Hydrogeologic Investigation
Eastside Milton-Freewater
Aquifer Recharge and Recovery Project

June 2019

Prepared by Northwest Land & Water, Inc., for the Walla Walla Basin Watershed Council

NORTHWEST Land & Water, INC. Consulting in Hydrogeology

Walla Walla Basin Watershed Council

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Introduction

The Walla Walla Basin Watershed Council (WWBWC) has been working for over two decades to improve water resource conditions throughout the Walla Walla Basin in both Oregon and Washington. As part of these efforts, it has been pursuing managed aquifer recharge (MAR) projects that divert water from the Walla Walla River (WWR) during high-flow periods in winter and spring. The goal of the MAR work has been to increase groundwater storage and raise water levels in the shallow alluvial aquifer, which have declined significantly during the past 50 to 100 years. This work is designed, in part, to mimic the natural floodplain processes that occurred during spring freshets for thousands of years before Euro-American settlement and the associated river channelization. Although the MAR efforts have focused on both states, four to five times more water has been recharged at Oregon sites, owing in large part to the difference in regulatory requirements.

These ongoing MAR efforts are improving water resource conditions within the basin; however, the WWBWC is also interested in recovering stored water for beneficial uses that would otherwise be met using stream flow. Aquifer recharge (AR) and recovery (R), referred to as ARR in this report (a sub-category of MAR), presents an opportunity for doing just this. Where it can be implemented successfully, ARR would give local farmers a source of irrigation water during late spring and summer. The ARR water would be pumped from an aquifer to effectively replace the diversion of surface water from the WWR during the late spring / summer season, leaving it instream for fish and other aquatic species. Maintaining WWR flows in the Eastside vicinity is important for salmonid migration, particularly in the lower-flow months of June through September.

To investigate the potential for ARR, the WWBWC initiated a 2015 study for the "Eastside alluvial aquifer," where an initial phase of this MAR / ARR evaluation had already been completed (NLW, 2015). This report summarizes the methodology and results of work conducted for this project by Northwest Land & Water, Inc., (NLW) in collaboration with WWBWC staff.

A quality assurance project plan (QAPP) was developed, and the plan was approved by Washington Department of Ecology (WDOE). The data QA processing are summarized in **Appendix A**.

Project Goals

The goal of this project is to provide information that will help the WWBWC and its partners decide whether to advance this ARR project to a second phase. If pursued, Phase II would not only improve our understanding of the fate of WWR water that is recharged at an existing infiltration gallery but it would also shed more light on ARR feasibility in the Eastside alluvial aquifer.

Scope of Work & Previous Investigations

This report summarizes the methodology and results of the ARR investigations, which were scoped in January 2015, initiated in spring 2015, and rescoped in February 2016. Tasks included:

- Constructing and equipping five monitoring wells
- Developing cross sections to show the subsurface hydrostratigraphy
- Contouring water level data to identify the general direction of groundwater flow
- Performing hydraulic tests and analyses to examine the distribution of aquifer properties and identify favorable areas for ARR
- Amending the scope in 2017 to include monitoring and qualititatively assessing infiltration from the existing infiltration gallery

NLW issued two previous memoranda documenting the progress of this ARR investigation. The first (NLW, 2015) summarizes the drilling and construction of five monitoring wells. The second (NLW, 2016) summarizes hydrogeologic characterization work conducted using information from 15 wells (including the five monitoring wells). This work included developing an understanding of the local hydrostratigraphy and setting up a database using Viewlog for constructing hydrogeologic cross sections. Viewlog is a software application that not only allows us to organize and interpret subsurface data but also produces images that are useful for visualizing subsurface conditions.

The 2016 memo also recommended additional work, including expanding the Viewlog database with information from other wells in the area, conducting aquifer tests, and using hydraulic tomography to estimate aquifer parameters between the river and monitoring wells. The results of these additional investigations are summarized in this report, along with a more detailed account of tasks covered in the two previous memos.

Project Area

Figure 1 is a map showing the project area. This area was targeted for evaluation because of existing infrastructure: a WWR diversion structure at the Nursery Bridge and a pipeline (not shown) that conveys water along Eastside and Grant Roads. **Figure 1** also shows a constructed infiltration gallery that is setup to receive WWR water from the Eastside pipeline.

Diversion Infrastructure & Potential

The Eastside pipeline (not frost-protected as currently built) has a capacity of approximately 10 cubic feet per second (cfs). Water would most likely be diverted to an AR facility during the high-flow period from February through May. Diverting 10 cfs for 100 days will remove a total of 1,984 acre-feet (AF) of water from the WWR. The existing Eastside diversion water right is 5 to 7 cfs, depending on time of year.

Under a successful ARR program, as much as 7 cfs could be left instream while irrigators withdraw this amount from aquifer storage. Note that 7 cfs represents a significant instream benefit — 25 percent of the 7-day low flow of 28 cfs in the WWR during the period of May through September 2015.

Hydrogeologic Conditions

One goal of this investigation was to develop a more robust conceptual model of the project area's hydrostratigraphy. To achieve this goal, 267 additional wells were incorporated into the existing Viewlog database. Of the 267 wells, 124 were successfully located using address mapping and, in some cases, first-hand knowledge. The well locations are accurate to the "parcel" scale — that is, to the scale of individual tax lots.

The well log data was digitized prior to incorporation and included drilled and constructed depth, texture of sediment or rock layer, water-bearing zones and water level, and construction information (open or screened interval). We also incorporated a digital elevation model (DEM) of ground surface into the Viewlog database. Driller's logs were obtained from the Oregon Water Resources Department's online well log viewer.

The preliminary cross sections developed for this project (NLW, 2016) were edited and expanded along four alignments (A–A', B–B', C–C', and D–D') using the additional well log data.

Hydrostratigraphy

Figures 1, 2, and **3** show an alignment map and two cross sections, A–A' and B–B'. The sections roughly parallel Eastside and Grant Roads. The alluvial stratigraphy in this area can be grouped into two general categories:

- **Alluvium**: An upper, relatively permeable layer
- **Older Sediments** (also comprised of alluvium): A lower, less permeable layer with local water-bearing zones

In addition, basalt occurs in the southern part of Section A–A' in Well 6475 and is inferred in Section B–B' due to the proximity of the two sections.

The relation between the stratigraphy of GSI (2007), Newcomb (1965), and the hydrostratigraphy of this report is approximately as follows:

- The relatively coarse textured, medium to high permeability **alluvium** corresponds to the Quaternary coarse unit of GSI and the Recent alluvium of Newcomb. Note that the **alluvium** may locally contain a minor amount of GSI's Quaternary fine unit.
- The relatively finer textured, low to medium permeability **older sediments** correspondence to GSI's and Newcomb's nomenclature is less discernible. The **older sediments** may be equivalent to GSI's Quater-

nary fine unit or their Mio-Pliocene fine unit (with minor interbeds of Mio-Pliocene coarse unit). Alternatively, the **older sediments** may correspond to Newcomb's old gravel and clay of Pleistocene age.

Most wells in the area produce groundwater from the upper alluvial layer (**alluvium**), which features water-bearing zones and/or coarse-textured sediments. Constructed with or without screens ("open"), these wells typically tap layers where water-table conditions dominate, although semiconfined or confined water-bearing zones occur locally.

The **alluvium** (upper layer) and **older sediments** (lower layer) may locally contain some of the same sediments; however, the **older sediments** also include more clay, silt, and/or clay- or silt-bound sand and gravel. They also contain some water-bearing zones but these zones tend to be thinner than those in the **alluvium**.

Cross sections A–A' and B–B' also indicate the largest thickness of unsaturated zone soils occur in the southern part of the project area. Specifically, Well GW_152 (152 on **Figures 2** and **3**) has an unsaturated zone thickness of approximately 65 feet, whereas Well GW_161 (161 on **Figure 3**) has a thickness of approximately 25 feet. Wells GW_160 and 162 have unsaturated zone thicknesses of approximately 35 and 20 feet, respectively.

Groundwater Flow Patterns

Although the water levels in the wells (shown as inverted triangles on the cross sections, **Figures 2 and 3**) were measured during different years, their elevation along both sections suggest a hydraulic gradient component from south to north, except in Wells GW_152 and 6475 at the south end of Section A–A'.

At the five monitoring wells constructed for this project — GW_152 (UMAT 57434), 160 (Well Tag 111671), 161 (Well Tag 111672), 162 (Well Tag 111673), and 163 (Well Tag 112703) — groundwater levels have been measured and recorded at 15-minute intervals for about 3 years. This data has been referenced to feet mean sea level based on a GPS survey by WWBWC **Appendix H**). Groundwater elevations for monitoring Wells GW_152, 160, 161, and 162 were contoured to identify flow direction and gradient, as shown in four "time-series" maps at 3-month intervals (**Figure 4**).

Each of the four maps reveals a similar pattern: a general hydraulic gradient direction from the WWR to the northeast; gradient magnitude is approximately 0.01. This pattern corroborates our conceptual model, which indicates that the WWR recharges the Eastside alluvial aquifer; it also supports the WWBWC's multi-year seepage studies, which show the WWR as losing water in a reach from river mile 44.9 to 47.7, which corresponds to Station M2 to Station M8 at the Tum-a-Lum Bridge. This "losing" reach includes the WWR along the west boundary of the Eastside Milton-Freewater project area.

The northeasterly groundwater gradient in the shallow alluvial aquifer is consistent with the historic and recent topographic gradient. Both Mullan's (1858) map and WWBWC's (2017) recent 5-foot topographic contour map show that surficial ground topography and paleochannels dip downgradient to the north-northeast.

In sediments that are relatively homogenous and isotropic, the hydraulic gradient direction is generally a good proxy for groundwater flow direction. However, alluvial-fluvial fan deposits typically contain buried paleochannels; if this is the case for the Eastside alluvial aquifer, it is possible that coarse-textured channel deposits promote preferential groundwater movement. The orientation of such channels is expected to range from northwest to north to northeast, based on the morphology and regional occurrence of the WWR fan system near Milton-Freewater. Given these channel orientations, it is possible that the local groundwater flow direction differs somewhat from the hydraulic gradient direction to the northeast (**Figure 4**).

Hydraulic Testing & Analysis

Between May 2015 and November 2016, a set of "tests" (**Figure 5, 5a-e**) were conducted to…

- Understand how aquifer parameters are spatially distributed
- Estimate how much water could be recharged
- Identify optimal ARR locations
- Quantify the yield from potential ARR recovery wells

Three types of tests were conducted: pumping tests, slug tests, and "passive" monitoring tests. The pumping and slug tests were analyzed using standard hydrogeologic parameter estimation methods. The passive tests were analyzed based on "visual" relationships and hydraulic tomography.

Pumping Tests

Well 1111

A traditional pumping test was conducted at Well 1111 (**Figure 5a**), also known as the Eastside School Well (ESW).

Methodology

On November 7, 2016, Widner Electric removed the existing pumping equipment[1] from the well and set a 3-hp submersible. On November 7 and 9, step- and constant-rate pumping tests were conducted. The step-rate test lasted 0.4 hours (**Appendix A**); the constant-rate test lasted 11 hours, during which the well was pumped at an average rate of 74.1 gpm (**Figure 6**). Flow was measured using two methods: an ultrasonic strap-on meter (Seametrics J-wave) and a 40-gallon drum and stopwatch. Water levels in the pumped well and the two monitoring wells (GW_162 and 163) were measured with Solinst Leveloggers® and a manual water-level sounder. Water levels were barometrically compensated.

Results

Water level trends before, during, and after testing are shown on **Figure 6**. A drawdown response was observed in the pumped well and in GW_162 and _163, which are located 261 and 260 feet, respectively, from Well 1111. The pre-test data for Well 1111 and GW_162 showed a declining water level trend, which was removed prior to analysis[2].

The north-south alignment and cross section C–C' (**Figures 1 and 7**) shows the local stratigraphy and the configuration of wells near Well 1111. In this vicinity, three water-bearing zones are separated by poorly permeable sediments (well logs 1111, GW_162, GW_163, and 5805 in **Appendix B**) . This subsurface stratigraphy likely explains the drawdown trends observed in the pumped well and two observation wells. In Well 1111 (**Figure C1, Appendix C**), drawdown follows a typical "Theis" type of response during early time but flattens significantly after 1 hour of pumping and then again after 3 hours of pumping. The slope change after 1 hour is interpreted as leakage from the overlying water-bearing zone, where GW_162 is screened. Evidence for this leakage is indicated by the drawdown trend for GW_162 (**Figure C2, Appendix C**), which shows a response within 1–2 minutes after pumping begins.

The results of the analysis of the early drawdown data for Well 1111 (Cooper and Jacob, 1946) and the mid-time data for GW_162 (Neumann and Witherspoon, 1969, leaky aquifer model) are summarized in **Table 1**. Because of the leakage, we were able to estimate parameters for the low-permeability aquitard separating the two water-bearing zones that supply water to Well 1111 and GW_162.

Like the Well 1111 drawdown trend, the data for GW_162 and GW_163 (**Figure C3, Appendix C**) show a substantial slope flattening beginning at 3 hours into the test. This flattening most likely reflects the effect of test water discharging into the open field to the south approximately 100 feet from Well 1111 wellhead. Although the discharge water influenced testing after 3 hours, the data collected was sufficient to characterize the subsurface at Well 1111 site. The "discharge water response" in the three wells (**Figures C1–C3**) did provide valuable information, however, by demonstrating that these zones are hydraulically connected to surface infiltration and to each other.

Well 5239

On May 3 and 4, 2016, an existing irrigation well (Well 5239) was pumped for the first time of the season (**Figure 5b**). The test was designed to accommodate the irrigator and allow him to apply the pumped water to his nearby apple orchard.

Methodology

Well 5239 was pumped for approximately 1.4 days at a variable rate ranging from 186 to 224 gpm (**Figure 8**);

[1] *This equipment was re-installed after testing.*
[2] *Well 1111 and GW_162 data were detrended by adding a rate of 0.1116 and 0.1534 feet/day, respectively*

the pumping rate was measured using a BM Technologies ultrasonic flow meter, which was strapped to the discharge line downstream of the wellhead. Flow rate from the meter was recorded for the first 10.5 hours of the test on May 3 and for 7 hours on May 4.

During the test, water levels were measured in the pumped well and in four observation wells, which included monitoring Well GW_161 and two private wells (5225 and 5232). All water level data was barometrically compensated. Water levels were measured in the pumped well using a micro-Diver sensor and in the monitoring and private wells using Solinst Leveloggers. In addition, water levels were measured manually at all wells using a sounder.

Results

Water level trends before, during, and after testing are shown on **Figure 8**. A drawdown response was observed not only in the pumped well but also in GW__161 and Well 5232, which are located 1,099 and 1,039 feet away from Well 5239, respectively. Pre-test water levels for the pumped well were declining slightly (5 to 2 hours before pumping) and then flattened (2 to 0 hours before pumping). The pre-test water levels for GW_161 and Well 5232 were relatively flat. None of the water level data required correction. Well 5225, which is 848 feet from pumped Well 5239, showed no response.

The north-south alignment and cross section D–D' (**Figures 1 and 9**) shows the local stratigraphy and the configuration of wells near Well 5239. In this vicinity, well logs for 5239, 56140, GW_161, and 5199 (**Appendix B**) indicate the occurrence of a single, semiconfined to unconfined aquifer. Well 5225 and much of Well 5232 are completed in lower-permeability sediments that are inferred to comprise much of the older sediments unit. However, well 5239 is also completed in a thin, water-bearing zone that is hydraulically connected to the shallow, higher-permeability alluvial aquifer.

- The drawdown trend for pumped Well 5239 (**Figures C4 and C5, Appendix C**) is relatively steep for the first 10 minutes and generally flat from 10 to 200 minutes (except during short-term variations in pumping rate). From 200 to approximately 600 minutes, the slope steepens.
- The drawdown trend for observation well GW_161 (**Figure C6 and C7, Appendix C**) is relatively flat up to 80 minutes but steepens from 80 to 300 minutes and becomes even steeper from 300 to 600 minutes (except during short-term variations in pumping rate).
- The drawdown trend for observation Well 5232 (**Figure C8, Appendix C**) is flat up to 300 minutes and steepens from 300 to 600 minutes (except during short-term variations in pumping rate).
- Recovery data for pumped Well 5239 (**Figures C9 and C10, Appendix C**) shows a shallow early recovery time (large t/t') trend and a steep late recovery time (small t/t') trend.

The multi-slope trends observed in these wells during the drawdown and recovery periods indicate that the local aquifer system is unconfined to semi-confined, highly transmissive, and features a nearby low-permeability boundary.

Table 1 summarizes the aquifer parameters estimated from the drawdown and recovery data for Well 5239 and from drawdown for Wells GW_161 and 5232. Aquifer transmissivity is relatively large based on the early time data for Well 5239 and the mid-late time data for Well GW_161. The late-time transmissivity is smaller and reflects the presence of an aquifer boundary or low-permeable zone.

Well 56140

On March 14, 2016, an existing irrigation well (Well 56140) was pumped prior to the irrigation season (**Figure 5c**). The test was designed to pump water via 3-inch irrigation pipe that fed 18 sprinklers. The water was applied to the local farmer's pasture, adding moisture to the soil profile for the spring growing season.

Methodology

Well 56140 was pumped for 6 hours at a variable rate ranging from 94 to 104 gpm (**Figure 10**); the pumping rate was measured using a BM Technologies ultrasonic flow meter, which was strapped to the discharge line downstream of the wellhead.

During the test, water levels were measured in the pumped well and in three observation wells, which included monitoring Well GW_161 and two irrigation wells (5239 and 5199). Water level data for GW_161 was barometrically compensated. Water levels were measured in the pumped well and irrigation Well 5199 using a manual sounder.

Results

Water level trends before, during, and after testing are shown on **Figure 10**. A drawdown response was observed not only in the pumped well but also in GW_161 and Well 5199, which are located 253 and 587 away from Well 56140, respectively. Pre-test water levels for the pumped well and GW_161 were relatively flat. None of the water-level data required correction. Other wells monitored wells showed no response.

The north-south alignment and cross section D–D' (**Figures 1 and 9**) show the local stratigraphy and the configuration of wells near Well 56140. In this vicinity, well logs for 5199, GW_161, 56140, and 5239 (**Appendix B**) indicate the occurrence of a single, semiconfined to unconfined aquifer. Well 5225 and much of Well 5232 are completed mostly in the lower-permeability sediments that are inferred to be part of the older sediments unit.

- The drawdown trend for Well 56140 (**Figure C11, Appendix C**) shows variation during the 6-hour test period that reflects not only the variations in pumping rate but also the difficulty we experienced in measuring water levels manually. A single line was fit to the entire data set to provide a rough estimate of transmissivity.
- The drawdown trend for observation Well GW_161 is relatively steep during early time (prior to 10 minutes) and late time. (**Figure C12, Appendix C**). The drawdown trend from 10 to 80 minutes is relatively flat. Estimates of transmissivity based on late-time drawdown data (from 80 to 360 minutes) through early time recovery data (360 to 800 minutes) are lower (**Figure C13, Appendix C** and **Table 1**) than those derived from the early drawdown data, possibly reflecting a nearby low-permeability boundary. Note that on-off pumping at a nearby well likely accounts for variation in the recovery trend after 800 minutes.
- The drawdown and recovery data for observation Well 5199, which are limited, indicate a transmissivity similar to that for Wells 56140 and GW_161 (**Figure C14** and **Table 1**). Analyses of this data, however, do not yield a realistic storage coefficient, suggesting a lagged response caused by fine sediments at Well 5199 (skin effect) or between Wells 56140 and 5199.

The multi-slope trends observed in GW_161 during the drawdown period are consistent with those observed during the pumping test at Well 5239. This indicates that the local aquifer system is unconfined to semi-confined and highly transmissive and that it features a nearby low-permeability boundary.

Slug Tests

Slug tests were performed at each of the five monitoring wells (GW_152, 160, 161, 163, and 163) to gain an understanding of the hydraulic properties at these locations (**Figure 5**). Tests were conducted during the weeks of November 7 and 14, 2016.

Methodology

At each monitoring well, a “slug” consisting of an Acetal rod with dimensions of 5 feet x 1.5 inches was lowered into the column of water (“slug in”) and later raised out of the water column (“slug out”). The water level response was measured using the existing Solinst sensor set to a 1-second collection frequency. Water levels were also measured manually. Because the tests lasted only minutes, no barometric corrections were necessary. A pre-test trend was removed from monitoring Well GW_161[3]; pre-test trends in the other wells were relatively flat. The Bouwer-Rice (1976) method was used to estimate the hydraulic conductivity of the aquifer adjacent to each monitoring well screen.

Results

Water levels measured before, during, and after the slug test are shown on (**Figure 11**). Responses were

[3] *GW_161 slug ‘In’ data were detrended by adding a rate of 0.0005 feet/minute*

"damped" within the screened interval of Wells GW_152 and _162 and "poorly damped" at Wells GW_160, _161, and _163. A damped response is characterized by a trend of exponential data decay, whereas the poorly damped response had a rapid and/or oscillating water-level response following the slug in or out. As such, we expect hydraulic conductivity to be lower at GW_152/162 than at GW_160/161/163. The analysis of data trends corroborates this (**Figures C15 – C22**, **Appendix C**; **Table 2**).

A comparison of hydraulic conductivity (*K*) estimated from slug tests and pumping tests is shown in **Table 3** below. The values from the slug and pumping tests for GW_161 compare favorably. The values for GW_162 differ by an order of magnitude, however the pumping test value of 1 foot/day is estimated for the non-pumped overlying aquifer and is sensitive to the choice of the leaky model parameters.

Table 3. Comparison of *K*s (feet/day)

	GW_161	GW_162
Slug Test	320	20, 20
Pump Test	290, 570, 610	1

Passive Tests

Walla Walla River & Monitoring Wells

A "passive aquifer test" was conducted to assess the distribution of hydraulic properties between the WWR and the five monitoring wells that were installed for this project. The test involved using monitoring data — groundwater level and river stage — that was available for the project area. As previously noted, water levels were recorded at the monitoring wells at 15-minute intervals for 1.5 years, from July 2015 through November 2016. Stream gauge data was available from a station on the WWR (Station M4, **Figure 5d**) located just upstream of the project area. This analysis used a subset of the available monitoring data — from November 2015 through March 2016 — because three storm events occurred during this time, raising river stage enough to impact water levels in the wells.

The data was analyzed by Dr. Jim Yeh's group (University of Arizona) using *hydraulic tomography*. This mathematical solution estimates aquifer parameters and, in particular (for this analysis), hydraulic diffusivity (*D*), based on the degree to which river stage variations impact groundwater levels in the aquifer. *D* represents the rate at which pressure changes propagate through the aquifer. It equals transmissivity divided by storage coefficient (two dimensions) or hydraulic conductivity divided by specific storage (one and three dimensions).

The first step in this analysis involved preparing hydrographs for groundwater levels and streamflow during the test period. A model domain was established that encompasses the five wells and includes the river as one boundary. Water level and stage data were input for the test period, and the finite-element, variably saturated, flow model VSAFT2 was run to estimate the distribution of *D*.

Figure 12 is a hydrograph showing how river stage correlates to water levels in the five monitoring wells during the test period (November 2015 through March 2016). All of the wells show a response to the three storm events; this response is smallest at GW_152 and largest at GW_162. The differences in the magnitude and lag time of the response for each well reflect aquifer heterogeneity and distance to the river.

Figure 13 shows the resulting *D* field. Values are highest at Wells GW_162/163 and lowest at GW_152, with intermediate values occurring at GW_160 and _161. *D* provides an indication of the degree to which changes in hydraulic gradient influence the amount of groundwater that can be stored; a low value — such as that observed at GW_152 — bodes well for "retaining" recharged water in place.

Appendix D contains a brief description of hydraulic tomography and additional graphs/maps developed for Dr. Yeh's *D* estimation analysis.

Well 6475 & GW_152

A passive test was conducted to help answer a question of interest: What, if any, impact does pumping from the underlying basalt aquifer have on groundwater in the Eastside alluvial aquifer?

For this test (**Figure 5e**), irrigation Well 6475, which yields water from basalt, was equipped with a Seametrics DL-76W datalogger to record continuous flow measurements. Water levels were also monitored in GW_152, a nearby alluvial aquifer monitoring well, using a Solinst sensor. This monitoring was conducted from May through September 2016 and collected at a 1-minute frequency.

Data from the test are shown on **Figures 14** and **15**. The pumping history shows an "on-off" cycling events to meet farm irrigation demands. Although the water level data for Well GW_152 shows an undulating pattern, it does not visually correlate with these events in the underlying basalt aquifer. There does not appear to be a direct and rapid hydraulic connection between basalt Well 6475 and overlying alluvial Well GW_152. However, no conclusion can be made about leakage between these two aquifers on a seasonal time scale.

Infiltration Analysis

Although infiltration testing was not part of this project's original scope (through 2017), we can estimate a range of infiltration scenarios for diverted and recharged WWR water based on parameters estimated above, the Johnson Recharge Site infiltration rates WWBWC (2017a), and an analysis of Well 1111 pumping-test discharge water infiltration. Note: see next section for amended scope **Infiltration Testing**, 2018 - 2019.

Discharge water from the Well 1111 pumping test formed a relatively stable 'wet' area and 'ponded' water depth within approximately one hour after testing began. If we assume that the discharge water "average" wetting front moved downward through the 20-foot vadose zone under a unit hydraulic gradient and encountered the water table within the range of 180 to 400 minutes after pumping began (see **Figures 7** and **C3)**, then a set of calculations result in a range of infiltration rate and vertical hydraulic conductivity (**Table 4**).

Using the calculation 1, 2, and 3 in **Table 4**, and assuming these rates are sustainable, then the estimated area necessary to infiltrate 10 cfs of WWR water is in the range of 0.5 to 1.1 acres. Note that the statement "these rates are sustainable" above relies on the assumption that the mounding of water beneath the infiltration basin does not limit infiltration rate.

To better examine mounding effects beneath a basin where 10 cfs of WWR water are infiltrated for a 100-day period, the Hantush (1967) model was used to simulate the growth of a groundwater mound. **Table 5** results suggest that the necessary infiltration basin area may be on the order of 4 to 5 acres near GW_152 and _160, where the local underlying aquifer limits the rate at which infiltrated water moves laterally.

The results shown in **Tables 4 and 5** collectively suggest that a goal of infiltrating 10 cfs of WWR water for 100 days may be feasible, although there is substantial uncertainty in the infiltration basin area necessary to accomplish this goal. The analysis of infiltration suggests that the infiltration goal could be met with basin areas in the range of 1 to 5 acres. Field testing is essential to validate infiltration rates and basin area.

Note that none of the infiltration analyses above account for the development of a low-permeable skin that typically forms on the bed of an infiltration basin.

Infiltration Test

This project's scope was amended to include monitoring and qualitative analysis of infiltration testing at the infiltration gallery (**Figure 1**) which operated for the first time during the period from March 21 through May 15, 2018. The gallery was not operated in spring 2019.

Tracking the occurrence, movement, and storage of infiltrated WWR can be accomplish through monitoring infiltration rate and downgradient water level changes in monitoring wells. However, in a shallow alluvial aquifer such as occurs in the Eastside Milton-Freewater area an infiltration "signal" in the hydrograph of montoirng wells may be confounded by changes in WWR stage and local irrigation and domestic well pumping. To potentially improve tracking of infiltrated WWR, we tested and monitored several "intrinsic" water quality parameters, prior to, and during, the spring 2018 gallery infiltration period. These parameters included:

- Stable isotopes of hydrogen and oxygen
- Specific conductance (SC), and
- Temperature

Results of the stable isotope analysis (**Appendix E**) did not show a significant difference between spring-season WWR water and groundwater from the shallow alluival monitoring wells. It is likely that a substantial portion of the natural recharge to the Eastside shallow alluvial aquifer is from spring-season WWR water that infiltrates through the river bed, and thus, infiltration gallery water comprised of WWR spring-season flow would be isotopically similar to the shallow alluvial groundwater. Thus, stable isotopes where not believed to be a good WWR water infiltration tracking tool. It is worth noting that if at some time in the future winter-season WWR water is infiltrated, then the winter isotopic signature may differ from the shallow alluvial groundwater and stable isotopes may be a good tracking tool under these condtions.

SC, temperature, and groundwater levels for monitoring wells GW_152, 160, 161, 162, and 163 are shown as time-series graphs in **Appendix F**. Note that the "top" row of three graphs show SC, temperature, and flow rate for WWR water infiltrated via the gallery. Also note that first page in the **Appendix F** shows a time-series period for spring 2018, and the second page for spring 2018 – spring 2019.

The time-series data indicate the following:

- The SC, temperature, and water level data confirm an infiltration response in GW_152 and 160—the two nearest monitoring wells—during and after the 56 days of spring 2018 infiltration at the gallery.
- Dissolution of solids in the unsaturated zone between the infiltration gallery and the water table accounts for higher total dissoved solids which reflect the higher SC values.. This is a process that historically occurred during "overbank" flood events along distributary channels in the Walla Walla alluvial fan system. Unlined ditches/canals subject to seasonal wetting-drying-wetting would also carry dissolved solids to the local water table.
- While the pattern of water level rise and decline in GW_161 likely shows the infiltration gallery water signal occuring in this monitoring well, there are two other signals, namely a rise/fall in WWR stage and local irrigation well pumping that complicate the interpretation of the GW_161 trend. Further work is needed to better discern the infiltration gallery's response in GW_161. SC and temperature show small increases suggesting potential infiltration gallery water occurrence at GW_161 (see "Recommendations" section).
- The pattern of water level rise at GW_162 and 163 is more ambiguous than in GW_161, in part, because 162 and 163 are closest to the WWR and more strongly affected by its stage variation. SC and temperature show small increases suggesting potential infiltration gallery water occurrence at GW_162 (see "Recommendations" sections). The time-series for GW_163 is relatively small because its SC/temperature sensor was taken from another site and placed in GW_163 in late spring 2018.

Summary & Interpretation

Figures 16 and **17** show the results of the test analyses and our current understanding of how ARR could work in the Eastside area.

Key Hydraulic Features & ARR Significance

Figure 16 is a map of hydraulic conductivity (*K*) and transmissivity (*T*) results calculated from the pumping and slug tests[4]. It shows that *K* and *T* are lowest at GW_152 and highest in the vicinity of Wells 5239 and 56140 (along Grant Road). Intermediate values occur in the GW_160, GW_162/163, and Well 1111 vicinity. Also, the inferred position of a local hydrostratigraphic feature — an inferred "boundary" of a potential alluvial channel — is shown on **Figure 16**. Sediments are more permeable to the west of the inferred boundary and less permeable to the east.

Based on this parameter distribution, the alluvial channel "boundary,"the northeasterly hydraulic gradient, and the infiltration test time-series data, groundwater from the existing infiltration gallery moves in a generally north direction with a likely northeast component. The area north and northeast of the existing infiltration gallery would support multiple high-capacity wells that could be used for "recovering" stored water at individual well rates of 250 to 500 gpm (approximately 0.5 to 1 cfs) or more.

---

[4] *For visual clarity, K and T symbols are shown 'west' and 'east', respectively, of the tested wells in* ***Figure 16****.*

Proposed ARR Concept

Figure 17 shows an ARR concept map based on the data that has been collected and interpreted to date. It illustrates how WWR water could be diverted to infiltration basins and/or galleries in the Well GW_152 and 160 vicinity during winter and spring. Water recharged at these facilities would fill the unsaturated soil beneath this area, move slowly northeast, and ultimately be withdrawn from recovery wells completed in the shallow alluvial aquifer along Grant Road (in the Well 5239/56140 vicinity) and other locations to the north-northeast.

The GW_152 and 160 area appears to be favorable for recharge because it features more 30 to 60 feet of unsaturated soil beneath land surface. In addition, the infiltration test at the existing infiltration gallery adjacent to GW_152 indicated approximately 5 feet of water level rise for an infiltration rate of approximately 0.7 cfs during the 56-day infiltration period in spring 2018.

The Grant Road area appears to be favorable for recovery because the northeasterly hydraulic gradient (about 0.01) occurs consistently throughout the year and would move water from the recharge area toward a potential shallow alluvial aquifer — a buried “channel” that is locally “bounded” near Wells 5239 and 56140. In addition, the relatively high *T* in this area would support pumping from properly located recovery wells that yield 250 to 500 gpm (approximately 0.5 to 1 cfs) or more. Preliminary estimates suggest total recovery rates of 5 to 7 cfs may be feasible using 5 to 10 wells placed along a 3,000- to 4,000-foot wellfield alignment.

Note that this ARR concept needs to be demonstrated by conducting additional analyses, as outlined below in the “Recommendations” section. The recharge component of this concept could be demonstrated by ongoing infiltration of WWR water in the GW_152 and 160 vicinity and quantifying infiltration rates and storage changes. To demonstrate the recovery component, additional well log interpretation, hydraulic boundary delineation, tracer / travel time testing, and recovery well and aquifer capacity analysis will be needed.

Recommendations

The following work is recommended to advance Phase II of the Eastside MAR / ARR project:

Planning

- Update costs in the project “template” (**Appendix G)** as new information affects the cost ranges per unit of water.
- Use results from other project analyses of environmental flows and water rights on the WWR to identify available water for recharge and investigate water rights procurement.
- Consider localized MAR in the GW_162/163 vicinity or other similar areas along Eastside Road with the goal of enhancing habitat in a future WWR side-channel. Such a side-channel could be constructed between the WWR mainstem and Eastside Road. Because this area features perched groundwater, a MAR project has the potential to discharge cold, winter/spring water to the side-channel, thereby creating cool-water refugia for fish and other species along the WWR reach north of Nursery Bridge.

Field Investigations

- Identify existing wells that could be used to monitor alluvial water levels to the west, south, and east of the infiltration gallery and the GW_152 vicinity, and then install water-level sensors in these wells. If none can be configured with sensors, consider drilling additional monitoring wells.
- Design and implement a work plan to trace / track the storage, movement, and travel time of infiltrated WWR water. Such a plan will include high resolution measurements of infiltration flow rate and up- / down-gradient water levels. Tracing, travel times, and mixing of infiltrated water may be improved not only with the “intrinsic” water quality monitored in spring 2018 – spring 2019, but by potentially using a site model, field restivitiy, bromide, and/or sulfur hexafluoride. Each of these “tools” should support information that is needed for AR and R limited license development or expansion.

- Infiltrate WWR at the gallery in the GW_152 vicinity, ideally, at maximum capacities rates and for the longest duration possible.
- Locate and map the entire Eastside pipeline and its fittings via an accurate survey.
- Continue data collection from water level, SC, and temperature sensors in monitoring wells GW_152, 160, 161, 162, and 163. These data will further characterize groundwater variation and trends which, in turn, will allow improved infiltration signal response discernment for the period during, and the two months after, the spring 2018 infiltration gallery event.

Additional Analysis

- Interpret all well logs to distinguish the shallow alluvial aquifer from older sediments.
- Conduct a hydraulic boundary analysis of the buried alluvial channel using the existing pumping test data in the vicinity of Wells 5239 / 56140 / GW_161 and Grant Road.
- Integrate results of the 56-day, spring 2018 infiltration gallery event into the existing conceptual model of the Eastside alluvial aquifer. This will improve understanding of the fate of infiltrated water, and how/where to optimally "recover" water. Note that analysis of the 2018 event data should include WWR-stage trend removal to better discern the infiltration event signal.
- New parameter estimates coupled with more well log interpretation (plus surveyed well locations) would facilite better site modeling of expanded Eastside infiltration. Such analyses would also show optimal placement of "recovery" wells for aquifer recharge and "recovery" (ARR) and support elements of a limited license.
- Conduct a wellfield analysis to identify the optimal locations and number of recovery wells required to withdraw 5 to 7 cfs of recharged WWR water in the Grant Road vicinity.

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Northwest Land & Water, 2016. Interim results of hydrostratigraphic assessment and pumping tests, Eastside Milton-Freewater, OR, Memorandum dated June 24, 2016 (included in **Appendix H)**.

WWBWC, 2017. Eastside ASR Characterization Pumping Test GPS Survey Map 'with 5-foot contours' (included in **Appendix H**).

WWBWC, 2016. Water Year 2015, Oregon Walla Walla basin aquifer recharge report, Final report, February 2016.

Disclaimer

NLW's professional services were performed, its findings obtained, and this report prepared in accordance with generally accepted hydrogeologic practices at this time and in this area, exclusively for the use of Walla Walla Basin Watershed Council and the other project partners (Technical Work Group, Oregon Watershed Enhancement Board, and Washington State Department of Ecology). This warranty is in lieu of all other warranties, expressed, or implied.

Tables

Table 1. Aquifer Parameters from Pumping Tests

Parameter	Symbol	Units	1111 Pumped & Observed (Drawdown, partial penetration)	1111 Pumped & Observed (Drawdown, full penetration)	1111 Pumped & GW_162 Observed (Drawdown, early time)	5239 Pumped & Observed (drawdown, early time)	5239 Pumped & Observed (drawdown, late time)	5239 Pumped & GW_161 Observed (drawdown, mid-late time)	5239 Pumped & 5232 Observed (drawdown, mid-late time)	56140 Pumped & Observed (drawdown)	56140 Pumped & GW_161 Observed (drawdown-recovery, early dd & early rc time)	56140 Pumped & GW_161 Observed (drawdown-recovery, late dd - early rc time)	56140 Pumped & 5199 Observed (drawdown-recovery, late dd - early rc time)
Test Date	---		11/9/2016	11/9/2016	11/9/2016	5/3/2016	5/3/2016	5/3/2016	5/3/2016	3/14/2016	3/14/2016	3/14/2016	3/14/2016
Aquifer Thickness	b	feet	25.2	5.0	25.2	20.7	20.7	37.0	9.0	41.2	41.2	35.8	85.6
Aquitard Thickness	b'	feet	---	---	20	---	---	---	---	---	---	---	---
Analysis Method	---		C-J	C-J	N-W	C-J	C-J	Theis	Theis	C-J	Theis	Theis	Theis
Calculated Hydraulic Conductivity	K	gpd/ft2	1,100	5,600	8	7,100	2,200	2,200	2,000	3,000	4,600	4,300	1,600
		ft/d	150	750	1	950	290	290	270	400	610	570	210
		cm/s	0.1	0.3	0.0004	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1
Transmissivity	T	gpd/ft	28,100	28,100	190	147,600	44,500	81,300	17,800	124,500	190,100	152,500	140,200
		ft2/d	3,800	3,800	---	19,700	5,900	10,900	2,400	16,600	25,400	20,400	18,700
Storage Coefficient or Specific Yield	S or S_y	---	---	---	---	---	---	0.02	0.005	---	0.005	0.01	---

Table 2. Aquifer Parameters from Slug Tests

Parameter	Symbol	Units	Slug In 152	Slug Out 152	Slug Out 160	Slug Out 161	Slug In 162	Slug Out 162	Slug Out 163 lo	Slug Out 163 hi
Date	---		11/10/2016		11/17/2016	11/8/2016	11/16/2016		11/16/2016	
Aquifer Thickness	b	feet	14.7	14.7	16.5	32.5	16.0	16.0	7.5	7.5
Hydraulic Conductivity	K	gpd/ft2	60	40	3,100	2,400	150	150	1,400	3,100
		ft/d	8	5	410	320	20	20	190	410
		cm/s	0.003	0.002	0.1	0.1	0.007	0.007	0.07	0.1
Average Hydraulic Conductivity		ft/d	7		410	320	20		300	
Calculated Transmissivity	T	gpd/ft	880	590	51,000	77,900	2,400	2,400	10,500	23,300
Calculated Average Transmissivity		ft2/d	100		6,700	10,400	320		2,300	

Table 4. Estimated Range of Infiltration Rate and Hydraulic Conductivity through Vadose Zone near Well 1111

Calculation	Depth to Water Below Ground (Travel distance)	Discharge Water Travel Time (Ground surface to water table)	Estimated Average Linear Velocity	Assumed Vadose Zone Water-Filled Porosity	Calculated Flux or Infiltration Rate	Assumed Vertical Hydraulic Gradient	Estimated Vertical Hydraulic Conductivity	Calculated Area to Infiltrate 10 cfs
	(feet)	(day)	(feet/day)	unitless	(feet/day)	unitless	(feet/day)	(acre)
1	20.86	0.125	167	0.25	42	1	42	0.5
2	20.86	0.208	100	0.25	25	1	25	0.8
3	20.86	0.278	75	0.25	19	1	19	1.1

Table 5. Modeled[1] (Hantush, 1967) Feasibility of 10 cfs for 100 days

Scenario	Infiltration Rate	Basin Area Needed for Infiltration of 10 cfs	Mound Rise at Day = 100 after Infiltration of 10 cfs for 100 days	Average Vadose Zone Thickness[5]	Model Results Indicate Feasible ?
	(feet/day)	(acre)	(feet)	(feet)	
1-1	4.5[2]	4.4	48.5	50	yes
1-2	9.0[3]	2.2	52.2	50	no
1-3	25[4]	0.8	57.5	50	no

Notes:

[1] *Averaged hydraulic conductivity = 208 ft/d (based on GW_152 of 7 ft/d and GW_160 of 410 ft/d)*
Averaged aquifer thickness = 17 ft (based on GW_152 of 18.5 ft and GW_160 of 15 ft)

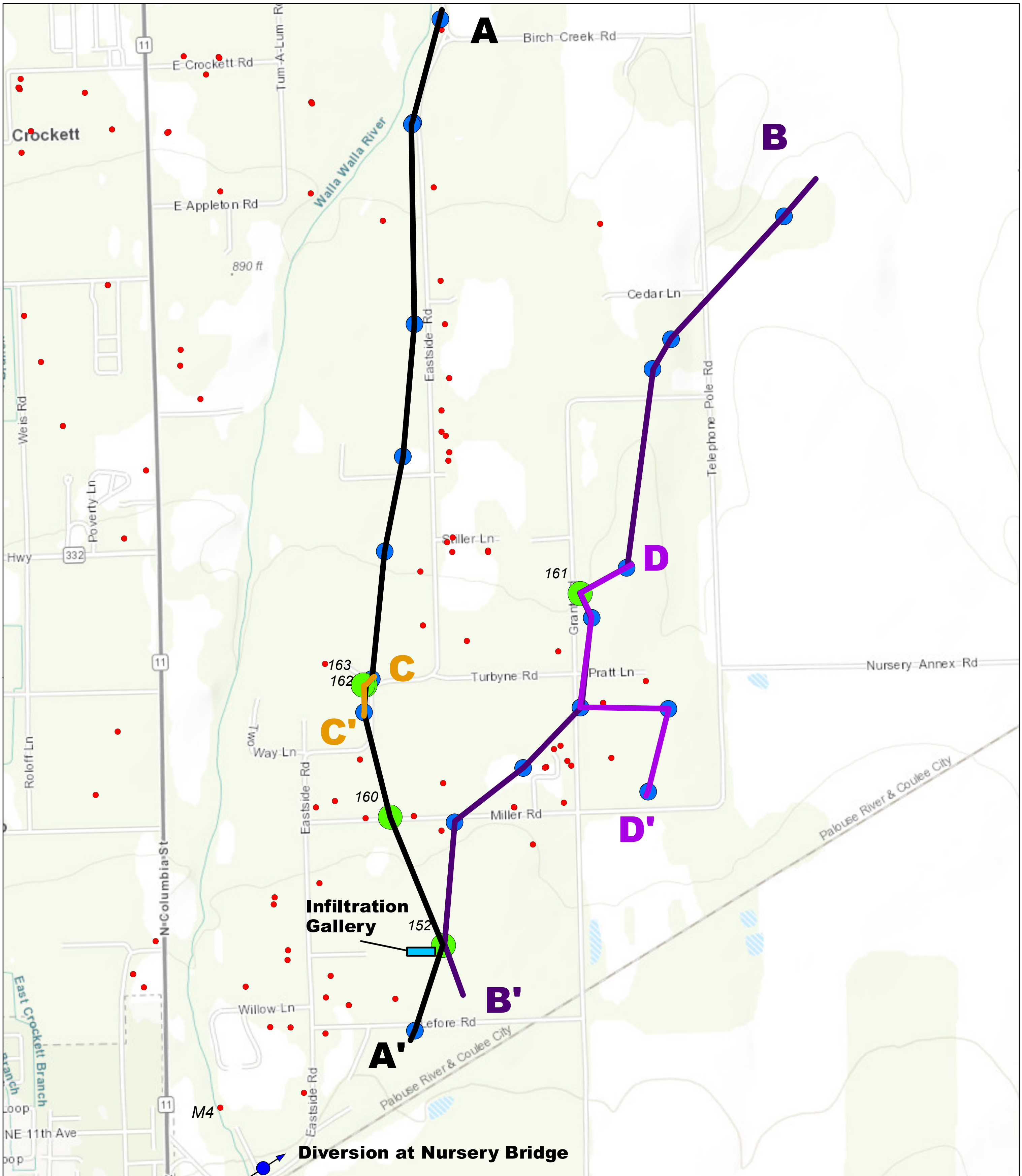
[2] *1/2 the Johnson site infiltration rate*

[3] *Based on Johnson Recharge Site --*
Volume of water recharged = 1,379.94 acre-feet
Period of water recharged = 51 days
Infiltration basin area = 3 acres

[4] *Well 1111 discharge water infiltration rate*

[5] *Average of GW_152 (65 feet) and GW_160 (35 feet)*

Figures



Legend

- Monitoring Well
- Other Cross Section Well
- Other Project Well
- Cross Section Alignments

N

500 250 0 500 Feet

Figure 1
Project Area and
Cross Section Alignments

Eastside Milton-Freewater MAR
WWBWC

NORTHWEST Land & Water, INC.

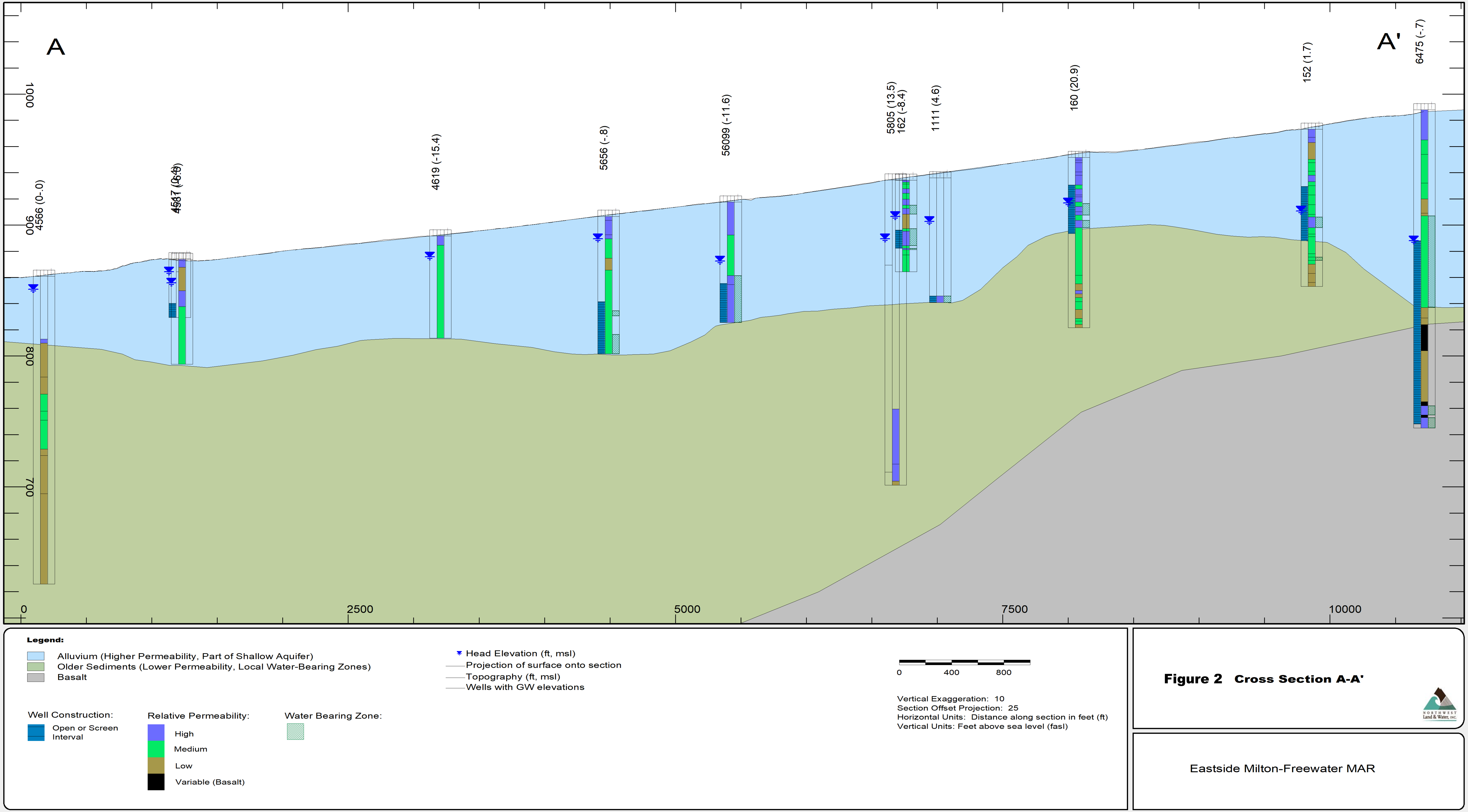
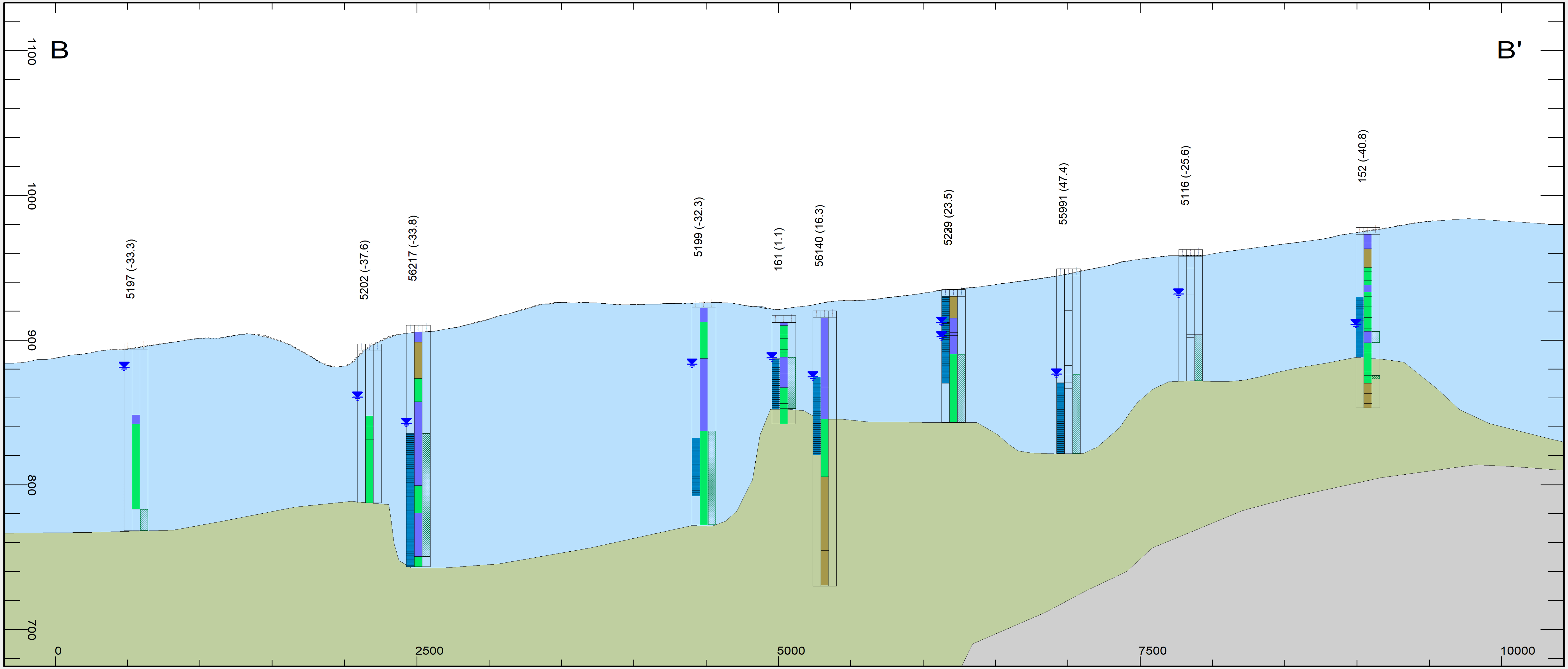


Figure 2 Cross Section A-A'

Eastside Milton-Freewater MAR



Legend:

Alluvium (Higher Permeability, Part of Shallow Aquifer)
Older Sediments (Lower Permeability, Local Water-Bearing Zones)
Basalt

Head Elevation (ft, msl)
Projection of surface onto section
Topography (ft, msl)
Wells with GW elevations

Well Construction:
Open or Screen Interval

Relative Permeability:
High
Medium
Low
Variable (Basalt)

Water Bearing Zone:

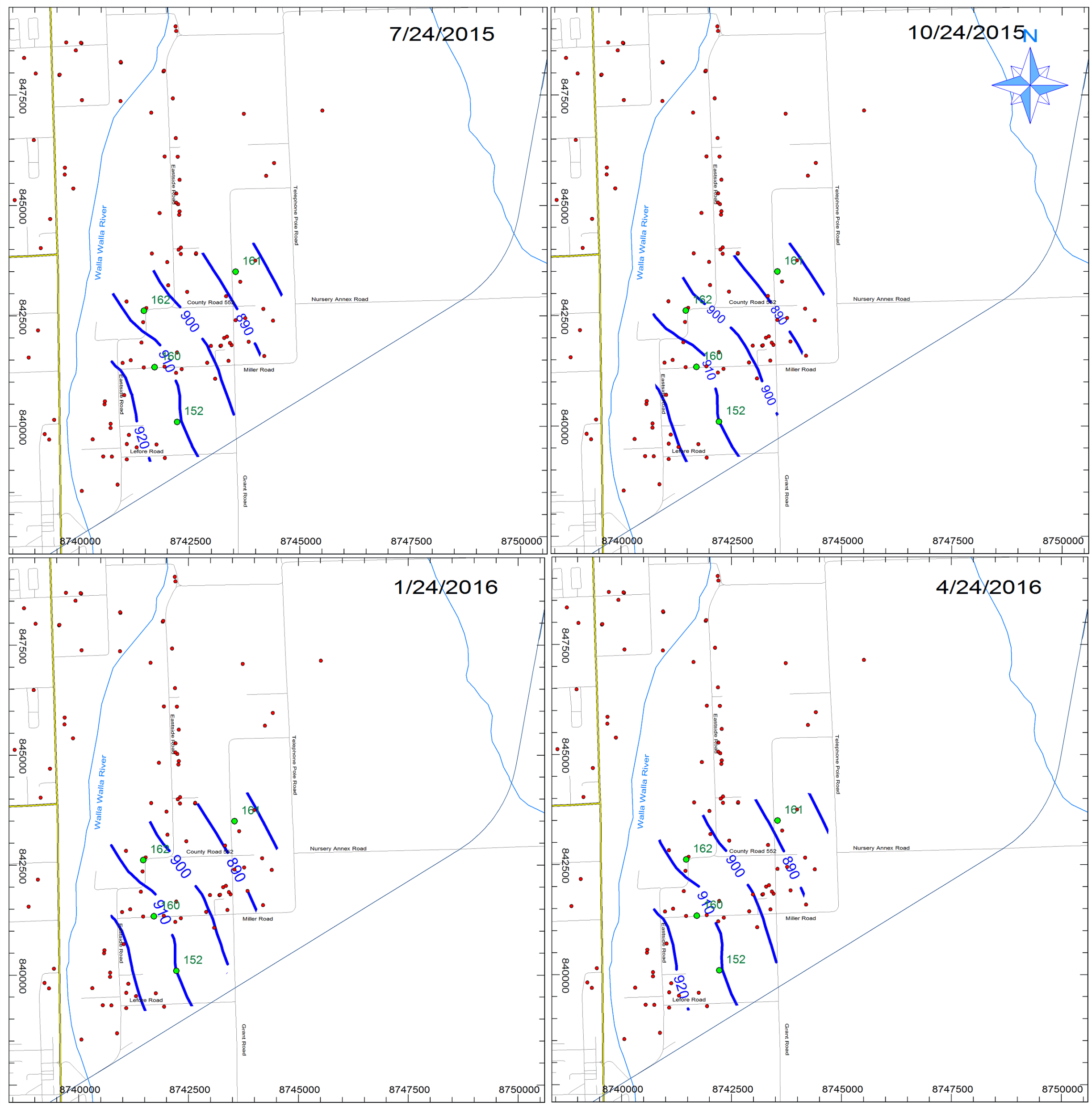
0 400 800

Vertical Exaggeration: 10
Section Offset Projection: 110
Horizontal Units: Distance along section in feet (ft)
Vertical Units: Feet above sea level (fasl)

Figure 3 Cross Section B - B'

NORTHWEST Land & Water, INC.

Eastside Milton-Freewater MAR



Legend:

- Roads
- Express/Highway
- Railway
- River/Stream
- Lake
- Wells
- Wells for contouring

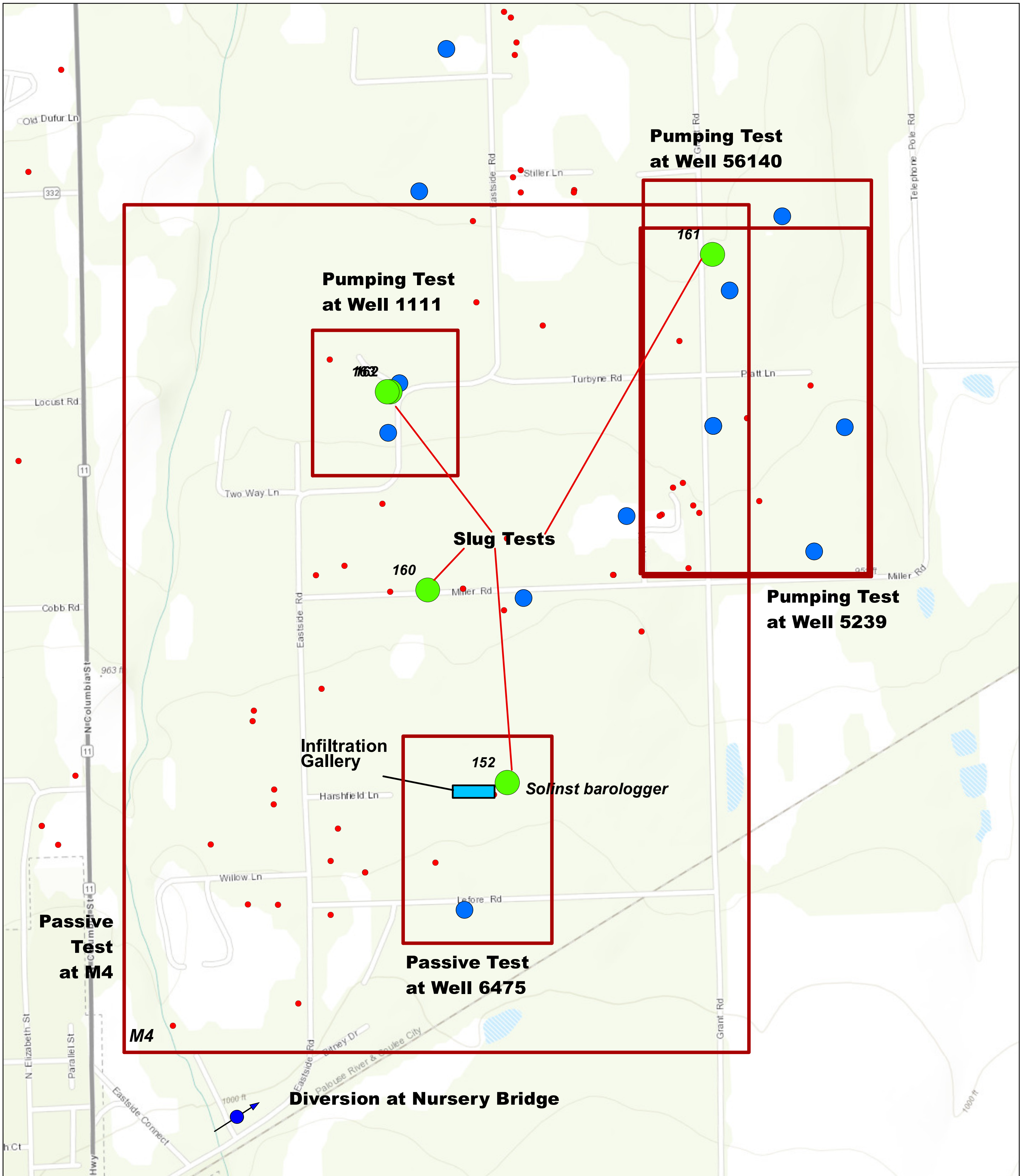
Groundwater Contours
Contour Line Start: 870 Step: 10 Stop: 940

Units: SPCS Oregon North (NAD 83, ft)

Figure 4 Groundwater Contour Time Series

NORTHWEST Land & Water, INC.

Eastside Milton-Freewater MAR



Legend

- Monitoring Well
- Other Cross Section Well
- Other Project Well

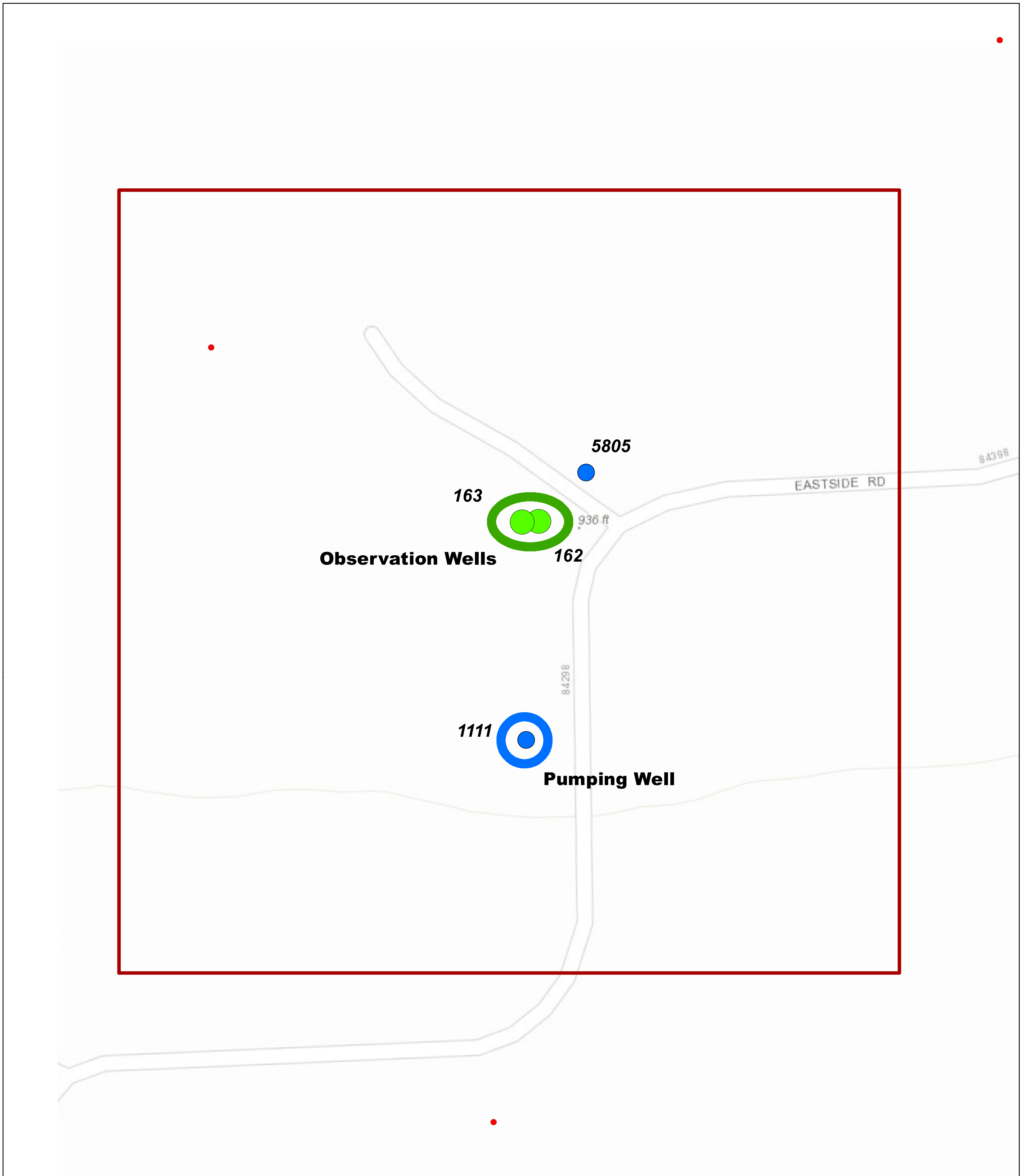
N

330 165 0 330 Feet

Figure 5
Test Areas

Eastside Milton-Freewater MAR
WWBWC

NORTHWEST Land & Water, INC.



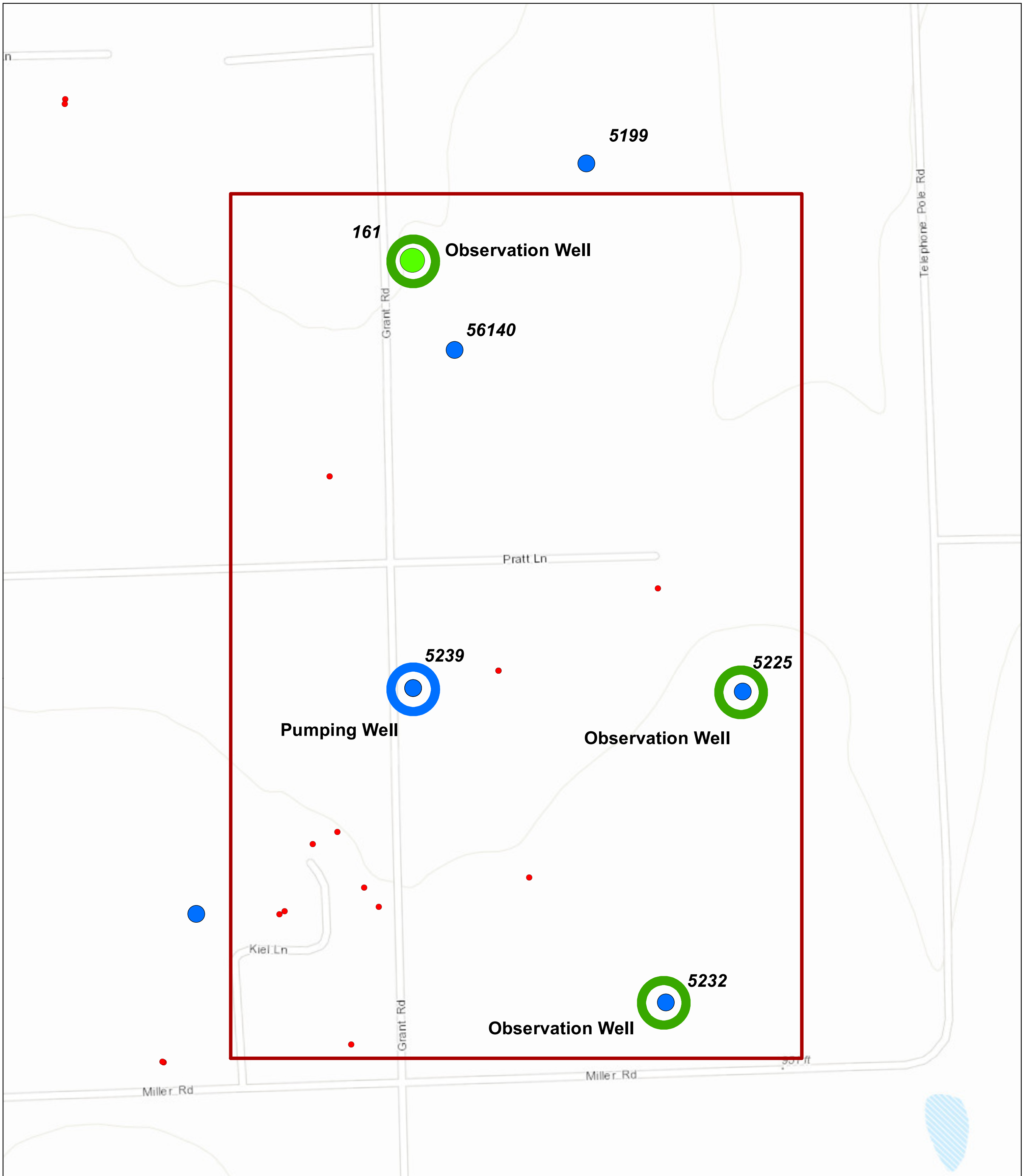
Legend

- Monitoring Well
- Other Cross Section Well
- Other Project Well

Figure 5a
Pumping Test
at Well 1111

Eastside Milton-Freewater MAR
WWBWC

NORTHWEST Land & Water, INC.



Legend

- Monitoring Well
- Other Cross Section Well
- Other Project Well

N

130 65 0 130 Feet

Figure 5b
Pumping Test
at Well 5239

Eastside Milton-Freewater MAR
WWBWC

Northwest Land & Water, Inc.

Legend

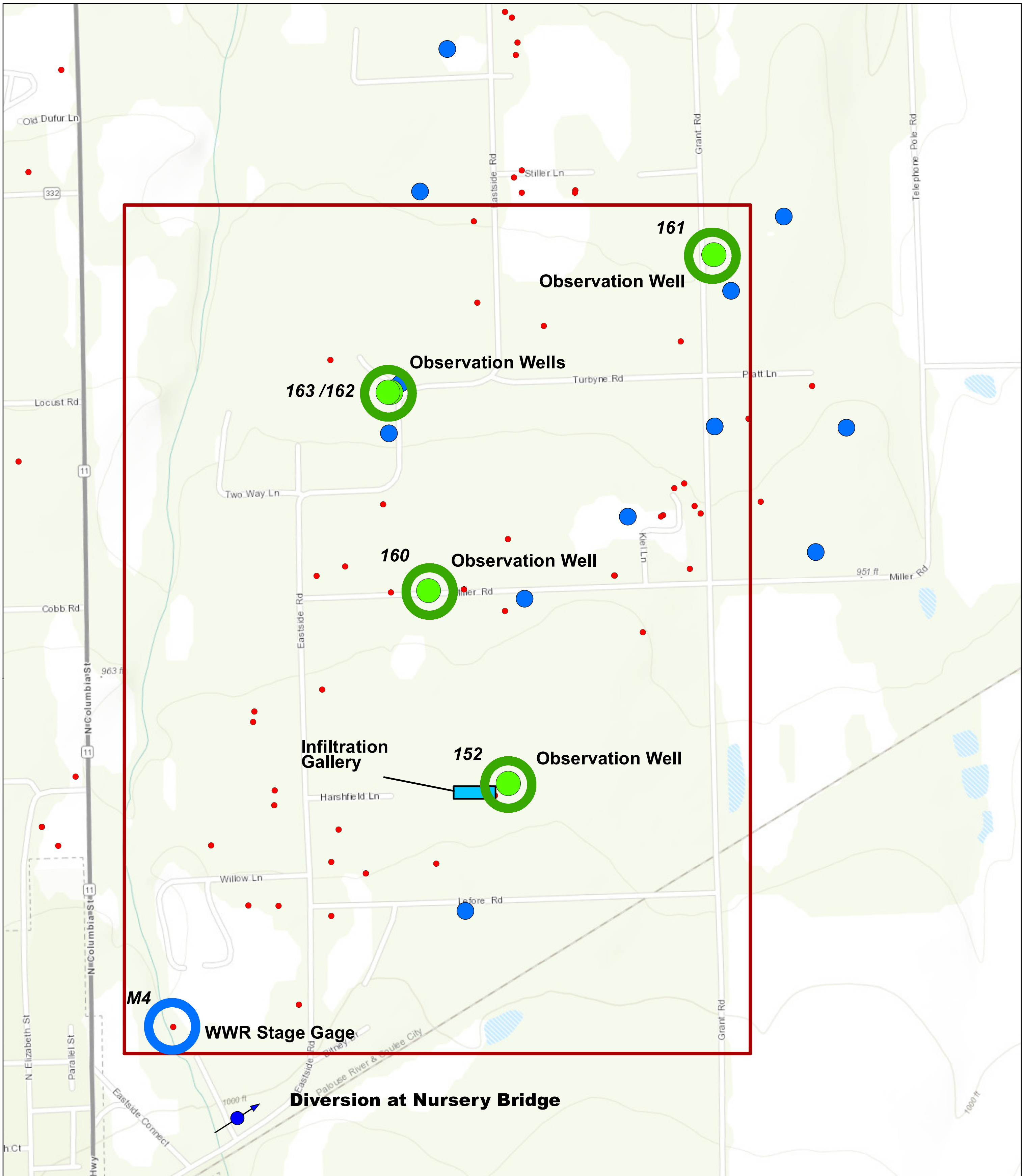
- Monitoring Well
- Other Cross Section Well
- Other Project Well

N

130 65 0 130 Feet

Figure 5c Pumping Test at Well 56140

Eastside Milton-Freewater MAR
WWBWC



Legend

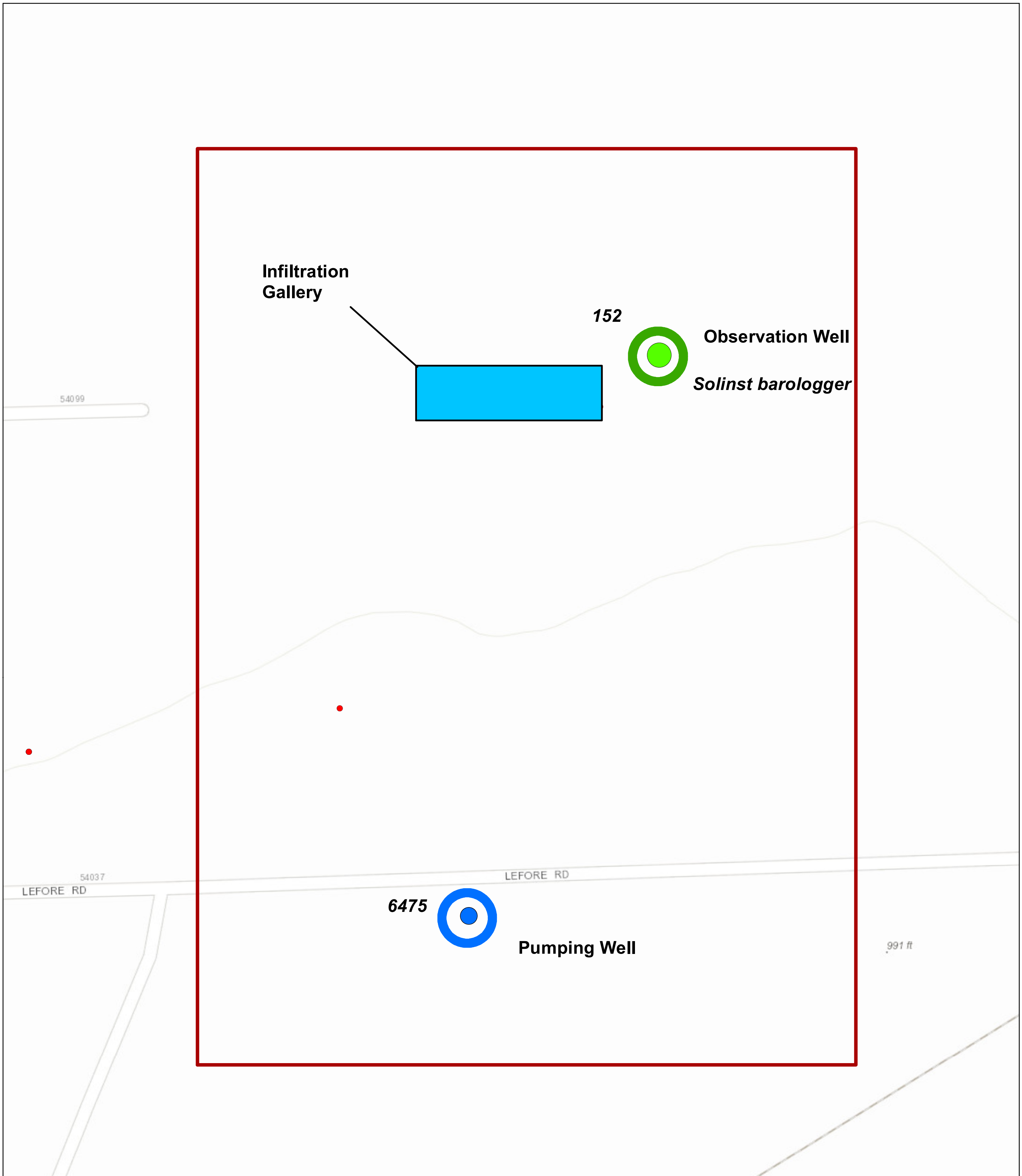
- Monitoring Well
- Other Cross Section Well
- Other Project Well

N

330 165 0 330 Feet

Figure 5d
Passive Test at Stage Gage M4

Eastside Milton-Freewater MAR
WWBWC



Legend

- Monitoring Well
- Other Cross Section Well
- Other Project Well

N

75 37.5 0 75 Feet

Figure 5e
Passive Test at Well 6475

Eastside Milton-Freewater MAR
WWBWC

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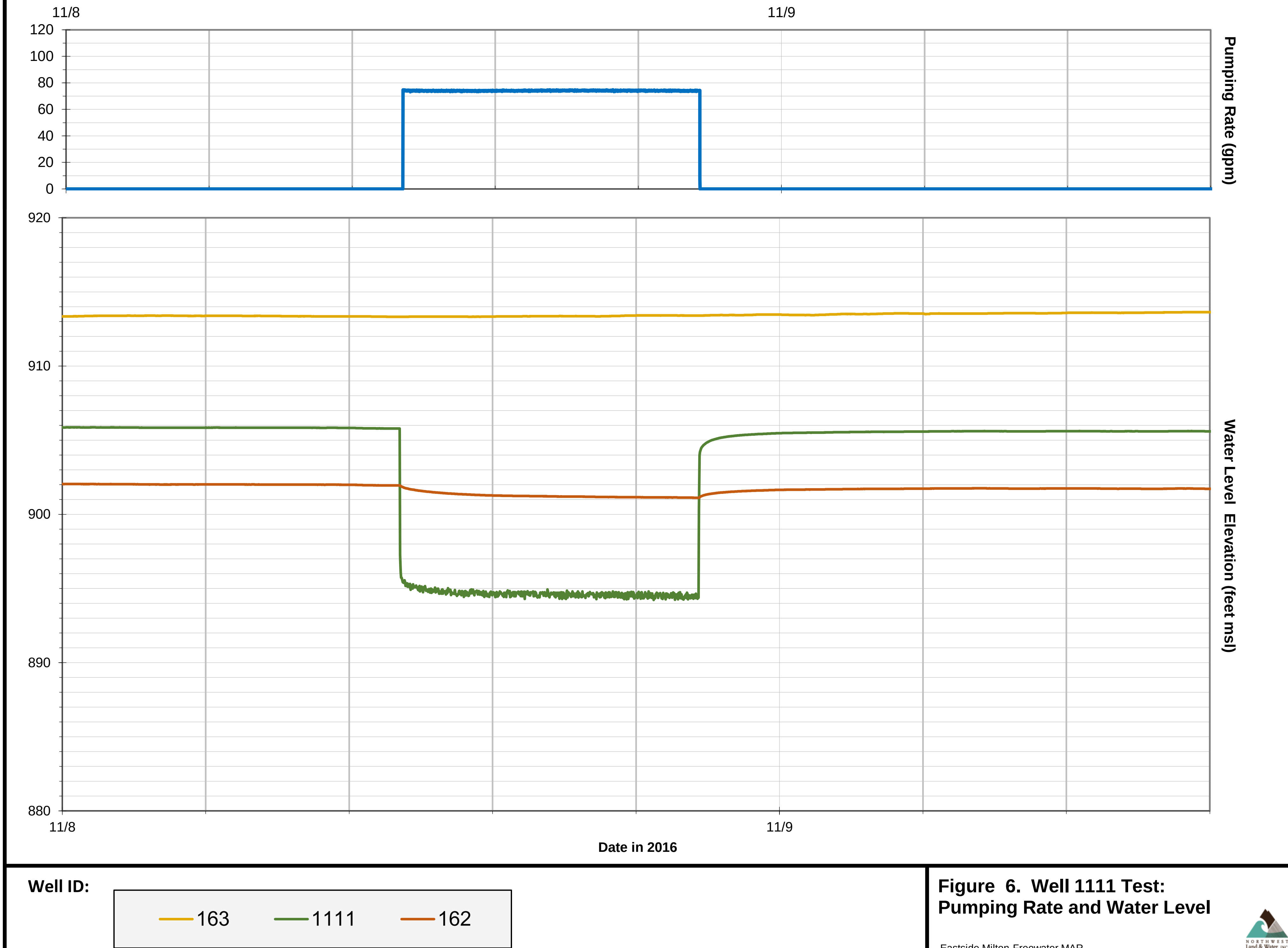
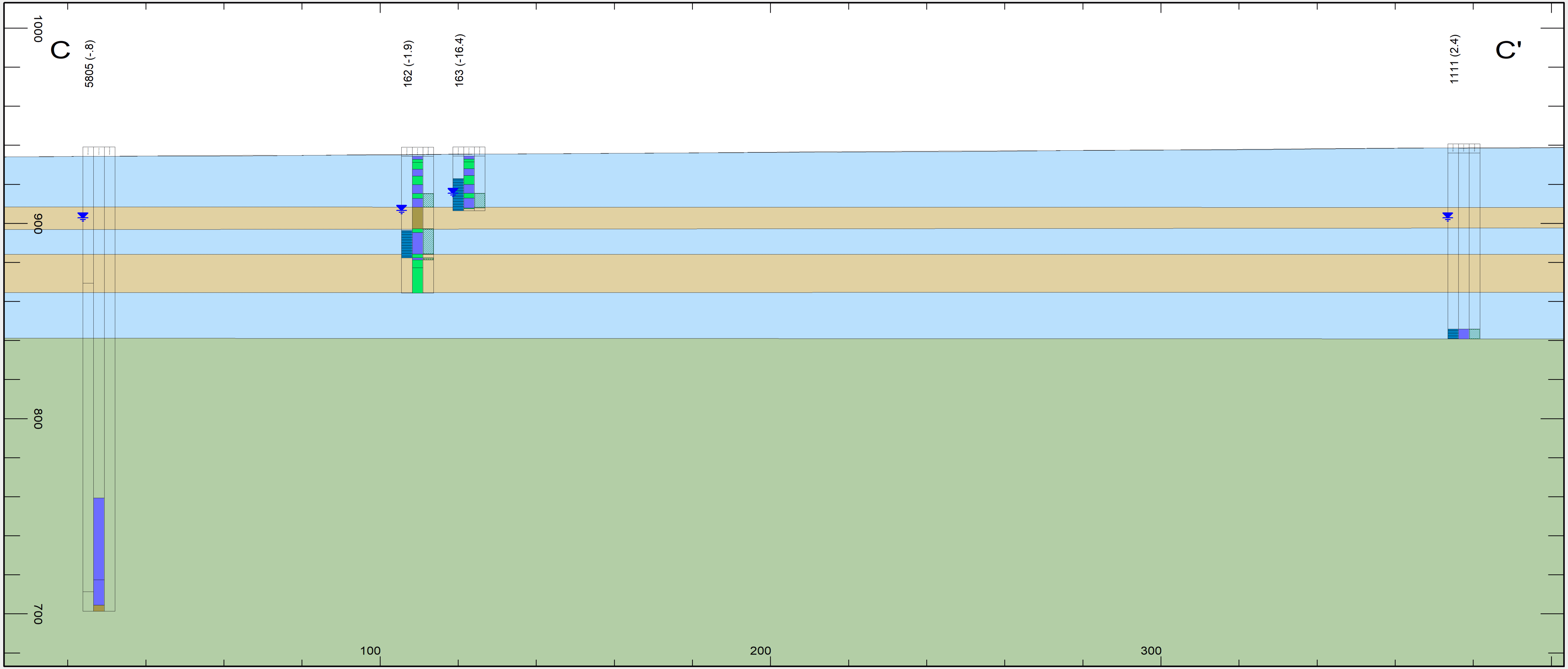


Figure 6. Well 1111 Test: Pumping Rate and Water Level

Eastside Milton-Freewater MAR
WWBWC



Legend:

- Alluvium (Water Bearing Aquifer)
- Alluvium (Aquitard)
- Older Sediments (Lower Permeability, Local Water-Bearing Zones)
- Basalt

Well Construction:
- Open or Screen Interval

Relative Permeability:
- High
- Medium
- Low
- Variable (Basalt)

Water Bearing Zone:

- Head Elevation (ft, msl)
- Projection of surface onto section
- Topography (ft, msl)
- Wells with GW elevations

0 20 40

Vertical Exaggeration: .5
Section Offset Projection: 25
Horizontal Units: Distance along section in feet (ft)
Vertical Units: Feet above sea level (fasl)

Figure 7 Cross Section C-C'

Eastside Milton-Freewater MAR

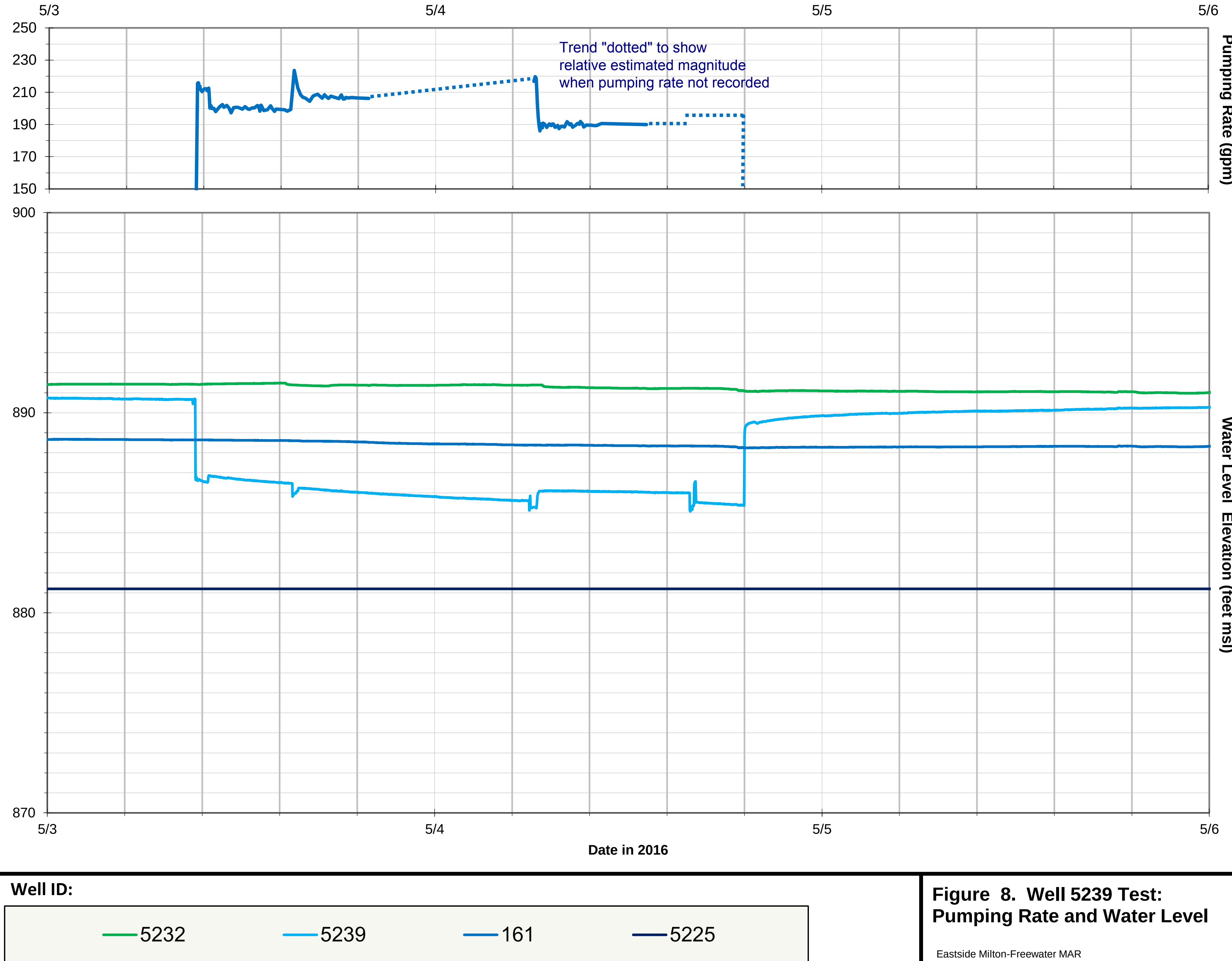
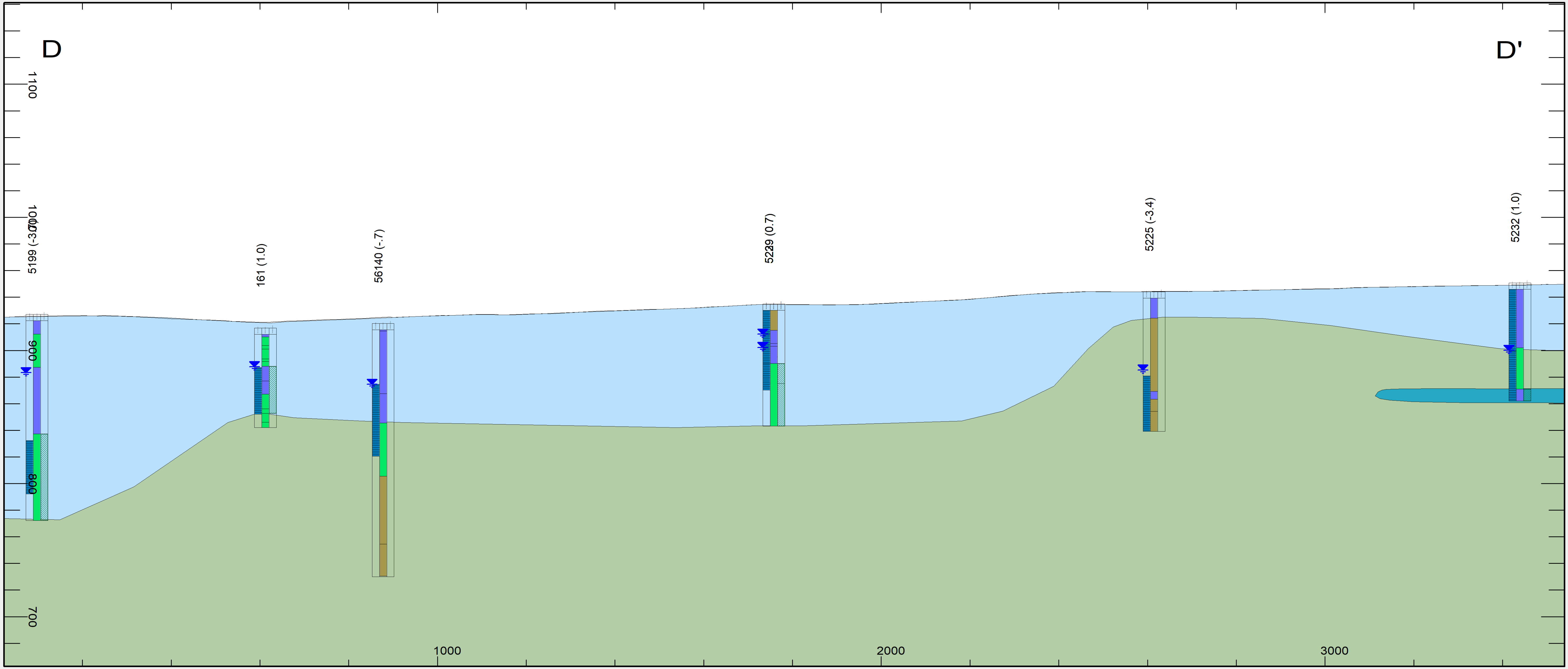


Figure 8. Well 5239 Test: Pumping Rate and Water Level

Eastside Milton-Freewater MAR
WWBWC



Legend:

- Alluvium (Higher Permeability, Part of Shallow Aquifer)
- Older Sediments (Lower Permeability, Local Water-Bearing Zones)
- Local Water-Bearing Zone
- Basalt

Well Construction:
- Open or Screen Interval

Relative Permeability:
- High
- Medium
- Low
- Variable (Basalt)

Water Bearing Zone:

- Head Elevation (ft, msl)
- Projection of surface onto section
- Topography (ft, msl)
- Wells with GW elevations

0 200 400

Vertical Exaggeration: 3
Section Offset Projection: 25
Horizontal Units: Distance along section in feet (ft)
Vertical Units: Feet above sea level (fasl)

Figure 9 Cross Section D-D'

Eastside Milton-Freewater MAR

Drawing prepared by SSM 9/27/2017

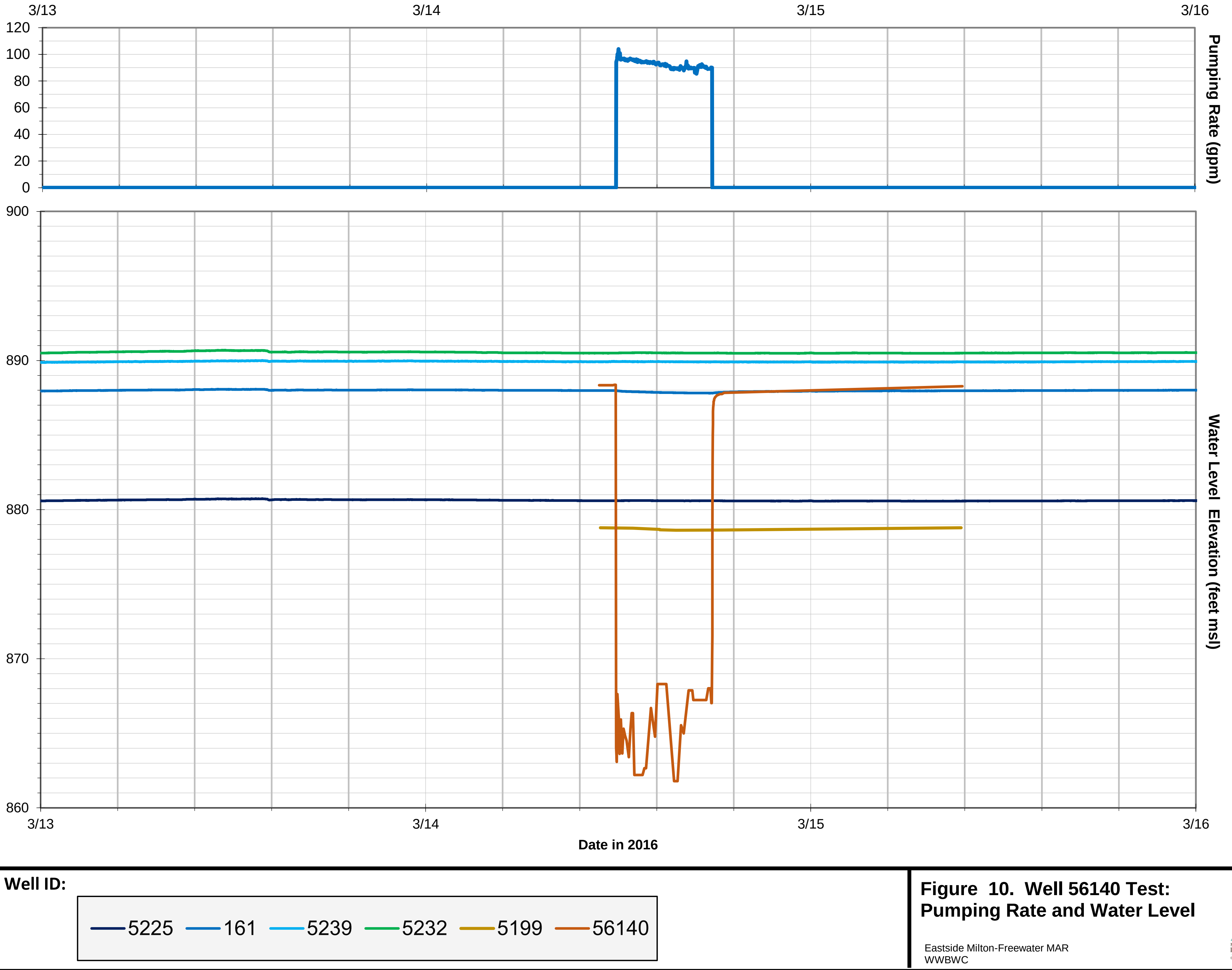


Figure 10. Well 56140 Test: Pumping Rate and Water Level

Eastside Milton-Freewater MAR
WWBWC

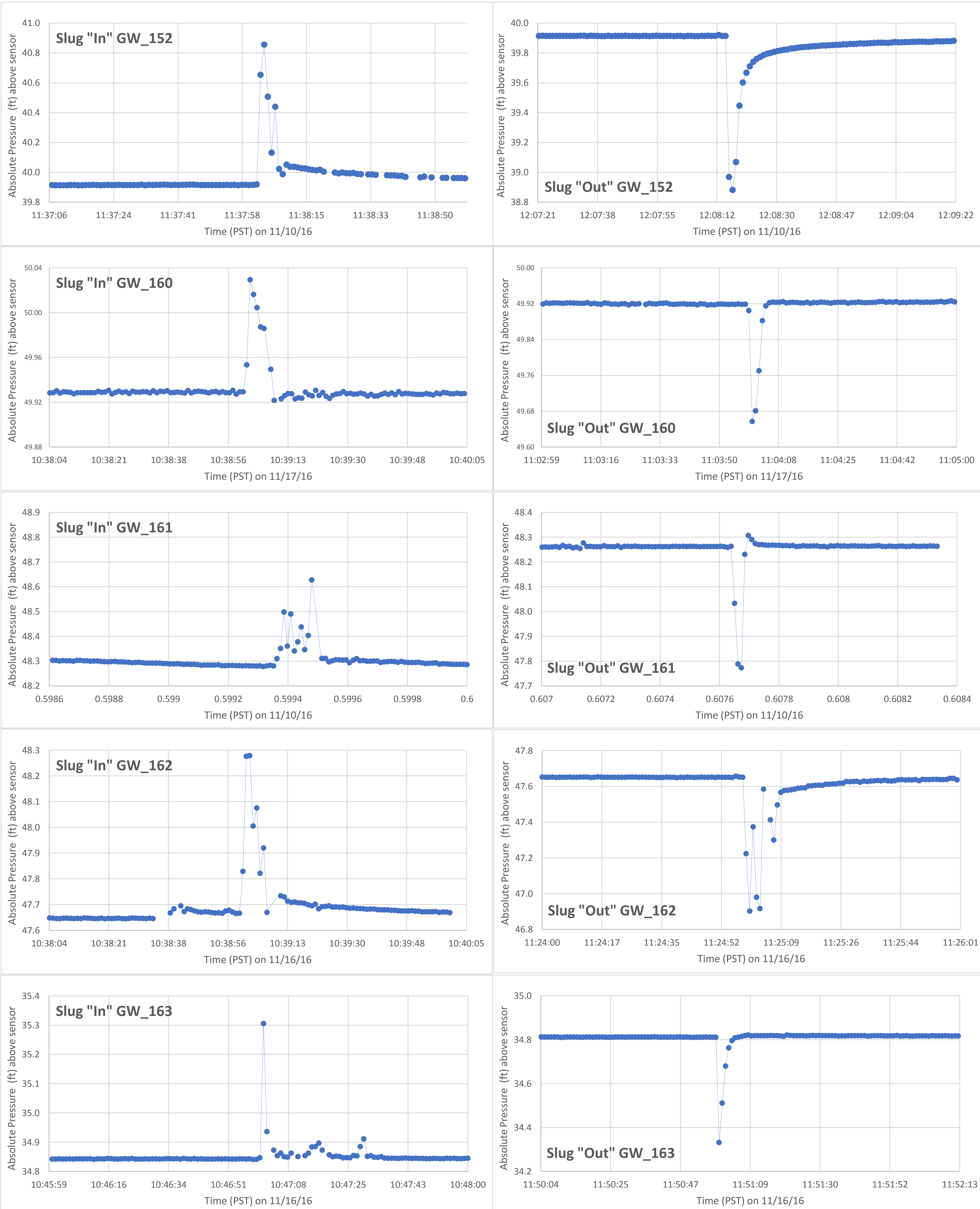


Figure 11 Pre-, During-, and Post-Slug Test Water Level at Monitoring Wells

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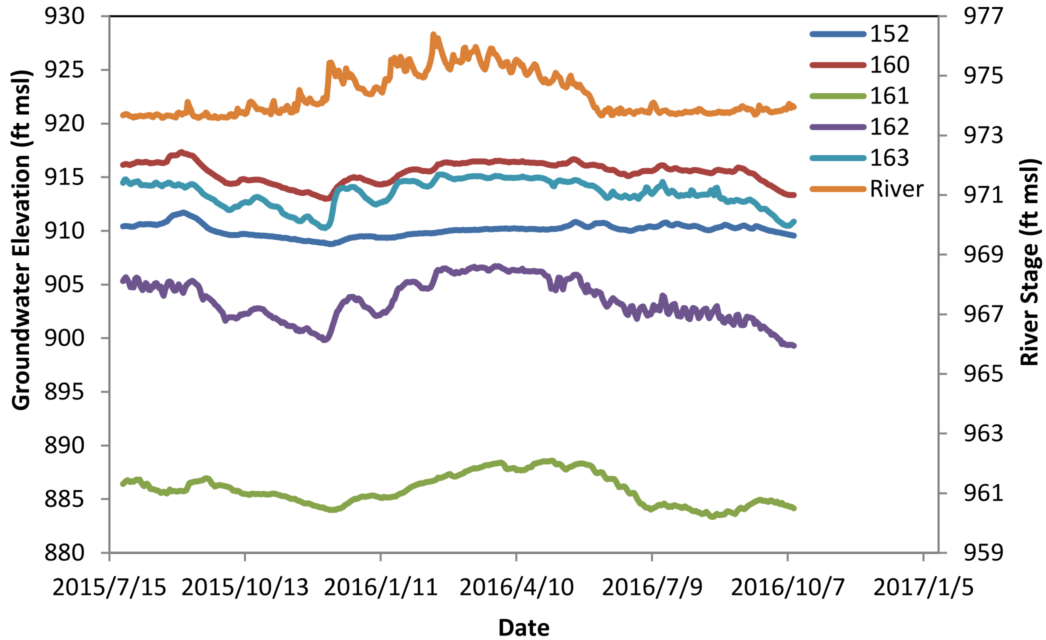
Figure 12. WWR Stage (M4) and Monitoring Well Hydrographs *(upper and lower graphs identical, but lower graph is annotated to show storm events and corresponding well response)*



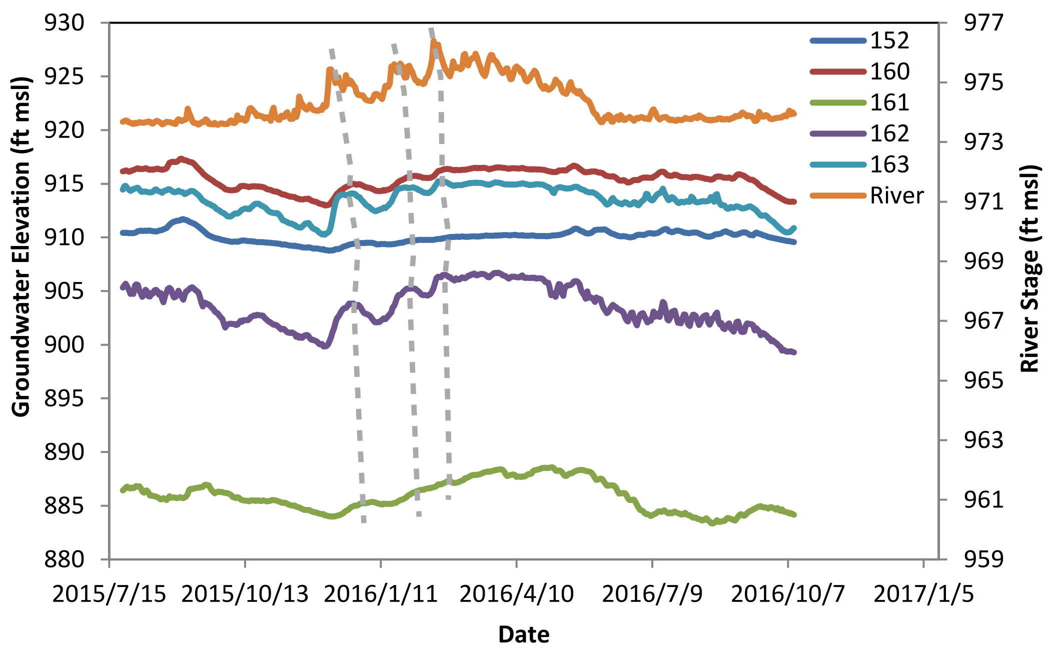
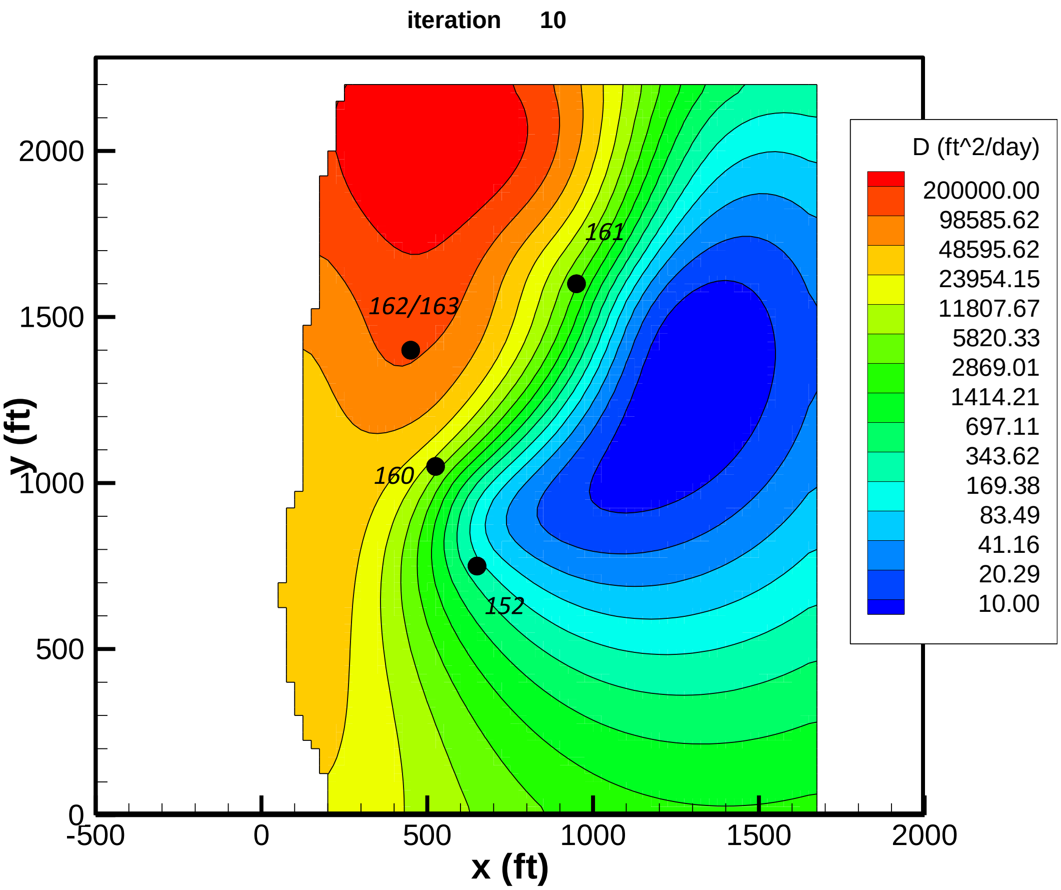


Figure 13. Hydraulic Diffusivity Field



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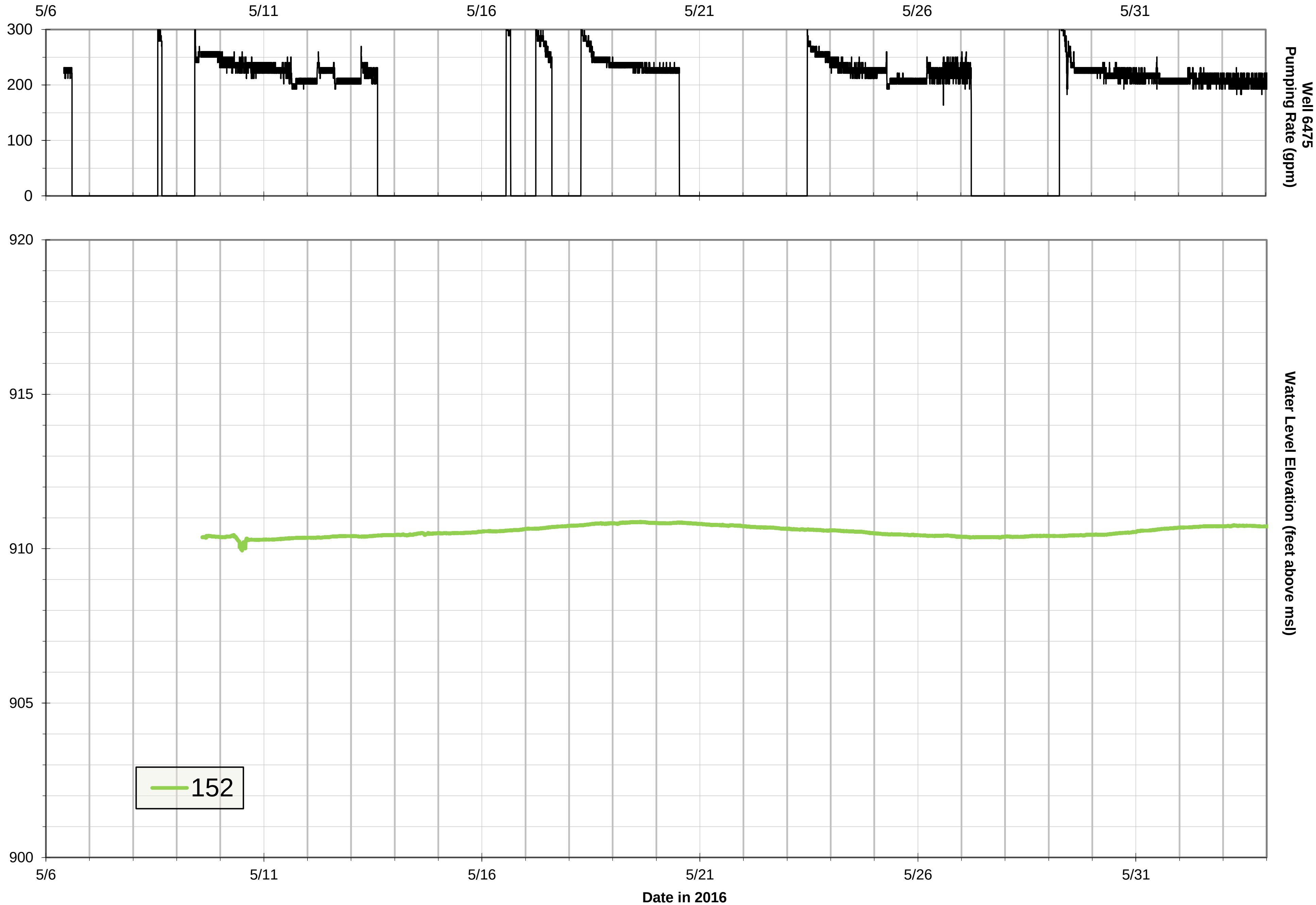

Figure 14. Well GW_152 Water Level and Well 6475 Pumping, May 2016

Eastside Milton-Freewater MAR
WWBWC

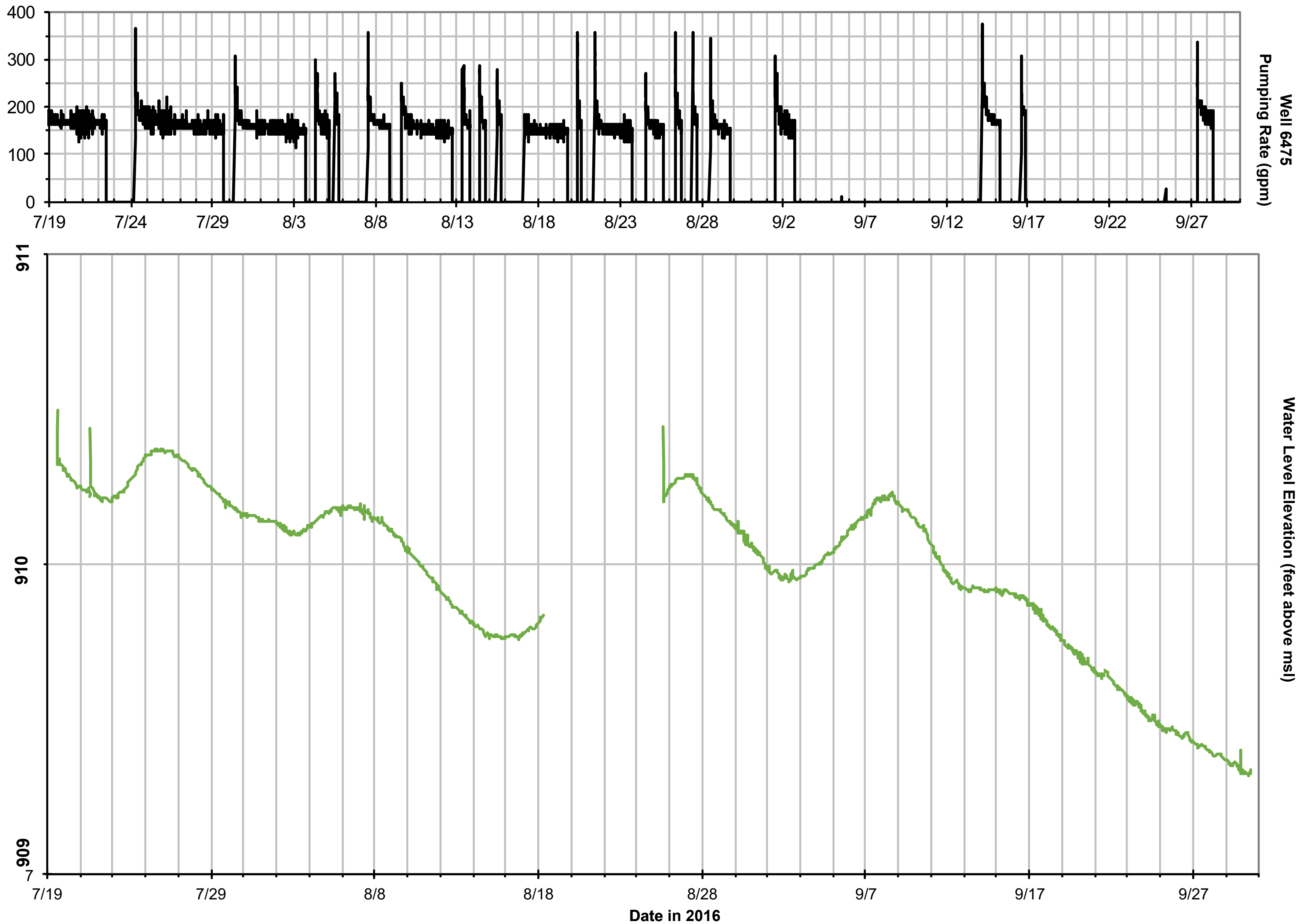

Figure 15. Well GW_152 Water Level and Well 6475 Pumping, Jul 19 - Sep 29, 2016

Eastside Milton-Freewater MAR
WWBWC

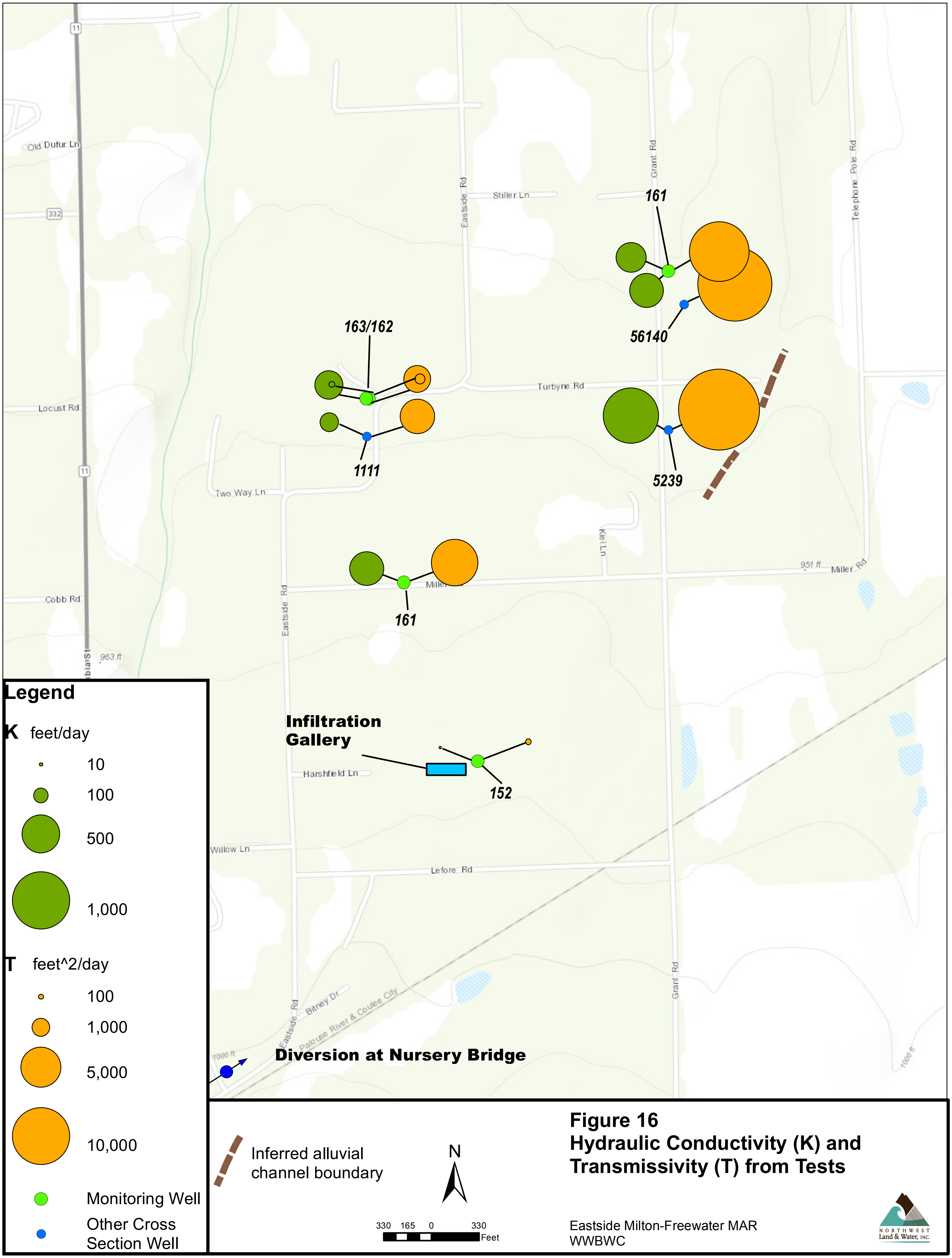

Figure 16
Hydraulic Conductivity (K) and Transmissivity (T) from Tests

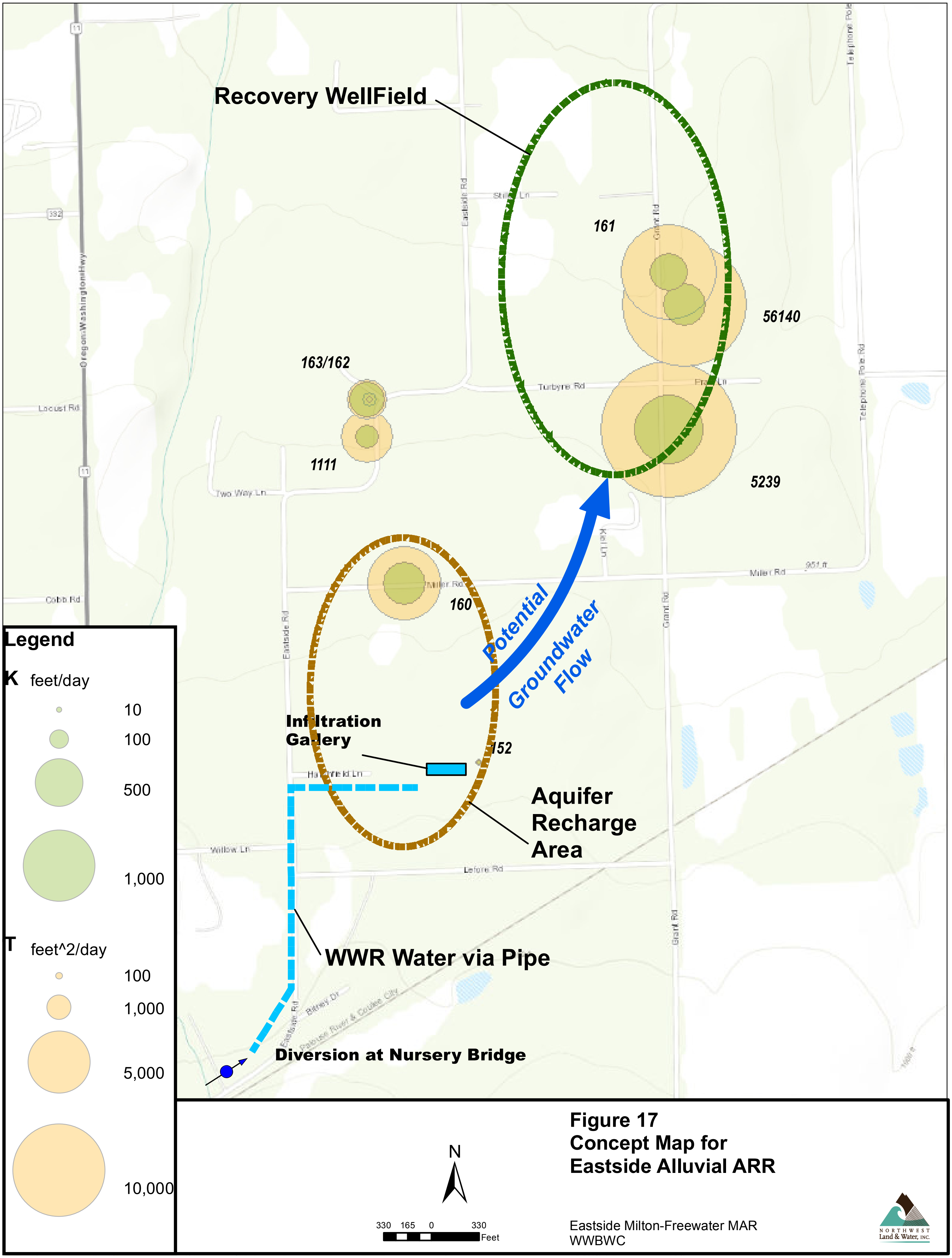

Figure 17
Concept Map for Eastside Alluvial ARR