.2	916	4,581
TOTAL OUT	2,338	100	1,040	4,736

Sub-Area 4

The water budget for Sub-Area 4 is somewhat different than the other upland areas because it includes bedrock inflow. Because it is mostly pediment, there is no diffuse infiltration. The water budget for Sub-Area 3 can be written as:

$$BR\_IN = + WL\_OUT + A1\_OUT \pm \Delta S,$$

where:

BR_IN, bedrock inflow;
ΔS, changes in storage;
WL_OUT, withdrawals from wells; and
A1_OUT, outflow to Sub-Area 1 (same as A4_IN for Sub-Area 1).

Sub-Area 4 Inputs

The bedrock inflow is the only input for Sub-Area 4 and is calculated in the same manner as A4_IN was calculated for Sub-Area 1, which shows that about 1,200 acre-ft/yr flows across the 4,000-ft above mean sea level (amsl) potentiometric contour (fig. WB-15). The probable range is from 830 to 1,670 acre-ft/yr.

Sub-Area 4 Outputs

Well Withdrawals

2009 air photos show that there are eight homes in Sub-Area 4, using a rate of 435 gpd per home as in Sub-Area 1, groundwater withdrawn by wells is approximately 4 acre-ft/yr, and are probably in the range from 3.6 to 4.5 acre-ft/yr.

Outflow to Sub-Area 1

Outflow to Sub-Area 1 is the same as that calculated as bedrock inflow and is about 1,200 acre-ft/yr. The probable range is from 830 to 1,670 acre-ft/yr.

Sub-Area 4 Summary

Because BR_IN and A1_OUT have the same value, they by definition add to zero within the budget. The result is that the only loss to the area’s water budget is due to consumptive use by wells. However, the potential loss due to consumptive groundwater use is so small that it is well below the uncertainty in the calculations and can be considered to be zero.

Total outflow for Sub-Area 4 is about 1,260 acre-ft/yr. Consumptive use through wells accounts for about 0.3% of the total outflow (about 4 acre-ft/yr). The budget for Sub-Area 4 is summarized in table WB-5.

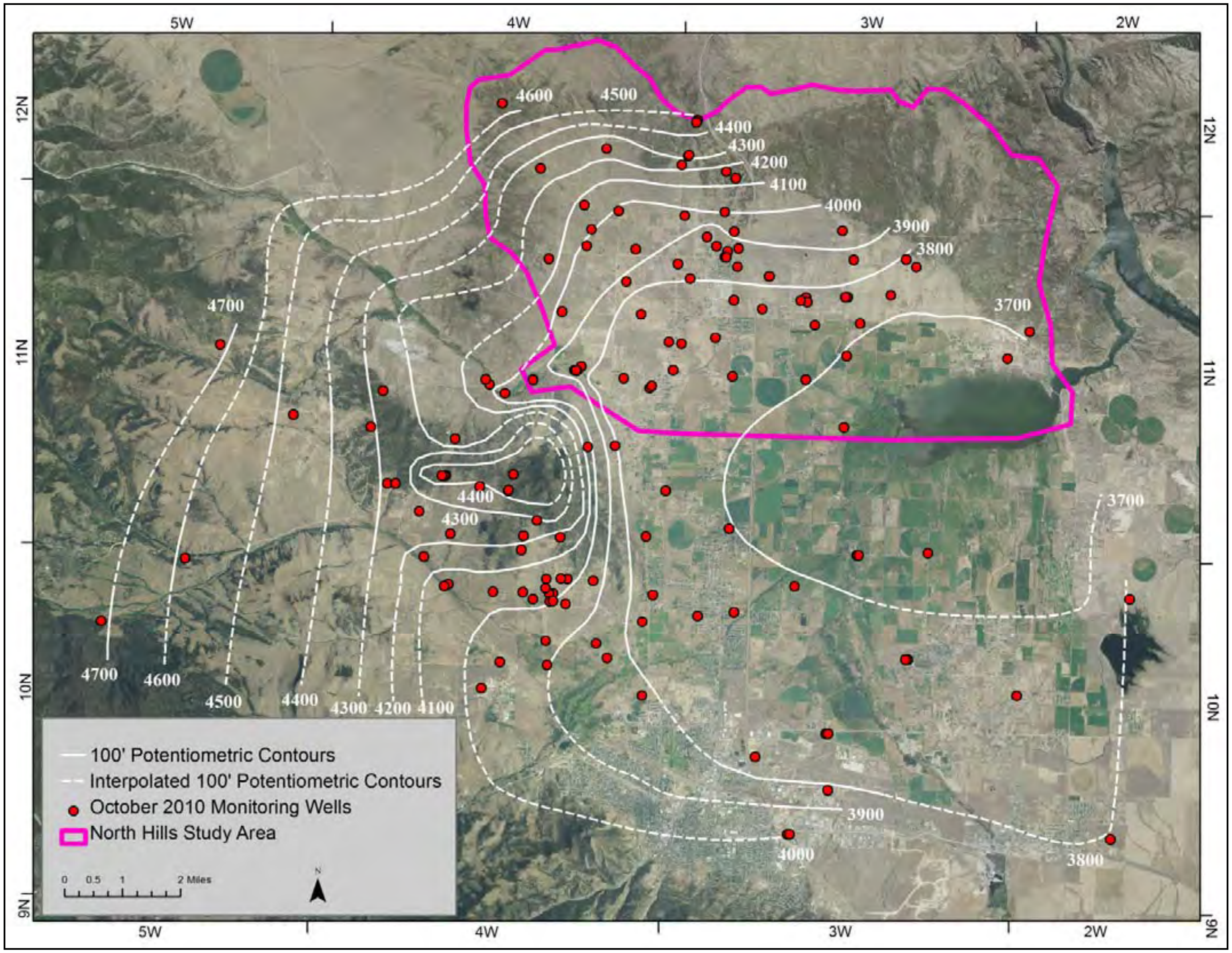


Figure WB-15. This composite potentiometric surface map (October 2010 data) indicates that groundwater flow is from the hills adjacent to the Helena Valley to Lake Helena. The greater spacing of the contours in the valley indicates that the aquifer is more permeable.

Table WB-5
Sub-Area 4 Water Budget
Calculated Values in Acre-Feet per Year

INPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Bedrock Inflow	1,252	100	834	1,669
OUTPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Well Withdrawals	3.9	0.3	3.6	4.5
Outflow to Sub-Area 1	1,204	99.7	834	1,669
TOTAL OUT	1,256	100	838	1,673

Combined Groundwater Budget

The total groundwater budget for the North Hills study area is the mathematical combination of the sub-area budgets. During the summation, terms that contain values for flow between sub-areas cancel out. The result is:

$$SC_{al}\_IN + BR\_IN + D\_INF + SC\_INF + IC\_INF + IR\_INF = SD\_OUT + LH\_OUT + WL\_OUT \pm \Delta S,$$

where:

SC_{al}_IN, inflow from Silver Creek alluvium at SC3;
BR_IN, bedrock inflow at Sub-Area 4;
D_INF, diffuse infiltration (forested hills of Sub-Areas 2 and 3);
SC_INF, Silver Creek infiltration;
IC_INF, irrigation canal infiltration;
IR_INF, irrigation recharge (irrigated areas);
SD_OUT, groundwater flow to streams and drains;
LH_OUT, groundwater flow to Lake Helena;
WL_OUT, withdrawals from wells; and
ΔS, change in storage.

For the area-wide budget, the adjusted-to-zero values were used for Sub-Area 1, and best-estimate values were used for all other sub-areas (table WB-6 and fig. WB-16). The area-wide budget has an apparent 3 percent water deficit, which is well within the uncertainty of the analysis. It is reasonable that there is some deficit because hydrographs in some parts of the North Hills study area have consistent downward trends.

Table WB-6
North Hills Water Budget
Calculated Values in Acre-Feet per Year

INPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	percent	Minimum	Maximum
Silver Creek Alluvium Inflow	19.6	0.1	13.9	27.8
Bedrock Inflow	1,252	9.3	834	1,669
Diffuse Infiltration	4,380	32.4	3,942	4,818
Silver Creek Infiltration	936	6.9	876	1,071
Irrigation Canal Leakage	2,499	18.5	2,339	2,858
Irrigation Recharge	4,421	32.7	4,138	5,057
TOTAL IN	13,508	100	12,143	15,501
OUTPUTS				
	Best Estimate		Probable Budget	
	acre-ft/yr	Percent	Minimum	Maximum
Discharge to Drains	3,129	22.5	2,704	3,304
Discharge to Lake Helena	9,733	69.9	8,411	10,280
Well Withdrawals	1,066	7.7	959	1,172
TOTAL OUT	13,927	100	12,074	14,757

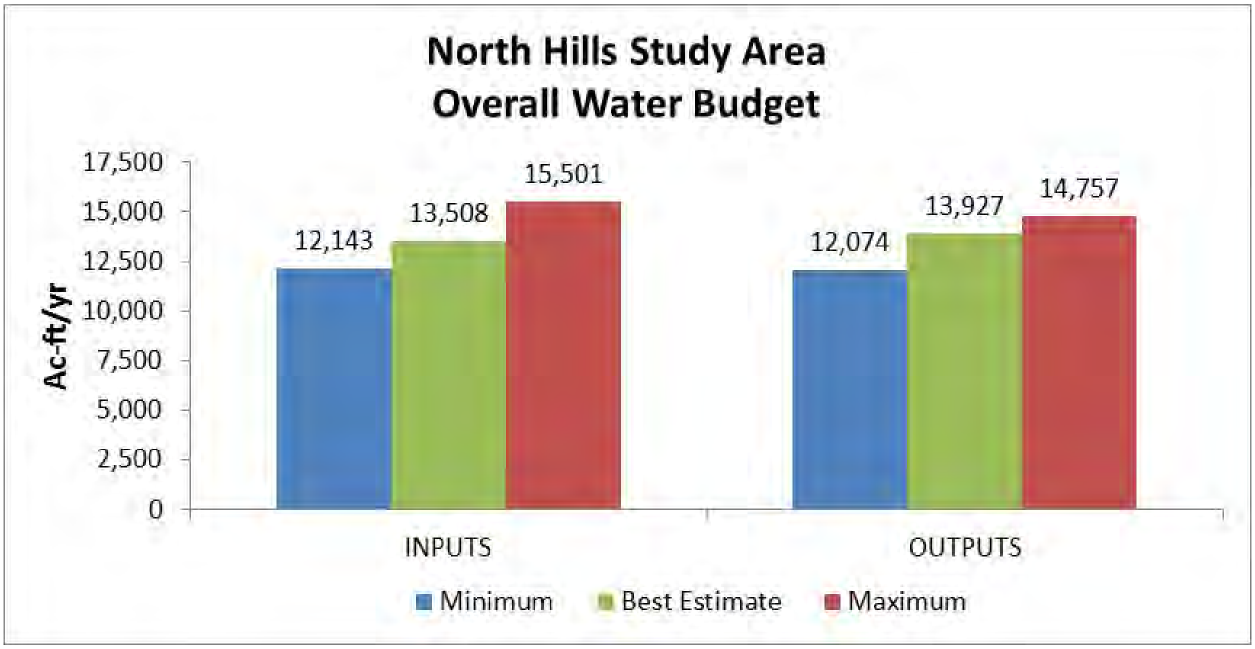


Figure WB-16. Overall water budget for the North Hills study area.

SUMMARY

While there may be an overall deficit in the North Hills study area groundwater budget, it is slight, and cannot be definitively measured using a water budget. That there is a deficit is shown by some hydrographs that have consistent downward trends, which are localized to areas where bedrock and Tertiary aquifers are used for high-density housing developments.

Overall, the North Hills area transmits about 13,750 acre-ft of water per year as groundwater. The probable range is from 12,000 to 15,500 acre-ft per year. Wells withdraw about 8 percent of the total flow (1,070 acre-ft/yr). Sub-Area 2 has the highest percentage of water used by wells (19 percent), and that is the area with the clearest evidence for falling water levels.

The results of this analysis were used to constrain the groundwater model prepared for the North Hills study area (Waren and others, 2013). Numerical modeling can evaluate the likelihood that the aquifer can come into equilibrium with current stresses, or if the current level of development exceeds the aquifer's ability to supply water over the long term. If current development can be supported, the level of development that can be sustained will also be evaluated.

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APPENDIX WB-A—Distribution of Domestic Consumptive Use

Table WB-A1
Calculation of Total Consumptive Water Use in the North Hills (acre-ft/yr)
(Analysis of 2009 aerial photographs used to determine the number of homes)

Area	Sub-Area 1	Sub-Area 2	Sub-Area 3	Sub-Area 4	North Hills
Number of Homes	874	991	277	8	2,150
Consumptive Use Estimates					
DNRC (477 gpd/home)	467	530	148	4.3	1,150
Townview Subdivision (408 gpd/home)	400	453	127	3.7	983
Ranchview and Skyview (420 gpd/home)	411	467	130	3.8	1,012
Northstar Subdivision (506 gpd/home)	496	562	157	4.5	1,219
Average (453 gpd/home)	444	503	141	4.1	1,091
Average Excluding Northstar (435 gpd/home)	426	483	135	3.9	1,029

Table WB-A2

Calculation of Consumptive Use in the Pumping Centers Over Time (acre-ft/yr)

	Year	Homes	Consumptive Use Estimates		
			400 gpd/res	435 gpd/res	500 gpd/res
Pumping Center A	1995	130	58	63	73
	2005	312	140	152	175
	2009	441	198	215	247
Pumping Center B	1995	78	35	38	44
	2005	189	85	92	106
	2009	250	112	122	140
Pumping Center C	1995	120	54	59	67
	2005	241	108	118	135
	2009	274	123	134	154

Table WB-A3

Consumptive Use in Pumping Center A by Month (acre-ft)

Using 435 gpd/residence

	Percent by month	1995	2005	2009
Jan	0.3	0.2	0.5	0.6
Feb	0.3	0.2	0.5	0.6
Mar	0.4	0.3	0.6	0.9
Apr	0.6	0.4	0.9	1.3
May	10.2	6.4	15.5	21.9
Jun	18.2	11.5	27.7	39.1
Jul	26.2	16.5	39.8	56.3
Aug	26.4	16.6	40.1	56.8
Sep	14.2	8.9	21.6	30.5
Oct	2.4	1.5	3.6	5.2
Nov	0.5	0.3	0.8	1.1
Dec	0.2	0.1	0.3	0.4
Total	100	63	152	215

Table WB-A4
Consumptive Use in Pumping Center B by Month (acre-ft)
Using 435 gpd/residence

	Percent by month	1995	2005	2009
Jan	0.3	0.1	0.3	0.4
Feb	0.3	0.1	0.3	0.4
Mar	0.4	0.2	0.4	0.5
Apr	0.6	0.2	0.6	0.7
May	10.2	3.9	9.4	12.4
Jun	18.2	6.9	16.7	22.2
Jul	26.2	10.0	24.1	32.0
Aug	26.4	10.0	24.3	32.2
Sep	14.2	5.4	13.1	17.3
Oct	2.4	0.9	2.2	2.9
Nov	0.5	0.2	0.5	0.6
Dec	0.2	0.1	0.2	0.2
Total	100	38	92	122

Table WB-A5
Consumptive Use in Pumping Center C by Month (acre-ft)
Using 435 gpd/residence

	Percent by month	1995	2005	2009
Jan	0.3 0.2		0.4	0.4
Feb	0.3	0.2	0.4	0.4
Mar	0.4	0.2	0.5	0.5
Apr	0.6	0.4	0.7	0.8
May	10.2	6.0	12.0	13.6
Jun	18.2	10.6	21.4	24.3
Jul	26.2	15.3	30.8	35.0
Aug	26.4	15.4	31.0	35.3
Sep	14.2	8.3	16.7	19.0
Oct	2.4	1.4	2.8	3.2
Nov	0.5	0.3	0.6	0.7
Dec	0.2	0.1	0.2	0.3
Total	100	59	118	134

GEOPHYSICAL INVESTIGATIONS

Geophysical Investigations in the North Helena Valley

A summary of geophysical methods employed in conjunction with the North Hills and Scratchgravel Hills Ground Water Investigations

Kirk B. Waren

Bouguer gravity anomaly data from the U.S. Geological Survey (USGS) were contoured and evaluated by Ground Water Investigation Program (GWIP) staff as part of the Helena-area GWIP investigations. Also, the Geophysical Engineering Department of Montana Tech of the University of Montana conducted several geophysical surveys that used a variety of methods within the study area.

Regional Bouguer gravity survey data were obtained from the USGS and combined with previously mapped aquifers (Kucks, 1999; Madison, 2006; fig. 1). The boundary between the bedrock and Tertiary aquifers is generally between the 160 and the 162.5 Mgal intermediate contour. The prominent low-gravity area in the central part of the Helena Valley, south of Lake Helena, is thought to represent a thickness of unconsolidated sediments approaching 6,000 ft (Noble and others, 1982). There is a secondary gravity low near the northward extension of the Quaternary aquifer west of Interstate 15.

Numerous geophysical methods were applied by the Montana Tech Geophysics Department in the North Hills study area to explore which methods might produce useful products for the GWIP program, test equipment, and train students. The fieldwork resulted in student-authored reports under oversight by the Geophysical Department professors. These reports are considered draft products that primarily demonstrate the capabilities of the methods, rather than refined products. Nevertheless, the reports contain useful information and serve as applied geophysics examples to area residents, consultants, and government agencies. The reports are available on the GWIP website to read or download at: http://mbmg.mtech.edu/gwip/gwip.asp.

Electrical, electromagnetic, and seismic geophysical surveys conducted in 2010 demonstrated that these methods have potential for identifying shallow sand and clay lenses, the water table, and in some cases depth to bedrock (R. Ainsworth, B. Andreas, M.Bray, A. Dutton, J. Hyde, B. Kaphammer, and M. Klug, written commun., 2010; N. Kunstek and Z. Woodward, written commun., 2010; B.Williams, and D. Sunwall, written commun., 2009). Use of these methods at a site in 2011 further demonstrated a capability of characterizing the Helena Valley Fault (U.Celik, M. Desjardins, T. Gilskey, D. Hicks, T. Hutson, B. Kuhn, D. Majeau, C. Meis, and A. Roos, written commun., 2011). Gravity and magnetic surveys demonstrated the potential to gather some area-wide information concerning faults, the depth to bedrock, and igneous bodies (A. Dutton, B. Kaphammer, J. Hyde, M. Bray, M. Klug, B. Andreas, and R. Ainsworth, written commun., 2010; U. Celik, M. Desjardins, T. Gilskey, D. Hicks, T. Hutson, B. Kuhn, D. Majeau, C. Meis, and A. Roos, written commun., 2011).

Electrical and electromagnetic methods applied during 2009 and 2010 included Schlumberger surveys, time domain electromagnetic (TDEM) surveys, low induction loop-loop inductive surveys, and dipole-dipole and Geonics EM-31 and EM-34 small loop frequency domain electrical resistivity surveys. Most of these surveys were conducted near sec. 8, T. 11 N., R. 3 W. on State-owned land between Montana Avenue and Interstate 15, and also on the O'Reilly Ranch on the east side of Interstate 15. The geophysical methods provided interpreters with a sense of variability in the surficial Quaternary or Tertiary materials, but did not provide much information useful to the current GWIP studies about the aquifer beneath the water table. These methods may have potential to evaluate small areas or areas with more contrasting conditions at depths of up to 50 ft. The utility of these applications likely would have been improved if cuttings or samples from nearby boreholes were available to compare to the geophysical properties. The dipole-dipole method employed on the State land and on the O'Reilly Ranch on the east side of I-15 seemed especially applicable to defining clay and sand lenses in the generally unsaturated colluvium. A seismic refraction survey conducted on the walking path west of Montana Avenue demonstrated that these methods might be able to determine water table and rock-type changes at depths up to about 90 ft, but lack of quality-control data limited the evaluation of the methods at this site.

Electrical, electromagnetic, and seismic methods were applied in 2011 at a site located along the Helena Valley Fault (U. Celik, M. Desjardins, T. Gilskey, D. Hicks, T. Hutson, B. Kuhn, D. Majeau, C. Meis, and A. Roos, written commun., 2011). Conductivity surveys using EM-31 and EM-34 small loop frequency domain, dipole-dipole resistivity surveys, and a seismic refraction survey suggest that there are actually two faults about 150 to 300 ft apart and that the fault zones are about 90 to 100 ft wide. The survey data also suggest that near land surface the faults dip to the south at about 64 degrees, but the dip increases to near vertical at depth.

Gravity and magnetic surveys were conducted over a large area (figs. 2, 3). The gravity survey provides some evidence of faults in the subsurface bedrock beneath the pediment. The depths and geometry presented in the cross sections along Applegate Drive and Montana Avenue seemed quite abrupt and severe, as depths to bedrock plummet from about a few hundred yards to about 1,500 to 3,000 ft below land surface near Valley View Road along the Applegate Drive profile, and just north of Valley View Road along Montana Avenue (fig. 2). This location is proximal to the northern lobe of the Quaternary aquifer mapped by Madison (2006); Applegate Drive is on the western edge of the lobe. The magnetic survey and the gravity survey both suggest that bedrock is displaced down to the south along Applegate Drive near its junction with Valley View Road. To the south, at Lincoln Road, there are gravel pits that are more than 60 ft deep in Quaternary alluvium. The data in figures 2 and 3 should be considered most accurate along the black lines of the surveys. Additional gravity and magnetic surveys were conducted in 2011. Results from these surveys further illustrate the capability of gravity and magnetic methods to assess depth to bedrock. Comparison with well log data suggests the depths to bedrock may be significantly less than that determined by the geophysical methods. For example, well logs suggest bedrock lies at depths of about 400 ft near the fault shown at 4 km from bedrock in figure 10 of A. Dutton, B. Kaphammer, J. Hyde, M. Bray, M. Klug, B. Andreas, and R. Ainsworth, written commun., (2010), whereas their figure suggests a bedrock depth of about 900 m (nearly 3,000 ft).

The geophysical projects that provided the most relevant information for the North Hills Ground Water Investigation Study were the assessment of the Helena Valley Fault using electrical, electromagnetic, and seismic methods, and the gravity survey of the northwest part of the Helena Valley. The assessment of the Helena Valley Fault led to immediate improvements in GWIP's understanding of the fault planes and breccia zones near an aquifer test site. The gravity surveys suggest the presence of additional, east–west-oriented, buried faults that displace bedrock downward to the south. These faults are located about a mile north of Lincoln Road, where well log data and the slope of the potentiomentric surface also suggest rapid thickening of coarse valley-fill sediments.

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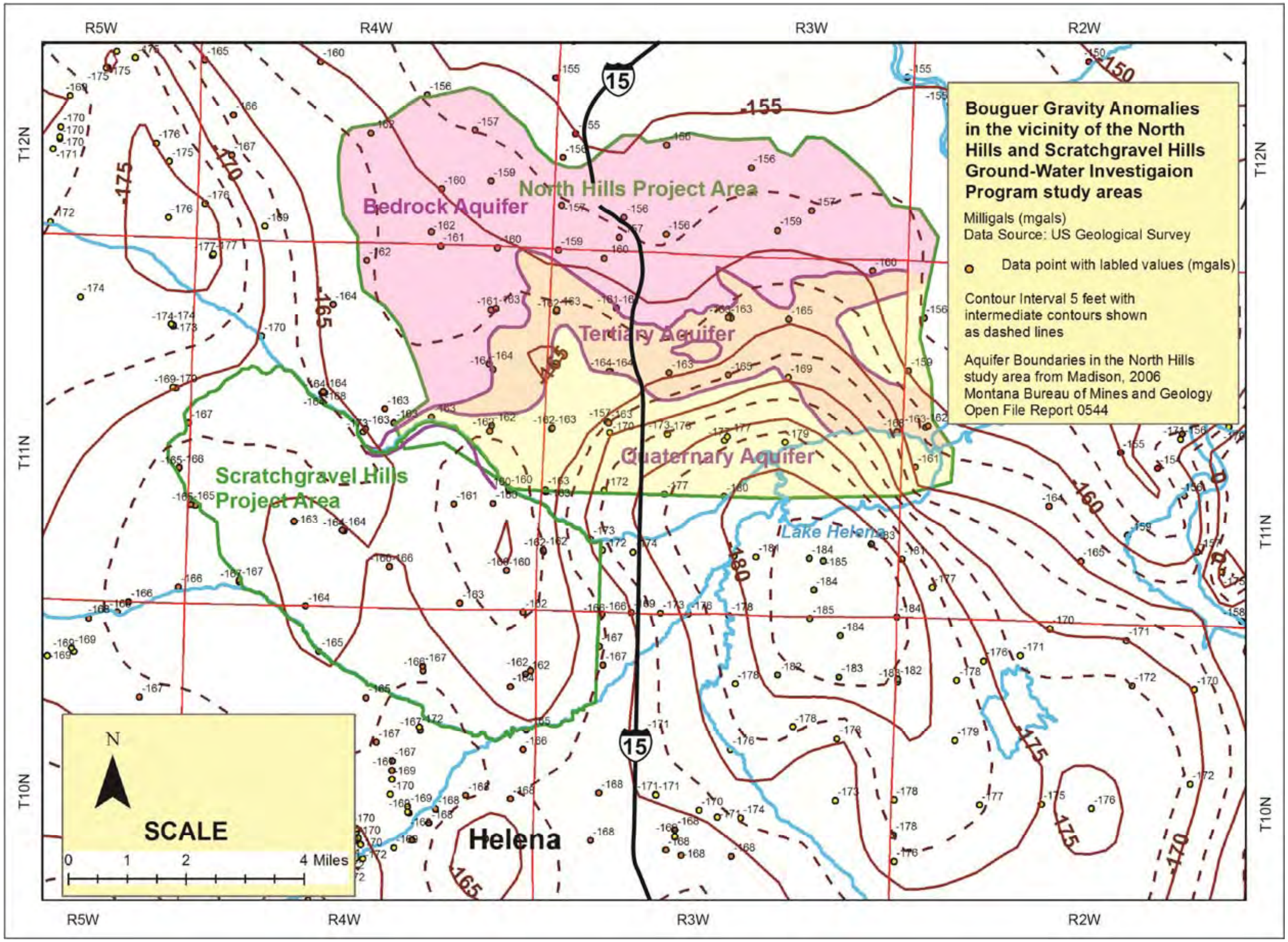

Figure 1. Bouguer gravity anomalies mapped using U.S. Geological Survey data.

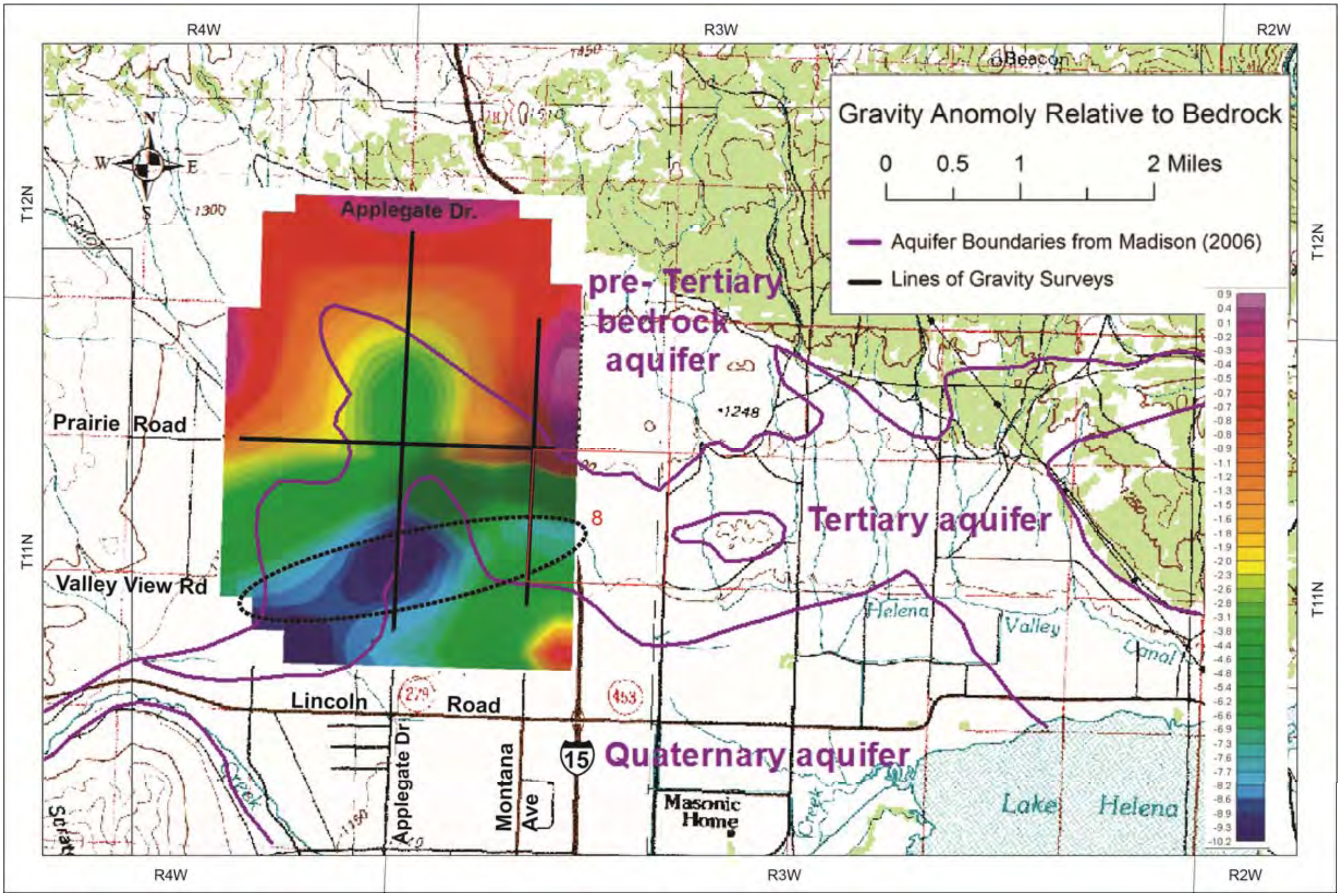

Figure 2. Gravity anomaly relative to bedrock, provided by the Montana Tech Geophysics Department. The colors display increasing negative gravity anomaly, from red in the northern part of the image, where bedrock is within a few feet of the surface, to the deep blues in the southern part, where bedrock is buried by many hundreds of feet of valley fill sediments. The dashed oval encompasses a low in the gravity data that indicates the presence of a fault (Dutton and others, 2010). Gravity anomaly scale is in mGal.

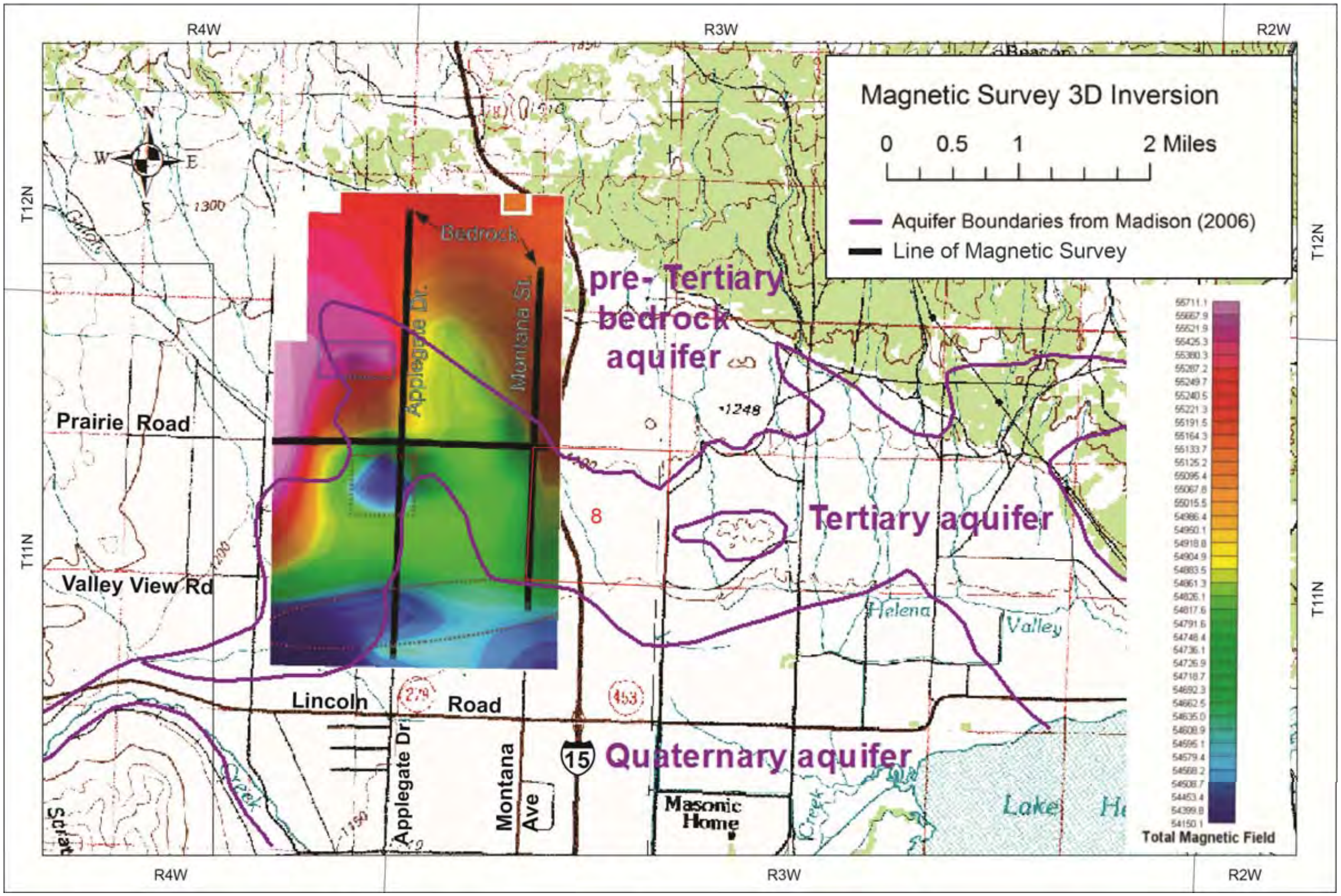

Figure 3. Total magnetic field relative to bedrock, provided by the Montana Tech Geophysics Department. The colors display decreasing magnetic anomaly, from red in the northern part of the image, where bedrock is within a few feet of the surface, to the deep blues in the southern part, where bedrock is buried by many hundreds of feet of valley fill sediments. The dashed oval notes a trench of magnetic low trending southwest to northeast which is associated with a fault (Dutton and others 2010). Magnetic field values are in nanoteslas (nT).

WATER CHEMISTRY

The following tables and maps summarize the water-quality sampling effort in the North Hills study. All sample results are available in the Ground Water Information Center (GWIC) (http://mbmggwic.mtech.edu/) for each site, using its GWIC ID number.

This sampling was conducted to gain information on the water quality throughout the study area and to evaluate its seasonal variability. The effect on groundwater quality from septic system effluent was also a major focus.

Table WQ-1 identifies groundwater sites that were sampled, the dates they were sampled, and the parameters analyzed. Figure WQ-1 shows the locations of the sampling sites.

Table WQ-2 identifies surface-water sites that were sampled, the dates they were sampled, and the parameters analyzed. Figure WQ-2 shows the locations of the sampling sites.

Table WQ-3 provides a complete list of analytical parameters for a standard sample. Selected samples were also analyzed for different isotopes and Organic Waste-Water Chemicals (OWCs; a.k.a. pharmaceuticals).

Table WQ-4 provides sample results for major ions, presented as milliequivalants, and as constituent percents. These values were used to display constituents on Piper and Stiff diagrams. Results for other parameters are available on GWIC.

Table WQ-1. North Hills Groundwater Sampling Summary

GWIC ID	Site Name	Aquifer	Well Depth (ft)		Sample Dates				Isotope Sample Dates					OWCs
									O & D***	Sulfur	Nitrate	Radon		
5854	USGS * MASONIC WEST	110ALVM	65		15-Apr-10	1-Sep-10	ns		6/2/2010	ns	ns	ns		ns
64730	HEDDEN, BRETT AND KIRA	400SPKN	170		14-Apr-10	18-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
64774	COLE CONNIE	400SPKN	420		14-Apr-10	18-Aug-10	06-Oct-10		ns	ns	ns	10/6/2010		4/28/2011
64798	CHASE, ERIC	110UDFD	85		07-Apr-10	17-Aug-10	06-Oct-10		5/25/2010	4/7/2010	ns	10/6/2010		4/28/2011
65316	SMELKO, DANIEL B.	111ALVM	97		06-Apr-10	12-Aug-10	07-Oct-10		ns	ns	ns	ns		ns
66319	WALTHER JAMES	400SPKN	300		14-Apr-10	20-Aug-10	ns		ns	ns	ns	ns		ns
128054	TUCKER LISA	400SPKN	390		06-Apr-10	18-Aug-10	06-Oct-10		ns	ns	ns	10/6/2010		ns
138527	WALTHER JAMES	400SPKN	356		14-Apr-10	20-Aug-10	07-Oct-10		ns	ns	ns	10/7/2010		ns
143645	SALISBURY JEFF AND JUDY	400SPKN	174		ns	21-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
144725	STOLP, JUSTIN AND STACY	400SPKN	192		06-Apr-10	18-Aug-10	06-Oct-10		ns	ns	ns	10/6/2010		ns
144726	CROWLEY PAT	120SNGR	240	*	06-Apr-10	17-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
145957	PURCELL WILLIAM S	400GRSN	115		06-Apr-10	17-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
152551	HEDDEN ROGER	400GRSN	170		16-Apr-10	20-Aug-10	30-Sep-10		ns	ns	8/20/2010	9/30/2010		ns
176010	NYSTRAND ROBERT	120SDMS	259		06-Apr-10	17-Aug-10	06-Oct-10		ns	ns	ns	10/6/2010		ns
178386	PETROSKY JEFF & ANGELE	400SPKN	98		06-Apr-10	18-Aug-10	06-Oct-10		ns	ns	ns	10/6/2010		ns
180976	DONOHUE DAVE	400SPKN	370	**	07-Apr-10	21-Aug-10	30-Sep-10		5/25/2010	4/15/2010	8/24/2010	9/30/2010		ns
187438	NJOS KAL	400SPKN	120		07-Apr-10	20-Aug-10	05-Oct-10		5/25/2010	4/7/2010	8/20/2010	10/5/2010		ns
191532	LCWQPD - NORTH HILLS WELL	111ALVM	100		15-Apr-10	19-Aug-10	20-Oct-10		6/1/2010	4/15/2010	ns	10/20/2010		ns
191534	LCWQPD - GRAVEL PIT WELL	111ALVM	100		ns	19-Aug-10	20-Oct-10		ns	ns	ns	10/20/2010		ns
191537	LCWQPD - LINCOLN AND MONTANA	110ALVM	43		ns	19-Aug-10	20-Oct-10		ns	ns	ns	10/20/2010		ns
194435	HEDDEN, MICHAEL AND CRISTIE	400SPKN	57		07-Apr-10	18-Aug-10	30-Sep-10		5/25/2010	4/7/2010	ns	9/30/2010		ns
198749	RAND MICHAEL AND CYNTHIA	400SPKN	340		16-Apr-10	21-Aug-10	30-Sep-10		ns	ns	8/24/2010	9/30/2010		ns
202175	WINSLOW, LYNN AND TRUDY	400GRSN	98		14-Apr-10	18-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
206026	BRENSDAL KEN	400GRSN	200		14-Apr-10	20-Aug-10	30-Sep-10		ns	ns	8/20/2010	9/30/2010		ns
206393	KREI ROBERT D.	400GRSN	177		14-Apr-10	18-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		ns
227906	STEVENS, JERRY	110ALVM	49		16-Apr-10	12-Aug-10	07-Oct-10		ns	ns	ns	10/7/2010		ns
243352	WOEHL HERMAN	400SPKN	156		ns	21-Aug-10	05-Oct-10		ns	ns	ns	10/5/2010		4/27/2011
257064	MBMG COLLINS DRIVE	110ALVM	55		ns	19-Aug-10	20-Oct-10		ns	ns	ns	10/20/2010		ns

Aquifer Codes

110ALVM	Quaternary Alluvium
110UDFD	Cenozoic Undifferentiated
111ALVM	Holocene Alluvium
120SDMS	Tertiary Sediments
120SNGR	Tertiary Sand & Gravel
400GRSN	Bedrock - Greyson Shale
400SPKN	Bedrock - Spokane Shale

* Duplicate sample collected 4/16/10 with different sample team
** Duplicate sample collected 4/7/10 with different sample team
*** Oxygen and Dueterium isotopes of water molecules
ns - not sampled
OWCs = Organic Waste-Water Chemicals

GWIC - http://mbmggwic.mtech.edu/

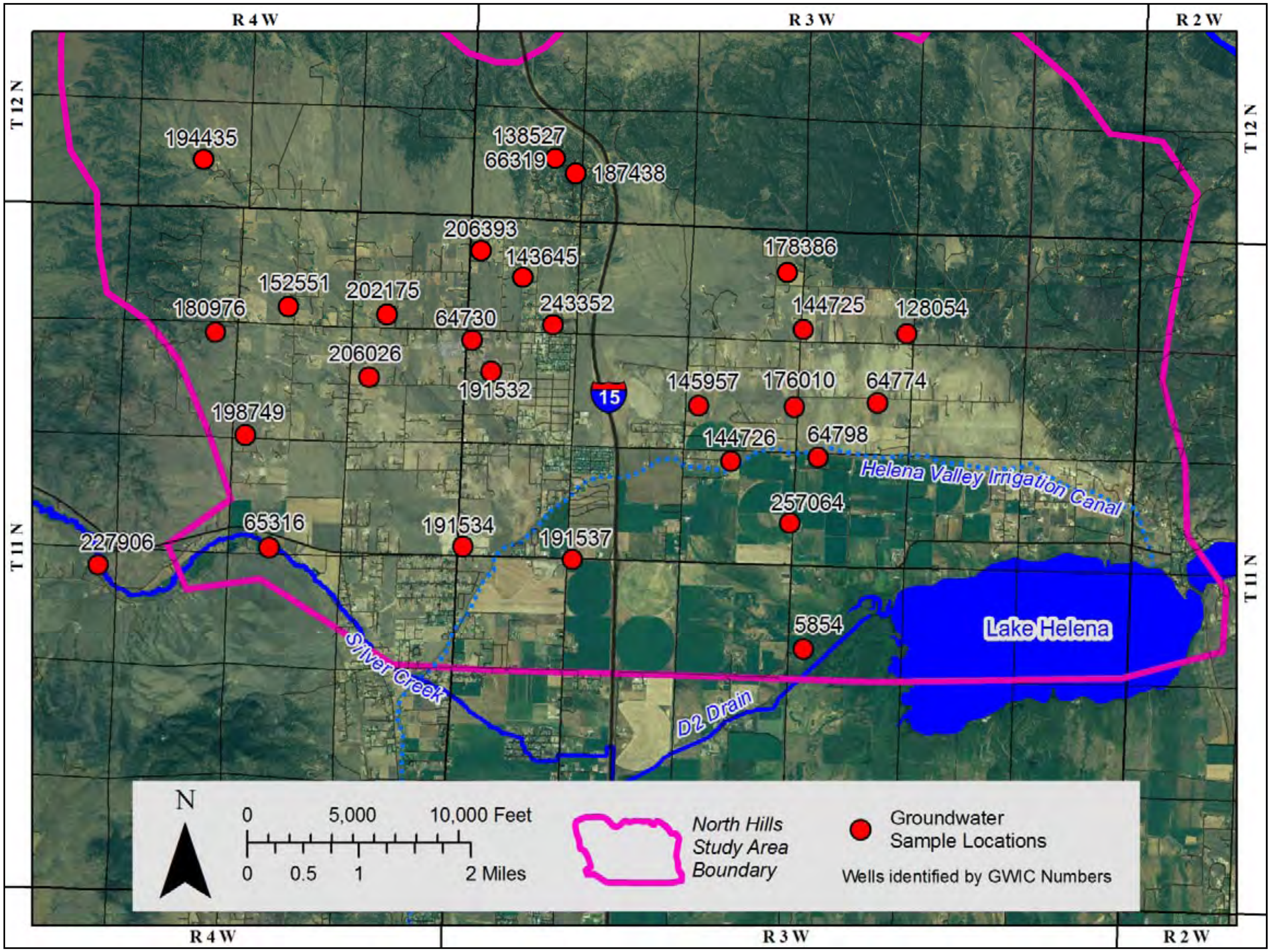

Figure WQ-1. A total of 87 groundwater samples were collected at 28 sites in the North Hills. Numbers designate the GWIC ID number for each site (http://mbmggwic.mtech.edu/).

Table WQ-2. North Hills Surface-Water Sampling Summary

GWIC ID	Site Name	Site Type		Sample Dates				Isotope Sample Dates	
								Oxygen	Sulfur
255052	HVID D-2-2.3-1 (DA)	Drain		4/6/2010	8/12/2010	10/11/2010		3/2/2010	ns
255069	HVID D-2-2.3-2L (DC)	Drain		4/6/2010	8/13/2010	10/11/2010		ns	ns
255071	HVID D-2-0.7-1 (DD)	Drain		4/7/2010	8/12/2010	10/11/2010		4/7/2010	4/7/2010
255072	HVID D-1_UPPER (DE)	Drain		4/6/2010	8/13/2010	10/11/2010		ns	ns
255074	HVID D-0 ARMSTRONG (DG)	Drain		4/6/2010	ns	ns		ns	ns
254994	SILVER CREEK; SW-SC1	Stream		4/7/2010	8/12/2010	10/8/2010		ns	ns
255000	SEVENMILE CREEK * 7M-SW1	Stream		4/7/2010	8/13/2010	10/11/2010		ns	ns
255001	SILVER CREEK; SC-2 * SC-SW2	Stream		4/6/2010	8/12/2010	10/8/2010		ns	ns
255059	TENMILE AT GREEN MEADOWS * 10M-SW1	Stream		4/6/2010	ns	ns		ns	ns
256969	LAKE HELENA CAUSEWAY	Stream		4/7/2010	8/13/2010	10/11/2010		3/3/2010, 4/7/2010	4/7/2010
257316	TENMILE CREEK AT MCHUGH LANE	Stream		ns	8/12/2010	10/7/2010		ns	ns
256972	HVID-1 (MCHUGH LN)	Irrigation Canal		5/4/2010	8/12/2010	ns		5/4/2010	5/4/2010

ns - not sampled

GWIC - http://mbmggwic.mtech.edu/

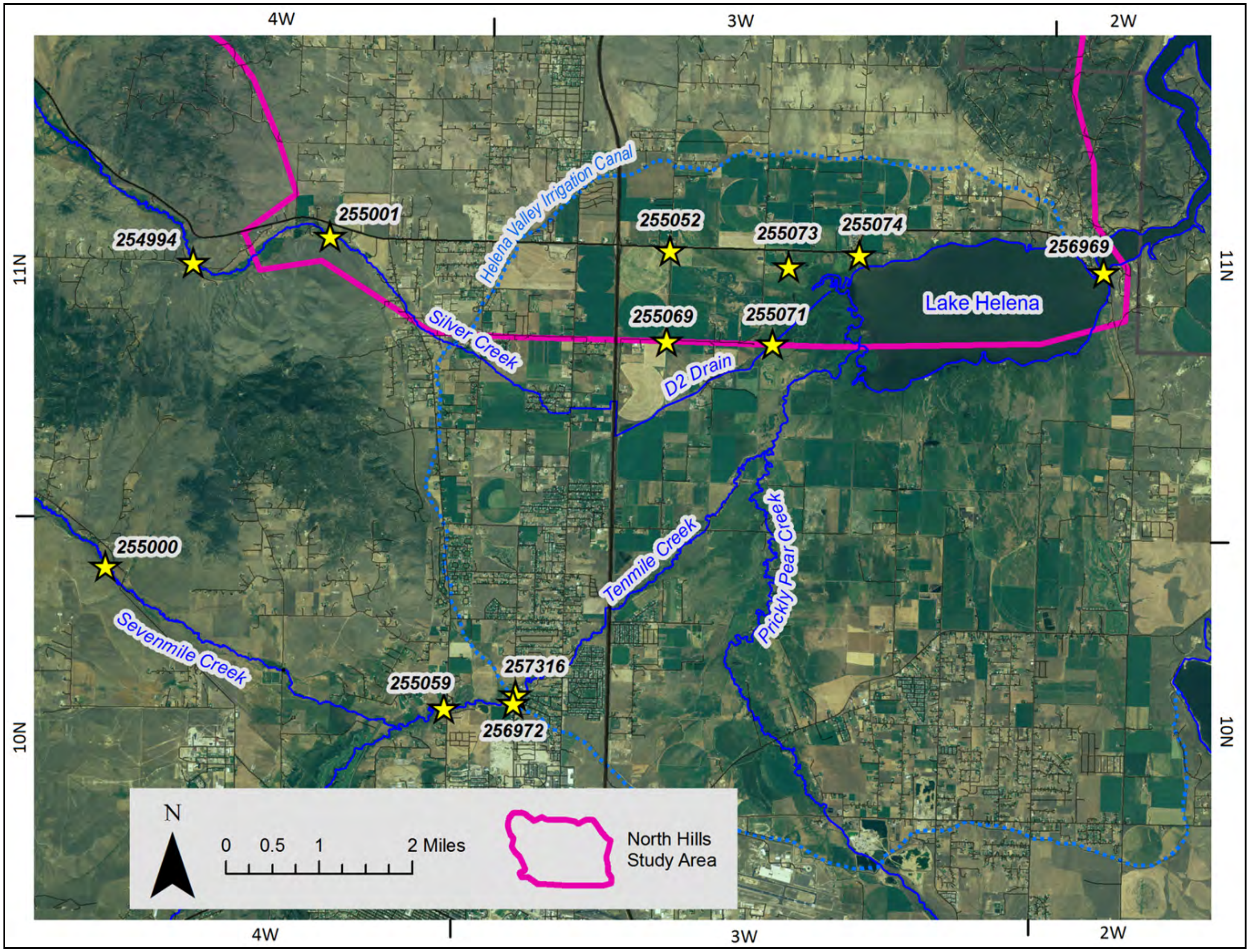

Figure WQ-2. A total of 30 surface-water samples were collected at 12 sites in and near the North Hills. Numbers designate the GWIC ID number for each site (http://mbmggwic.mtech.edu/).

Table WQ-3
Analytical parameters and units used for reporting water samples collected in the North Hills study area

Major Ions		
Calcium	Ca	mg/L
Magnesium	Mg	mg/L
Sodium	Na	mg/L
Potassium	K	mg/L
Iron	Fe	mg/L
Manganese	Mn	mg/L
Silica	SiO_2	mg/L
Bicarbonate	HCO_3	mg/L
Carbonate	CO_3	mg/L
Chlorine	Cl	mg/L
Sulfate	SO_4	mg/L
Nitrate	as N	mg/L
Fluoride	F	mg/L
Orthophosphate	as P	mg/L

Field Parameters		
Field Conductivity	Field SC	μmhos
Field pH	Field pH	---
Water Temperature	T	^{o}C

Other Parameters		
Total Dissolved Solids	TDS	mg/L
Sum of Dissolved Constituents	---	mg/L
Lab Conductivity	Lab SC	μmhos
Lab pH	Lab pH	---
Nitrite	as N	mg/L
Nitrate + Nitrite	as N	mg/L
Total Nitrogen	as N	mg/L
Hardness	as $CaCO_3$	mg/L
Alkalinity	as $CaCO_3$	mg/L
Ryznar Stability Index	---	---
Sodium Adsorption Ratio	SAR	---
Langlier Saturation Index	---	---
Phosphate (TD)	as P	mg/L

Trace Elements		
Aluminum	Al	μg/L
Antimony	Sb	μg/L
Arsenic	As	μg/L
Barium	Ba	μg/L
Beryllium	Be	μg/L
Boron	B	μg/L
Bromide	Br	μg/L
Cadmium	Cd	μg/L
Cerium	Ce	μg/L
Cesium	Cs	μg/L
Chromium	Cr	μg/L
Cobalt	CO3	μg/L
Copper	Cu	μg/L
Gallium	Ga	μg/L
Lanthanum	La	μg/L
Lead	Pb	μg/l
Lithium	Li	μg/L
Molybdenum	Mo	μg/L
Nickel	Ni	μg/L
Niobium	Nb	μg/L
Neodymium	Nd	μg/l
Palladium	Pd	μg/L
Praseodymium	Pr	μg/L
Rubidium	Rb	μg/L
Silver	Ag	μg/L
Selenium	Se	μg/L
Strontium	Sr	μg/L
Thallium	Tl	μg/L
Thorium	Th	μg/L
Tin	Sn	μg/L
Titanium	Ti	μg/L
Tungsten	W	μg/L
Uranium	U	μg/L
Vanadium	V	μg/L
Zinc	Zn	μg/L
Zirconium	Zr	μg/L

mg/L = milligrams per liter
μg/L = micrograms per liter
μmhos = micromhos per centimeter at 25^{o}C.

Table WQ-4. North Hills Groundwater Quality Samples

			Milliequivalents							Constituent Percent					
Gwic Id	**Site Name**	**Sample Date**	**Na**	**K**	**Ca**	**Mg**	**Cl**	**HCO3**	**SO4**	**Na+K**	**Ca**	**Mg**	**Cl**	**HCO3**	**SO4**
5854	USGS * MASONIC WEST	15-Apr-10	0.80	0.07	0.17	0.41	0.50	0.83	0.05	60%	12%	28%	26%	43%	3%
5854	USGS * MASONIC WEST	1-Sep-10	0.90	0.07	0.27	1.70	0.45	1.12	0.71	33%	9%	58%	16%	40%	26%
64730	HEDDEN, BRETT AND KIRA	14-Apr-10	0.60	0.02	1.66	1.52	0.21	3.33	0.37	16%	44%	40%	5%	84%	9%
64730	HEDDEN, BRETT AND KIRA	18-Aug-10	0.63	0.02	1.74	1.55	0.20	3.23	0.36	17%	44%	39%	5%	84%	9%
64730	HEDDEN, BRETT AND KIRA	5-Oct-10	0.59	0.03	1.76	1.58	0.20	3.27	0.36	16%	44%	40%	5%	82%	9%
64774	COLE CONNIE	14-Apr-10	2.31	0.13	2.17	0.56	0.55	2.75	2.29	47%	42%	11%	10%	48%	40%
64774	COLE CONNIE	18-Aug-10	2.51	0.14	2.33	0.58	0.54	2.81	2.30	48%	42%	11%	10%	49%	40%
64774	COLE CONNIE	6-Oct-10	2.59	0.14	2.48	0.63	0.55	2.78	2.30	47%	42%	11%	10%	49%	41%
64798	CHASE, ERIC	7-Apr-10	0.88	0.04	1.83	1.06	0.29	2.80	0.71	24%	48%	28%	8%	72%	18%
64798	CHASE, ERIC	17-Aug-10	0.94	0.03	1.85	1.10	0.29	3.10	0.71	25%	47%	28%	7%	74%	17%
64798	CHASE, ERIC	6-Oct-10	0.97	0.04	1.93	1.19	0.28	2.95	0.69	24%	47%	29%	7%	74%	17%
65316	SMELKO, DANIEL B.	6-Apr-10	1.20	0.11	4.94	3.21	0.45	6.36	2.08	14%	52%	34%	5%	71%	23%
65316	SMELKO, DANIEL B.	12-Aug-10	1.45	0.13	5.34	3.51	0.56	7.02	3.34	15%	51%	34%	5%	64%	30%
65316	SMELKO, DANIEL B.	7-Oct-10	1.71	0.13	5.49	3.72	0.52	7.29	3.24	17%	50%	34%	5%	66%	29%
66319	WALTHER JAMES	14-Apr-10	0.96	0.04	1.65	3.07	0.22	4.96	0.90	18%	29%	54%	4%	81%	15%
66319	WALTHER JAMES	20-Aug-10	1.00	0.04	1.67	3.11	0.18	4.85	0.85	18%	29%	53%	3%	82%	14%
128054	TUCKER LISA	6-Apr-10	1.34	0.20	2.37	0.47	0.65	2.27	1.60	35%	54%	11%	14%	49%	34%
128054	TUCKER LISA	18-Aug-10	1.50	0.21	2.31	0.46	0.62	2.54	1.50	38%	52%	10%	13%	53%	31%
128054	TUCKER LISA	6-Oct-10	1.61	0.23	2.41	0.51	0.60	2.29	1.51	39%	51%	11%	13%	50%	33%
138527	WALTHER JAMES	14-Apr-10	0.94	0.04	1.94	3.31	0.29	5.44	0.92	16%	31%	53%	4%	81%	14%
138527	WALTHER JAMES	20-Aug-10	0.98	0.04	1.99	3.37	0.28	5.22	0.94	16%	31%	53%	4%	81%	15%
138527	WALTHER JAMES	7-Oct-10	1.01	0.04	2.13	3.55	0.26	5.35	0.89	16%	32%	53%	4%	82%	14%
143645	SALISBURY JEFF AND JUDY	21-Aug-10	0.77	0.03	2.15	1.17	0.65	2.46	0.92	19%	52%	28%	15%	59%	22%
143645	SALISBURY JEFF AND JUDY	5-Oct-10	0.80	0.03	2.31	1.28	0.69	2.52	0.95	19%	52%	29%	16%	58%	22%
144725	STOLP, JUSTIN AND STACY	6-Apr-10	1.82	0.05	2.88	1.58	0.90	1.71	2.53	30%	45%	25%	17%	33%	49%
144725	STOLP, JUSTIN AND STACY	18-Aug-10	1.94	0.05	2.74	1.51	0.88	3.07	2.53	32%	44%	24%	13%	47%	39%
144725	STOLP, JUSTIN AND STACY	6-Oct-10	1.98	0.05	2.84	1.60	0.88	2.92	2.46	31%	44%	25%	14%	46%	39%
144726	CROWLEY PAT	6-Apr-10	1.10	0.06	3.15	0.93	0.98	2.93	1.52	22%	60%	18%	18%	53%	27%
144726	CROWLEY PAT	16-Apr-10	1.21	0.06	3.11	0.96	0.61	3.03	1.56	24%	58%	18%	11%	56%	29%
144726	CROWLEY PAT	17-Aug-10	1.08	0.06	3.29	0.80	0.55	3.09	1.50	22%	63%	15%	10%	58%	28%
144726	CROWLEY PAT	5-Oct-10	1.12	0.07	3.08	0.89	0.66	2.81	1.52	23%	60%	17%	13%	55%	30%
145957	PURCELL WILLIAM S	6-Apr-10	1.27	0.05	3.58	1.44	0.67	3.48	2.30	21%	57%	23%	10%	53%	35%
145957	PURCELL WILLIAM S	17-Aug-10	1.61	0.05	4.80	1.90	1.11	3.72	3.52	20%	57%	23%	13%	44%	42%
145957	PURCELL WILLIAM S	5-Oct-10	1.46	0.05	3.84	1.59	0.72	3.48	2.53	22%	55%	23%	11%	51%	37%
152551	HEDDEN ROGER	16-Apr-10	0.86	0.04	3.89	2.25	3.83	2.77	0.57	13%	55%	32%	52%	37%	8%
152551	HEDDEN ROGER	20-Aug-10	0.90	0.04	3.87	2.31	3.75	2.74	0.55	13%	54%	32%	51%	37%	8%
152551	HEDDEN ROGER	30-Sep-10	0.81	0.03	4.04	2.19	3.77	2.99	0.56	12%	57%	31%	50%	39%	7%
176010	NYSTRAND ROBERT	6-Apr-10	2.53	0.10	2.11	0.76	0.90	3.14	1.94	48%	38%	14%	15%	52%	32%
176010	NYSTRAND ROBERT	17-Aug-10	2.87	0.11	2.12	0.77	0.95	3.40	1.81	51%	36%	13%	15%	55%	29%
176010	NYSTRAND ROBERT	6-Oct-10	2.87	0.11	2.20	0.82	0.95	3.02	1.81	50%	37%	14%	16%	52%	31%

Table WQ-4. North Hills Groundwater Quality Samples (cont.)

				Milliequivalents								Constituent Percent						
Gwic Id	Site Name	Sample Date		Na	K	Ca	Mg	Cl	HCO3	SO4		Na+K	Ca	Mg		Cl	HCO3	SO4
178386	PETROSKY JEFF & ANGELE	6-Apr-10		1.88	0.03	2.42	1.57	0.73	2.82	2.27		32%	41%	27%		12%	48%	39%
178386	PETROSKY JEFF & ANGELE	18-Aug-10		2.19	0.03	2.72	1.75	1.10	3.24	2.78		33%	41%	26%		15%	45%	39%
178386	PETROSKY JEFF & ANGELE	6-Oct-10		2.41	0.03	2.96	1.87	0.92	2.90	2.61		34%	41%	26%		14%	45%	40%
180976	DONOHUE DAVE	7-Apr-10		0.91	0.03	2.90	3.85	2.36	4.30	0.67		12%	38%	50%		31%	56%	9%
180976	DONOHUE DAVE	7-Apr-10		0.99	0.03	3.19	4.28	2.74	4.38	0.68		12%	38%	50%		35%	56%	9%
180976	DONOHUE DAVE	21-Aug-10		0.99	0.03	2.83	3.88	2.63	4.41	0.64		13%	37%	50%		33%	55%	8%
180976	DONOHUE DAVE	30-Sep-10		0.90	0.03	2.99	3.60	2.37	4.67	0.63		12%	40%	48%		30%	59%	8%
187438	NJOS KAL	7-Apr-10		1.39	0.04	4.06	2.91	1.10	5.59	1.61		17%	48%	35%		12%	62%	18%
187438	NJOS KAL	20-Aug-10		1.44	0.04	3.73	2.76	1.12	5.44	1.37		19%	47%	35%		14%	66%	17%
187438	NJOS KAL	5-Oct-10		1.37	0.04	3.86	2.88	1.14	5.47	1.32		17%	47%	35%		14%	66%	16%
191532	LCWQPD - NORTH HILLS WELL	15-Apr-10		0.58	0.02	1.81	1.22	0.21	3.25	0.39		17%	50%	34%		5%	83%	10%
191532	LCWQPD - NORTH HILLS WELL	19-Aug-10		0.66	0.02	2.04	1.31	0.20	3.05	0.38		17%	51%	32%		5%	82%	10%
191532	LCWQPD - NORTH HILLS WELL	20-Oct-10		0.62	0.02	2.05	1.35	0.21	3.32	0.39		16%	51%	33%		5%	83%	10%
191534	LCWQPD - GRAVEL PIT WELL	19-Aug-10		1.57	0.07	3.93	1.75	2.99	1.94	1.78		22%	54%	24%		43%	28%	26%
191534	LCWQPD - GRAVEL PIT WELL	20-Oct-10		1.48	0.07	4.14	1.90	3.70	2.12	1.64		21%	54%	25%		48%	27%	21%
191537	LCWQPD - LINCOLN AND MONTANA	19-Aug-10		0.84	0.09	1.95	0.86	0.28	2.70	0.68		25%	52%	23%		7%	72%	18%
191537	LCWQPD - LINCOLN AND MONTANA	20-Oct-10		0.77	0.09	1.88	0.86	0.25	2.65	0.68		24%	52%	24%		7%	73%	19%
194435	HEDDEN, MICHAEL AND CRISTIE	7-Apr-10		0.38	0.02	2.21	1.42	0.07	3.44	0.51		10%	55%	35%		2%	85%	12%
194435	HEDDEN, MICHAEL AND CRISTIE	18-Aug-10		0.42	0.03	2.12	1.40	0.07	3.27	0.49		11%	53%	35%		2%	84%	13%
194435	HEDDEN, MICHAEL AND CRISTIE	30-Sep-10		0.35	0.02	2.24	1.32	0.07	3.55	0.50		9%	57%	33%		2%	85%	12%
198749	RAND MICHAEL AND CYNTHIA	16-Apr-10		1.07	0.04	1.41	2.67	0.26	3.96	0.62		21%	27%	51%		5%	76%	12%
198749	RAND MICHAEL AND CYNTHIA	21-Aug-10		1.07	0.04	1.30	2.57	0.22	4.01	0.58		22%	26%	52%		4%	79%	11%
198749	RAND MICHAEL AND CYNTHIA	30-Sep-10		0.95	0.03	1.50	2.38	0.23	4.03	0.59		20%	31%	49%		5%	78%	11%
202175	WINSLOW, LYNN AND TRUDY	14-Apr-10		0.53	0.03	2.63	1.41	0.22	3.65	0.62		12%	57%	31%		5%	79%	13%
202175	WINSLOW, LYNN AND TRUDY	18-Aug-10		0.54	0.03	2.64	1.41	0.22	3.72	0.60		12%	57%	30%		5%	80%	13%
202175	WINSLOW, LYNN AND TRUDY	5-Oct-10		0.51	0.03	2.69	1.42	0.22	3.72	0.61		12%	58%	31%		5%	80%	13%
206026	BRENSDAL KEN	14-Apr-10		1.76	0.05	4.27	4.45	3.33	3.38	4.57		17%	41%	42%		29%	29%	39%
206026	BRENSDAL KEN	20-Aug-10		1.54	0.04	3.11	3.40	1.86	3.60	2.51		20%	38%	42%		23%	44%	31%
206026	BRENSDAL KEN	30-Sep-10		1.62	0.05	4.29	4.02	2.75	3.95	3.45		17%	43%	40%		26%	38%	33%
206393	KREI ROBERT D.	14-Apr-10		0.69	0.03	2.17	1.44	0.26	3.72	0.64		17%	50%	33%		6%	78%	14%
206393	KREI ROBERT D.	18-Aug-10		0.74	0.03	2.35	1.52	0.26	3.55	0.63		17%	51%	33%		6%	78%	14%
206393	KREI ROBERT D.	5-Oct-10		0.65	0.03	2.30	1.51	0.26	3.67	0.64		15%	51%	34%		6%	78%	14%
227906	STEVENS, JERRY	16-Apr-10		1.45	0.06	4.71	3.27	0.39	6.31	2.70		16%	50%	34%		4%	67%	29%
227906	STEVENS, JERRY	12-Aug-10		1.29	0.05	4.60	3.24	0.38	5.73	2.61		15%	50%	35%		4%	65%	30%
227906	STEVENS, JERRY	7-Oct-10		1.47	0.05	4.77	3.37	0.39	6.66	2.61		16%	49%	35%		4%	69%	27%
243352	WOEHL HERMAN	21-Aug-10		0.89	0.03	2.54	1.55	0.77	3.10	1.09		18%	51%	31%		15%	60%	21%
243352	WOEHL HERMAN	5-Oct-10		1.05	0.04	2.50	1.94	0.89	3.11	1.15		20%	45%	35%		17%	58%	22%
257064	MBMG COLLINS DRIVE	19-Aug-10		1.49	0.03	2.83	1.96	0.60	4.28	1.78		24%	45%	31%		9%	64%	26%
257064	MBMG COLLINS DRIVE	20-Oct-10		1.40	0.03	2.86	2.04	0.60	3.83	1.85		23%	45%	32%		9%	60%	29%