Application: 41H 30127867 **T01S, R05E, Section 26**

Applicant: FLIR Systems Inc. **Gallatin County**

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Montana Department of Natural Resources Water Management Bureau

January 29, 2021

Aquifer Test Report

Introduction

The applicant requests three points of diversion (extraction wells), a flow rate of 700 gallons per minute (gpm) and a volume of 831 acre-feet (AF) per year for an open loop geothermal system that will discharge back into the same source aquifer via four injection wells. Submersible pumps within the wells will be interfaced with variable-frequency controllers that will receive a flow-demand signal from the heat-exchange system in the building. The submersible pumps' flow rates will be variable throughout the year and will provide a combined flow up to a peak of 700 gpm.

This investigation examines the details of a 72-hour aquifer test performed on the middle extraction well identified as the Montana Bureau of Mines and Geology Groundwater Information Center (GWIC) # 304056. The aquifer test included measuring drawdown and recovery in the test and two nearby observation wells. Two 8-hour drawdown and yield tests were performed on the east and west extraction wells (GWIC #s 304057 and 303698, respectively).

This report will analyze the aquifer test data collected. Extended analysis of these test data involves matching analytical groundwater solutions to observed drawdown data. Aquifer test analyses provides a basis for evaluating adequacy of diversion, physical availability of groundwater, and adverse effect to existing groundwater and surface water users

The FLIR Systems Inc. proposed geothermal system and wells are located within the Bozeman Solvent Site Controlled Groundwater Area. The analysis within this report is limited to the physical quantity of groundwater and does not discuss groundwater quality or migration of contaminants of concern.

Hydrogeologic Setting

All extraction and injection wells are located in Township 1 South, Range 5 East, Section 26, in Bozeman, Gallatin County (**Figure 1**). The middle, east, and west extraction wells (GWIC #s 304056, 304057, and 303698) are 181, 181, and 206 feet below ground surface (bgs), respectively. The four injection wells (GWIC #s 305205, 305206, 305207, 305208) are all 120 feet bgs, respectively.

The surficial geology is mapped as Quaternary braided plain alluvium deposits of cobbles, boulders, sand, silt and clay up to 30 feet thick (Vuke et al., 2014). The Quaternary sediments are underlain by Tertiary Madison Valley member silt, siltsone, sandstone and conglomerates, in some parts of the valley up to 300 feet thick (Vuke et al., 2014). The extraction wells are screened in Tertiary sediments. The injection wells are shallower but still screened in the upper portion of the Tertiary sediments.

The Gallatin Valley Quaternary and Tertiary aquifer system contains shallow unconfined, semi-confined (leaky confined), confined, and possibly even perched groundwater (English, 2018). Generally, groundwater and surface water flows from southeast to northwest across the valley and is recharged by irrigation, stream losses, and ditch leakage ultimately discharging to the Gallatin River (Hackett et al. 1960).

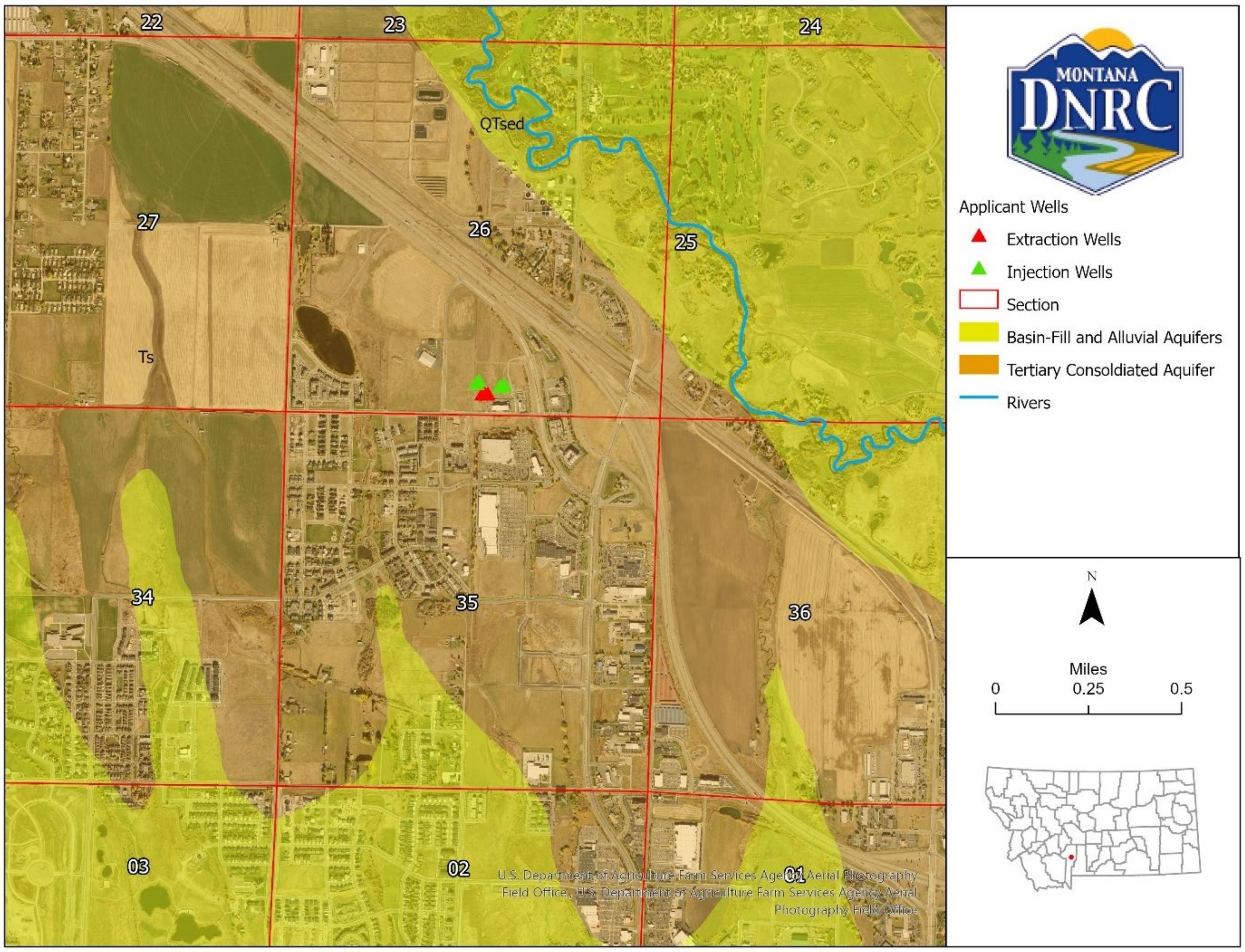

Figure 1: Project location and surficial geologic map with extraction and injection wells (modified from Vuke et al., 2014).

Aquifer Testing: Data Collection, Compilation

The water levels in the pumping well (middle extraction well, GWIC # 304056) and observation wells (east extraction well GWIC # 304057 and west extraction well GWIC # 303698) were collected using Solinst® data loggers and pressure transducers. The raw data were converted to depth to water based on a manual measurement with an electric tape and subsequently converted to drawdown which is the difference between the water level at a specified time after pumping starts and the static water levels observed at time (t = 0).

Background static water levels in the pumping well and observation wells were monitored for 49 hours between March 20, 2020 and May 22, 2020 (**Figure 2**). Water levels in the pumping well and monitoring wells were static prior to the pumping test.

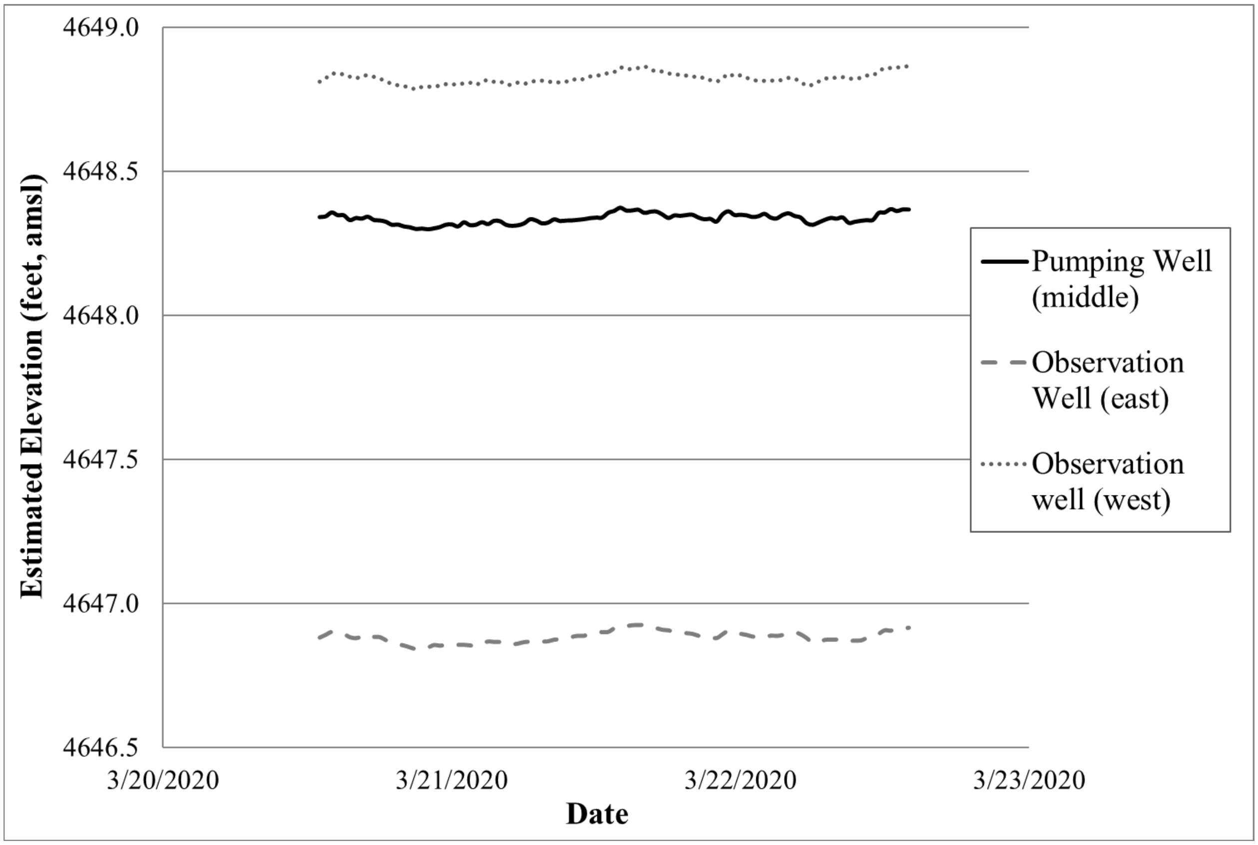

Figure 2: Arithmetic plot of groundwater elevation in feet above mean sea level (amsl) prior to the aquifer test.

The 72-hour aquifer test started on March 23, 2030, at 8:18 AM and is time (t=0) for the computation of drawdown (**Figure 3**). The test continued without interruption, until 8:21 AM on March 26, 2020, at an average flow rate of 240 gpm. The discharge was measured using a Siemens flow meter and conveyed in buried storm sewer piping approximately 1,097 feet to north where it was discharged to a storm water surge pond.

The maximum drawdown in the pumping well was 45.39 feet below the static water level of 9.14 feet below top of casing (btc). The west observation well is 50 feet from the pumping well and exhibited a maximum drawdown of 12.38 feet below the static water level of 7.93 feet btc. East observation well is 50 feet from the pumping well and exhibited a maximum drawdown of 17.9 feet below the static water level of 7.5 btc.

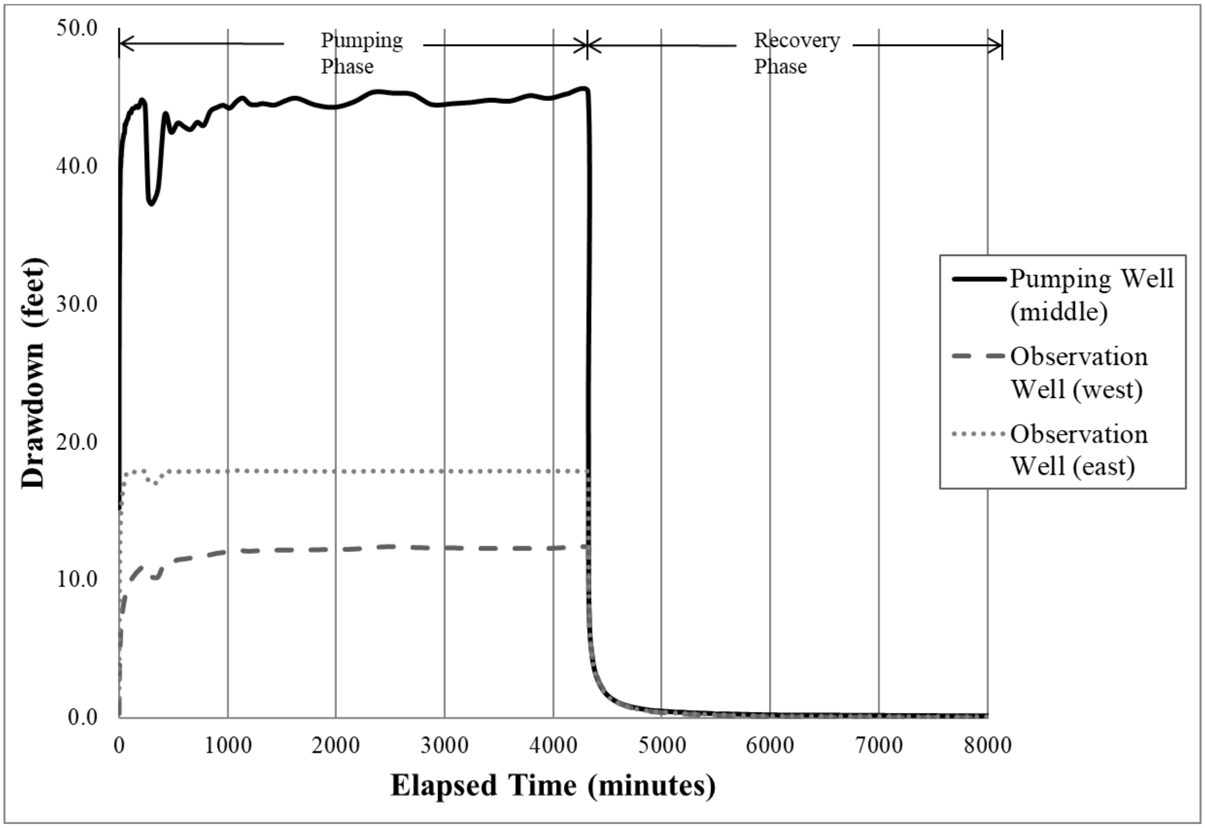

Figure 3: Arithmetic plot of drawdown and recovery data for the pumping well and observation wells.

Aquifer Testing: Analysis

AQTESOLV® (HydroSOLVE, Inc., 2007) was used to analyze drawdown from the aquifer test to obtain estimates of aquifer properties. AQTESOLV® is an analytical modeling software that uses image well theory and the principle of superposition to simulate aquifer stress tests. Known well, aquifer, and aquitard characteristics from well logs and previous investigations are input into the model. Each well gets a spatial location in the AQTESOLV® model. Calculated aquifer drawdown and pumping rates from the aquifer test are input into the model. Using this compilation of data, the aquifer system properties including transmissivity (T) and storativity (S) are adjusted by automatic matches and fine-tuned with trial and error in AQTESOLV® to derive a best-fit visual match between the drawdown data and the drawdown modeled by AQTESOLV®.

Neuman-Witherspoon (1969) derived a solution for unsteady flow to a fully penetrating well in a confined two-aquifer system with a leaky aquitard between them. The solution assumes a line source for the pumped well and therefore neglects wellbore storage. The Neuman-Witherspoon (1969) solution can simulate variable-rate tests including recovery through the application of the principle of superposition in time. The method is capable of analyzing drawdown data for wells completed in the pumped aquifer, the unpumped aquifer or in the aquitard. Wells in the aquifer are assumed to be fully penetrating; wells in the aquitard may be partially penetrating (HydroSOLVE, Inc., 2007).

The Neuman-Witherspoon (1969) solution is demonstrated here to best simulate aquifer drawdown in the confined two-aquifer system and has the following assumptions:

- aquifer has infinite areal extent;
- aquifer is homogeneous, isotropic and of uniform thickness;
- aquifer potentiometric surface is initially horizontal;
- control well is fully penetrating;
- flow to control well is horizontal;
- aquifer is leaky;
- flow is unsteady;
- water is released instantaneously from storage with decline of hydraulic head;
- diameter of control well is very small so that storage in the well can be neglected;
- aquitard has infinite areal extent, uniform vertical hydraulic conductivity and storage coefficient, and uniform thickness;
- flow in the aquitard is vertical.

The analyzed drawdown response for the west and east observation wells are shown in **Figures 4 and 5.** The derivative of the drawdown data supports a leaky confined aquifer response.

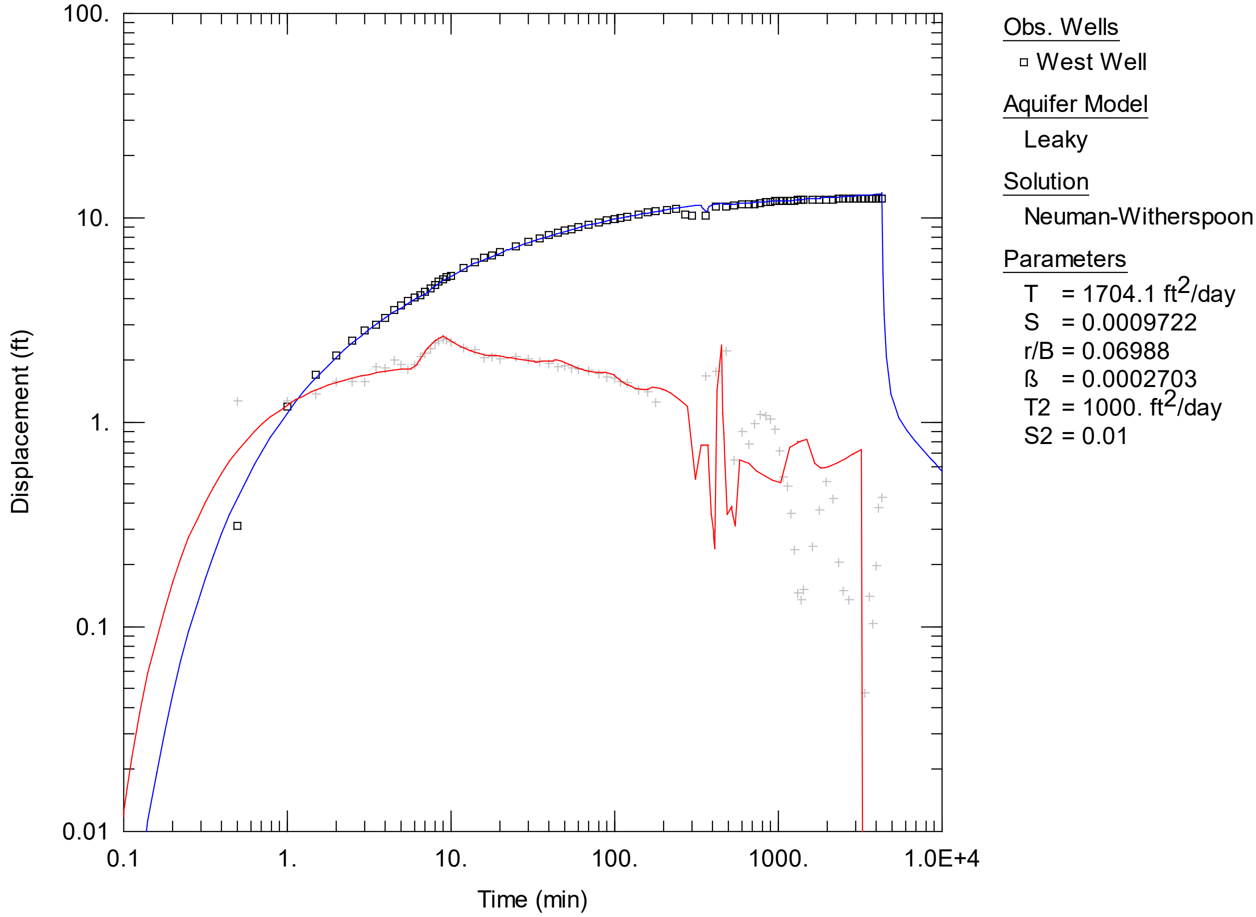

Figure 4. Newman-Witherspoon (1969) 72-hour drawdown and derivative analysis in the west observation well (GWIC # 303698).

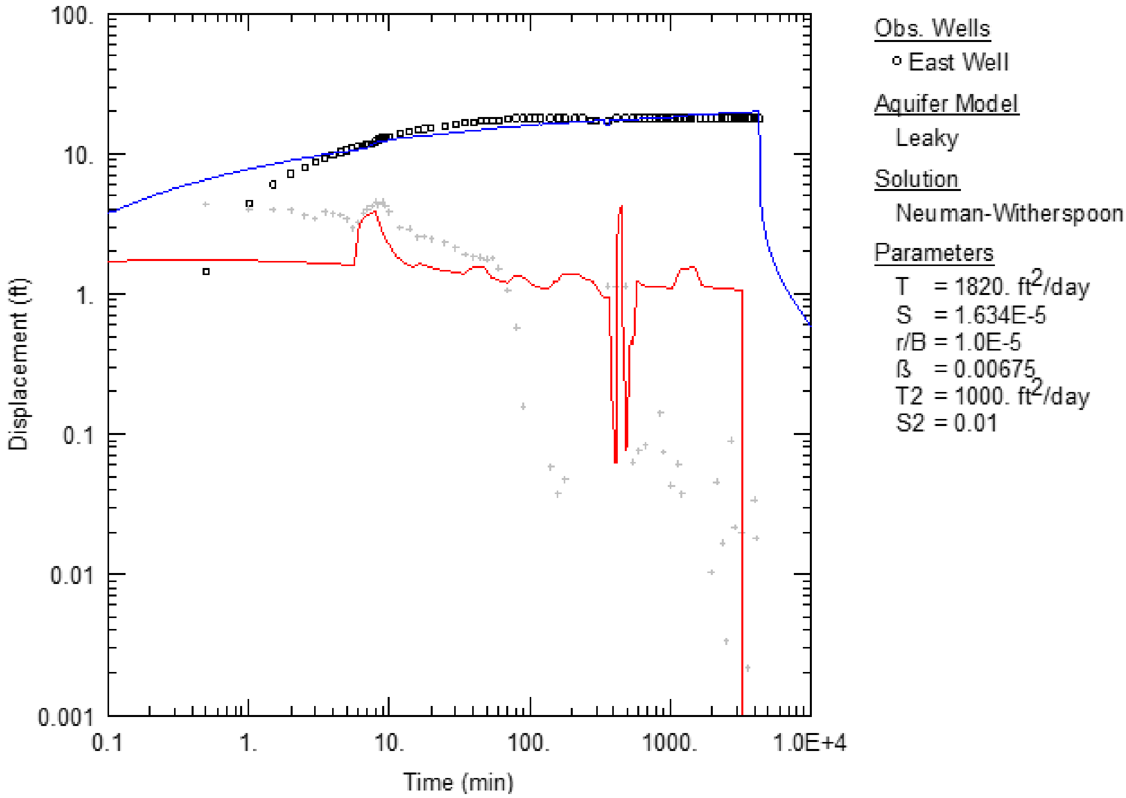

Figure 5. Newman-Witherspoon (1969) 72-hour drawdown and derivative analysis in the east observation well (GWIC # 304057)

The aquifer transmissivity of 1,704 ft^2/day and storativity of 0.001 generated from the Neuman-Witherspoon (1969) solution for the west observation well drawdown response (**Figure 4**) is recommended for use in evaluating permit criteria. The results of the aquifer test analysis are summarized in **Table 1**. The Neuman-Witherspoon (1969) solution for the west observation well resulted in a better type curve and derivative curve match compared to the other solutions.

Table 1: Aquifer Test Analysis Summary.

Aquifer Test Phase	Observation Well (GWIC #)	Analysis Solution	Transmissivity (T) (ft^2/day)	Storativity (S)
Middle Pumping- 72 hour	West Observation Well (303698)	Neuman and Witherspoon (1969)	1,704	0.001
Middle Pumping- 72 hour	East Observation Well (304057)	Neuman and Witherspoon	1,820	0.00002

Other Aquifer Parameter Data

Drawdown for the 8-hour drawdown and yield tests for the west well (GWIC # 303698) and east well (GWIC # 304057) with the middle well as the observation well is shown in **Figure 6 and Figure 7**. This west well test was conducted at an average of 361 gpm and had 98 feet of well drawdown. The east well test was conducted at an average of 373 gpm and had 69 feet of well drawdown.

The transmissivity of 1746.9 ft^2/day and storativity of 0.0004 generated from the Neuman-Witherspoon (1969) leaky confined aquifer solution for the west-well, 8-hour test (**Figure 6)** has comparable aquifer properties to the 72-hour test (**Table 1**). While the aquifer properties generated for the 8-hour east well pumping test are lower when compared to the recommend aquifer properties (**Figure 7**).

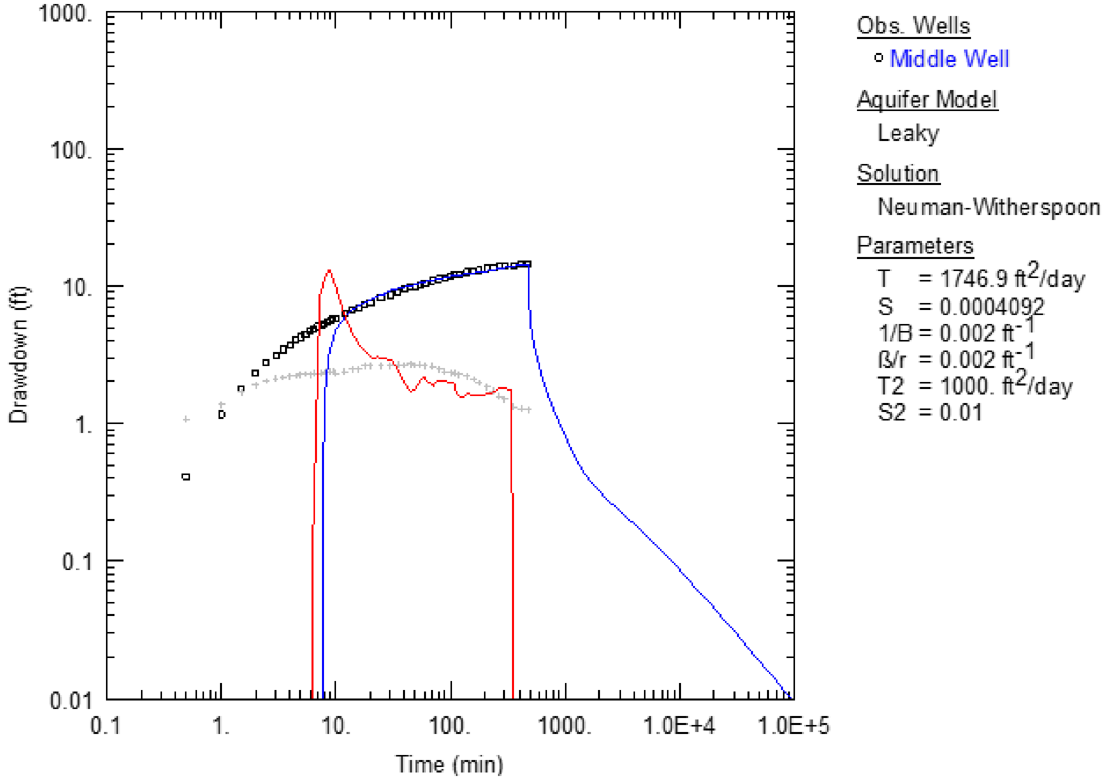

Figure 6. Neuman-Witherspoon (1969) 8-hour drawdown and derivative analysis for the west pumping well (GWIC # 303698).

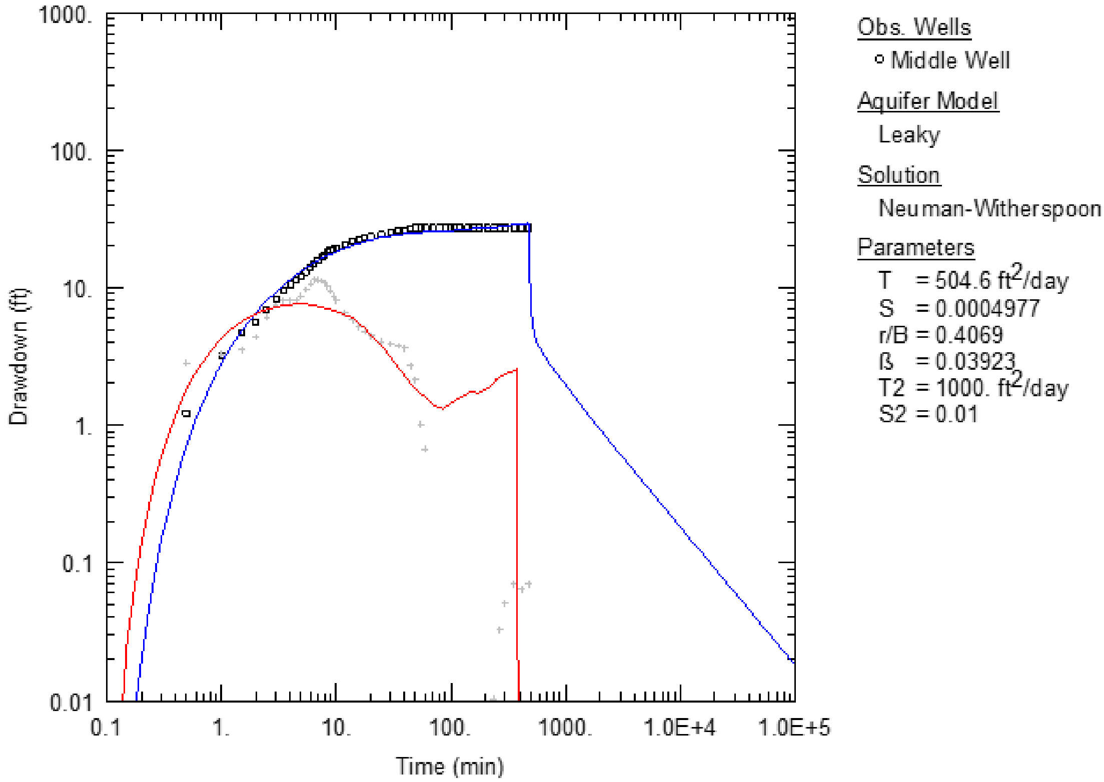

Figure 7. Neuman-Witherspoon (1969) 8-hour drawdown and derivative analysis for the east pumping well (GWIC # 304057).

After querying the MBMG Groundwater Information Center (GWIC) database for aquifer test data, additional aquifer tests were found and their data is summarized in **Table 2**. Transmissivity for the Tertiary aquifer is variable (**Table 2**), yet a predicted transmissivity of 1,704 ft^2/day from the FLIR 72-hour aquifer test analyses is reasonable for a well completed in the Tertiary aquifer of the Gallatin Valley.

Table 2: Documented aquifer tests near the proposed wells.

Water Right # or Reference	GWIC #	Distance away from applicant (miles)	Aquifer Test Solution	Aquifer Test Length (hours)	Pumping Rate (gpm)	Draw-down (ft)	T (ft^2/day)	Aquifer
41H 30115127	296973	2.1	Theis (1935)	72	206	130	5,545	Quaternary /Tertiary
41H 30109060	292561	2.8	Cooper-Jacob (1946)	76	397	73	28,000	Tertiary
41H 30009188	183089	3.4	Cooper-Jacob (1946)	24	150	155	179	Tertiary
41H 30048037	95855	3.5	Neuman-Witherspoon (1969)	72	435	94	940	Tertiary
41H 30010803	215306	4.4	Cooper-Jacob (1946)	72	200	93	4,680	Quaternary /Tertiary

Adequacy of Diversion and Physical Availability: Analysis

The sum of the flow rates pumped during the aquifer test and drawdown and yield tests exceeded the maximum requested rate (**Table 3**).

Table 3: Pumping tests rates and well responses.

Pumping Well	GWIC ID #	Duration	Flow Rate	Static Water Level	Maximum Drawdown	Remaining water column above perforations
		(hr)	(GPM)	(ft)	(ft)	(ft)
West	303698	8	361	8.64	89.3	22.1
Middle	304056	72	240	9.14	45.4	75.5
East	304057	8	373	8.52	69.4	42.1

Drawdown is modeled for the period of diversion for each of the 3 pumping wells and 4 injection wells assigning each well 1/3 of the pumping and 1/4 of the injection schedule in **Table 4**, a calculated well efficiency for the production wells, and adding interference drawdown. The modeling is done using the Neuman-Witherspoon solution (1969) for a leaky confined aquifer with the following inputs: T = 1,704 ft^2/day, S = 0.001. The monthly pumping schedule in **Table 4** is based on the pumping schedule provided in the Application. The injection rates are equal to the estimated pumping rates. The well efficiency is calculated from modeling each well's respective aquifer test and dividing the predicted drawdown by the observed drawdown to get a well efficiency. The actual drawdown with well loss is calculated by applying the well efficiency to the theoretical maximum drawdown of each well (**Table 5**). The total maximum drawdown is the sum of the actual drawdown in each pumping well and modeled well interference drawdown from all the other pumping and injection wells. Note that the well interference drawdown is negative (e.g., groundwater mounding) for the east and west wells as a result of modeling the injection wells. The last column in **Table 5** gives the remaining available water column for each of the pumping wells which is equal to the available drawdown above the perforations of each well minus total drawdown.

Table 4. Pumping schedule provided by the applicant for each year of pumping/injection for the proposed wells.

Days	Pumping Rate (gpm)	Injection Rate (gpm)
0	350	-350
61	525	-525
170	700	-700
255	525	-525
322	350	-350

Table 5: Remaining available water column for pumping wells.

Applicant Monthly pumping schedule for all 3 wells for 1 year.									
Well	Well Total Depth	Pre-Test Static Water Level	Available Drawdown above bottom	Well Efficiency	Predicted Additional Drawdown including well loss		Predicted Additional Drawdown from Interference	Total Drawdown	Remaining Available Water Column
	(ft)	*(ft btc)*	*(ft)*	*(%)*	*theoretical*	*actual (w/well loss)*	*(ft)*	*(ft)*	*(ft btc)*
West	206.0	8.64	121.4	34	28.1	82.8	-5.4	77.4	43.9
Middle	181.0	9.14	110.9	51	28.1	54.7	1.5	56.2	54.7
East	181.0	8.52	121.5	45	28.1	62.3	-4.8	57.5	64.0

An evaluation of physical groundwater availability for evaluating legal availability was done by calculating groundwater flow through a Zone of Influence (ZOI) corresponding to the 0.01-foot drawdown contour. While the source aquifer is locally semi-to leaky confined, an unconfined solution, T from permit # 41H 30115127, and Specific Yield (S_y) of 0.1 (Lohman, 1972) is used for the physical availability and adverse effect analysis which is consistent with other permit application analysis for the source aquifer. Modeling is performed using the Theis (1935) solution, T = 5,545 ft^2/day, S_y = 0.1, and a constant pumping rate of 515.2 gpm (equivalent to the requested volume) for the three pumping wells and –515.2 gpm for the injection wells, during the period of diversion. The pumping wells will be modeled as one well due to their close proximity and the 4 injection wells will be modeled as two wells, with one half of the injection rate located at 250 feet to the northwest of the pumping wells and the other half of the injection rate located at 350 feet to the northeast of the pumping wells. **Figure 8** shows the extent of the 0.01-foot drawdown contour. The width equals 18,000 feet and is truncated at the East Gallatin River to the east. Appendix A is a list of all the groundwater rights that are located within the 0.01 drawdown contour that need to be evaluated for legal demand. The calculation for groundwater flow (Q) through the delineated area is given by **Equation 1** and is 998,100 ft^3/day or 8,363 AF/year.

$$Q = TWi \qquad \text{Equation 1}$$

where:

T = Transmissivity = 5,545 ft^2/day

W = Width of Zone of Influence = 18,000 ft (average in the direction of groundwater flow)

i = Groundwater gradient (from English (2018) water level contour map) = 0.01 ft/ft.

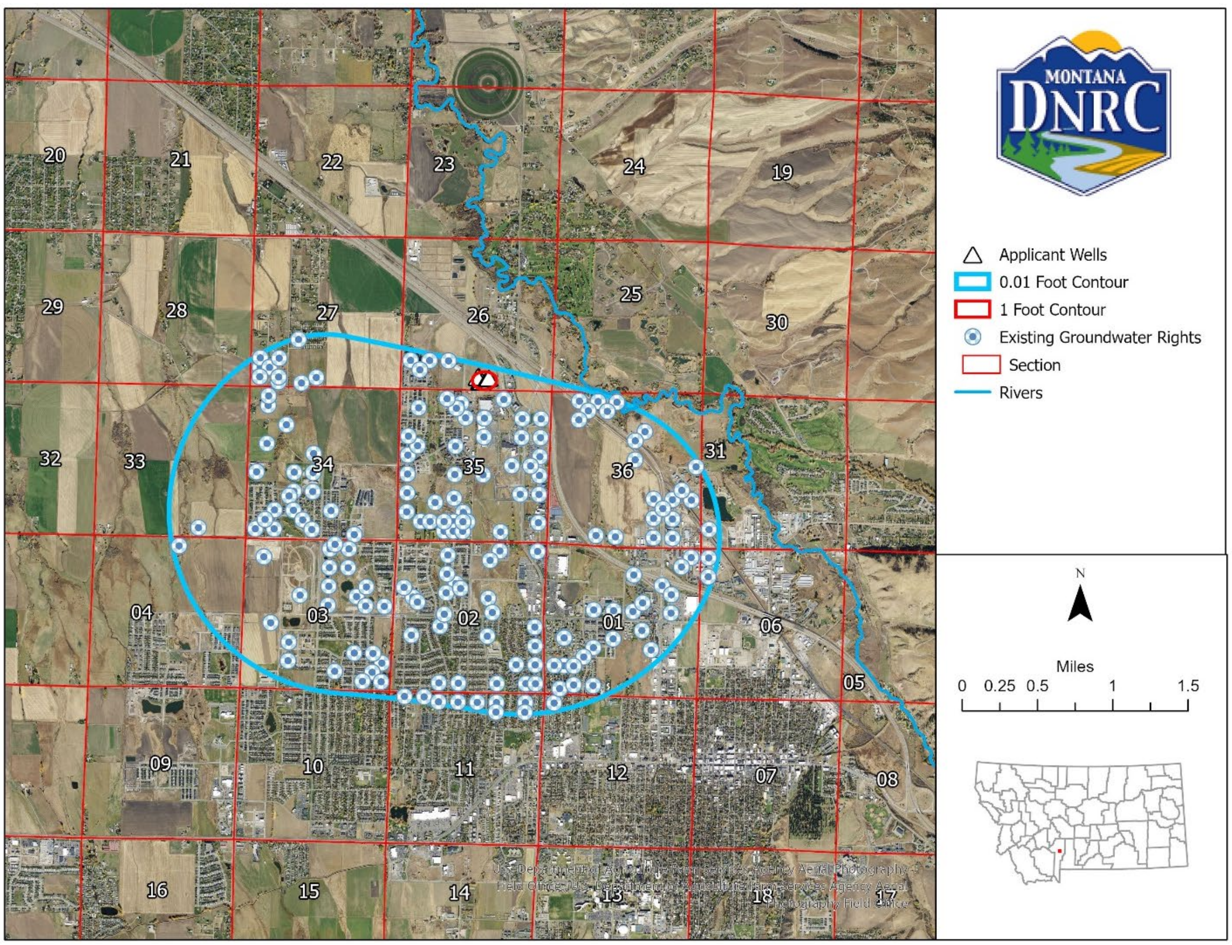

Figure 8. Predicted 0.01-foot and 1-foot drawdown contours and groundwater rights.

Adverse Effect: Analysis

The drawdown in existing wells was evaluated using the Neuman-Witherspoon (1969) solution with the following inputs: T = 5,545 ft^2/day, S_y = 0.1, and the pumping schedule (**Table 4)** provided by the applicant for five years. The pumping wells were modeled as one well and the injection wells were modeled as two wells, one to the northwest and one to the northeast and each with half the injection volume. Drawdown is largest at the 255th day of the fifth year of pumping. Drawdown in excess of 1 foot occurs in wells at a maximum of 600 feet from the proposed pumping wells **(Figure 8).** There are no water rights in the source aquifer that are predicted to experience drawdown greater than 1-foot.

Conclusions and Recommendations

- The aquifer transmissivity of 1,704 ft^2/day and storativity of 0.001 generated from Neuman-Witherspoon (1969) solution for the west observation well are recommended for use in evaluating adequacy of diversion. A regional aquifer transmissivity of 5,545 ft^2/day and specific yield of 0.1 for an unconfined gravel and sand aquifer are recommended for use in evaluating physical availability and adverse effect.

- For the adequacy of diversion/physical availability analysis, the pumping wells were modeled at a varied pumping rate based on a pumping schedule provided by the applicant. Based on this modeling analysis and well efficiencies calculated from the pumping wells individual aquifer tests, the west, middle and east pumping wells could experience 77.2, 56.2 and 57.5 feet of drawdown, respectively.

- Forward modeling was used to extrapolate drawdown over a radial distance using the aquifer properties estimated from drawdown data. There are 241 groundwater rights in the water right database within the ZOI and the groundwater flow is equal to 8,363 AF per annum.

- There are no water rights in the source aquifer that are predicted to experience drawdown greater than 1 foot.

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