Identifying hydrologic recharge connections in the Moscow sub-basin

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Summary

During the last century groundwater levels have been declining with rates of 30 cm yr^{-1} or more in the Moscow sub-basin (150 km^2). This sub-basin is located on the Washington-Idaho border (USA). The groundwater systems are fairly complex, with multiple basalt flows underlain by protruding basement metamorphic/granitic ridges, paleo-valleys and interwoven with sand/gravel inter-beds. Previous studies found vertical infiltration is limited in the area. Nevertheless, recharge to Wanapum and Grande Ronde aquifer might occur through preferential flow-paths, called paleo-channels. Knowing the source locations of recharge to the basalt aquifers in the Moscow sub-basin is vital for understanding the long-term sustainability of its water resources and for developing solutions which enhance aquifer recharge and protect the drinking water sources for future generations. In this study, presenting field observations and groundwater modelling, such recharge locations were identified. Samples of 12 wells downstream the Moscow waste water treatment plant have been sampled for caffeine. Here the main stream, the Paradise Creek, runs directly over the basalt. Caffeine is known to be conservative and often present in human waste water, so it can be used as a tracer. One well contained enough detectable caffeine, suggesting human waste water infiltrated west of Moscow. Discharge measurements in the Paradise Creek also suggested infiltration occurs west of Moscow from the Paradise Creek directly into the Wanapum basalt aquifer. In addition, field results of 9 months of long-term, high-frequency isotopic sampling of 24 wells (depth 23 - 213 m) northeast of Moscow show large variations over time, up to 1.4±0.1 ‰ in ^{18}O. This presents a relatively fast (± 2-5 weeks) response to the precipitation isotopic signature. Temperature measurements of these wells show an average drop in temperature of 8.4ºC from July (2013) until January (2014). These large seasonal temperature fluctuations are in line with the characteristics of an infiltration area with a low porosity and are also indications of fast recharge pathways. The isotopic signature, temperature and EC data of these wells show indications of recharge in the proximity of the Moscow Mountain. It is suggested by the data that recharge occurs in lateral flow paths from the Moscow Mountain, since the sampled wells reached below thick, restrictive layers. Also the Soil Moisture Routing (SMR) model indicated the Moscow Mountain is a source of recharge. This one layer grid based model performs best in the Moscow sub-basin's soil characteristics; shallow soils above restrictive fragipan layers. The SMR model calculated the average daily infiltration rate for the period 2001-2008. The infiltration rate is highest at the Moscow Mountain (up to 2.0 mm d^{-1}). This output was used as infiltration on top of a groundwater model: GMS Modflow. A steady state model was constructed based on 207 borehole-descriptions. This steady state model was able to reconstruct the estimated total average discharge of 0.7 m^3 s^{-1} for the streams in the Moscow sub-basin. With this model the ranges and sensitivity of physical properties were tested. The model showed that all net groundwater fluxes to the Wanapum Aquifer originate from the Moscow Mountain and mainly flows through weathered, decomposed granite at the granite/basalt inerface. Also a transient GMS Modflow model was constructed using monthly average infiltration rates calculated by SMR for the period 2001-2008. However, this model was not able to show the 30 cm yr^{-1} decline of groundwater in the Moscow sub-basin, and further development of the transient model was suggested.

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1. Introduction

1.1 Problem Description

Declining ground water levels due to a growing human population and increased groundwater pumping are a main concern in the world. A large part of the human population is depending on fresh water from aquifers (WWDR1 2001).

In the Pullman-Moscow region in the USA, which is located on the border of Idaho and Washington State, groundwater level declination is occurring already since people started to exploit the aquifer in the early 20th century (Laney et al. 1923). The Moscow sub-basin is part of the Palouse basin, which is located on the eastern part of the Columbia River Basalt Group (CRBG). The CRBG aquifer is a main source of fresh water in the area (Tolan et al. 1989). Despite curtailed groundwater pumping since 1992, aquifer levels have continued to decline at 30 cm yr^{-1} or more. Dropping groundwater levels are a net result of pumping rates exceeding the recharge in the area. Recharge pathways have been identified, however these require fundamental review and detailed testing (Bush and Garwood 2005; McKenna 2001; Fairley et al. 2005; Robischon 2006; Brooks and Grader 2011; Dijksma et al. 2011). Pullman-Moscow groundwater systems are fairly complex with multiple basalt flows underlain by protruding basement metamorphic/granitic ridges, paleo-valleys and interwoven with sand/gravel inter-beds (Grader 2011). Knowing the source locations of recharge to the basalt aquifers in the Moscow sub-basin is vital for understanding the long-term sustainability of the water resources and for developing solutions which enhance recharge and protect the quality of these drinking water sources for future generations.

Groundwater levels in the shallow aquifer recover in response to reduced pumping indicating that recharge occurs to the shallow aquifer. The presence of tritium in water samples recently taken from the Wanapum (upper aquifer) and in some wells in the upper portion of the Grande Ronde (deeper aquifer) suggest that both these aquifers receive recharge to some extent (Carey 2011). However there is no clear evidence indicating *where* recharge is occurring in the Moscow sub-basin.

1.2 Hypothesis

Using a spatially distributed hydrologic analysis approach, Dijksma et al. (2011) showed that it is possible that recharge occurs only in certain regions in the Moscow sub-basin. They suggested two regions of the Moscow sub-basin with the greatest potential for recharge:

1. Paleo-channels draining from high elevation forested regions on the Moscow Mountain range, recharging the aquifers at the granite/basalt interface.
2. Direct vertical recharge from streams running directly over basalt (e.g., Paradise Creek near the state line).

1.3 Research Question

The research question and sub-questions are:

- Where does recharge of the aquifers occur in the Moscow sub-basin?
    - Does aquifer recharge occur at the granite/basalt interface?
    - Does aquifer recharge occur vertically from streams running directly over basalt?
    - How large are these aquifer recharge fluxes?

1.4 Objectives

In this study the two primary groundwater recharge hypotheses have been investigated. This has been done by a combination of field observations and groundwater modelling, as described below. The field approach was meant to indicate the recharge locations. The modelling approach was meant to quantify the amount of recharge. These methods were:

1. Establishing long-term, high-frequency isotopic sampling to investigate the hypothesis that fast recharge pathways exist draining from the Moscow Mountain to the aquifers.
2. Examining spatial patterns in the isotopic response, temperature and electrical conductivity of wells to determine if large paleo-channels or paleo-valleys can be identified and related to well log data.
3. Testing wells near the city of Moscow waste water treatment plant for caffeine to determine whether the surface water downstream of the waste water treatment plant is a source of recharge to the aquifer. At this location the surface water runs directly over the basalt
4. Measuring flow discharge at several locations in the creeks running through the Moscow sub-basin to see whether creeks are gaining or losing water.
5. Making a spatial estimation of the amount of water infiltration through the restrictive soils by using a Soil Moisture Routing (SMR) model.
6. Quantifying the amount of water entering at the granite/basalt interface by using a stationary GMS Modflow model.
7. Simulating the groundwater level decline by using a transient GMS Modflow model.

1.5 Outline

In chapter 2 the study area is described based on its land use, soils, climate, watersheds, geology and hydrogeology. Different recharge hypothesizes will be discussed, as well as the influence of humans on the groundwater levels. In chapter 3 the field methods are described for investigating the recharge hypothesizes. These include isotopic sampling, caffeine sampling and discharge, temperature and electrical conductivity measurements. In chapter 4 the model methods are described. These include the Soil Moisture Routing model and GMS Modflow model. In chapter 5 and 6 the field setup and model setup is described. In chapter 7 and 8 respectively the field results and model results are presented. In chapter 9 the results are discussed, and in chapter 10 the conclusions and recommendations are presented.

2. Area Description

2.1 Introduction

The study-area is the Moscow sub-basin (46.68º - 46.83ºN and 116.87º - 117.04ºW) which is located in the Palouse Basin (46.63º - 47.09ºN and 116.45º - 117.36ºW) (Figure 2.1). The Moscow sub-basin measures approximately 150 km^2 which is part of the Palouse Basin measuring 2050 km^2 (Bush 2005). The Palouse basin is located on the border of Washington state and Idaho. It can be subdivided in two large river basins; the North Fork Palouse River and South Fork Palouse River basin. These are consisting of smaller watersheds, of which the Paradise Creek watershed is covering the study area (Figure 2.2). Pullman and Moscow are the largest towns in the Palouse Basin, with a population in 2010 respectively of 29,799 and 23,800 people, which is respectively 33% and 30% of the total population in the Palouse Basin (United States Census Bureau 2012).

Figure 2.1 The Moscow sub-basin is located in the Palouse Basin, which is located on the border of Idaho/Washington state (black point).

Figure 2.2 Palouse Basin, subdivided in the two main watersheds (WRCC): South Fork Palouse River (SFPR) and North Fork Palouse River (NFPR). Red line shows the Moscow sub-basin.

Figure 2.3 shows the digital elevation map of the Moscow sub-basin. The highest point is the Moscow Mountain in the northeast of the sub-basin. The northern, eastern and southern boundaries of the Moscow sub-basin are based on the topographical water divides. The western boundary is partly located on the border of Idaho and Washington State.

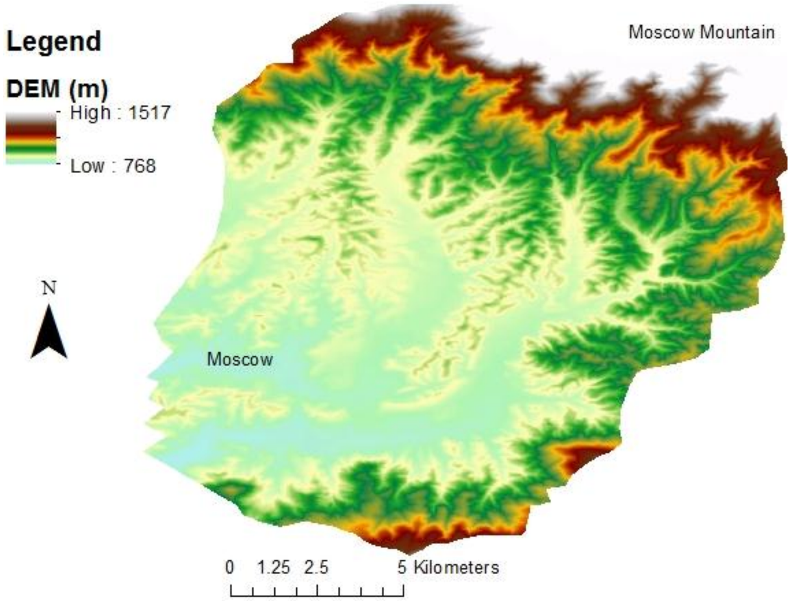


Figure 2.3 Digital elevation map (DEM) of the Moscow sub-basin, in meter above mean sea level (+amsl). Highest point is the Moscow Mountain in the northeast.

In this chapter the land use, soils, climate, surface water, geology and hydrogeology will be described. These aspects are important for the understanding of recharge pathways in the area. Although the study area is the Moscow sub-basin which is part of the Palouse Basin, the Palouse Basin has been included in this chapter to understand the topography on a larger scale.

2.2 Land use

At the end of the 19th century non-irrigated agriculture turned out to be very effective in the Palouse basin. This caused a rapid growth of settlements in the area (Meinig 1968). In the Palouse Basin more than half the land is used for non-irrigated agriculture nowadays. The crops being cultivated are mainly wheat, barley, peas and lentils. Another important land use type is pine forest, which covers almost one third of the area in the Palouse Basin. Rangeland and urban areas are less present, they are relatively small (MRLC 2006).

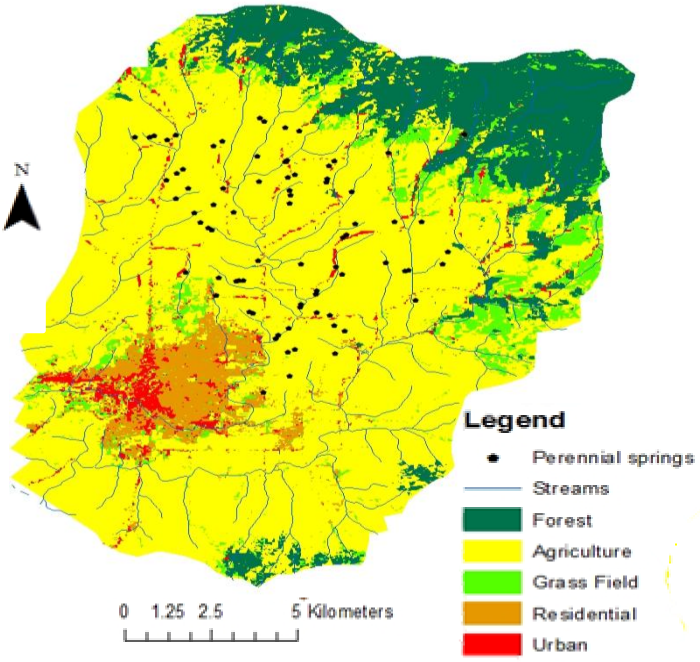


Figure 2.4 Land use, spring and stream locations for the Moscow sub-basin (after Dijksma et al. 2011).

The land use of the Moscow sub-basin is very similar to the rest of the Palouse Basin. Agriculture measures 71% of the total land, 15% is covered by forest, 6% by grass fields and 8% is covered by urban area (Figure 2.4). The land use is important for infiltration estimations since the land use affects the potential evaporation rates which has an effect on the amount of infiltration.

2.3 Soils

Figure 2.5 shows the soils with argillic characteristics in the Moscow sub-basin. An argillic horizon is defined by the Soil Survey Staff (1999) as *"a measurable vertical increase in the percentage of clay or fine clay in comparison to the overlying A horizon, and the presence of coatings of oriented clay on ped and pore surfaces, the so-called argillans or clay skins"*. These argillic properties result in a low permeability, causing seasonal perched water tables (McDaniel et al. 2001). In the forested regions, argillic soils are mostly absent. The forested region is mainly composed of highly permeable andisols.

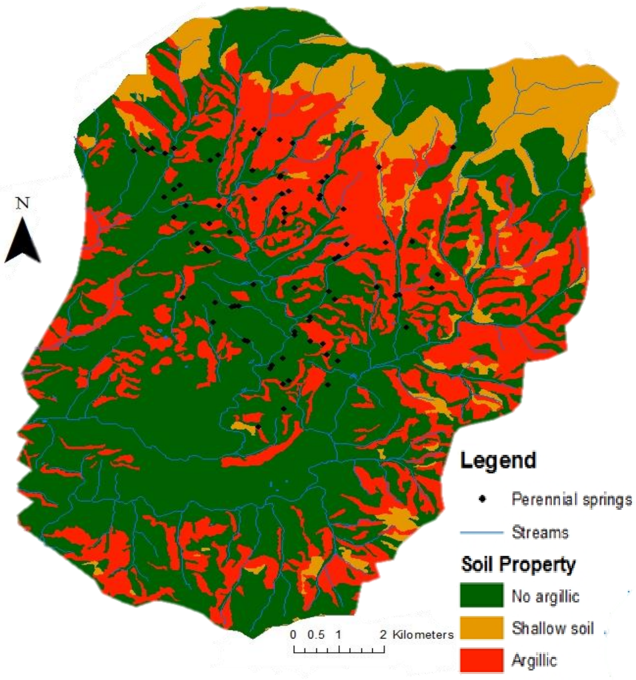


Figure 2.5 Soil with argillic properties in the Moscow sub-basin (after Brooks and Grader, 2011).

Figure 2.6 shows pictures illustrating the heterogeneity of the soil properties in the Moscow sub-basin. Large rocks (up to 30 cm) were found on a farmer's field (left picture), as well as thick clay layers at the surface combined with overland flow from perched water tables (middle and right picture).

Remarkable is the presence of perennial springs (Figure 2.5), which are related to the presence of the restrictive argillic characteristics. At the location of the city Moscow no springs are found, which is probably due to human influence by draining all springs at the city location (pers. comm. Brooks and Dijksma, 2014).

Figure 2.6 Soils in the Moscow sub-basin. Left) large rocks (up to 30 cm) are found in the field. Middle). The white spots are thick clay layers, resulting in argillic soils. Water flows coming from springs flow overland. Right) exposed argillic layer at 30cm depth.

The soil properties are an important factor for infiltration, since infiltration is depending on the infiltration capacities of the soil. Dijksma et al. (2011) found for the Paradise Creek watershed that the largest part of the inftilration would occur in the forested regions, since the argillic properties are mainly absent here. In this study the soil properties are also taken into account by using a SMR model as input for the groundwater model.

2.4 Climate

2.4.1 Climate classification

The Köppen-Geiger Classification System classifies the climate in Moscow as “snow dry, warm summer (Dsb)”. This classification system is based on gridded estimates of precipitation and temperature, interpolated by using the elevation and weather stations. The model has been developed by Oregon State University. The definition of the Moscow climate is as follows: *“A climate where there is at least one month colder than -3 ºC and summers are dry and warm. This climate is usually at even higher elevations near locations that are warm temperature with dry, hot summers”*

2.4.2 Weather Stations

There are two weather stations in Moscow, Idaho; one at the University of Idaho campus (810.8 m +amsl) and one SNOTEL weather station on the Moscow Mountain (1432.6 m +amsl), SNOTEL being the national snow survey and water-supply forecasting service (NRCS). Monthly climate averages of the University of Idaho weather station are shown in table 2.1 and Figure 2.7.

Table 2.1 Monthly climate averages of University of Idaho weather station from the period 7/11/1893 to 31/3/2013 (WRCC 2013)

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual**
Average max. Temperature (°C)	1.6	4.6	8.7	13.8	18.6	22.6	28.3	28.2	22.9	15.6	6.9	2.4	14.5
Average min. Temperature (°C)	-5.2	-3.3	-0.8	2.0	5.1	7.9	10.1	9.8	6.7	2.9	-0.8	-3.9	2.6
Average total precipitation (mm)	76.5	55.4	59.7	49.3	52.3	42.4	18.0	20.1	30.5	47.8	78.0	74.9	604.8
Average total snowfall (mm)	408.9	223.5	127.0	30.5	2.5	0.0	0.0	0.0	0.0	7.6	139.7	320.0	1264.9
Average snow depth (mm)	101.6	50.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.8	25.4

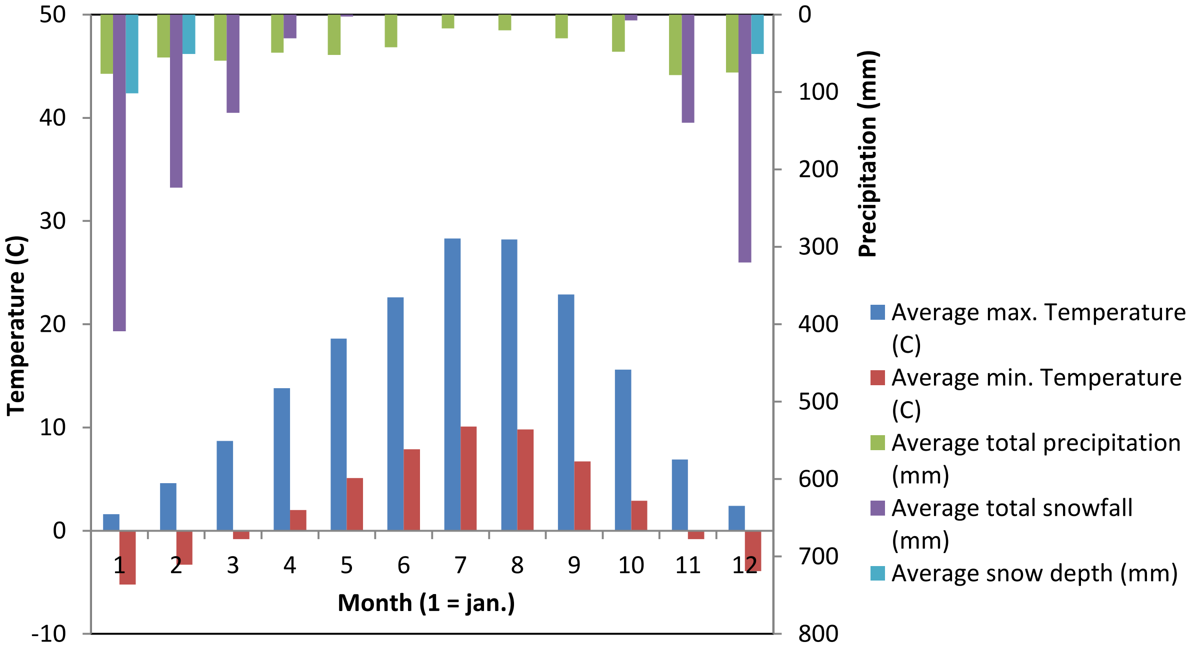


Figure 2.7 Monthly climate averages of University of Idaho weather station from the period 7/11/1893 to 31/3/2013 (WRCC 2013)

2.4.3 Temperature

The temperature in Moscow varies from an average minimum temperature of -5.2 ºC in January to an average maximum temperature of 28.3 ºC, and a yearly average of 8.5 ºC (Table 2.1 & Figure 2.7). The Moscow Mountain is the highest point in the Moscow sub-basin (Figure 2.3) with the lowest temperatures. The annual average temperature at the Moscow Mountain was 6.4 ºC in the period 2001-2009, measured by the SNOTEL weather station.

2.4.4 Precipitation

In the Palouse Basin precipitation exists in the form of rain and snow. Mean annual precipitation in the Palouse Basin varies from 457 mm in Colfax to 1270 mm on the Moscow Mountain (Figure 2.8). The Moscow Mountain receives twice the amount of precipitation compared to Moscow (WRCC 2013). These spatial precipitation differences between east and west suggest recharge is more likely to occur in the east of the basin than in the west. Snowfall occurs from October to May in Moscow. Most precipitation falls in winter, and the summers are relatively dry. Leek (2006) suggests that precipitation seems to have decreased in Pullman and increased in Moscow, according to the 1895-2005 precipitation data of NOAA National Climate Center (2005) (Figure 2.9). Regression lines made by Leek (2006) show a change of precipitation of ~1.4 mm yr^{-1} and -1.2 mm yr^{-1} for respectively Moscow and Pullman. Although the precipitation has not shown statistically significant changes for both cities from a simple regression, there seems to be a small precipitation increase in Moscow and decrease in Pullman.

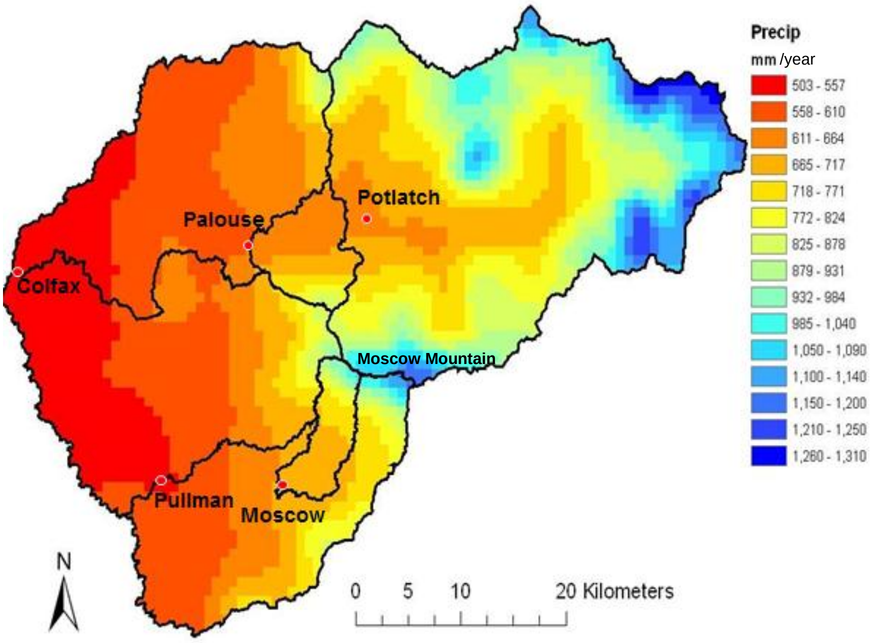


Figure 2.8 Average annual precipitation in the Palouse Basin. Precipitation suggests recharge is more likely to occur in the east (PRISM, after Brooks & Grader, 2011)

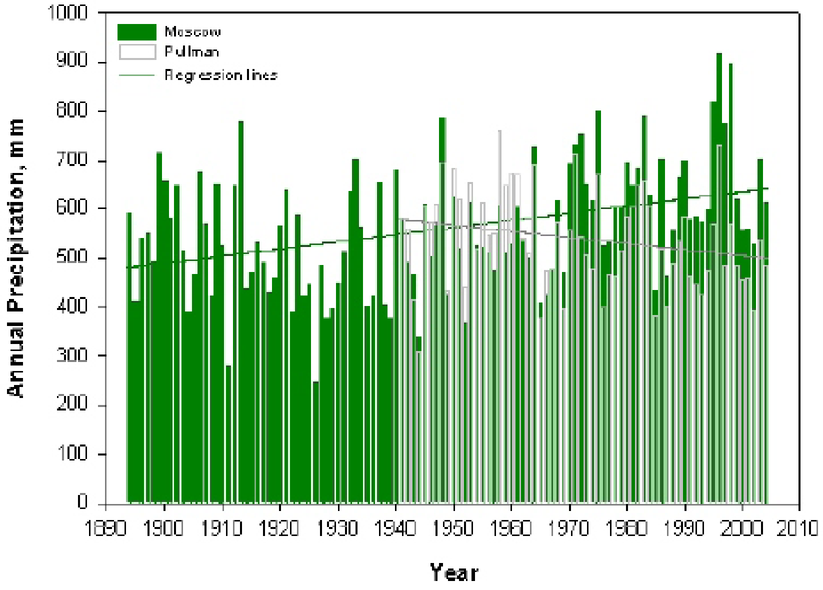


Figure 2.9 Precipitation for Moscow and Pullman according to 1895-2005 precipitation data of NOAA National Climate Center (2005). Regression lines made by Leek (2006) show a change of precipitation of ~1.4 mm yr^{-1} and -1.2 mm yr^{-1} for respectively Moscow and Pullman. However, these changes are not significant (Leek, 2006).

2.4.5 Evapotranspiration

The evapotranspiration affects the potential available water for water infiltration. Evapotranspiration can be subdivided in the potential evapotranspiration (ET_{pot}) and the actual evapotranspiration (ET_{act}). The ET_{pot}, which is the amount of water that would transpire if sufficient water is present, can differ from the ET_{act}. The ET_{act} is the actual amount of water that transpires and depends on the availability of the water from the soil and vegetation. In cases where less water is available than the ET_{pot}, the ET_{act} is lower than the ET_{pot}

($ET_{act} \leq ET_{pot}$). Different methods exist to estimate the ET_{pot}. Below the methods for deriving the ET_{pot} and ET_{act} have been described, similar to the derivation done by the SMR model in §4.1.5.

2.4.5.1 Potential Evapotranspiration

To be able to estimate the ET_{pot}, the reference potential evapotranspiration (ET_0) should be calculated. The ET_0 is the potential evapotranspiration for grass. By using crop coefficients, which were earlier used by Brooks et al. (2007) and Dijksma et al. (2011), the ET_{pot} can be derived. The ET_0 used in this study was calculated from the minimum and maximum daily air temperature and the solar radiation by using the Hargreaves equation (1985) (Shahidian et al. 2012). The Hargreaves equation is based on ET_0 estimations from a precision lysimeter and weather data from Davis, California, over a period of eight years through regressions with five-day time steps. The ET_0 can be calculated by using equation 1:

$$ET_0 = 0.00551 * \mathrm{K}_T\ (\mathrm{T} + 17.78)(T_{max} - T_{min})0.5 * R_a \qquad (1)$$

Where K_T is an empirical coefficient (-) which is initially fixed at 0.17, T is the temperature in ºC and R_a is the extraterrestial radiation in MJ m^{-2} day^{-1} and can be obtained from tables based on local, climatological data (Samani 2000) or calculated (Allen et al 1998). The model has produced good results in climates around the world, since at least 80% of ET_0 can be explained by temperature and solar radiation. The big advantage of this ET_0 calculation is that it requires only T_{min} and T_{max}.

2.4.5.2 Actual evapotranspiration

The ET_{act} is derived according to the Thornwaite-Mather assumption, which is based on the soil moisture content and the ET_{pot}. The ET_{act} is equal to ET_{pot} at or above field capacity, and decreases linear below field capacity. At wilting point $ET_{act} = 0$. In between these two points the ET_{act} is linearly related to the soil moisture content (Steenhuis and Van der Molen 1986).

The annual ET_{act} for the Paradise Creek watershed was calculated by Fiedler (2007) averaging 498 mm, based on a simple water balance. Dijksma et al. (2011) calculated an ET_{act} of 511 mm for the Paradise Creek watershed, which is 71% of the total precipitation, based on a Soil Moisture Routing model. Figure 2.10 shows the ET_{act}/precipitation ratio for the Palouse Basin. The ratio is larger in the west than in the east of the Palouse Basin, so in the east more precipitation excess exists. This makes it more plausible recharge is occurring in the east. From September to March the precipitation is exceeding the ET_{act} in the Moscow area (Figure 2.11). If not stored in the snow pack, water will infiltrate in the soil or runoff by streams.

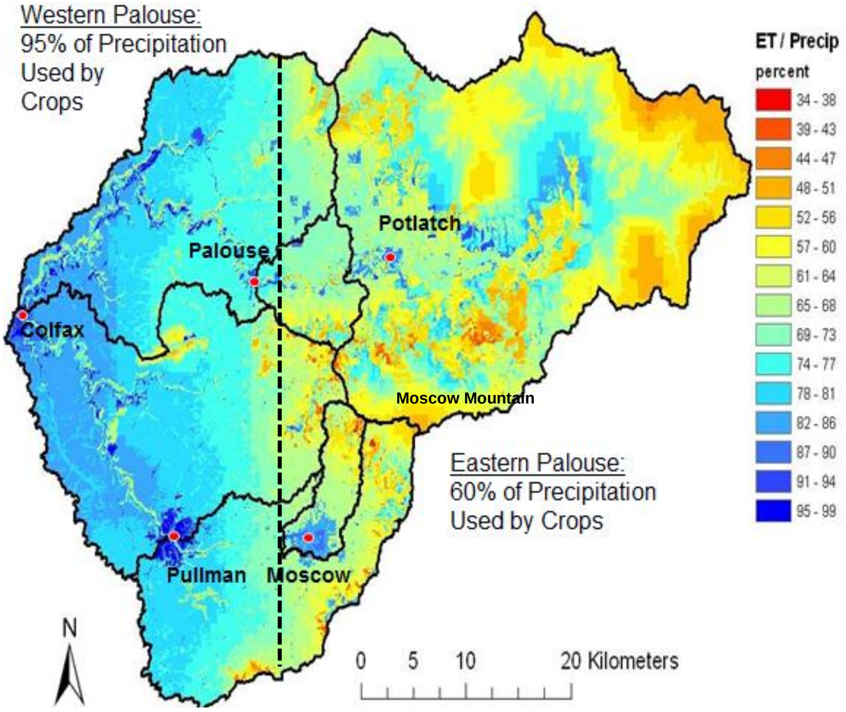


Figure 2.10 The ET_{act}/precipitation ratio for the Palouse Basin. The ratio is larger in the west compared to the east. This map suggests recharge is more likely in the east (after Brooks & Grader, 2011). Dotted line indicates the Idaho/Washington state line.

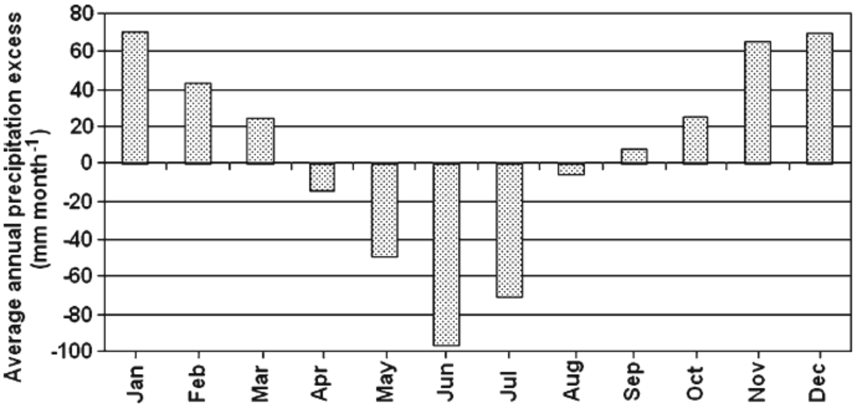


Figure 2.11 Average actual precipitation excess (P-ET_{act} (mm $month^{-1}$)) for period 1893–2004 at Moscow, Idaho, derived from total precipitation recorded by the Western Regional Climate Center using 90 m × 90 m grids (Western Regional Climate Center 2009, after Dijksma 2011)

2.5 Surface water

The South Fork Palouse River (SFPR) (Figure 2.2) can be subdivided into six sub-watersheds (Figure 2.12 & Table 2.2). The Paradise Creek and the upper part of the SFPR are the watersheds in the Moscow sub-basin. The watersheds lying in the Moscow sub-basin can be subdivided into smaller watersheds. To the east of the Paradise Creek, the Gnat Creek and Crumarine Creek are present, which are the upstream parts of the SFPR (Figure 2.13).

Table 2.2 Watersheds of the South Fork Palouse River (after WRCC)

	Total area (km^2)	Stream Length (km)
South Fork Palouse River (SFPR)	481	169
Mainstream SFPR	370	55
Four Mile Creek	186	31
Paradise Creek	87	32
Missouri Flat Creek	70	27
Spring Flat Creek	50	24

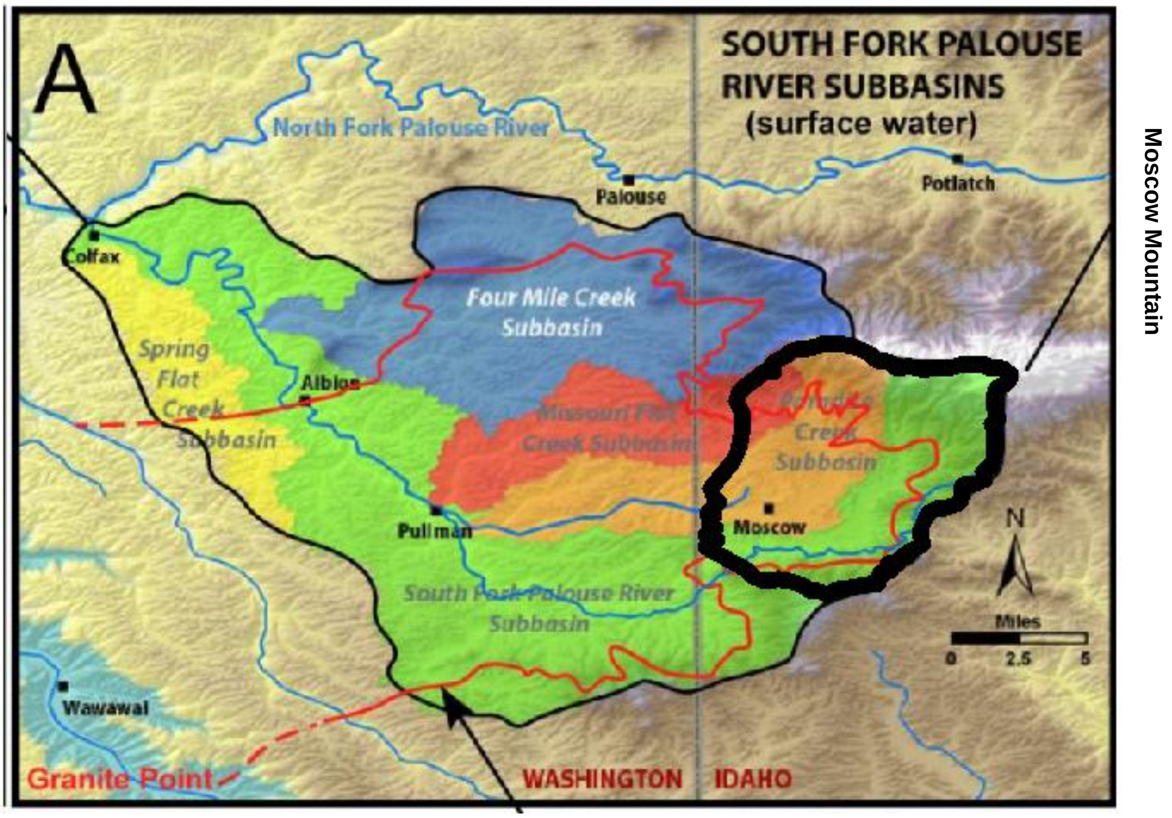


Figure 2.12 Watersheds in the Southern part of the Palouse Basin. Figure includes the granite/basalt interface (red line, by Grader 2011; after Bush 2005) and the Moscow sub-basin (thick, black line).

Figure 2.13 Streams in the Moscow sub-basins. The yellow cross is the University of Idaho campus. The orange cross is the WWTP.

Discharge measurements by the U.S. Geological Service show a yearly average discharge for the Paradise Creek of 0.21 m^3 s^{-1}, measured at the University of Idaho campus (west of Moscow), over the period of 1979 to 2012. Discharge measurements done in Pullman for the SFPR show a yearly average discharge of 1.11 m^3 s^{-1} over the period of 1935-2012. The Paradise Creek merges the SFPR before reaching Pullman (Figure 2.12), so 0.9 m^3 s^{-1} is originating from the SFPR and the remainder of the Paradise Creek downstream of the discharge measurements at the University of Idaho campus. This part of the Paradise Creek measured in Pullman also reflects the water use of Moscow, since the waste water treatment plant (WWTP) located downstream of the University of Idaho campus discharges its water on the Paradise Creek (Figure 2.12 & Figure 2.13).

An average stream loss of 6 mm d^{-1} was found by Rosenberry (2008) by using seepage meters at five different locations in the Paradise Creek streambed over a stretch of 500 m near the University of Idaho Groundwater Research Site. Dijksma et al. (2011) suggested this infiltration rate is negligible taking into account the total surface of the streams. They suggested the amount is very small (approximately 0.01 m^3 s^{-1}) compared to the total discharge by streams and to the expected recharge of the aquifers.

2.6 Geology

2.6.1 Introduction

The Columbia River Basalt Group (CRBG) was formed 17-6 million years ago, during Miocene and early Pliocene. Large eruptions from fissures or vents were estimated to cover 142,450 km^2 of the Earth's surface with the igneous rock. The first 1.5 million years of this 11 million year period were the most active. The estimated volume of the CRBG is between 148,000 km^3 and 222,600 km^3 (Bush and Seward 1992; Tolan et al. 1989; Reidel et al. 1989). The CRBG consists of approximately 120 to 150 individual basalt flows, with a thickness varying from 0.3 m to 122 m (Bush and Seward 1992; Foxworthy and Washburn 1963). The extension of the flows was limited due to Cretaceous age granitic mountain ranges in Northern Idaho. Buttes found nowadays in the landscape, which used to be the peaks of these mountain ranges, still prove the Cretaceous landscape had significant topographic relief, of which the valleys have been filled up by the basalt flows (Russell, 1897). The basalt flows which filled up the valleys were blocking the river channels and drainage systems. Lakes were formed on the edges of the basalt flows and deposited sediments of weathered granitic material on top and in front of the basalt formations. The next basalt flow would cover these sediments and the process of lake formation and sedimentation would repeat. These interbeds of sediments are called the Latah Formation, and occur specifically at the eastern margin of the CRBG, where the Palouse Basin is located (Figure 2.14 & Figure 2.19).

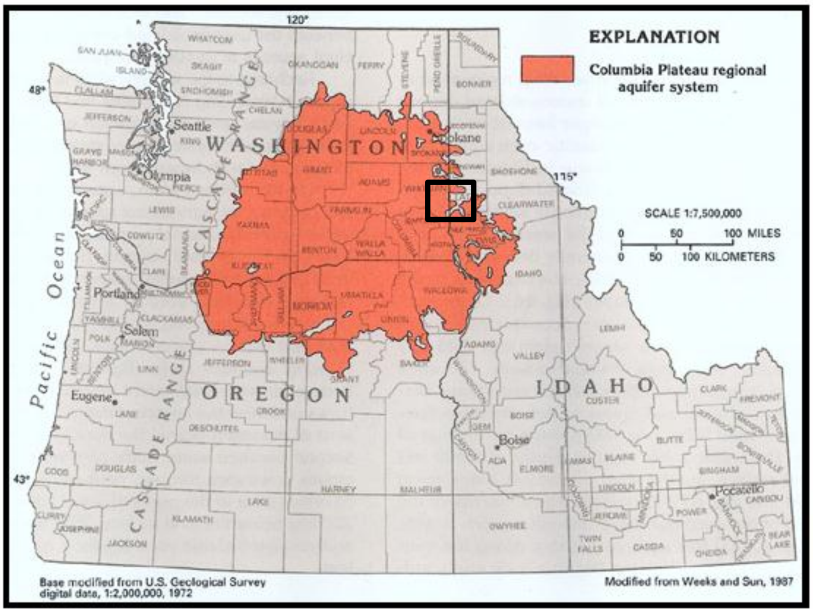


Figure 2.14 CRBG (in red) and the Palouse Basin (black square) at the eastern edge of the CRBG (U.S. Geological Survey)

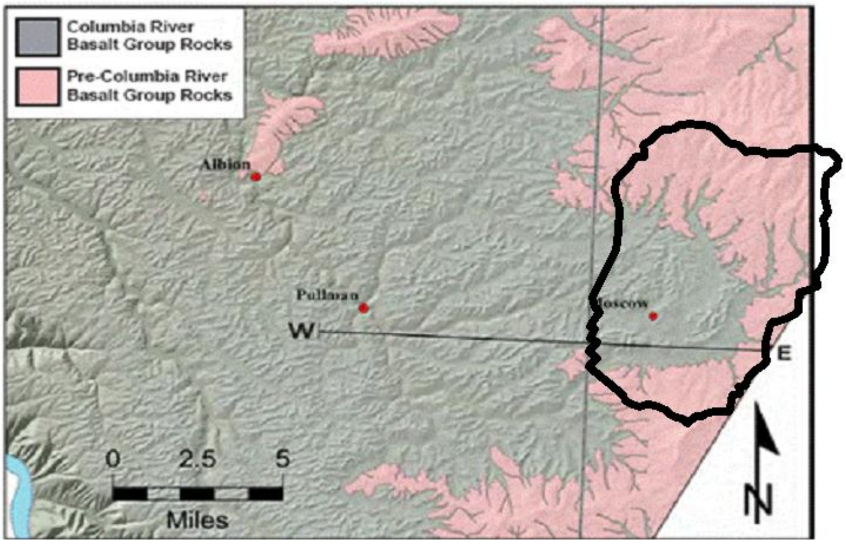


Figure 2.15 Moscow sub-basin in the eastern extent of the CRBG (after Bush 2005). Line W-E represents the cross-section in Figure 2.16.

The local geology is very important for understanding hydrological processes in the area. In this area the hydrology is very much related to the geology, since it is expected that the interbeds play a major role in the preferential water flow pathways considering groundwater recharge. Basalt flows are blocking the drainage systems, burying old drainage pathways and creating new ones. This makes this area on hydrogeological level very complex. The current drainage patterns are very likely associated with ancestral drainage patterns (Bush 1996; McKenna 2001; Fairley et al. 2006; Robischon 2006; Bennett 2009; Brooks and Grader 2011; Dijksma et al. 2011; Carey 2011).

As described above, the Moscow sub-basin is located in the eastern extent of the Palouse basin at the border of Washington state and Northern Idaho (USA). The Palouse Basin is in the eastern extent of the CRBG (Figure 2.14). Laney et al. (1923) showed groundwater and surface water catchment divides north and east of Moscow. These divides are forming the boundaries of the Moscow sub-basin, which have been defined by Bush (2005) (Figure 2.15).

The extension of the CRBG to the east was limited by the crystalline mountain ranges. These mountain ranges represent the hydrogeological boundaries of the sub-basin. The Moscow Mountain has a height of 1519 m and is located north of Moscow. Southeast of Moscow there is the Paradise Ridge with a height of 1128 m (Figure 2.15). The west boundary of the basin is a topographic high in the Grande Ronde basalt flow, approximately 1.6 km west of the state-boundary. In Figure 2.16 a cross-section of the Pullman-Moscow area is shown. It shows the different basalt flows coming into the Moscow sub-basin, with Latah Formation interbeds. The geological formations illustrated in Figure 2.16 will be further discussed in the next paragraphs.

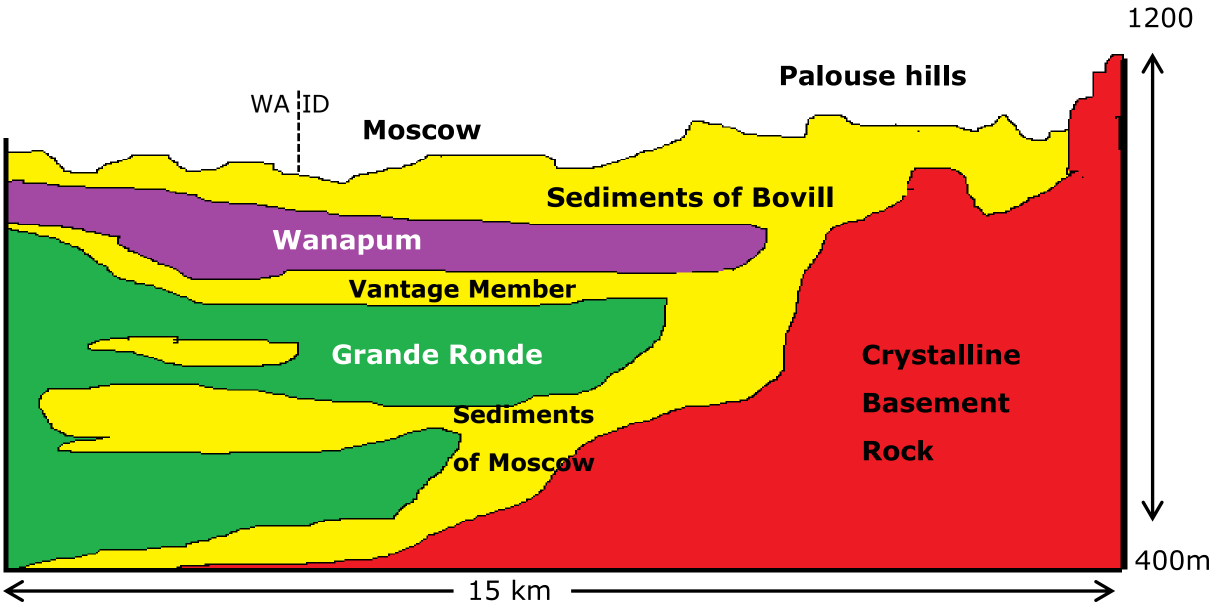


Figure 2.16 Geological cross-section of the Moscow sub-basin from west to east (after Grader 2011). Cross-section based on W-E line in Figure 2.14.

2.6.2 Crystalline Basement Rock

The oldest geological unit in the area is the basement rock, which consists of Cambrian metamorphic rocks, Pre-Cambrian metasediments of the Belt Series Supergroup, intruded by Cretaceous granites (Pierce 1998). The above mentioned boundary including the peaks and buttes in the recent landscape are part of the basement rock. The basement rock includes granites, gneisses, schists, quartzites and granodiorite (Russell 1897; Carey 2011; Provant 1995). Some fractures are found in the granitic mountain ridges. The amount of these fractures decreases with depth, so the crystalline basement rock can assumed to be impermeable. Small groundwater extractions from fractures in the granite are yielding up to 80 l min^{-1}, supplying some local households. However, these well yields are too small compared to basalt or sediment wells (Lum et al. 1990). Crosby and Chatters (1965) found the pre-basalt landscape had deep valleys with narrow ridges. The pre-basalt river drainage pattern is thought to be the current groundwater flow pattern. These ancient watersheds are called paleo-valleys.

2.6.3 CRBG

The five main CRBG-basalt formations in chronological order of deposition are the Imnaha, Picture Gorge Basalt, Grande Ronde, Wanapum and Saddle Mountains. Of these five main formations, 90% of the abstracted water in the Palouse Basin is coming from the Grande Ronde aquifer, which has a volume of 85% of the CRBG (Reidel et al. 1989; McKenna 2001). In the vicinity of Moscow and Pullman, the CRBG has a maximum thickness of respectively 400 to 610 m (Smoot and Ralson 1987). Figure 2.17 shows a conceptual model of the physical characteristics of CRBG basalt flows. The greatest groundwater flows occur in the highly fractured interflow zone which has a high porosity and high hydraulic conductivity. This interflow zone is the space between subsequent basalt flows. Also groundwater flow occurs in the fractured interiors of basalt flows and in between basalt columns. The size of the columns and fractures is depending on the cooling rate of basalt (DOE 1981). Figure 2.17 shows the aquifer zones are mainly at the top and bottom of a subsequent basalt flow. The bottom of a basalt flow tends to be blocky or columnar jointing and has some scattered vesicles, while the top has often many vesicles. The basalt interiors which have a low porosity and low conductivity often form confining layers, which makes vertical groundwater exchange very limited (DOE 1986). Little is known about the lateral continuity of interior fractures and this could be limited. Fractures can often form clastic dikes as a result of weathering and erosion processes. Fine clays depositions in the fractures are causing the percolation of water to be limited (Lin 1967).

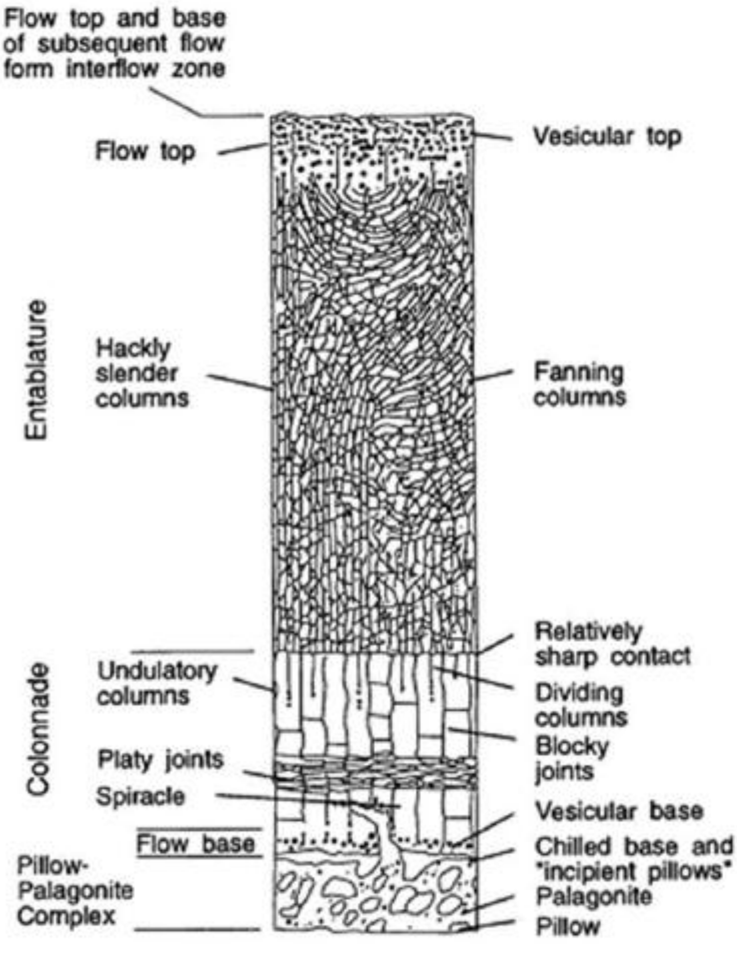


Figure 2.17 Conceptual model of a CRBG basalt flow (After Bush 1992; Swanson and Wright 1978)

In the next paragraphs the different basalt groups will be described.

2.6.3.1 Imnaha and Picture Gorge Basalt

The Imnaha and Picture Gorge formations play a minor role in the CRBG aquifer system because of their limited size. The Imnaha Basalt is the oldest formation (Miocene) of the CRBG and found in north-eastern Oregon, extending partly to Washington and Idaho (Vaccaro 1999). The Imnaha Basalt is found near the bottom of the deepest well of the Palouse Basin in Pullman. No Imnaha Basalt is present in the Moscow sub-basin (Owsley 2003). The Picture Gorge formation is only present in north-central Oregon where it is interlayered with the Grande Ronde basalt. Often this formation is included in the Grande Ronde (Vaccaro 1999).

2.6.3.2 Grande Ronde Basalt

The Grande Ronde origins from the Miocene, and is between 15.6 and 17.0 million years old (Reidel et al. 1989). As mentioned earlier, the Grande Ronde plays an important role in the CRBG aquifer system because of its relative volume (85% of CRBG). The Grande Ronde Basalt consists of as many as 131 individual, fine to very fine grained Miocene aphyric basalt flows. At the margins of the CRBG, these basalt flows are interbedded with Latah Formation sediments as well as separated of the Wanapum by Latah Formation sediments (Wright et al. 1973; Swanson et al. 1979; Anderson et al. 1987). No hydraulic connections have ever been detected between Grande Ronde and the Wanapum during aquifer tests (Douglas 2004). Almost 60% of the Grande Ronde total thickness of approximately 300 meters is estimated to consist out of interbeds due to the close proximity of sediment source rocks in the Moscow sub-basin (Lin 1967; Bush 2005). The interbeds and interflow zones of the Grande Ronde supply Moscow in 68% of the total water (PBAC 2011). Less seasonal fluctuation has been observed in the Grande Ronde compared to the Wanapum, which might indicate less recharge occurs (Moran 2011).

2.6.3.3 Wanapum Formation

The Wanapum basalt is approximately 14.5 – 15.4 million years old (Miocene), consists out of two to three flows, and is the second largest formation in the CRBG (Bush et al. 1998). The formation composes 6% of the total CRBG volume (Swanson et al. 1979; Anderson et al. 1987). The medium to coarse grained basalt is chemically different from the Grande Ronde due to its magnesium and titanium concentrations (Wright et al. 1973; Smoot and Ralston 1987, Provant 1995). The thickness ranges from 6 m to 76 m in wells in and around Moscow (Carey 2011).

The wells in the Wanapum are between 30 m and 152 m deep. In Pullman the Wanapum is not productive; this could be a result of an absent Latah Formation in the aquifer system (Bush 2005). Badon (2007) showed the Wanapum to be very compartmentalized and hydraulically poorly connected in east-west direction. It is believed that the Wanapum contains multiple connected aquifers divided by a leaky aquitard (Li 1991; Kopp 1994; Hernandez 2007; Bennett 2009). Seasonal fluctuations in the Wanapum and recovering groundwater levels indicate recharge is occurring to some extent.

2.6.3.4 Saddle Mountains Basalt

The youngest basalt formation is the Saddle Mountains Basalt. Most likely, these flows covered the paleo-channels which were incising into the Wanapum Formation (Provant 1995). Up to 3 meter of the medium to coarse grained flows (Hooper et al. 1985) were found in some wells in and around Moscow (Provant 2005; Owsley 2003; Bush 2006). Because of its small size, the Saddle Mountains Basalt is of minor importance considering groundwater extraction.

2.6.4 Latah Formation

The Latah Formation represents all the sediments which have been weathered from the crystalline basement rock during the period of eruptions (Laney et al. 1923). This formation has been deposited in between and at the edges of the basalt flows. The texture of the Latah Formation ranges from clay to sand and fine gravels. Lin (1967) showed that this formation origins from fluvial and a lacustrine environment, proofed by the laterally deposited layers which arose from the damming of stream drainages caused by basalt flows. Large amounts of clay were found in previous studies east of Moscow, which can be up to 30 m thick (Lum et al. 1990; Fairley 2006; Bush 2006). Also isolated lenses of sand and gravel are found. These lenses are hypothesized to be paleo-channels (Dijksma et al. 2011) and are depositions of old drainage systems. These paleo-channels could play a major role as conduits for groundwater flow, and are probably irregularly shaped. Old streams which have been incising into the clayey lacustrine depositions could reach the interbeds of the basalt flows.

The interbeds between basalt flows can have thicknesses of 0.3 to 92 m thick (Foxworthy and Washburn 1963). The thickness of these sediments decreases from east to west of Moscow. In the Moscow sub-basin 70% of the stratigraphy is made out of these sediments. The Latah Formation could be subdivided into different formations. In chronological order of deposition these sediments are called: Sediments of Moscow, Vantage Member and Sediments of Bovill. These sediments are described in the next paragraphs below.

2.6.4.1 Sediments of Moscow

The Sediments of Moscow covers the part of the Latah Formation which has been deposited in between the Grande Ronde, Imnaha and Picture Gorge Basalts. Laney et al. (1923) described these sediments as coarse sand and gravel fluvial deposits. Together with the basalt interbeds, these sediments form the main aquifer beneath Moscow. However, it is still unknown how much water is leaving the Moscow sub-basin to the West and how much vertical flow occurs within the Grande Ronde aquifer system (McVay 2007; Carey 2011).

2.6.4.2 Vantage Member

The Vantage Member is the deposition in between the Grande Ronde and Wanapum basalt. This deposition is composed out of sand and fine gravel interbedded with siltstone, claystone and shale. These coarser deposits are buried stream channels (Bush 2006).The thickness of the Vantage Member varies from 91.5 m in Moscow to zero meters just west of Pullman (Kopp 1994; Owsley 2003). The Vantage Members coarsens to the east and merges with the Sediments of Moscow on the eastern edge of the Moscow sub-basin (Figure 2.16). Because of the thicker and coarser sediments in the Moscow area the Vantage Member is a significant aquifer. However, also layers of lacustrine deposited clay depositions are found within the Vantage Member which act as aquitards (Kopp 1994). Bennett (2009) studied water levels in wells at different depths in the Vantage Member, and concluded from similar water levels little vertical water movement exists in the Vantage Member.

2.6.4.3 Sediments of Bovill (SOB)

The Sediments of Bovill (SOB) are the youngest sediments (Miocene) from the Latah Formation, and are overlying the Wanapum Basalt. However, in the part of the Moscow sub-basin not reached by the Wanapum, the SOB overlie the Vantage Member and Sediments of Moscow (Grader 2011). Recognized from their yellow and white clay content or large sand grains, these depositions consist of well sorted to poorly sorted sub-rounded sands, gravels and silts with kaolinite layers (Provant 1995; Hopster 2003). Like all depositions of the Latah Formation these sediments are derived from locally weathered granites and meta-sediments (Foxworthey and Washburn 1963; Petrich 1995). The SOB mainly consist of fluvial deposits with thin interbedded, fining upward sequences up to 1.5 m thick (Provant 1995).

Fairley et al. (2006) suggested the Wanapum fractures to be covered and filled with fine sediments up till 7.6 m thick, preventing the Wanapum to be recharged vertically. However, the fluvial deposits are expected to have a large lateral continuity of coarse sediments, following the old drainage system (Fairley et al. 2006). Dijksma et al. (2011) mapped a large amount of perennial springs in the SOB which could proof the existence of paleo-channels; preferential water pathways by coarse, fluvial, lateral and sinuous depositions. These paleo-channels could also have a vertical continuation, where the SOB are overlying the rest of the Latah Formation. In this way the aquifers can be recharged by paleo-channels reaching the interbeds.

Pierce (1998) has made an isopach map which shows the thickness of the SOB and a map with the sand-gravel/total thickness percentage (Figure 2.18). These maps are based on well-logs. The sand-gravel/total thickness percentage map shows different zones with high sand-gravel percentages. Zone i and ii are zones with respectively >80% and >40% of sand-gravels. These zones are located in between the crystalline basement rock and the basalt. Zone iii is a zone with 100% clay around the southern part of the city and is associated with a relative thin isopach. Zone iv and v are also 100% clay zones associated with a thick isopach.

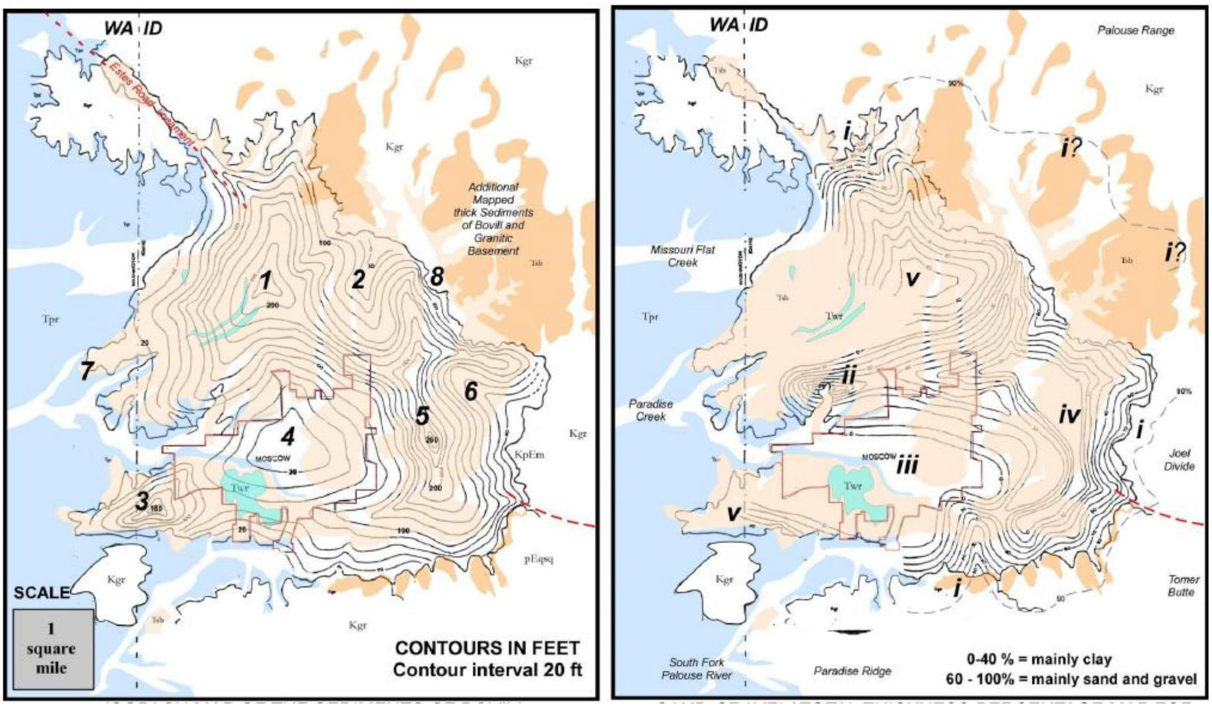


Figure 2.18 Maps of the Moscow sub-basin. Left: Isopach map of the Sediments of Bovill. Numbers are observations done by Grader (2011). Right: Sand-gravel/total thickness percentage map for the Sediments of Bovill (after Grader 2011; Pierce 1998). Numbers i-v indicate zones defined by Pierce (1998) and explained in the text above.

2.6.5 Palouse Formation

The Palouse Basin is known for the rolling hills formed 2-4 million years ago (Lin 1967). The Palouse Formation consists of Pleistocene age paleosols with eolian, volcanic, glacio-fluvial and glacial-lacustrine sediments (Lin 1967). Williams and Allman (1969) estimated the Palouse Basin to be covered for 75% by the Palouse Formation. The paleosols were formed in a process of soil development, when they got buried during intense loess deposition events. Alternately, paleosols and loess are found in the Palouse Formation (Krapf 1978; Reuter 1995). The source of this loess was located 150 km west of the Palouse Basin, in southwest Washington (Russell 1897; Smoot and Ralston 1987). The formation ranges from zero to 30 m thick (Kopp 1994) and thins from west to east (Badon 2007). The loess has locally very dense paleosol fragipans, which are eluvial subsurface soil horizons restricting water movement (O'Geen 2002; O'Geen et al. 2003; McDaniel et al. 2008). These fragipans are clay-rich, which is present for 25% in the loess deposits (Lin 1967). These fragipans are a result of chemical weathering and leaching and are very restrictive (Provant 1995). The earlier mentioned springs which occur in the SOB are also present in the Palouse Formation. These springs are probably a result of small perched aquifers hitting the land surface (Hopster 2003; Hernandez 2007).

2.6.6 Alluvium and Colluvium

Alluvium and colluvium material consists of Holocene streams, slope-wash and debris flow deposits at the land surface. Stream channels are incising the SOB, having to cut through the Palouse Formation. Almost 30% of the land surface in the Moscow sub-basin is covered by floodplain deposits, which consist of clay, sand and pebbles derived from weathered basalt and crystalline rock (Bush 2005).

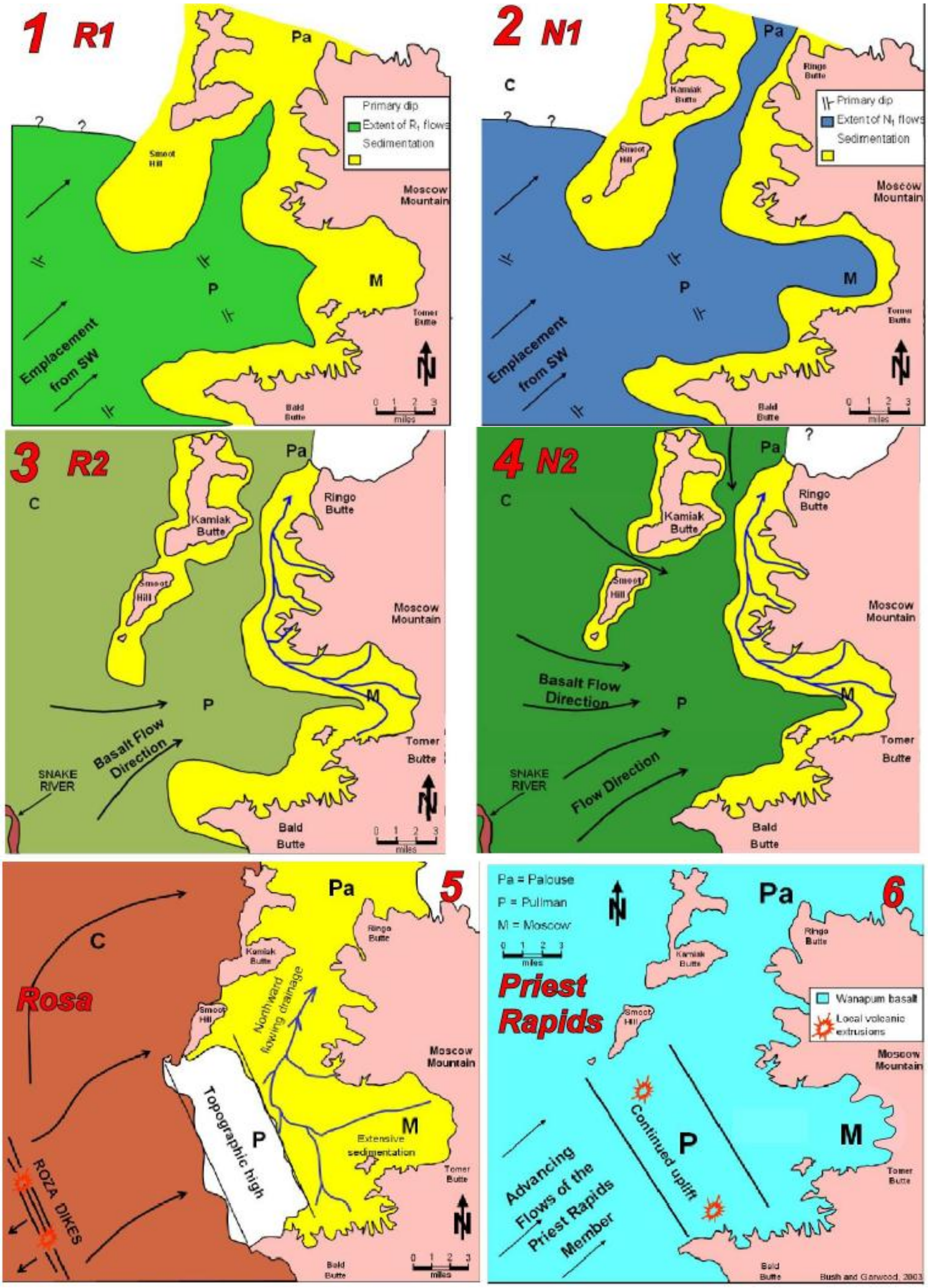


Figure 2.19 Paleographic evolution of successive basalt flows and effects on sedimentary environments and groundwater flow. M = Moscow. P = Pullman, Pa = Palouse, C = Colfax. Oldest to youngest events: 1-4) Grande Ronde Flows (development of northward drainage system, and deposition of Sediments of Moscow; 5) Wanapum flows and increased sedimentation in Moscow sub-basin; 6) Wanapum reaching Moscow sub-basin. (after Bush 2005; Grader 2011).

2.7 Hydrogeology

2.7.1 Hydraulic characteristics

The Moscow sub-basin is hydrogeologically very complex and contains multiple aquifers and aquitards. The main aquifer systems found in the area are the Grande Ronde aquifer system and the Wanapum aquifer system. Smaller ones are perched aquifer systems within the Latah Formation and Palouse Formation and small systems in the crystalline basement rock. These last ones only supply enough water for domestic or stock uses. The Grande Ronde aquifer system is the main groundwater resource system for the city of Moscow. The Wanapum aquifer is much less used (PBAC 2011). Aquifer systems are defined as the basalt flows including the interbeds of the Latah Formation.

Several studies have estimated the lateral hydraulic conductivity of Grande Ronde and Wanapum (Table 2.3). The large variety in hydraulic conductivity shows the heterogeneity of the basalt flows. The highest hydraulic conductivity values are probably due to the local geologic structure, thickening of interflow zones, thinning of individual lava flows or the presence of pillow lava complexes. Pillow lava complexes are mainly formed at the eastern extent of the CRBG where lava cools fast in the lakes which formed against the underlain lava flow (Swanson, 1967).

Table 2.3 Estimated hydraulic conductivities (m d^{-1}) of the Grande Ronde and Wanapum (after De Graaf 2011)

Grande Ronde	**Wanapum**	**Source**
0.03 – 7.9	0.03 – 7.9	Barker (1979)
1.56	1.56	Hansen et al. (1994) and Whiteman et al. (1994)
0.03 – 2.63 *	0.03 – 2.38 *	Vaccaro (1999)
K_h = 0.1-3.7 K_v = 3.1*10^{-5}	K_h = 0.1-0.2 K_v = 2.4*10^{-4} – 3.6*10^{-4}	Lum et al (1990)
8.64-8.64*10^{-9}	8.64-8.64*10^{-9}	Reidel et al. (2003)

*including the Latah Formation as interbeds

The Latah Formation is present in between the crystalline basement rock and the Wanapum and Grande Ronde (Figure 2.16). The Latah Formation is important considering recharge, since it is expected that recharge pathways can be found within this formation (§2.6.4). The Sediments of Bovill (SOB) are closest to the surface, and because of its heterogeneity the hydraulic characteristics of the SOB are barely understood. Sediment types in the SOB range from impermeable clays to pebble-sized gravels (Table 2.4). However, the infiltration rates will probably be controlled by the finer grained sediments. The mean hydraulic conductivity for SOB is probably in the range of sandy silt (Pierce 1998). Groundwater movement will mainly occur through layers of coarse sand which are predominantly found in paleo-channels (Pierce 1998; Grader 2011; Dijksma et al. 2011)

Table 2.4 Horizontal saturated hydraulic conductivity values representing sedimentary units in the Sediments of Bovill (after Pierce 1998).

Sediment	**K values (m d^{-1})**	
	Freeze and Cherry, 1979	*Domenico and Schwartz, 1990*
Clay (aquitard)	$6.1*10^{-8}$ – $6.1*10^{-4}$	$8.6*10^{-9}$ – $4.1*10^{-2}$
Sandy – Silt	0.091 – 9.1	0.078 – 43
Coarse Sand	9.1 – 91	0.078 – 518
Pebble-sized gravel	91 – 914	26 – $2.6*10^{3}$

Also for the youngest formation (Pleistocene) the hydraulic characteristics have been derived. Lum et al. (1990) estimated the horizontal hydraulic conductivity for the Palouse loess at 1.5 m d^{-1}, based on long term infiltration rates calculated by Williams and Allman (1969) and horizontal conductivity values from Freeze and Cherry (1979). The Palouse Formation is dominant in the west of the Palouse Basin. Therefore, infiltration to the groundwater system may be dominated by the hydraulic conductivity of the loess (Pierce 1998). In the east of the Palouse Basin, within the Moscow sub-basin, the SOB are dominant at the surface. The infiltration may be dominated by the hydraulic conductivity of the SOB.

2.7.2 Groundwater Flow Pattern

Leek (2006) constructed potentiometric surface maps for the Palouse Basin (Figure 2.20) using interpolated water level data from wells for the year 1990. The potentiometric surface map in the Wanapum Formation shows a clear decreasing trend from southeast to northwest. Water from the Moscow sub-basin is flowing west crossing the Idaho/Washington border. The Wanapum thins and becomes less productive towards the Pullman area (Leek 2006). Although the water levels in the Grande Ronde are approximately 80 m lower, the Grande Ronde potentiometric surface maps display a similar flow pattern as the Wanapum aquifer. Both Moscow and Pullman are abstracting water from the Grande Ronde. The hydraulic gradient from Moscow to Pullman was estimated to be $2.33*10^{-4}$ in 1960. However, the flow direction reversed in the 1980's and reached zero around the 1990's. These changes in groundwater flow are caused by increasing groundwater extractions over time, changing spatial precipitation differences and unknown recharge flows (Leek 2006). Difference between the Grande Ronde and Wanapum potentiometric surface is the strong dip to the Snake River in the Grande Ronde. Earlier models suggested groundwater flow towards the Snake River (Lum et al. 1990; PBAC 1992). However, Grande Ronde Snake River canyon walls were observed to be dry (Grader 2011). Bush (2005) found northwest trending structures from paleo-valleys west and east of Moscow and hypothesized water reaching the basement rock will flow in northwest direction through paleo-valleys (Figure 2.19).

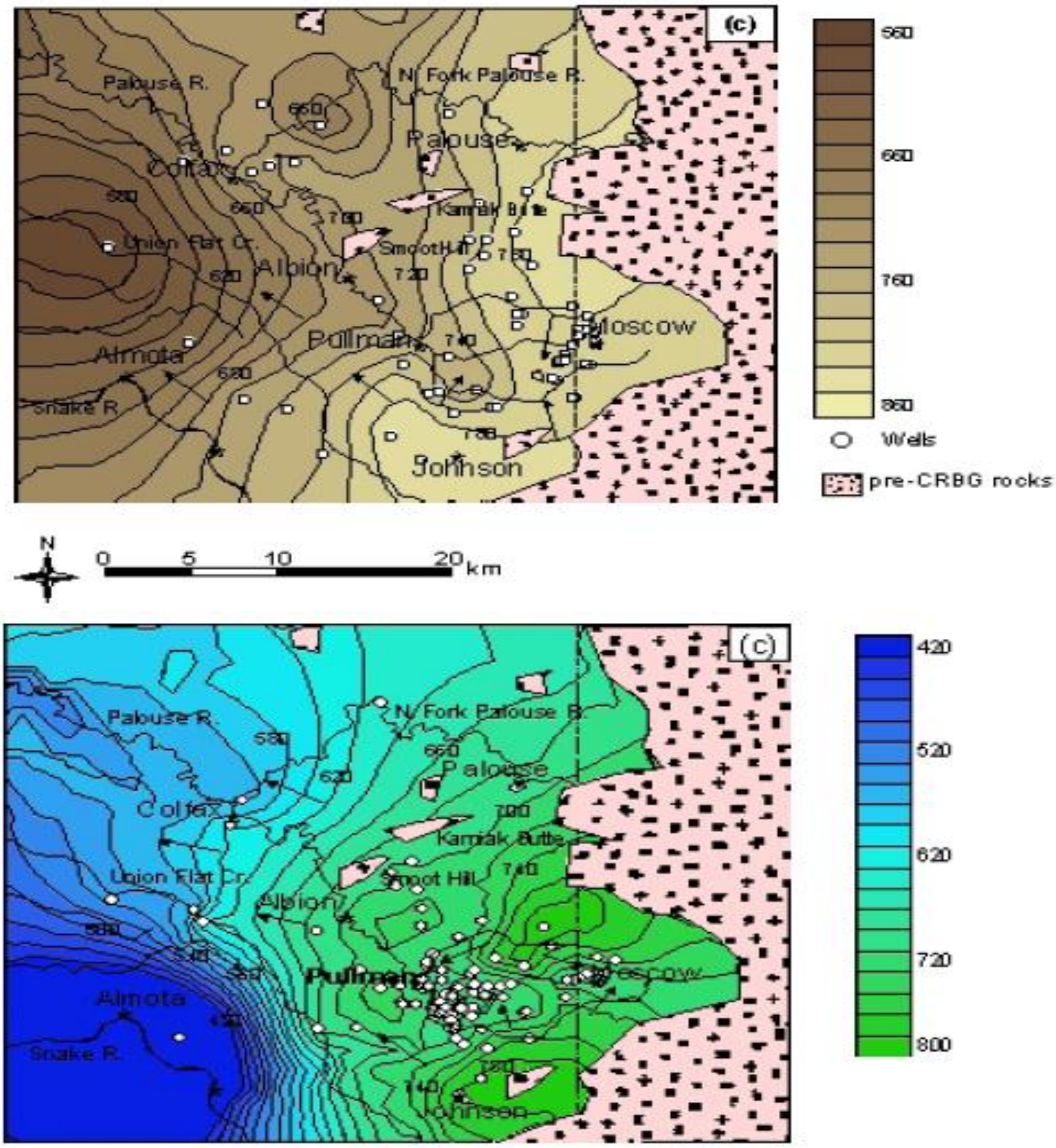
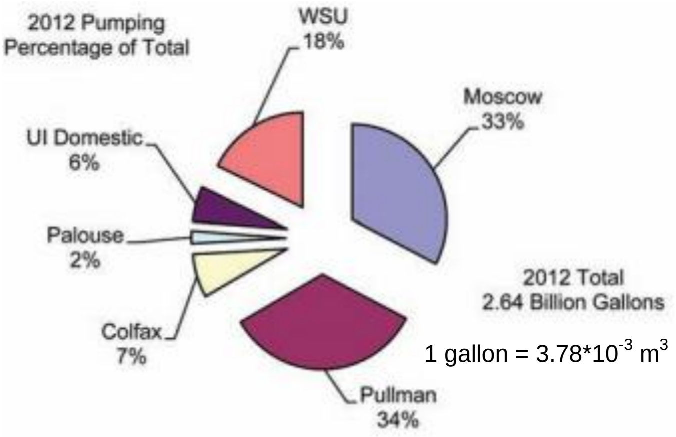


Figure 2.20 Contour maps of potentiometric surface (1990) of Wanapum aquifer (upper) and Grande Ronde aquifer (lower), showing the water levels (m), well locations and crystalline basement rock.

2.7.3 Human influence

Since 1884 humans influence the groundwater levels in the Moscow sub-basin. For this study human influence is important, since it has heavily affected the groundwater levels. Apparently the groundwater use is higher than the groundwater recharge. Groundwater was discovered in 1884, when the first artesian well was made in Pullman (Figure 2.24). In 1897, the wells were allowed to flow, so 11.400 m^3d^{-1} was wasted (Russel 1897). The first alarming messages came around 1920 from the Moscow City Council and Chamber of Commerce who noticed the decrease of groundwater levels. In the '60's and '70's hydrogeological studies started to come up in the Moscow-Pullman area to make estimates of the supplies (Robischon 2007). Nowadays, more than 60.000 residents in the Palouse Basin are depending on groundwater as drinking water supply. In total 10.0 million m^3 was pumped from the aquifers in 2012 from which Moscow and Pullman abstract the largest part (67%) (Figure 2.21) (PBAC 2012). Moscow pumped 32% in 2011 and 42% in 2012 from the Wanapum Formation (PBAC 2011; PBAC 2012). All other pumping entities pumped solely from the Grande Ronde Formation. In the Palouse Basin groundwater levels are declining consistently with approximately 30cm yr^{-1} (PBAC 2011). Leek (2006) has constructed hydrographs for the Palouse Formation, Wanapum Formation and Grande Ronde Formation over the period of 1930-2006. The



1 gallon = $3.78*10^{-3}$ m^3

Figure 2.21 Groundwater Pumpage in the Palouse Basin in 2012 (PBAC 2012)

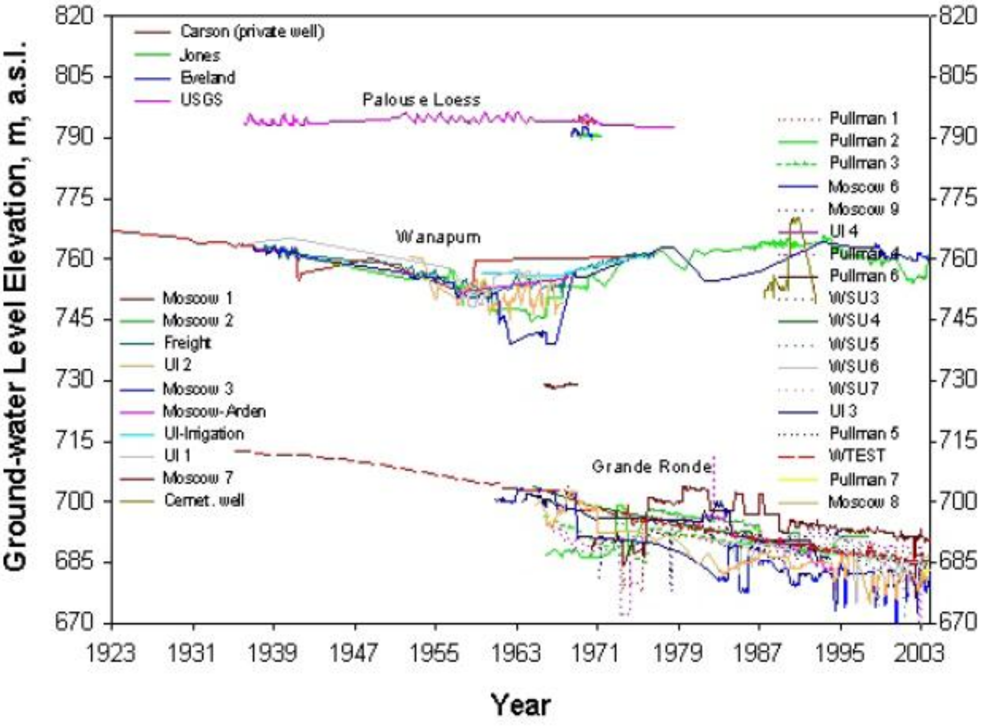


Figure 2.22 Composite ground-water hydrographs of major wells in the Palouse Basin (Leek 2006)

Wanapum groundwater levels dropped drastically in the '50's and '60's. When the Grande Ronde Formation became the main water resource, the Wanapum groundwater level recovered with approximately 15 cm yr^{-1} in the '70's and '80s (Figure 2.22) (PBAC 2008). The recovery of the groundwater level in the Wanapum Formation suggests recharge occurs. Although absolute values are still uncertain, it is thought that there is limited recharge to the Wanapum and very little recharge to the Grande Ronde (PBAC 2011).

Large water use differences exist between summer and winter, partly due to increased irrigation demand. The estimate of the baseline pumping was calculated as the annual average of the pumping levels for the winter months. Pumping above this average level can be considered non-baseline usage (PBAC 2012). In Moscow this non-baseline water use is 28.4% more than the average baseline pumping, which means the average water use for the year 2012 was 28.4% higher than the annualized January, February, November and December averages (Figure 2.23). This suggests the water use in the winter months is lower than in the rest of the year.

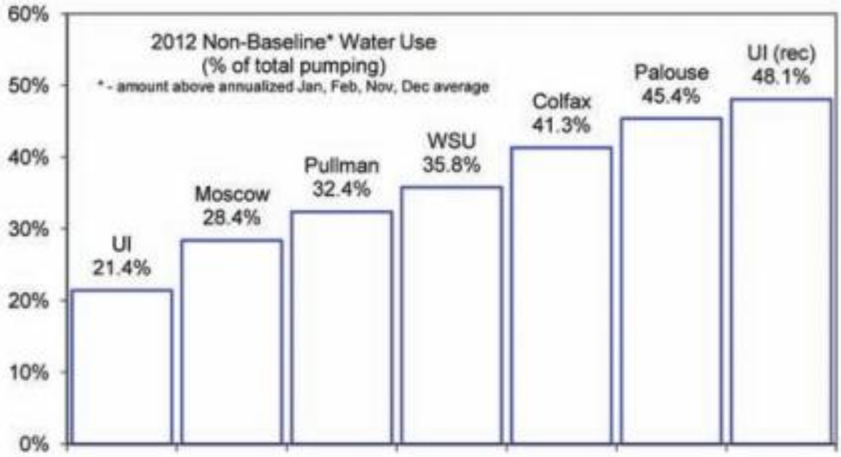
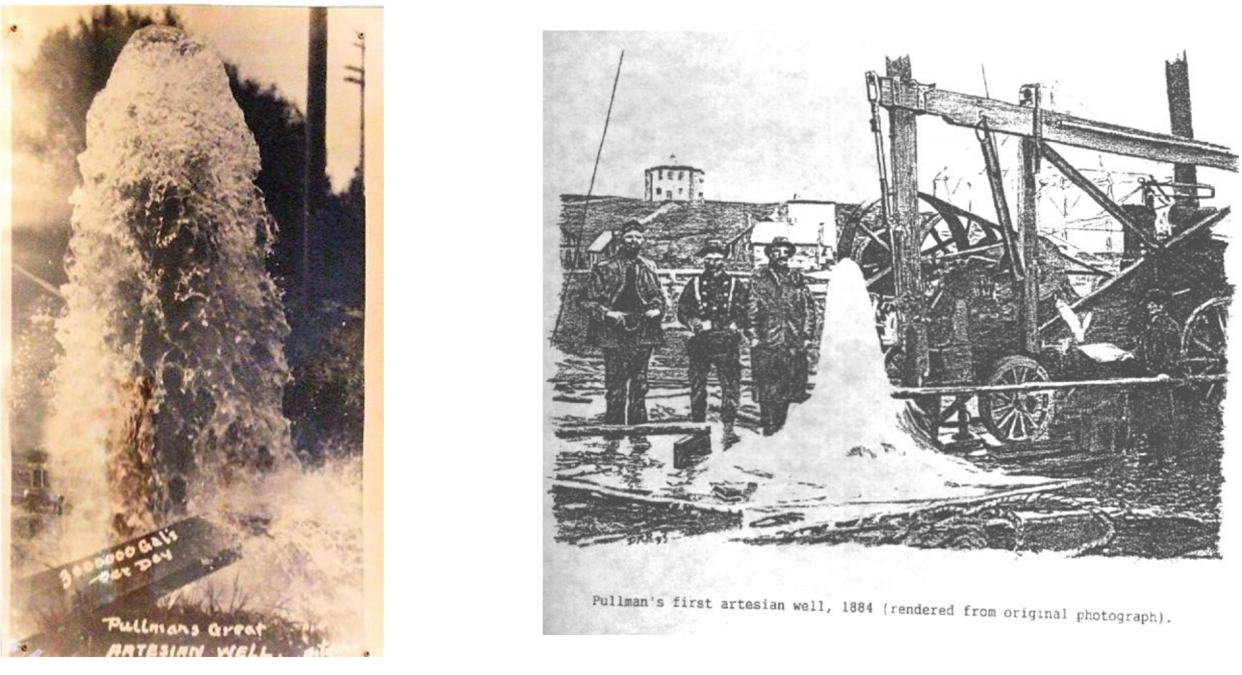


Figure 2.23 Non-baseline water use 2012 (PBAC 2012).



Pullman's first artesian well, 1884 (rendered from original photograph).

Figure 2.24 Pictures of the first artesian well in 1884. Water was wasted by keeping the wells open. (Robischon, 2007).

2.7.4 Recharge

Since 1960, several studies focusing on recharge rates to the Wanapum were done. By using water balance methods (Stevens 1960; Foxworthy and Washburm 1963; Barker 1979; Smoot and Ralston 1987; Bauer and Vaccaro 1990; Fiedler 2007) recharge rates were estimated in the range of 0.4-10.5 cm yr^{-1} (Table 2.5). O'Geen et al. (2005) used isotopes to estimate recharge rates and Muniz (1991) used vadose sampling and modelling with LEACHM. They estimated recharge at different hill slope positions in the range of 0.4 to 10.5 cm yr^{-1}.

Table 2.5 Studies estimating recharge rates to the Wanapum Formation (after Dijksma et al. 2011)

Study	**Recharge rate (cm yr^{-1})**	**Method**
Stevens 1960; Foxowrthy and Washburm 1963; Barker 1979	3	Water balance
Smoot and Ralson 1987; Bauer and Vaccaro 1990	7-10	Water balance
O'Geen et al. 2005; Muniz 1991	0.4-10.5	Isotope tracer study & vadose sampling and modelling with LEACHM
Fiedler (2007)	8.0	Water balance for Paradise Creek
Reeves 2009	5.1 (+/- 4.6)	Expert elicitation; Bayesian Model Averaging
Dijksma et al. 2011	6.9	Soil Moisture Routing model for Paradise Creek watershed

Three different recharge pathways are believed to exist:

1) Recharge occurs by vertical infiltration through the Palouse Formation and SOB

This recharge pathway is confirmed by Crosby and Chatter (1965) using C-14 dating. They concluded recharge received by the Wanapum aquifer comes from percolation through the loess and through basalt outcrops (Figure 2.25). Larson et al. (2000) used stable isotopes, and found similar signals between surface water and Wanapum water. Dijksma et al. (2011) suggests, that "*it is highly unlikely that the dominant-flow pathway towards the basalt formations is one-dimensional vertical flow*". This is based on the nearly impermeable layers within the SOB. The same conclusion was made by the study of Fairley et al. (2006) in which 53 boreholes have been made into the sediments. This study confirms that it is very unlikely recharge to the Wanapum Formation occurs vertically through the Palouse Formation and the SOB.

2) Recharge occurs from streams in close contact with basalt.

The hypothesis that recharge occurs in areas where the basalt is near the surface can also be justified by preliminary evidence. The Paradise Creek runs downstream from the University of Idaho campus (Figure 2.12 & Figure 2.13), where the SOB and thick continuous argillic layers are absent and where the basalt is very close to the surface. This suggests a higher probability of vertical recharge (Figure 2.25). Li (1991), Hernandez (2007) and Bennett (2009) found indications of connections between the Paradise Creek and wells hitting the upper aquifer, based on pumping tests. In addition, the waste water treatment plant (WWTP) (Figure 2.13) of Moscow sustains perennial flow downstream of the discharge point and therefore there is a greater opportunity for water to infiltrate than further upstream in the creek where the flow is intermittent in the summer. The precipitation near the state line exceeds crop uptake in this region and therefore there is a high potential for vertical leaching (Figure 2.10). Moxley (2012) recently provided strong evidence indicating that the South Fork of the Palouse River downstream of Pullman provides local recharge, by using isotope tracers. Carey (2011) also suggested that wells closer to streams were more likely to show a connection with the surface water. However, in many cases these streams dry up during the summer and therefore may not provide the magnitude of recharge observed in the Wanapum aquifer.

Provant (1995) and Pierce (1998) also considered stream loss in the eastern part of the Paradise Creek watershed, which has been quantified by Woelders (2009) who found an average infiltration rate of 6 mm d^{-1}, similar to Rosenberry (2008). However, this amount is negligible because of the small surface area of streams and lack of flow in summer time. For the entire Palouse Basin this would mean a recharge rate of 0.3 mm yr^{-1}, which is low compared to the recharge rates estimated in Table 2.5.

3) Recharge occurs through SOB paleo-channels

In this concept the following evidence supports the hypothesis that recharge occurs lateral through paleo-channels from the Moscow Mountain (Figure 2.25).

1. Moscow mountain receives twice the precipitation as the city of Moscow and as demonstrated by Dijksma et al. (2011) and Figure 2.10, the ‘excess’ precipitation is much greater in this region compared to other parts of the Palouse Basin.
2. Thick weathered granitic layers were found in wells in the forested area, which can conduct water well below the root zone (Appendix I).
3. The forest soils do not contain the thick clay layers that would impede vertical movement of water as found in the study of Fairley et al. (2006) (Dijksma et al. 2011).
4. The source of granitic weathered material within the SOB and the individual basalt flows likely came from the Moscow Mountain range (Foxworthy and Washburm 1964)
5. Furthermore, it is likely that some of these granitic layers may still be connected as ‘paleo-channels’ evidenced by the many perennial springs in the Moscow sub-basin below coarse sediments. (Grader 2011; Dijksma 2011; De Graaf, 2011).
6. Well logs typically show that the source of water is often a gravel or sand layer within the basalt (Appendix I).
7. Coarse depositions (more permeable) dominated near basement highs in the east, and fine deposition dominated to the west (Figure 2.18) (Pierce 1998).

8. Seasonal water table fluctuations have been observed in the SOB east of the basin with continued water flow and a single peak in August (wells of the Idaho Department of Water Resources, IDWR).
9. Vantage Member and the Sediments of Moscow were deposited in the same fashion as the SOB and are connected where the basalt is absent in the east of the Moscow sub-basin. Paleo-channels have been able to incise these sediments.

Paleo-channels are located in paleo-valleys (§2.6.4.3) which determine the direction of groundwater recharge. Where the paleo-channels hit the basalt or the Latah Formation interbeds, the basalts are recharged. Based on these preliminary findings, this study might confirm the direct connection between paleo-channels and groundwater in the basalt aquifers.

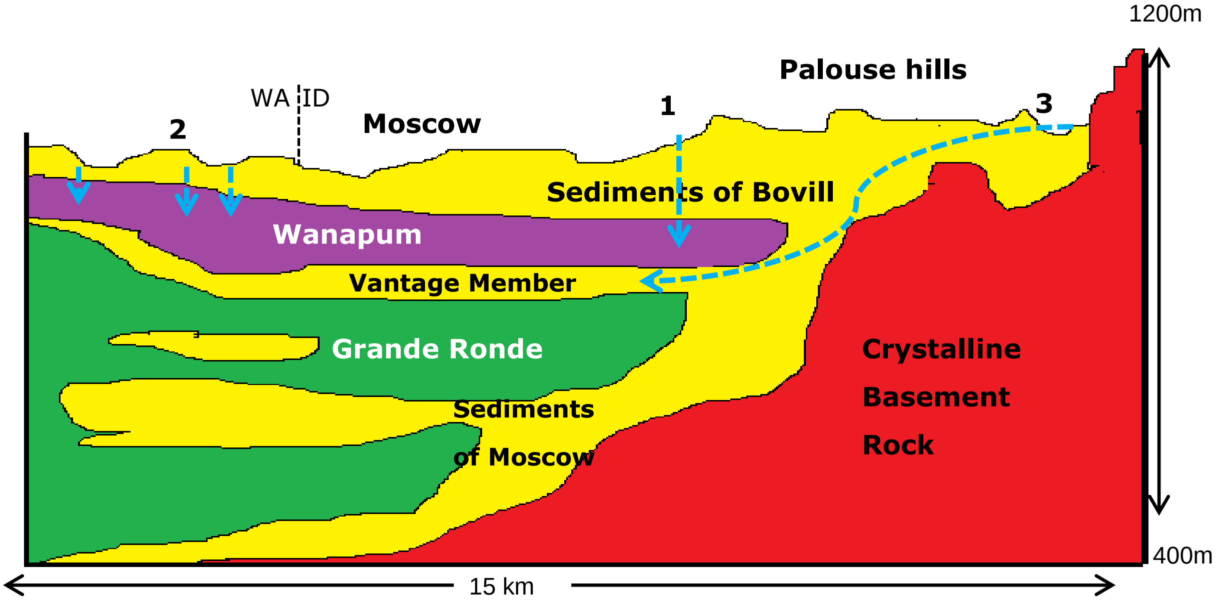


Figure 2.25 Geological cross-section of the Moscow sub-basin from west to east (after Grader 2011). Numbers 1-3 and blue arrows correspond to the recharge pathways mentioned above. Cross-section based on W-E line in Figure 2.14.

3. Field Methods

Tracers are used as one of the primary approaches to determine whether a hydrologic connection between two water bodies exists (e.g. precipitation and groundwater, or surface water and groundwater). Isotopic and caffeine tracers have been used to investigate if aquifer recharge zones exist in the Moscow sub-basin. The concept of these approaches is described below. Also discharge measurements, electrical conductivity and temperature measurements are used in this study, and explained in this chapter.

3.1 Isotopic Sampling

3.1.1 Suitability

Since the study of Urey (1947), stable isotope geochemistry has increasingly been used in Earth and cosmic sciences. Applications of isotope tracers have been very useful in providing new insights into hydrologic processes, because the small-scale variability gives an effective indication of catchment-scale processes (McDonnel and Kendall 1992; Buttle 1994). Rain and snow containing stable isotopes fall over a catchment and they form ideal tracers all year round (Sklash 1990). They are suited as a tracer because (Kendall and MacDonnell 1998):

- Different recharge durations, recharge locations and flowpaths cause distinctive “fingerprints”
- Isotopes (especially the ones used in this study) are relatively conservative in reactions with sediments or rock material. They keep their own fingerprint until they are mixed with different waters
- Water from an isotopic distinctive source, like water from snowmelt, can indicate a hydrologic connection if it is found along a flow path. No hydraulic measurements or models are needed.

3.1.2 Theory

The stable isotopes used in this study are oxygen and hydrogen isotopes. Oxygen knows three different isotopes: ^{16}O, ^{17}O and ^{18}O, of which the numbers indicate the mass of the isotopes. This mass difference is caused by different amounts of neutrons in the atoms. The definition of a stable isotope is an isotope that does not decay to other isotopes on geological time scales (Kendall and Macdonnell 1998). ^{16}O is the most present in oxygen (the ratio of oxygen-18 to oxygen-16 is 1:500), and the amount of ^{18}O depends on the amount of fractionation (isotope partitioning) (Drever 1982). Fractionation is a natural process which is explained below. The second isotope used is hydrogen, of which deuterium (^{2}H) is the isotope of interest. The ratio ^{2}H:^{1}H is 1:6410 (Kendall and Macdonnell 1998).

Stable isotope ratios are always reported relative to a standard, so only the difference between isotope ratios is of interest. Differences can be measured far more precisely than absolute ratios (Friedman and O’Neil 1977). This difference is expressed as delta (δ), which is the isotopic ratio of the sample per mil (‰). These ratios are calculated by equation 2:

$$\delta_x = \frac{R_x - R_{stand}}{R_{stand}} \times 10^3 \qquad (2)$$

δ_x is the difference in isotope ratio of sample x and a standard (‰), R_x is the isotope ratio and R_{stand} is the corresponding ratio of the standard. R is always written as the ratio of the heavy (rare) isotope to the light (common) isotope (Friedman and O'Neil 1977). A $\delta^{18}O$ value of +10 is enriched in ^{18}O by 1% relative to the standard. A $\delta^{18}O$ value of -10 means the sample is depleted in ^{18}O by 1% relative to the standard. The established standard for $^{18}O/^{16}O$ ratios is the Vienna Standard Mean Ocean Water (VSMOW). This VSMOW is useful as a standard since ocean water is known to have small oxygen isotopic variations of $^{+}/_{-}$ 1.5 ‰ (Welham 1987). Common use in isotopic research with $\delta^{18}O$ and $\delta^{2}H$ is to only present the results of $\delta^{18}O$ (also presented as ^{18}O) since both isotopes are related.

3.1.3 Fractionations

The main processes having effect on the oxygen and hydrogen isotopic compositions of waters in a catchment area are: (1) phase changes above or near the ground surface, and (2) mixing of different waters at or below the ground surface. At isotopic equilibrium, the forward and backward reactions of a particular isotope are identical. The equilibrium in the isotopic ratio changes during phase changes. When water condenses, the heavier water isotopes (^{18}O and ^{2}H) will become enriched in the liquid phase and depleted in the vapour phase. During evaporation the opposite happens, since lighter isotopes evaporate easier than heavier isotopes. The water gets enriched in ^{18}O. As air masses move across continents they lose water by rainout. They become more depleted in the heavy isotopes, because the heavy isotopes are raining out first (Dansgaard 1964; Gat 1980) (Figure 3.1). This is called the rainout effect.

The amount of enrichment is also depending on the temperature which is called the temperature effect (Kendall and MacDonnell 1998; Dutton et al. 2005). Mazor (1991) presented an empirical equation for the net effect of temperature, equation 3:

$$\delta^{18}O = 0.7 * T_a - 13‰ \qquad (3)$$

where T_a is the local mean annual air temperature. The temperature is the main factor in the isotopic ratio variations in precipitation, and leads to seasonal variations. The result is enriched ^{18}O values in summer and depleted values in winter. The temperature effect also results in differences by latitude. At higher latitudes the precipitation is more depleted in heavy isotopes, this is called the latitude effect (Mazor 1991).

Also the amount of precipitation an area receives is an important factor for the isotopic ratio. Intense precipitation events lead to more depleted ^{18}O values; this is called the amount effect. Also mountainous areas receive more precipitation and have lower temperatures (§2.4.4), so have more depleted, heavy isotopes in the precipitation. Depending on the location, ^{18}O concentrations decrease with 0.15 to 0.5 ‰ per 100 m of rise in elevation (Welham 1987).

All these effects are causing seasonal variation in the isotope signal of the precipitation. This makes the $\delta^{18}O$ and $\delta^{2}H$ isotopic signature of water a unique attribute largely defined by the changes of phase which occur from the point of evaporation/condensation in the storm cloud to the point where the water infiltrates through the soil (Kendall and Macdonnell 1998). The isotopic ratio is usually not affected by evaporation when reaching the deeper groundwater (Krishnamurthy and Bhattacharya 1991).

A relation exists between δ^2H and $\delta^{18}O$ from precipitation samples from all over the world, which is known as the Global Meteoric Water Line (GMWL) (Craig 1961). This line is calculated by equation 4:

$\delta^2H = 8 * \delta^{18}O + 10 * VSMOW$ (4)

Deviation of measured isotopic samples from the GMWL indicates how much the water has been subjected to evaporation since the raindrop formation (Figure 3.1). (Craig 1961; Kehew 2001). To use stable isotopes as a proper method for understanding the processes the water has been going through, a meteoric water line of the study area should be constructed from the precipitation. Anomalies to the local meteoric water line (LMWL) are a result of isotope fractioning. Comparison between the LMWL slopes of different water sources (precipitation, surface water, groundwater) can be used to determine potential enrichment or surface and groundwater connectivity.

Previous studies in the region (Carey 2011; Moxley 2012; Larson 2000) indicated ^{18}O decreases with depth below the soil surface. Interpreting of the variability in ^{18}O is therefore difficult. One indication of the relative proportions of ^{18}O and ^2H contained in the soil water is the deuterium-excess (d-excess). The d-excess value is the intercept of the LMWL for the particular source of water, and defined by equation 5 (Dansgaard 1964):

d-excess (‰) = $^2H - 8 * {}^{18}O$ (5)

The d-excess is a measure for tracing the past and present precipitation processes (Froehlich et al. 2002). A d-excess of a water source close to the d-excess of the MWL (d=10, equation 4) means a direct link exists with the precipitation.

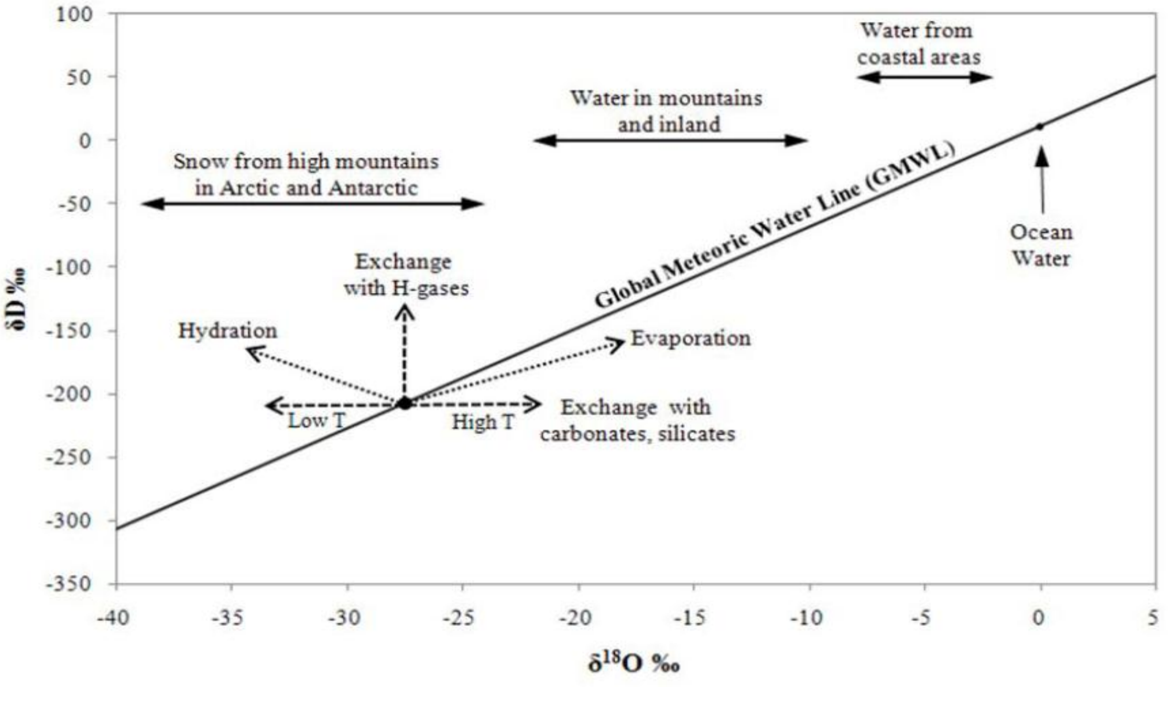


Figure 3.1 Processes caused variation in isotopic composition which can be derived from the deviation from the GMWL (after Carey 2011; Welham 1987; Kehew 2001). The figure also includes the rainout effect.

3.1.4 Application

In surface water applications the mean transient time that it takes for water to enter the soil and travel to the outlet of a watershed is determined by comparing the seasonal variability in stream water samples to the seasonal variability in the rain and snowmelt. If a hydrologic connection exists between two sources of water, similar but lagged temporal variability in the isotope signals is expected to be observed. Groundwater will experience the most lagged signal of the precipitation (Figure 3.2) (Changnon 1987).

The mean transit time can be approximated by convoluting tracer data using a transit time distribution as suggested by Maliszewiski and Zuber (1982) in equation 6:

$$\delta_{out}(t) = \int_{-\infty}^{t} \delta(t')g(t-t')dt' \qquad (6)$$

where δ_{out} *(t)* is the output δ^{18}O ratio, *t´* is the time of entry into the system, δ_{in} is the input δ^{18}O ratio, *g(t-t´)* is the mean transit time distribution function (e.g. tracer molecules travel time probability).

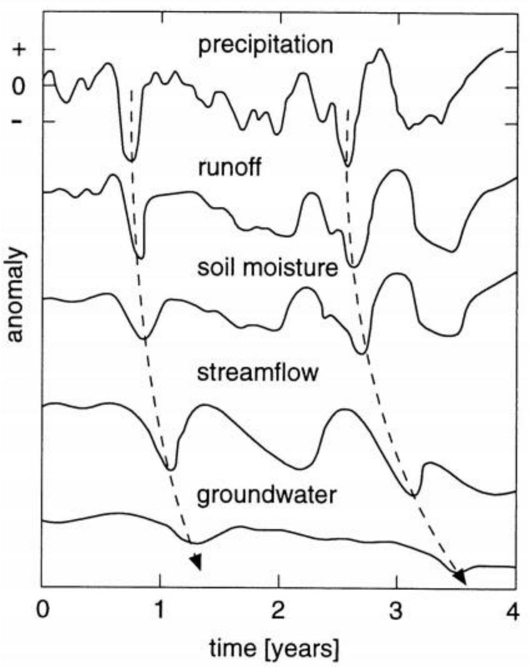


Figure 3.2 Example of propagation in a drought. Showing the lagged signal of a drought in precipitation to runoff, soil moisture, streamflow and groundwater (Changnon, 1987)

3.2 Caffeine Tracers

One unique tracer which has been used to detect a hydrologic connection to groundwater primarily in urban landscapes is caffeine. In North America the source of caffeine is almost exclusively related to sewage sources. Caffeine has been ranked number one drug worldwide. It is found in several beverages and medicines (Siegener and Chen 2002) and it is likely that the main source of caffeine is not the excreted part of consumed caffeine, but the disposal of unconsumed caffeine-containing beverages by disposing them or cleaning coffee cups in the sink (Seiler et al. 1999). Typical loads of caffeine are in the range of 16 mg d^{-1} $person^{-1}$ in untreated wastewater. Caffeine concentrations in treated waste water are very waste water- and WWTP-specific (Buerge et al., 2003). Since most WWTP's are not required to treat effluent for caffeine, the concentrations released to a stream through the effluent can be relatively large (Gardinali et al. 2002). Caffeine is a useful tracer since it is mobile in the soil and is not absorbed by soil-particles (Seiler et al. 2005) and is a conservative tracer (McGregor 2009). So far, several studies have focussed on the occurrence of caffeine in surface water and groundwater. Caffeine has been measured in surface waters and aquifers all around the world, and is found in ranges of 0.010-300 µg L^{-1} (Heberer et al. 1997; Drewes et al. 2003; Umari et al. 1995; Rogers et al. 1986; Paxeus and Schroder 1996; Buszka et al. 1994; Albaiges et al. 1986; Hillebrand et al. 2012; Sheldon and Hites, 1978; Buska et al., 1994; Seiler et al., 1999; Standley et al. 2000; Ternes et al. 2001; Weigel et al. 2001; Siegener and Chen 2002; Teijon et al. 2010; Strauch et al. 2008; Godfrey et al. 2007).

An example of such a study is from Teijon et al. (2010). Teijon et al. (2010) studied the amounts of pharmaceuticals and personal care products in the WWTP-influent and WWTP-effluent in the Llobregat river delta (Spain). Caffeine was found in more than 60% of the samples, with concentrations higher than 0.1 µg L^{-1}. The average caffeine concentration of the WWTP influent was 327 µg L^{-1} (range 58-609 µg L^{-1}) and from the effluent it was 140.5 µg L^{-1} (range 70-203 µg L^{-1}). The concentrations in the groundwater ranged from 4 to 505 µg L^{-1} with a mean of 63.6 µg L^{-1}.

Paxéus and Schröder (1996) found 37 µg L^{-1} of caffeine in the influent of a Swedish WWTP and 4 µg L^{-1} in its effluent. Buszka et al. (1994) reported concentrations of caffeine 1.3 to 2.4 µg L^{-1} up to 13.5 km downstream of a WWTP effluent point in Dallas, Texas. Buerge et al. (2006) found higher concentrations in the streams than in the WWTP effluents. Combined sewer overflows appeared to be the additional source. Also septic tanks are an important source of pharmaceuticals in groundwater (Godfrey et al. 2007).

3.3 Discharge measurements

Discharge measurements have been done to study whether or not creeks are losing or gaining water in the area. These measurements are done with a portable flow-meter, a FLO-MATE2000®. This portable flow-meter reports stream velocity in ft s^{-1}. 1 ft s^{-1} = 0.3048 m s^{-1}.

3.3.1 Selecting a cross-section

To get accurate flow measurements, the following site characteristics are required for the cross-section location (Rantz et al. 1982):

- The location should be within a straight part of the stream, and the flowlines should be parallel to each other and perpendicular to the stream flow measurements (SonTek/YSI, Inc., 2007).
- The location should be clear of plants and rocks, which will create eddies in the stream and disturb the measurements.
- There should be no eddies, slack water or excessive turbulence
- Water velocity should be >0.15 m s^{-1}
- A minimum depth of >3 cm is required, >15 cm is preferred

These requirements are hard to find in the natural environment. Rantz et al. (1982) suggests to engineer a desirable cross-section by moving vegetation and rocks away.

3.3.2 Set-up

When the best location has been selected, a tape-measure is stretched across the stream, so that the stream flow lines are perpendicular to the tagline. It should not touch the water surface. Twelve to twenty velocity measurements should be done in streams with a width <6m, whereas twenty to thirty a required in a stream with a width >6 m. One velocity measurement should never exceed 10% of the total stream discharge; otherwise a higher density of velocity measurements should be done at this part (Rantz et al. 1982).

3.3.3 Measuring

A standard top-setting wading rod has been used. The flow meter probe was attached to the wading rod. The wading rod has increments of 0.10 foot (3 cm) and allows it to estimate the depth with a 0.05 foot precision (1.5 cm). The appropriate depth was taken at each point in the cross-section. If the depth was <2.5 ft (75 cm) then the water depth was measured at 0.6 of the depth below the water’s surface at the measuring point. If the depth was >2.5 ft, stream velocity was measured at 0.2 and 0.8 of the total depth below the water's surface at the measuring point. A wading rod allows it to set these requirements (Rantz et al. 1982).

Both the depth and the velocity were documented at each point in the cross-section. By using the mid-section technique the total discharge was calculated, with equation 7:

$$Q = \Sigma\,(a * v) \qquad (7)$$

where Q is the total discharge ($m^3\ s^{-1}$), *a* is the individual area (m^2) of a rectangular subsection which is the product of the width (m) and depth (m), v is the velocity ($m\ s^{-1}$) of the current in subsection *a*.

In the mid-section method the velocity at each point represents the mean velocity in a rectangular subsection (Rantz et al. 1982) (Figure 3.3). For the calculation of the mid-section equation 8 is used:

$$q_x = v_x * \left[\frac{b_x - b_{(x-1)}}{2} + \frac{b_{(x+1)} - b_x}{2}\right] * d_x$$

$$= v_x * \left[\frac{b_{(x+1)} - b_{(x-1)}}{2}\right] * d_x \qquad (8)$$

where q_x is the discharge ($m^3\ s^{-1}$) through subsection x, v_x is the mean velocity ($m\ s^{-1}$) at point x, b_x is the distance (m) from initial point to point x, $b_{(x-1)}$ is the distance (m) from initial point to preceding point, $b_{(x+1)}$ is the distance (m) from initial point to the next point, and d_x (m) is the depth of the water at point x.

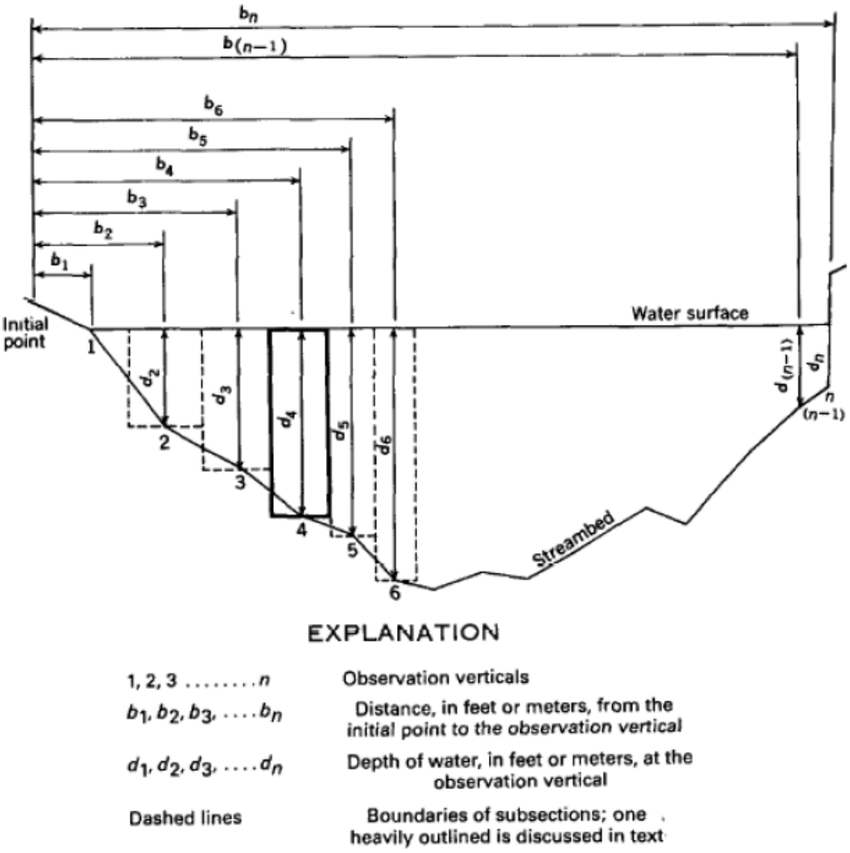


Figure 3.3 Mid-section discharge definition sketch (from Rantz et al. 1982)

3.4 Electrical Conductivity

Measurements of the electrical conductivity (EC) and temperature (§3.5) have been used during the isotope sampling, caffeine sampling and discharge measurements. The EC is a useful indicator for the residence time of the groundwater. EC is a measure for electrical conductance of the water, which depends on the amount of ionary components in the water. EC for fresh water is expressed as micro-Siemens per cm (µS cm^{-1}). Since EC is temperature dependent the EC is always transformed to 20ºC or 25ºC by an EC-measure device to be able to compare EC-values. Besides the residence time, EC of groundwater also depends on the pressure and parent material. The parent material's chemical composition determines how many ions are able to dissolve in the water, the pressure influences the chemical equilibrium and the residence time determines whether or not the equilibrium is reached (Van Lanen and Dijksma 2007).

Rainwater has a low EC. Rainwater is distillated seawater and a chemical fingerprint of seawater (Van Lanen and Dijksma 2007). Hiscock (2005) and Kok (2009) estimated the EC for rainwater in the Paradise Creek watershed to be in the order of 10 µs cm^{-1}.

For groundwater the EC is a good indicator of the source of the water, and the residence time of the water. If fast recharge pathways would exist, the groundwater EC is similar to the EC of rainwater or surface water. If recharge is a slower process the EC is affected by the parent material. The chemical composition of the rock dictates the chemical composition of the groundwater. If the EC fluctuates significant similar to the rain events, the groundwater is being recharged relatively fast. In that case, the EC reflects the effect of parent material during dry periods and the effect of rainwater during wet periods. During wet periods the influx of rock-ions is the same as during a dry period, but the amount of water would increase. So after a dry period the EC of the groundwater would be higher than after a wet period. If less EC fluctuations are measured than the effect of rain events on groundwater are smaller, so slower recharge pathways exist (Van Lanen and Dijksma 2007).

3.5 Temperature

Similar to the EC, temperature of groundwater can provide useful information on the source of the groundwater. If fast recharge pathways would exist, the groundwater temperature follows the daily cycle of the air temperature, smoothened out (Van Lanen and Dijksma 2012). Slower recharge pathways would result in a seasonal temperature cycle in the groundwater temperature. If recharge occurs slowly, no temperature variation is expected. The groundwater temperature corresponds with the long year averaged air temperature in the area. The long year averaged air temperature varies with the elevation of the infiltrated location, so the groundwater temperature could also indicate whether recharge occurs on the Moscow Mountain or at lower parts.

4. Modelling methods

In this chapter the concepts of the Soil Moisture Routing (SMR) model are explained (§4.1). SMR is used to calculate the infiltration, and used as recharge input in the Modflow model. To avoid confusion with aquifer recharge, the recharge input of Modflow is reported as “infiltration” in this report. Modflow is used for simulating the aquifer recharge. The Modflow model concepts are explained in §4.2.

4.1 Soil Moisture Routing model

4.1.1 Introduction

The infiltration in the area is very much depending on the soil-types (Dijksma et al. 2011). The Moscow sub-basin is known for its argillic soil properties and restrictive layers which cause perched water tables above a restricting layer (McDaniel et al. 2008). The argillic properties of the soils are spatially variable in the Moscow sub-basin (§2.3), which is an essential part to include in the groundwater modelling.

In this study the Soil Moisture Routing model (SMR) has been used. The SMR model concepts were first used in a hydrological model for shallow soils by Steenhuis and Norman (1986) which has been modified by Caraco (unpublished report 1992) and Zollweg (1994) into the geographic information system (GIS) - GRASS format. SMR is linked to GIS by sequences of PERL-commands within GRASS. This coupling with GIS makes it easy to display results and modify the model for different conditions (Stuart and Stocks 1993). Later the model has been adapted by Frankenberger (1996) and Frankenberger et al. (1998) by performing validation and sensitivity analyses for a watershed in the Catskills Region of New York State. This model performed best and is designed for soils with a relatively thin, permeable soil layer over a much less permeable fragipan layer, bedrock or other restricting layers, and with a steep topography, meaning the topography is the main cause of lateral flow (Boll et al. 1998). These soil characteristics are found in the Moscow sub-basin. The SMR model used in this study has been adapted and validated for the Palouse region by Brooks et al. (2007) and Brooks and Boll (2002).

4.1.2 Model concept

The SMR model is a grid-based water-balance model including the following processes: interception, evapotranspiration, subsurface lateral flow, deep vertical percolation and saturation-excess surface runoff (Figure 4.1). Brooks and Boll (2005) included snow accumulation and snowmelt into the SMR model. Assuming step-by-step quasi-steady state, the model tracks the flow into and out of grid cells, by using the basic mass balance equation 9 (Brooks et al. 2007):

$$Di\ \frac{d\theta i}{dt} = P(t)_i\ -\ ET(t)_i\ +\frac{\Sigma Q_{in.i}\ -\ \Sigma Q_{out.i}}{A}\ -\ L_i\ -\ R_i \qquad (9)$$

where i is the cell number, D_i (m) is the depth to a hydraulically restricting layer, θ_i (m^3 m^{-3}) is the volumetric moisture content of the cell, P (m d^{-1}) is the effective precipitation (rain and snowmelt), ET_i (m d^{-1}) is the actual evapotranspiration, $\Sigma Q_{in.i}$ (m^3 d^{-1}) is the lateral inflow from surrounding upslope cells, $\Sigma Q_{out.i}$ (m^3 d^{-1}) is the lateral outflow to surrounding downslope cells, L_i (m d^{-1}) is the vertical percolation out of the surface soil layer, R_i (m d^{-1}) is the surface runoff, A (m^2) is the area of the grid cell, and t (d) is the time.

Calculation of these water balance components is facilitated by GIS. GIS keeps track of the moisture stored in each cell at each time step, as well as the input parameters for each cell. The model components (Figure 4.1) will each be examined in detail in the following sections.

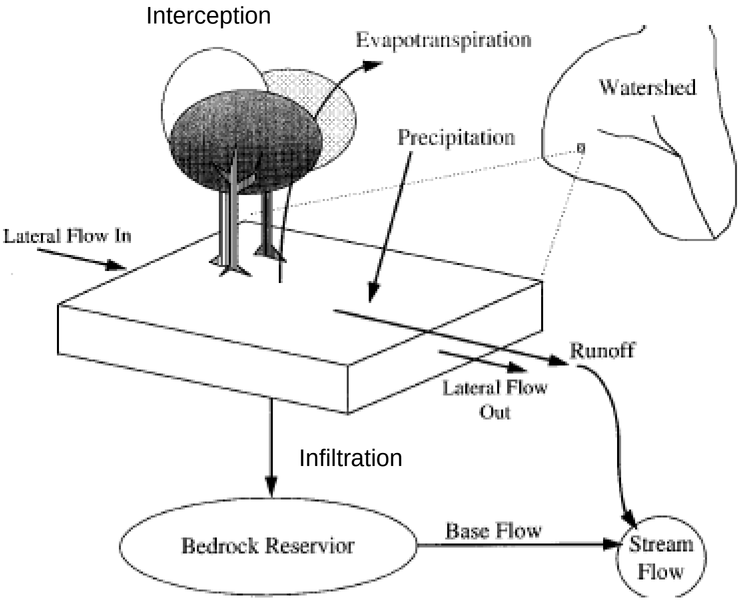


Figure 4.1 Conceptual SMR model, illustrating the water balance components for a grid cell. (Frankenberger et al. 1999)

4.1.3 Input and parameters

Unique for the SMR model is that it requires publicly available data and minimal calibration (Brooks et al. 2007). The simplicity of SMR allows a physical modelling basis without over parameterisation (Frankenberger et al. 1999). The input requirements include: daily weather data, land use data, a soil map, six soil parameters, and digital elevation data. Additionally a geology map and a road map have been added. The six soil parameters are: depth to restrictive layer, type of restrictive layer (fragipan, bedrock or impervious), saturated hydraulic conductivity, saturated moisture content, field capacity and percent rock fragments. Despite the minimal input requirements, modelling-results are as good as, or better than, more complex hydrology models (Johnson et al. 2003; Mehta et al. 2004; Dijksma et al. 2011).

4.1.4 Precipitation

Precipitation consists of rain and snow. Since no accurate snow data was available, the following assumption was made: if $T_{average}$ is larger than 3ºC all the precipitation is rain. If $T_{average}$ is smaller than 0ºC all precipitation is snow. If the $T_{average}$ is in between 0ºC and 3ºC the following equations 10 and 11 were used:

$$Rain(t)_i = \frac{T_{average.i}}{k} * P(t)_i \qquad (10)$$

$$Snow(t)_i = P(t)_i - Rain(t)_i \qquad (11)$$

Where i is the cell number, Rain(t)$_i$ is the total amount rain (m), T$_{average}$ is the mean daily temperature (ºC), k is a constant with the value of 3 (ºC), and Snow(t)$_i$ is the total amount of snow equivalent (m).

Snowmelt was calculated by the empirical relationship developed by U.S. Army Corps of Engineers (1960) which has been adapted by Brooks (2005). If temperature was below 0 ºC the snow would remain in the snow pack until the temperature would be above 0ºC. Snowmelt was estimated by a snowmelt-factor multiplied with the temperature.

$$\boldsymbol{M = mt + k, if\ t > 0\ °C} \qquad (12)$$

Where M is snowmelt (cm d^{-1}), t is the average daily temperature (ºC), m the snowmelt factor of 0.616 (forest) or 0.640 (cm ºC^{-1} d^{-1})

4.1.5 Evapotranspiration

The ET$_{act}$ is calculated for each cell by the Thorntwaite and Mather (1955) equation (§2.4.5.2). This equation relates ET$_{act}$ to daily ET$_{pot}$ vegetation and stage of growth and moisture content in the cell. The equation 13 and 14 are:

$$ET_{act,i} = c_i ET_{pot} \left(\frac{\theta_i - \theta_{wp}}{\theta_{fc.i} - \theta_{wp}}\right) \text{ for: } \theta_i < \theta_{fc.i} \qquad (13)$$

$$ET_{act,i} = c_i ET_{pot} \text{ for } \theta_i \geq \theta_{fc.i} \qquad (14)$$

Where i is the cell number, ET$_{act}$ is the actual evapotranspiration (m), ET$_{pot}$ is the potential evapotranspiration (m), c_i is a vegetation coefficient which is depending on the land use and day of the year derived by Jensen (1973), $\theta_{fc.i}$ is the moisture content at field capacity (m^3 m^{-3}), θ_{wp} is the moisture content at wilting point (m^3 m^{-3}), and θ_i is the average soil moisture content of cell i (m^3 m^{-3}). The ET$_{act}$ is equal to the ET$_{pot}$ when the soil moisture is above the field capacity in the cell.

4.1.6 Interception

Interception was also included in the SMR model. Interception is calculated for Spruce trees based on work by Lankreijer et al. (1999), who measured throughfall and precipitation of spruces trees in Uppsala, Sweden. The maximum storage of canopy was taken as 2.0 mm for forest and 1.0 mm for residential areas. During a rain event the evaporation from the canopy is assumed to be 0.04 mm h^{-1}. When there is no rain, it is assumed that evaporation from the canopy is 50% of the ET$_{pot}$.

4.1.7 Water table thickness and storage amount

Because of the restricting layer, the soil is partially saturated and partially unsaturated. A relation is made between the soil storage amount *S* to the saturated layer thickness *h*. Figure 4.2 shows the concept of storage in SMR (Brooks et al. 2007). The porosity decreases with depth according to equation (15):

$$\boldsymbol{\phi_s(z) = A_s(D - z) + \phi_{sb}} \tag{15}$$

$$A_s = \frac{\phi_{ss} - \phi_{sb}}{D} \tag{16}$$

Where ϕ_s is the porosity (-), z is the depth (m), A_s is the vertical porosity gradient as in equation 16 (m^{-1}), D the soil depth above the restricting layer (m), ϕ_{sb} is the porosity at the base of the soil layer (-), and ϕ_{ss} is the porosity at the soil surface (-).

The amount of water stored when the water table reaches S_{sat} (m) is calculated by integrating equation 15 from *z = 0* to *z = D*:

$$\boldsymbol{S_{sat} = \frac{A_s D^2}{2} + \phi_{sb} D} \tag{17}$$

The soil moisture content in the unsaturated zone ($z < D - h$) depends upon the thickness of the capillary fringe h_{cf}. Within the capillary fringe ($D - h - h_{cf} \leq z < D - h$) the soil moisture content is calculated as the difference between the saturated moisture content and the drainable porosity. The drainable porosity θ_{dp} is defined as function of *z* (Brooks et al. 2007):

$$\boldsymbol{\theta_{dp}\ (z) = Cz\ \ for\ D - h - h_{cf}\ \leq z < D - h} \tag{18}$$

where C is determined in field work by Brooks et al. (2004) in a hillslope experiment with perched water tables. Above the capillary fringe the drainable porosity is defined as the difference between the total soil porosity $\phi_s(z)$ and field capacity moisture content θ_{fc} (z):

$$\theta_{dp}\ (z) = \phi(z) - \ \theta_{fc}(z)\ for\ 0 \leq z < D - h - h_{cf} \tag{19}$$

The thickness of the capillary fringe is determined by the average difference between the porosity and field capacity moisture content divided by *C*. In shallow soils the entire soil depth can be within the capillary fringe (h_c > D). In that case equation 19 is not applicable, and the integration of equation 18 from *z* = 0 to *z* = *D* – *h* yields the change in storage when the water table drops from the soil surface to a new location. The total storage is (Brooks et al. 2007) as in equation 20:

$$S(h) = \ S_{sat} - \frac{C}{2}(D - h)^2 \tag{20}$$

If the water table is on the restricting layer (*h*=0), S_0 can be derived from equation 20 into equation 21:

$$S_0 = \ S_{sat} - \frac{C}{2}D^2 \tag{21}$$

By substitution of equation 21 in equation 20 *h* can be determined from S, using the formula:

$$h\ (S) = D - \ \frac{1}{C}[(CD)^2 - 2C(S - S_0)]^{0.5}\ for\ S \geq S_{fc} \tag{22}$$

$$h\ (S) = 0\ \ for\ S < \ S_{fc} \tag{23}$$

For deeper soils (*D*>*h*$_c$) an extra term is added to equation 21-23 to account for the section of the soil profile that has a constant drainable porosity (Brooks et al. 2007).

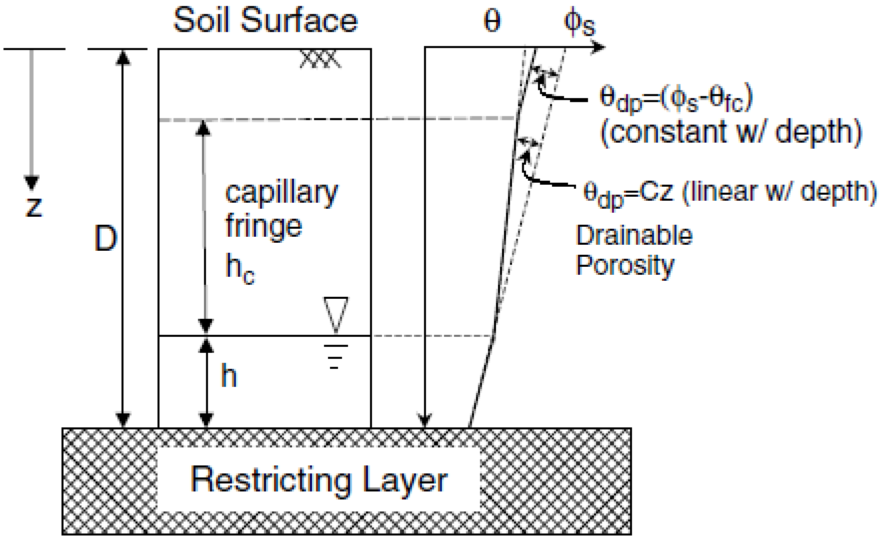


Figure 4.2 Partially saturated soil column with conceptual θ relationships, and exponential decrease of K_s with depth. The wedge shaped area in the θ(z) function represents the drainable porosity in depth units. (Brooks et al. 2007)

4.1.8 Subsurface lateral flow

The original SMR model has shallow subsurface lateral flow, (also called interflow), included in the water balance (Frankenberger et al. 1999). This component makes SMR suitable for landscapes with steep topographies. SMR approximates the quantity of interflow leaving each cell and dividing among its downhill neighbours by using Darcy's law using the kinematic approximation. This included the assumption that the hydraulic gradient is equal to the land slope of each cell. The lateral flow out of the cell is calculated with equation 24:

$$Q_{out.i} = w_i T_i(h)\beta_i \qquad (24)$$

where $Q_{out.i}$ is the lateral flow out of cell i ($m^3\ d^{-1}$), dh/dL is the land slope of cell i ($m\ m^{-1}$), w is the width of each cell i (m), $T_i(h)$ is the transmissivity of the soil profile at cell i ($m^2\ d^{-1}$),

The effective hydraulic conductivity is a double exponential relationship, developed by Brooks et al. (2004) based on outflow measurements from an 18 m long drain tile in a hillslope experiment. :

$$K_s(z) = K_{s1}e^{-f1z} + K_{s2}e^{-f2z} \qquad (25)$$

Where K_{s1} and f_1 are parameters that represent the contribution of flow from a shallow near-surface layer dominated by macropores, and the K_{s2} and f_2 are parameters that represent a general exponential decrease in K_s ith depth of the soil. The K_s is largest at the soil surface, because of macropores created by roots, foraging rodents, raw organic matter and tillage. Figure 4.3 shows an example of the exponential function as presented by Brooks et al. (2004), in which the black upper line represents this function.

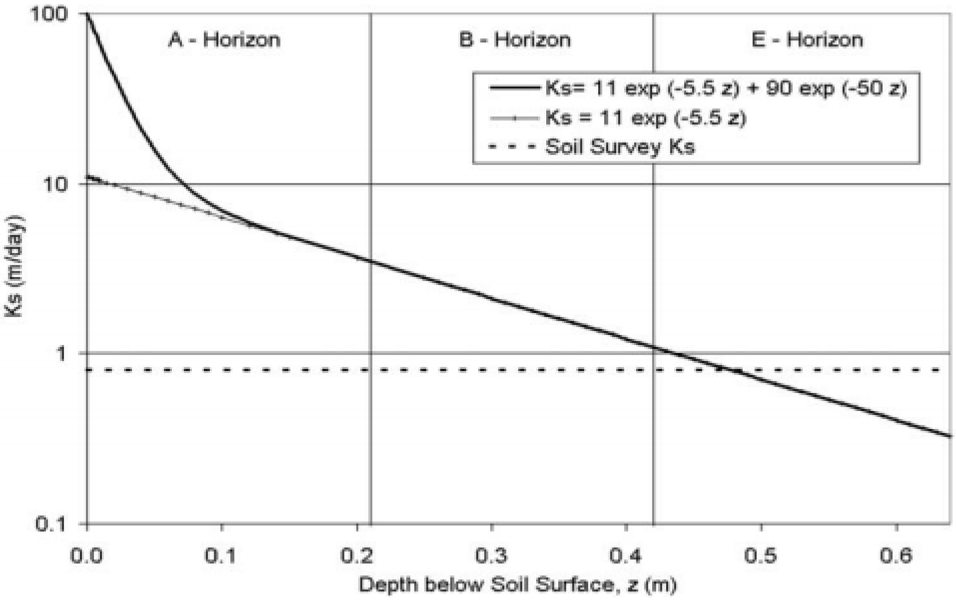


Figure 4.3 The lateral saturated hydraulic conductivity decreases exponential with the depth, results from Brooks et al. (2004). The upper formula (black line) has been used in this study for the lateral K_S.

Lateral unsaturated flow between cells is assumed to be negligible in SMR. The transmissivity is derived from equation 26 by integration over h (Brooks et al. 2007):

$$T(h) = \frac{K_{S1}}{f_1}(e^{-f1(D-h)} - e^{-f1D}) + \frac{K_{S2}}{f_2}(e^{-f2(D-h)} - e^{-f2D}) \qquad (26)$$

The lateral subsurface flow is routed to the downslope, neighbouring cells based on a slope-weighted average (Quinn et al. 1991), in which the elevation and distance between the cells are taken into account.

$$P_{ij} = \frac{(Z_i - Z_j)/L_j}{\sum_{j=1}^{n}[(Z_i - Z_j)/L_j]} \text{ for } Z_i > Z_j \qquad (27)$$

Where P_{ij} is the portion of the total flow out of cell I that is routed to neighbour cell j, Z_i is the elevation of the cell, Z_j is the elevation of the downslope cell, L_j is the distance from the center point of cell i to the center point of neighbour cell j, n is the number of downslope neighbour of cells i (n≤8).

4.1.9 Surface runoff

Surface runoff is caused by soil moisture exceeding the moisture storage in the soil profile. Moisture storage capacity is exceeded when the inputs (precipitation and lateral flow from uppslope cells) exceed the outputs (evapotranspiration, interception, lateral flow to downslope cells, percolation) by more than the available moisture storage in the soil profile. Surface runoff does not flow into neighbouring cells, but directly into the streams (Brooks et al. 2007).

4.1.10 Infiltration

For each soil type the restrictive layer below the shallow soil layer is known from soil surveys, and is differentiated into a fragipan layer, bedrock or other restricting layers (Boll et al. 1998). These restrictive layers have their own hydraulic characteristics. If a saturated layer is present in the soil, water can infiltrate into fractures or cracks in the fragipan or bedrock

(Frankenberger et al. 1999). Values for conductivities through a fragipan and bedrock vary widely in literature (Theil and Bornstein 1965; McCarty 1980; Dabney and Selim 1987; Smith and Wheatcraft 1993). Typical reported values for fragipan conductivities are in the range of 0.1-7 mm yr^{-1}. SMR uses the geometric mean of the extremes which is a value of 1 mm d^{-1} for the fragipan layers and 2 mm d^{-1} for the bedrock conductivities, which has been derived in the same way. Infiltration through the restrictive layer is stored in a single bedrock reservoir (Frankenberger et al. 1999).

4.1.11 Baseflow

Baseflow is simulated from the bedrock reservoir, using a simple linear reservoir model to drain the lumped groundwater reservoir. The baseflow reservoir coefficient has been determined directly from recession analysis of observed streamflow data by previous studies (Barnes 1939; Brutsaert and Nieber 1977).

4.1.12 Streamflow

The streamflow is simulated by summing up the surface runoff, baseflow and interflow from cells adjacent to streams.

4.2 GMS Modflow

4.2.1 Introduction

Modflow has been used to simulate groundwater flow in this study. Groundwater Modeling System 9.1 (GMS) was used as the graphical interface for Modflow. GMS9.1 is GIS-supported, which allows the interaction between SMR-simulations and Modflow. In the next paragraphs the basic physical laws and equations of Modflow are explained.

4.2.2 Groundwater flow equations

4.2.2.1 Darcy’s law

Darcy’s law is a key component of the Modflow model. Darcy’s law shows that flux is linear and proportional related with head loss and inverse proportional related to the distance along the average distance of the flow x. The hydraulic conductivity is the proportionality constant used in the equation of Darcy’s law, as equation 28 (Todd 1959):

$$q = -k\frac{\partial h}{\partial x} \qquad (28)$$

where q is the specific discharge (m d^{-1}), k is the hydraulic conductivity (m d^{-1}) and $\frac{\partial \mathrm{h}}{\partial \mathrm{x}}$ the head gradient in x direction (-).

Since groundwater flow is not one dimensional as it is expressed in the equation 16, this basic equation should be written into three dimensions. Darcy’s law can be written as a three dimensional flow equation (Schwartz and Zhang 2003), as in equation 29:

$$q = -k\nabla h \qquad (29)$$

where k can be expressed as:

$$k = \begin{matrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{matrix}$$

and,

$$\nabla h = \left(\frac{\partial h}{\partial x} i, \frac{\partial h}{\partial y} j, \frac{\partial h}{\partial z} m\right)$$

x, y and z are the flow directions and i, j and m are unit vectors along respectively the x, y and z flow directions. The equation can be simplified by assuming that k_{xx}, k_{yy} and k_{zz} have the same direction as respectively $\frac{\partial h}{\partial x}, \frac{\partial h}{\partial y}\ and \frac{\partial h}{\partial z}$ so only the diagonal k-values remain and the other k-values are zero. For the separate dimensions this leads to the following equations 30-32 (Schwartz and Zhang 2003):

$$q_x = -k_{xx}\frac{\partial h}{\partial x} \qquad (30)$$

$$q_y = -k_{yy}\frac{\partial h}{\partial y} \qquad (31)$$

$$q_z = -k_{zz}\frac{\partial h}{\partial z} \qquad (32)$$

4.2.2.3 Continuity principle

Together with Darcy's law, the continuity principle is a key component of the Modflow model. This principle shows that there is no water loss or water generated within the same volume. For a certain time period (Δt) the difference between the mass of water flowing in a certain volume, the mass of water flowing out the same volume and the sources within the volume, is the change in storage (equation 33). The mass balance is shown by Figure 4.4. The equation (34) shows the mass balance, and assumes that external flux can occur in addition to the fluxes in x,y,z direction:

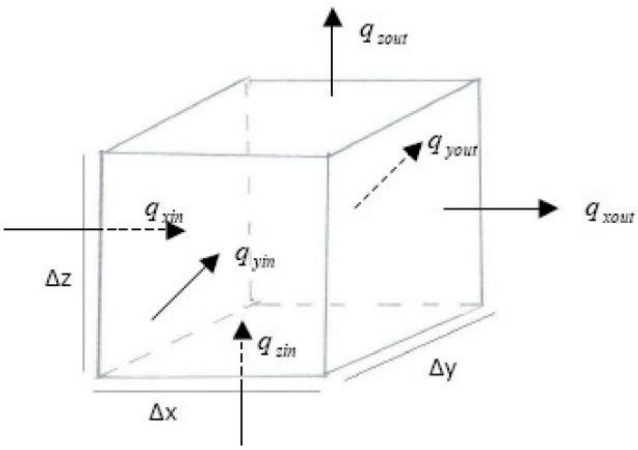


Figure 4.4 Mass balance based on the continuity principle.

$$Q_{in} - Q_{out} = Q_{stored}. \qquad (33)$$

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} + q_{ext} = S_s\frac{\partial h}{\partial t} \qquad (34)$$

where q_x,q_y and q_z are fluxes in the x,y,z direction (m d^{-1}), q_{ext} is the external flux like wells, precipitation, drainage, etc. (d^{-1}), t is the time (d), and S_s is the specific storage of the porous material (m^{-1}).

4.2.2.4 Application in Modflow

The combination of the above described groundwater equations lead to a partial differential equation on which Modflow is based, to describe dynamic saturated groundwater flow. This results in the following equation 35:

$$\frac{\partial}{\partial x}\left(k_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial h}{\partial z}\right) + W = S_s\frac{\partial h}{\partial t} \qquad (35)$$

where W is the volumetric flux representing sources and sinks of water (m d^{-1}), and S_s is the specific storage (m). This equation is a combination of Darcy's law on the left, and the continuity principle on the right.

This equation describes three dimensional saturated groundwater flow, under non-equilibrium conditions in a heterogeneous and anisotropic medium. An analytical solution of equation 35 is an algebraic expression giving h(x,y,z,t) such that the equation and its initial and boundary conditions are satisfied (USGS 2005), when the derivatives of h with respect to space and time are substituted in equation 35. One of the approaches to solve equation 35 is to use the finite-difference method which changes the equation from a continuous system to a finite set of discrete points in space and time. These discrete points are represented by the grid, in which each cell is a discrete point and cell sizes can vary throughout the grid. For the middle of the cell the hydraulic heads are calculated for specific time steps (block-centered formulation).

The numerical method solving this equation needs initial conditions and boundary conditions, which are respectively the starting heads for each cell and the property of the boundary. A boundary condition can be a Dirichlet or Neumann boundary. A Dirichlet boundary means the head in the cell is fixed for a certain value so water could flow in or out the boundary cell. A Neumann boundary means the flux into the boundary cell is fixed. The Neumann boundary is mostly used in case there is no flow, so the fixed flux is set to zero.

Developing the groundwater flow equation into a finite difference form follows from the application of the continuity principle; meaning the sum of all fluxes of each cell must be equal to the rate of change in storage within the cells, assuming the density of groundwater is constant. The derived equation 36 is:

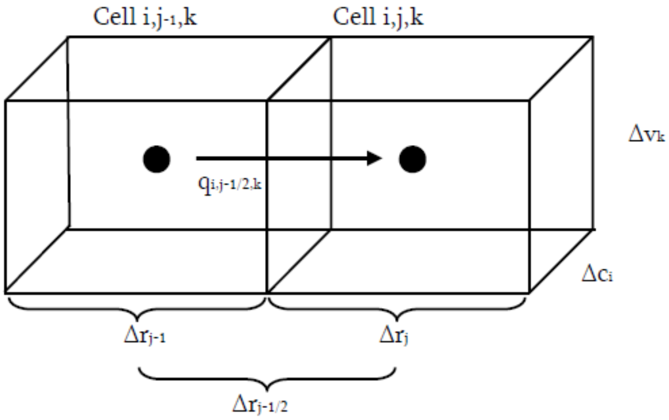


Figure 4.5 Flux between two cells in Modflow (McDonald and Harbaugh 1988).

$$\Sigma Q_s = S_s \frac{\partial h}{\partial t} \Delta V \qquad (36)$$

where Q_s is the flow rate into the cell (m^3 d^{-1}), and ΔV is the change of volume of a specific cell (m^3). At a certain change in head (Δh), the term on the right hand side is equivalent to the volume of water taken into storage over a certain time interval (Δt).

Figure 4.5 shows the flow from one cell to the other. This is given by Darcy's law as equation 37:

$$Q_{i,j-1/2,k} = KR_{i,j-1/2,k}\Delta c_i \Delta v_k \, \frac{h_{i,j-1,k} - h_{i,j,k}}{\Delta r_{j-1/2}} \qquad (37)$$

where $KR_{i,j-1/2,k}$ is the effective hydraulic conductivity in the row between the nodes i,j,k and i,j-1,k calculated as a harmonic mean (m d^{-1}), $c_i \Delta v_k$ is the surface area between the cells (m^2), and $\Delta r_{j-1/2}$ is the distance between the centre of the cells (m). The cell constants KR, Δr, Δc and Δv are combined in a single constant by Modflow called the hydraulic conductance (m^2 d^{-1}). This constant is defined in the following equation 38 (Mcdonald and Harbaugh 1988):

$$CR_{i,j-1/2,k} = \frac{KR_{i,j-1/2,k}\Delta c_i \Delta v_k}{\Delta r_{j-1/2}} \qquad (38)$$

Substitution of this equation in equation 37 leads to the following equation 39:

$$Q_{i,j-1/2,k} = CR_{i,j-1/2,k} \left(h_{i,j-1,k} - h_{i,j,k}\right) \qquad (39)$$

This equation also applies for the adjacent cells in x,y,z-direction. The conductance in columns is indicated by CC and vertical conductance is CV. To take into account the external flows into the cell from features or processes like e.g. streams, drains, evaporation or wells, additional terms to equation 39 are required. External flows are represented by:

$$a_{i,j,k,n} = P_{i,j,k,n} \, h_{i,j,k} + q_{i,j,k,n} \qquad (40)$$

where $a_{i,j,k,n}$ represents the flow from the N^{th} external source into cell i,j,k (m^3 d^{-1}), $p_{i,j,k,n}$ is a constant (m^2 d^{-1}) and $q_{i,j,k,n}$ is a constant (m^3 d^{-1}).

The partial differential equation of the groundwater flow equation (35) can be simulated by a backward-difference equation. A backward-difference equation is used because of the numerical stability of the method. Figure 4.6 shows a hydrograph of head values at cell i,j,k. An approximation to the time derivative of head at time t^m is obtained by equation 41:

$$\frac{\Delta h_{i,j,k}}{\Delta t} \cong \frac{h_{i,j,k}^{m} - h_{i,j,k}^{m-1}}{t^{m} - t^{m-1}} \qquad (41)$$

where t^m and t^{m-1} the time is at which the flow terms is evaluated and the time that precedes t^m respectively. The head associated with these times are described has $h_{i,j,k}^{m}$and $h_{i,j,k}^{m-1}$ respectively. Thus by using a backward-difference approach, the time derivative in Figure 4.6 is evaluated based on the change in head at the node over a time interval that precedes and ends with the time at which the flow is evaluated. This leads to the backward-difference equation for cell i,j,k:

$$CR_{i,j-\frac{1}{2},k}\left(h_{i,j-1,k}^{m} - h_{i,j,k}^{m}\right) + \ CR_{i,j+\frac{1}{2},k}\left(h_{i,j+1,k}^{m} - h_{i,j,k}^{m}\right)$$

$$+ CC_{i-\frac{1}{2},j,k}\left(h_{i-1,j,k}^{m} - h_{i,j,k}^{m}\right) + \ CC_{i+\frac{1}{2},j,k}\left(h_{i+1,j,k}^{m} - h_{i,j,k}^{m}\right) +$$

$$+ CV_{i,j,k-\frac{1}{2}}\left(h_{i,j,k-1}^{m} - h_{i,j,k}^{m}\right) + \ CV_{i,j,k+\frac{1}{2}}\left(h_{i,j,k+1}^{m} - h_{i,j,k}^{m}\right)$$

$$+ P_{i,j,k,n}\, h_{i,j,k}^{m} + q_{i,j,k} = S_{s\ i,j,k}\left(\Delta r_j \Delta c_i \Delta v_k\right) \frac{h_{i,j,k}^{m} - h_{i,j,k}^{m-1}}{t^m - t^{m-1}} \tag{42}$$

Equation 42 can be rearranged so that all terms containing heads at the end of the current time step are grouped on the left-hand side, and all terms independent of the head at the end of the current time step on the right-hand side:

$$CR_{i,j-\frac{1}{2},k} h_{i,j-1,k}^{m} \ + \ CR_{i,j+\frac{1}{2},k} h_{i,j+1,k}^{m} \ + \ CC_{i-\frac{1}{2},j,k} h_{i-1,j,k}^{m} + CC_{i+\frac{1}{2},j,k}\ h_{i+1,j,k}^{m}$$

$$+(-\,CV_{i,j,k-\frac{1}{2}} - \ CC_{i-\frac{1}{2},j,k} - CR_{i,j-\frac{1}{2},k} h_{i,j-1,k}^{m} - CR_{i,j+\frac{1}{2},k} - \ CC_{i+\frac{1}{2},j,k}$$

$$-CV_{i,j,k+\frac{1}{2}} + + P_{i,j,k,n} \ - S_{s\ i,j,k}\, \Delta r_j \Delta c_i \Delta v_k) h_{i,j,k}^{m} + \ CV_{i,j,k-\frac{1}{2}}\, h_{i,j,k-1}^{m}$$

$$+ CV_{i,j,k+\frac{1}{2}}\left(h_{i,j,k+1}^{m} - h_{i,j,k}^{m}\right) \ = \ -q_{i,j,k} - \ S_{s\ i,j,k} - \left(\Delta r_j \Delta c_i \Delta v_k\right) h_{i,j,k}^{m-1}\left(t^m - t^{m-1}\right) \tag{43}$$

At each time step the set of finite difference equations is reformulated for each grid cell in the Modflow model in which the head is set free to vary with time. The heads at the end of the time step calculated by the equation make up the known heads for the next time step. In case there is a steady state situation, the right hand side of equation 43 will be reduced to $-q_{i,j,k}$ only.

Equation 43 can be written for each variable-head cell in a matrix form:

$$[A]\{h\} = \{q\} \tag{44}$$

where [A] is a matrix of the coefficients of head, from the left side of equation 43, for all active cells in the grid, {h} is a vector of head values at the end of time step m for all cells in the grid, and {q} is a vector of the constant terms at the right-hand side of equation 43 for all cells in the grid.

The vector {q} and the terms that comprise [A] are assembled by Modflow through a series of subroutines. Then these are transferred to subroutines that solve the matrix equations for the vector {h}.

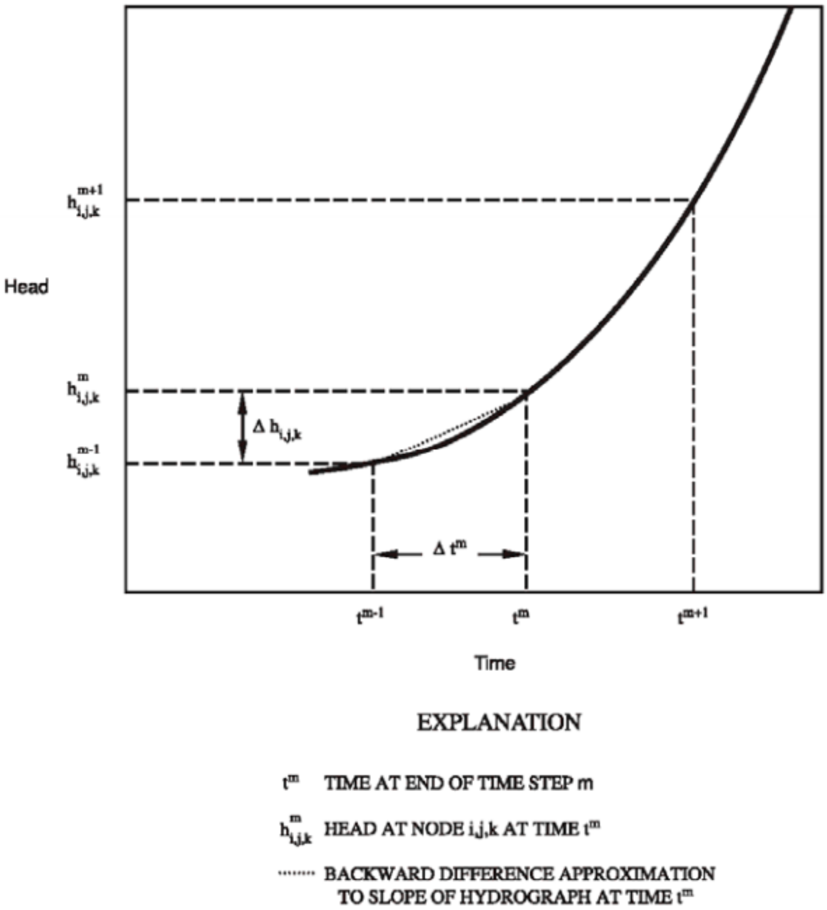


Figure 4.6 Hydrograph for cell i,j,k (Macdonald and Harbaugh 1988)

4.2.3 Used packages

The fundamental components of Modflow were described above. However, Modflow is used for solving hydrologic problems. For that reason the program is divided into packages. Various parts of groundwater flow equation (43) are divided into the packages, which will be described here.

Basic package

The basic package includes the global options which are fundamental program options. Computational time intervals, grid size and cell sizes, state of cells (wet or dry), activity of cells (active or inactive), boundary conditions, and initial values are all included in this basic package.

Layer Property Flow (LPF) package

The LPF package is a flow package in which the horizontal and vertical hydraulic conductivity are calculated for each layer. Modflow computes the cell by cell hydraulic conductance (CR) based on the geometry of the layers and the K values of each cell. Other options of the LPF package are the wet-dry option (Figure 4.7). The wet-dry option states whether cells are allowed to become dry, which means the head value is below the bottom elevation of the cell. For successful iteration results this option is sometimes set to “no dry cells allowed” since a Modflow model will not convert if a cell continuously switches between a wet and dry state.

Another option in the LPF package is setting layer types to confined or unconfined. Setting all conditions to confined will result in a faster converting of the model. The confined option means the horizontal conductance is calculated as K*D, where D is the total thickness of the cell. The unconfined option would calculate the horizontal conductance as K*H, where H is the water height in the cell (Figure 4.7). This assumption can be made when: D-H << D_{total}, where D_{total} is the total thickness of the model. In this case the overestimation of the horizontal conductance can be neglected.

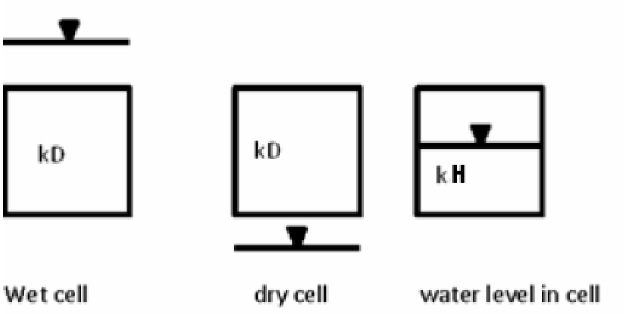


Figure 4.7 Possible states of cells in Modflow. Right figure only accounts for unconfined cells.

Geometric Multi-Grid (GMG) package

The GMG package is a solver package, used to solve finite difference equations in Modflow, according to the theory described above. Each solver has its own advantages and disadvantages. This solver was chosen since the conversion went much faster compared to the other solvers which were tried.

Recharge Package

The recharge package has been used to simulate the infiltration through the soil. As mentioned before, the recharge input is reported here as “infiltration” to avoid confusion with the aquifer recharge. For each cell a infiltration value has been assigned, and in case of a transient model also for each stress period. The units of infiltration are in m d^{-1}. By multiplying the infiltration with the surface area the total infiltration flow rate is calculated in m^3 d^{-1}. In Modflow three infiltration options are available (Figure 4.8): 1) infiltration only on top layer, 2) infiltration at specified vertical cells, and 3) infiltration at the highest active cells. The last option was chosen. When cells would fall dry, the infiltration switches to the underlying active cell.

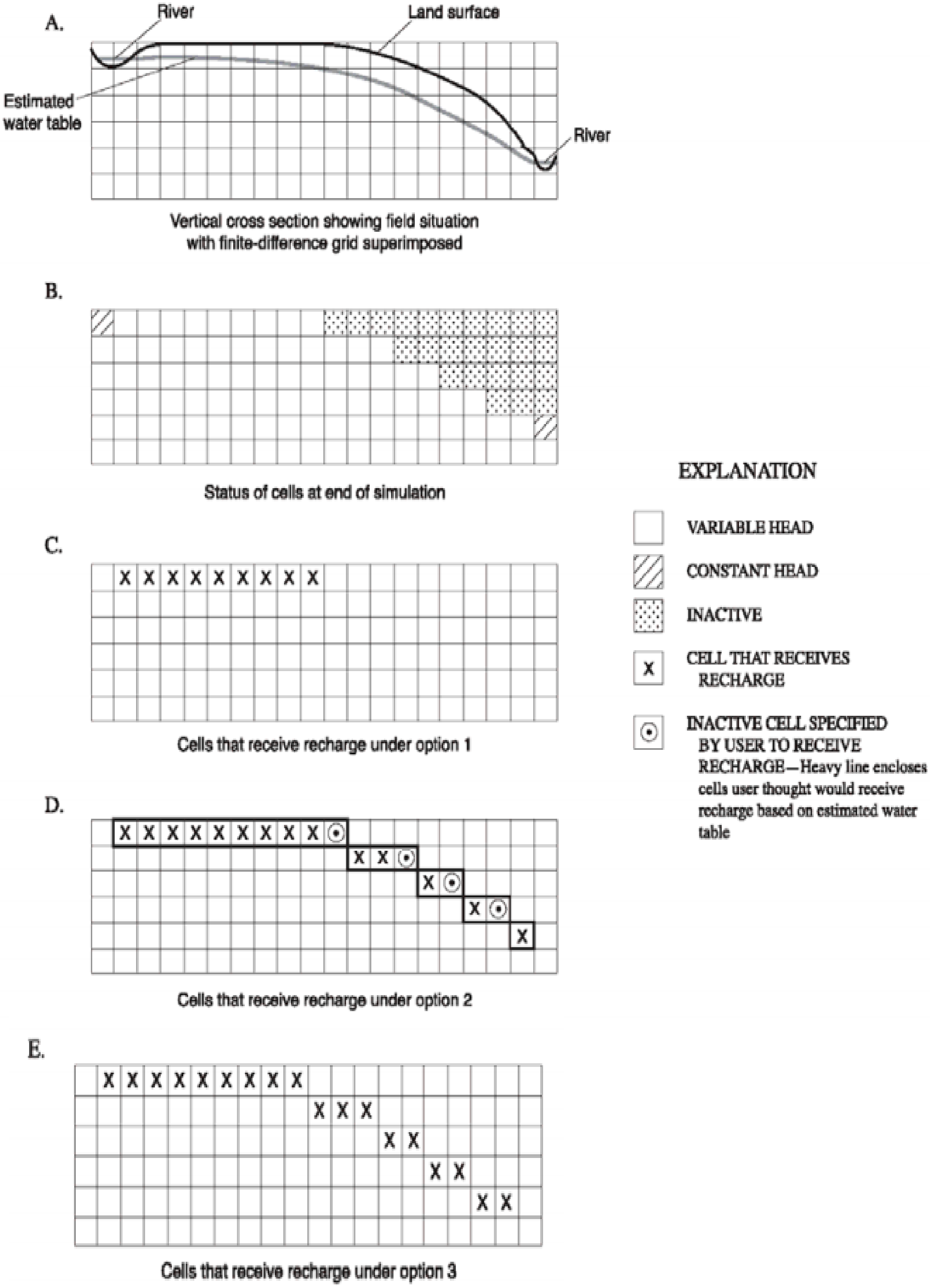


Figure 4.8 Different options in the recharge package, showing which cells receive infiltration under each option. (McDonald and Harbaugh 1988)

Well Package

Wells were included in the model. For each well a pumping rate has been assigned, which has a unit of m^3 d^{-1}. The well package also has an option to include the top elevation of the screen level and bottom elevation of the screen level, to indicate at which depth the water is abstracted.

Drain Package

To simulate the springs in the area the drain package has been used. As long as the water table is above the elevation of the drain, water flows out of the spring (Figure 4.9 and Figure 4.10). The higher the elevation differences between the water table and the elevation of the drain, the larger the outflow. This relation between outflow and elevation is affected by the conductance (m^2 d^{-1}) of the fill material surrounding the drain. If the water table would drop below the elevation, the drain has no effect.

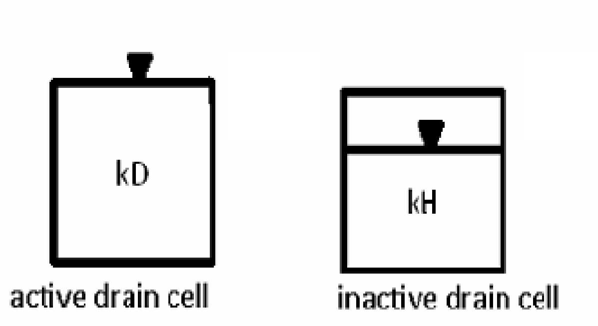


Figure 4.9 Drain cells representing springs.

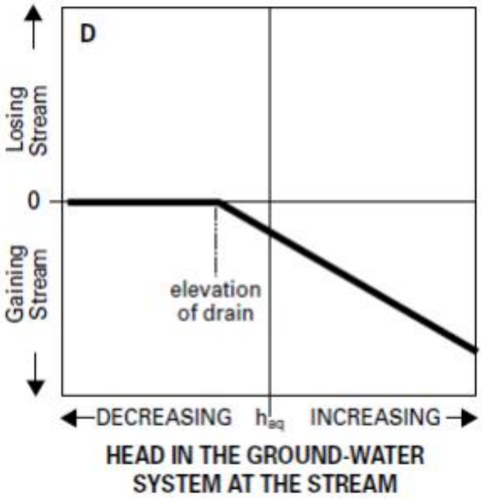


Figure 4.10 Flux-head relation of drains in Modflow

River Package

The river package has been used to simulate all the streams in the area. Figure 4.11 shows the flux-head relation of rivers. Streams can be losing depending on the elevation of the river bottom. River parameters include the bottom elevation, stage and conductance (m^2 d^{-1}) which can be assigned per river segment. The flow between the groundwater and stream water is given by the equation 45:

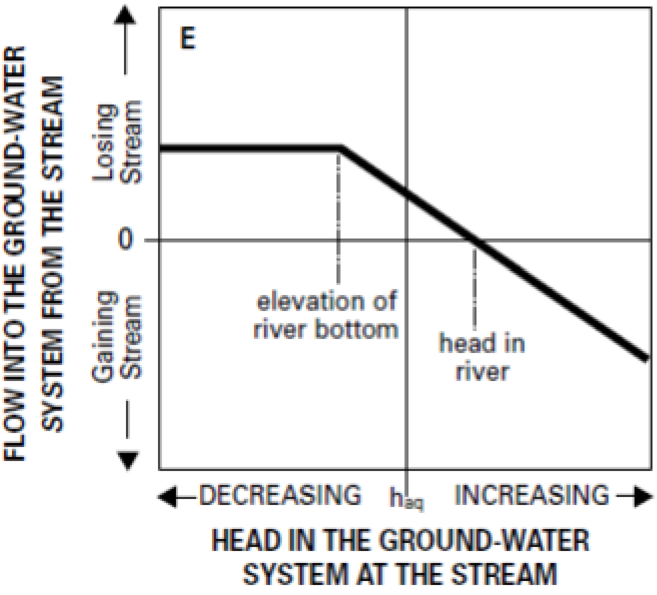


Figure 4.11 Flux-head relation of rivers in Modflow

$$Q_{riv} = c_r(H_{riv} - h_{i,j,k}) \quad (45)$$

where Q_{riv} is the flow between the stream and groundwater (m^3 d^{-1}), H_{riv} is the head in the stream (m), $h_{i,j,k}$ is the head at the node underlying the stream (m), and c_r the hydraulic conductance (m^2 d^{-1}) of the stream-aquifer interconnection (Figure 4.12) which can be calculated as in equation 46:

$$c_r = \frac{kLW}{M} \quad (46)$$

where k is the hydraulic conductivity of the streambed, L is the length of the stream, W the stream width (m), and M the thickness of the streambed layer (m). Equation 29 shows that the interaction between the groundwater and surface water is only present at the bottom of the stream and assumes the walls of the streams are impermeable. This is conceptualized by Figure 4.13.

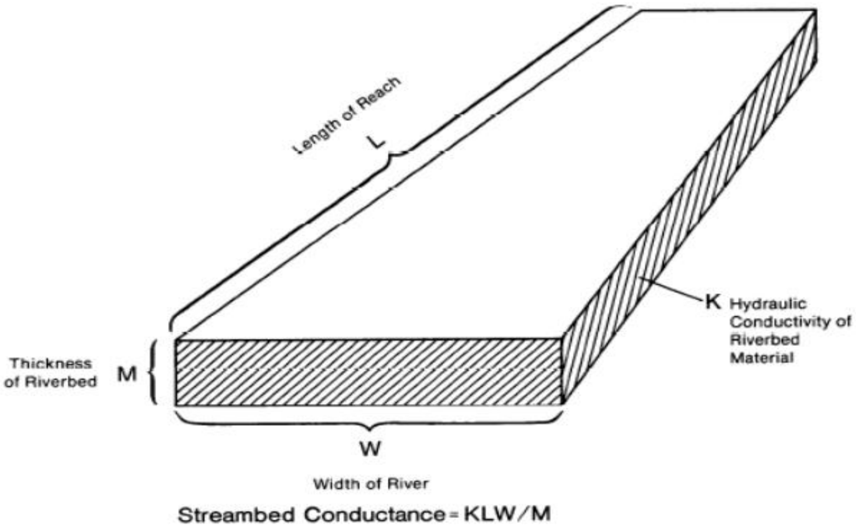


Figure 4.12 Streambed conductance as used in the river package

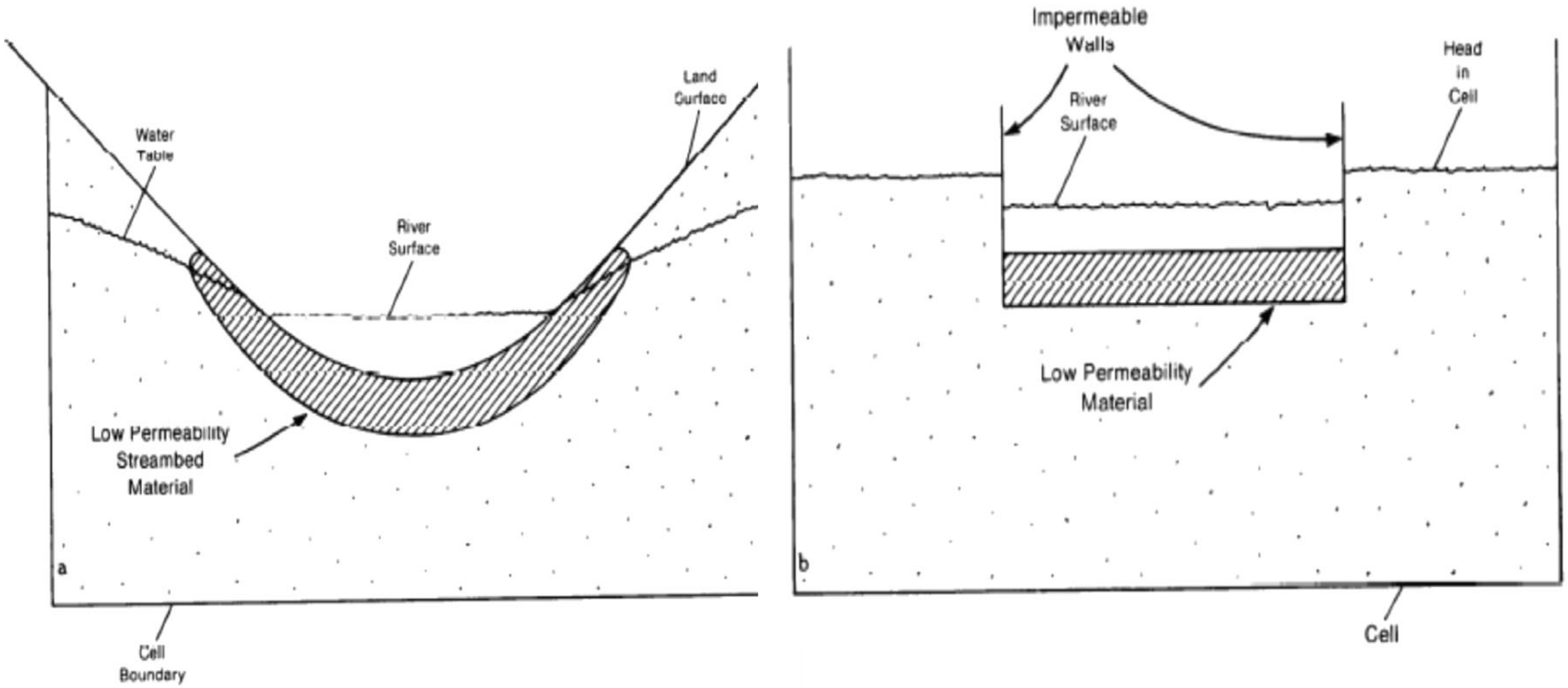


Figure 4.13 The real-life situation in a) where groundwater and stream flow also interact from the sides, is simplified to interaction only from the bottom and the stream walls are assumed to be impermeable, in b).

5. Field setup

The isotopic sampling was done to test the first hypothesis (§1.2), to indicate whether aquifer recharge occurs from the Moscow Mountain through the SOB into the aquifer. This is indicated by arrow 3 in Figure 2.25. The isotopic sampling was combined with temperature and EC measurements (§3.4 and §3.5). The caffeine sampling has been used to test the second hypothesis (§1.2), to indicate whether the Paradise Creek which runs directly over the basalt west from Moscow is losing water. This is indicated by arrow 2 in Figure 2.25. Caffeine can only be used in this part of the Moscow sub-basin, since it is downstream of many human activity which is related to caffeine concentrations in water (§3.2). Also discharge in the creeks around Moscow has been measured to find whether streams are losing or gaining water.

5.1 Isotopic Sampling

Within the Palouse Basin δ^{18}O and δ^{2}H has been measured on groundwater samples as a mean to distinguish unique pools of water (Larson 2000). In general, the water in the Grande Ronde aquifer has a more depleted isotopic signature than the water in the Wanapum and shallow loess aquifers. Carey (2011) collected samples from multiple wells through the city of Moscow and the rural regions north of Moscow and showed highly variable δ^{18}O and δ^{2}H values throughout the sample region. However, no measurements were repeated and surface water samples were not collected. This limits the ability to identify specific hydrologic connections to surface water. Moxley (2012) investigated the temporal variability in isotopic signatures between surface water and ground water in the South Fork of the Palouse River downstream of Pullman. With this approach, seasonal variability in stream, precipitation and groundwater isotopic signatures were observed. However, not all precipitation events were collected and the used sample frequency limited the determination of mean transient times between the surface water and ground water. Both Moxley (2012) and Carey (2011) emphasised the need for high frequency sampling to better understand the hydrologic connections between surface water and ground water.

Over the last two years long term precipitation and surface water isotopic data have been collected from the Crumarine Creek watershed as part of a Joint Venture Agreement between the University of Idaho and the USDA-FS Rocky Mountain Research Station (Sánchez-Murillo et al., unpublished data, Figure 5.1 and Figure 5.2). The δ^{18}O concentrations ranged from -27.68 to -7.01 ‰ with an average of -15.17 ‰ in precipitation and -15.53 to -14.53 ‰ with an average of -15.08 ‰ in the Crumarine Creek. According to Sánchez-Murillo et al. (unpublished data, 2013) a strong correlation exists between the ^{18}O signature, EC of the Crumarine Creek and precipitation (Figure 5.2). This correlation shows that the ^{18}O increases during summer and fall, and decreases during winter with the onset of snowmelt in early December. Figure 5.2 shows the response of measured ^{18}O and EC to the snowmelt peak in the winter of 2012. This snowmelt peak was traced back in the ^{18}O signature and EC of the streams, indicated by the low in the graph of Figure 5.2. Preliminary convolution modelling for the Crumarine Creek watershed indicate a mean transit time of 8.3 ± 0.2 months (Sánchez-Murillo et al., unpublished data).

De Graaf (2011) has measured the temperature and EC for springs in the Paradise Creek watershed in the period of March-May 2010. She found little fluctuations in the EC for several springs and concluded the springs were fed by deeper groundwater with long flow paths.

These data show the possibility of using the isotope signal and EC as a tracer in the Moscow sub-basin. For shallow groundwater systems the mean transit time can be in the order of months whereas for deeper larger groundwater systems this lag could be in the order of years.

In this study the isotopic sampling was done in the north-east of Moscow and covered several geological units, which are described in chapter 2. Two springs and 21 wells were measured once every two weeks and one deeper well once every four weeks. These wells are described in Appendix I&V. The sampling was done from 22-05-2013 and continues until May 2015. In this study the first 9 months of results are presented from the sampling until 02-01-2014. These wells and springs were selected during a larger preliminary sampling campaign in the area, which covered 49 wells and 3 springs (Figure 5.4). This sampling campaign occurred from 17-04-2013 until 22-05-2013, in which the wells and springs have been sampled 2-3 times to see whether fluctuations in the isotopic signal would occur over a time-period of 2-4 weeks. Sanchez-Murillo (unpublished data, 2013) has measured event-based ^{18}O and ^{2}H in precipitation (N=203) and streamflow in Crumarine Creek (N=244) and the South Fork of the Palouse River (N=195) since June 2011. This record provides the isotopic baseline necessary to investigate hydrologic connections to groundwater similar to the approach of Moxley (2012).

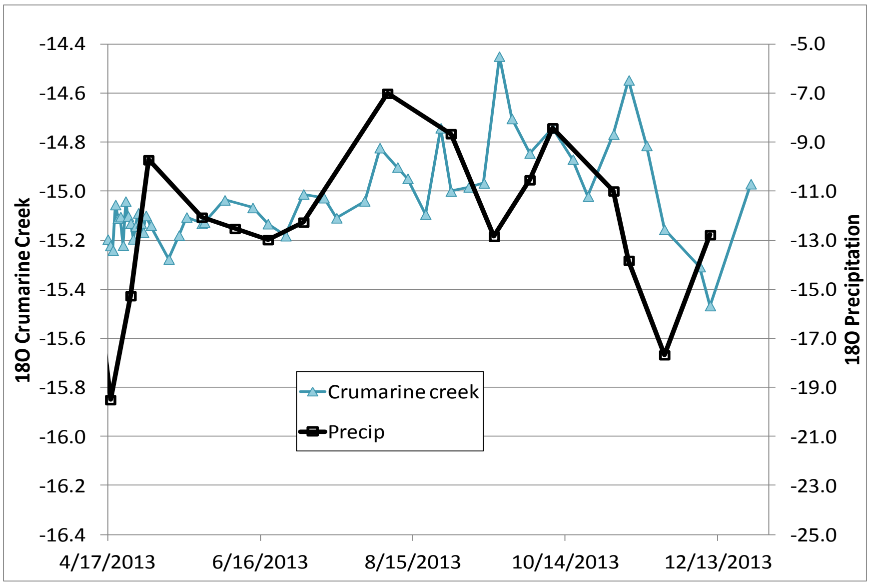


Figure 5.1 ^{18}O results for precipitation and Crumarine Creek samples (unpublished data from Sánchez-Murillo). Crumarine Creek seems to respond to the ^{18}O precipitation signature.

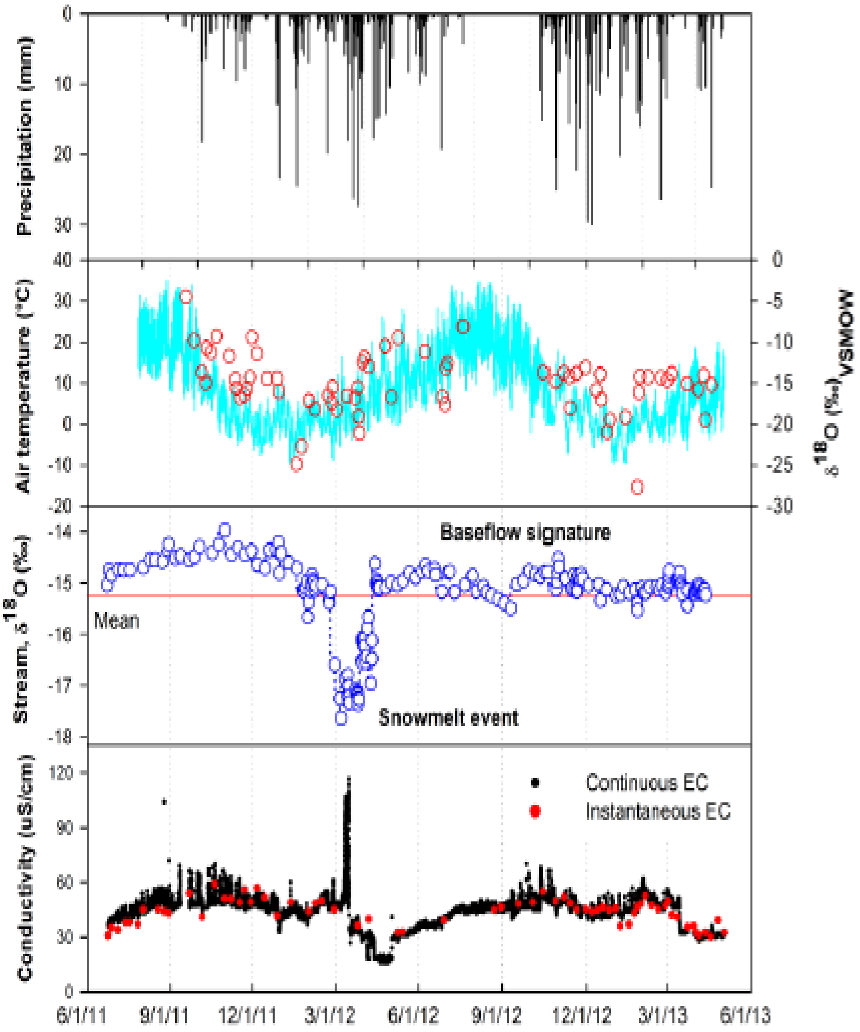


Figure 5.2 Monitoring of the Crumarine Creek and weather, including precipitation, ^{18}O (stream and precipitation), and electrical conductivity (EC).

5.1.1 Well selections

A selection from the preliminary sampling was made based on the following criteria, in chronological order of importance:

- Permission was needed from the well-owner for a 2-year sampling campaign of his/her well or spring.

Permission was asked by stopping by at all the well/spring-addresses. The owners from the wells and springs which have been selected were informed by a letter (Appendix III). Accessibility of the well or a tap connected to the well should be good.

Some wells and taps were supplied with locks. To prevent from contacting the owner each time when a sample had to be taken, the wells with locks were excluded.

- Information of the well should be known.

All wells have a well-ID in the database of the Idaho Department of Water Resources (IDWR). This well-ID makes it possible to find information of the well from when the well was drilled. This information exists of well logs including well size and depth, geology, depth to water, water levels, flow rate at moment of drilling and construction method. The information is documented by a state-licensed well-driller. Most of the wells back to 1987 are included in this IDWR-database. Wells from 1997 or younger contain a well tag number, which makes the process of finding the information much shorter. However, many wells exists which are from before 1997 or 1987. These wells don't have any identification number. Other methods to find out what the well-ID is, was by asking the well-owners if they knew who the owner of the house was in the time of when the well was made. The names of those persons were also included in the database. However, the names of previous owners were not always known.

- The well should get its water only from one geological layer

Many wells get water from different geological layers. Since the flow-path of the water is of interest, well-water should only come from one geological layer. This information is found in the IDWR-database. It has been documented in which layers water was found by the driller. Also the construction of the well is documented. If the well is perforated at multiple locations at layers containing water, than the well was not further selected.

- Good coverage of the research area and geological units (Figure 5.5)

In the ideal situation in which all wells would be accessible and get their water from only one layer, this is the most important criterion. Wells should cover all together the crystalline rock, Latah Formation and the Wanapum Formation at the north-eastern part of Moscow. The SOB and Palouse Formation are hard to distinguish from each other in well logs. In the east of Moscow the SOB have their maximum thickness and the Palouse Formation has its minimum thickness, so expected is that the main part of the sediments are part of the Latah Formation.

- Good coverage of different $\delta^{18}O$ and $\delta^{2}H$ concentrations of the well/spring and different sizes of fluctuations, in the preliminary sampling period.

The δ^{18}O and δ^{2}H values from the wells and springs should cover different concentrations. Enriched water is often related to younger water and depleted water to older water (Carey 2011). Higher values for δ^{18}O in groundwater could mean recharge occurs fast. However, too high values for δ^{18}O could also indicate evaporation occurred, which sometimes happens in very shallow (>4m) wells or wells with aerated storage systems. These wells were excluded. Low values for δ^{18}O could indicate recharge occurs slowly. These wells were also selected since fluctuations of the δ^{18}O could still indicate recharge occurs.

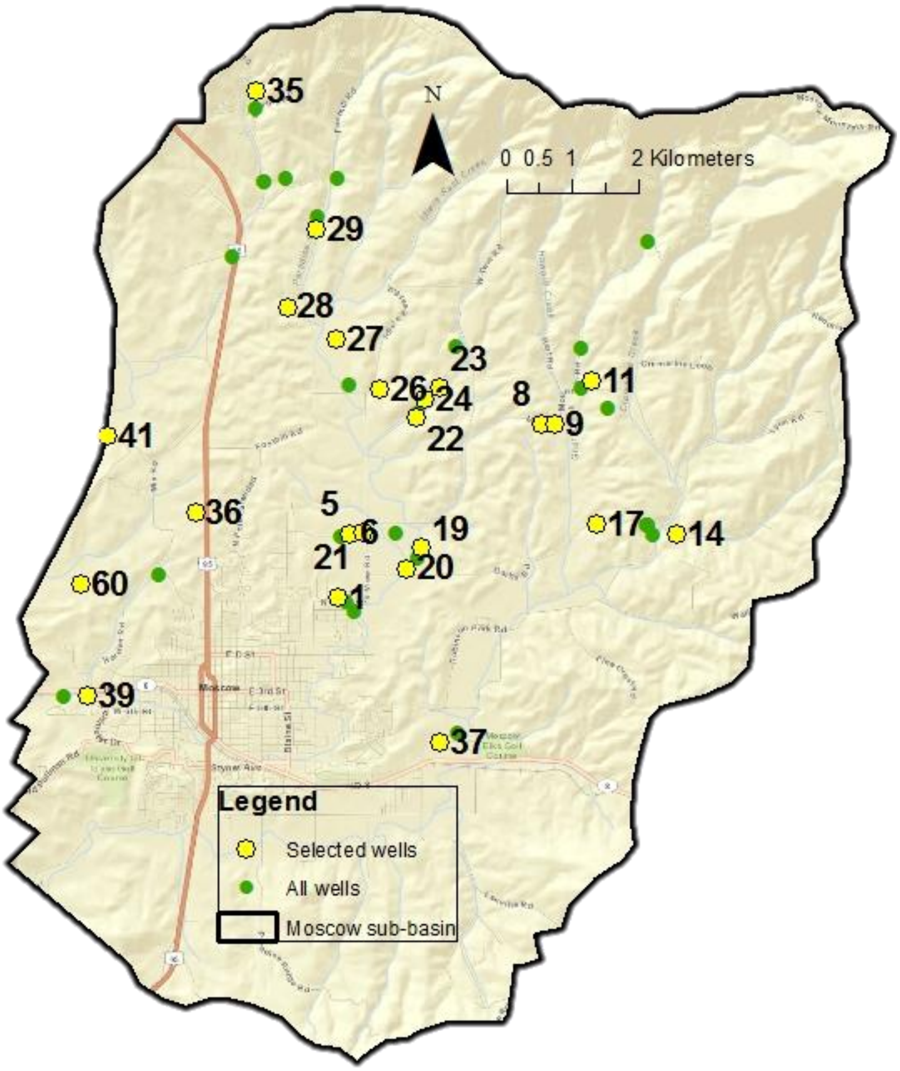


Figure 5.4 Overview of all wells of the preliminary sampling and selected wells

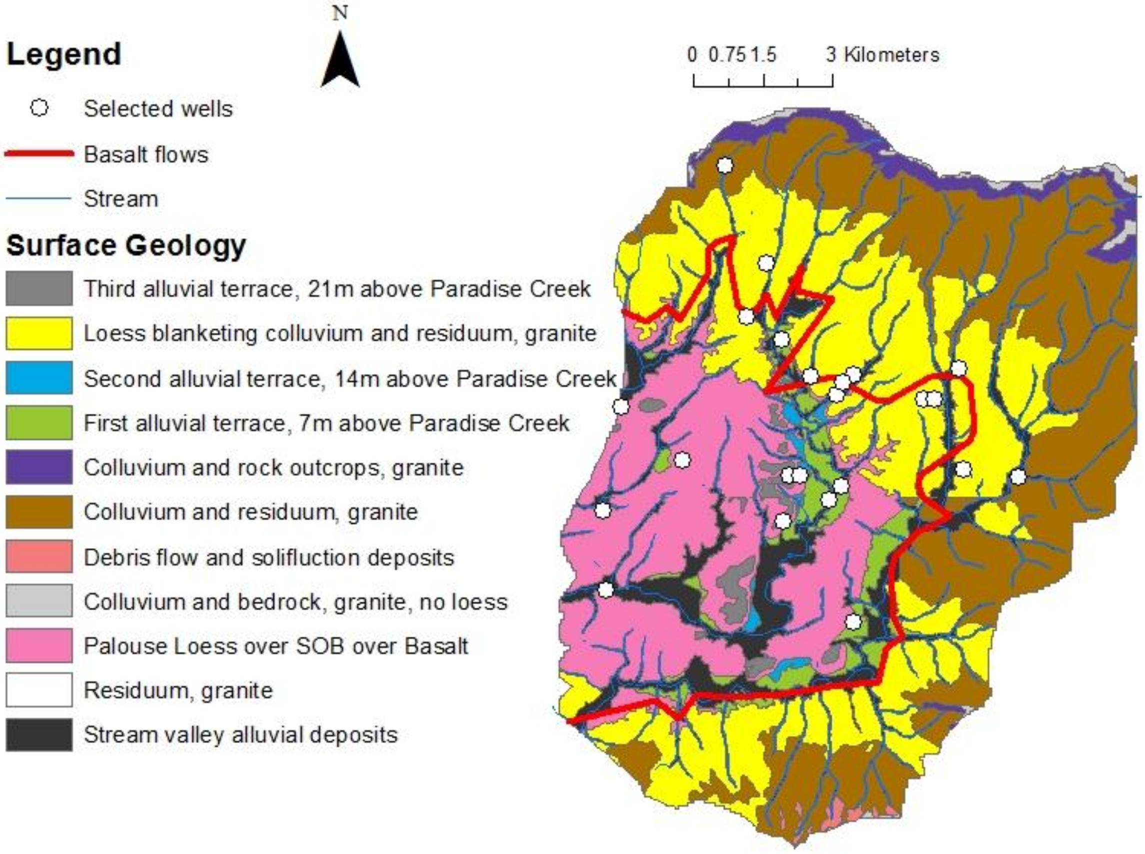


Figure 5.5 ^{18}O sample locations within the Moscow sub-basin over the surficial geology map

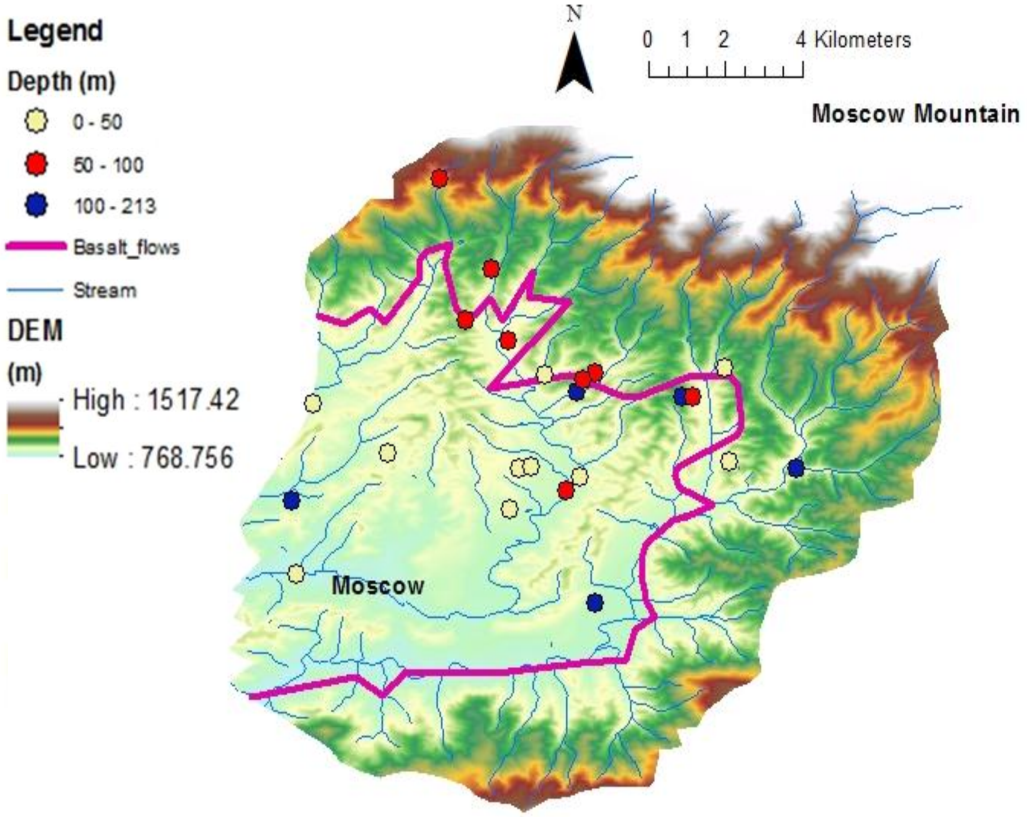


Figure 5.6 Depth of the ^{18}O sampled wells, overlaid over the Digital Elevation Map and the roads layer

5.1.2 Sampling procedure

Once every two weeks the wells and springs were sampled, except IDWR 3 (#60) which has been sampled once a month (Figure 5.4 and Appendix I). One sampling session would happen within the same day. Sampling was done from either the well itself with a bailer or from a tap outside the house which has a straight connection with the well and would not go through a filter (Figure 5.7). To prevent from getting water which had been sitting for a while in the pipelines, the water would flow for several minutes. Water stored in the pipelines near the surface is warmer than groundwater in summer, and colder in winter. By measuring the temperature of the outflowing water it was checked if the temperature would stabilize. If the temperature would not change any further a sample was taken, and the temperature, EC and pH were measured.

Figure 5.7 Well sampling

In spring #19 a small PVC pipe was installed to sample the spring before it would evaporate during overland flow. The sampling was done by using a hand-pump. The PVC pipe was covered with a cap to prevent precipitation falling in. Spring #6 was sampled from the hose which was attached to the spring.

Samples were taken in 4 ml clear glass bottles with a plastic cap, capped tightly, with no head space, sealed with parafilm. The samples were stored upside down in a fridge at 4°C. This process ensured that no air bubble remained that would allow gas exchange within the sample.

5.1.3 Analysis

The samples were analysed with a Picarro® L1102-i isotopic water liquid analyser by wavelength-scanned cavity ringdown spectroscopy (WS-CRDS) to measure the $\delta^{18}O$ and $\delta^{2}H$ of the samples (Figure 5.8). These were run by the Idaho Stable Isotopes Laboratory in the College of Natural Resources at the University of Idaho. Samples are inserted into a 2 mL glass vial and loaded into the machine's auto-sampler. Samples were analysed six times to take out the memory effects. The average was taken from the last 4 or 5 measured samples. Samples containing sediments were filtered beforehand.

Figure 5.8 The Picarro® L1102-I isotopic water liquid analyser

Two different internal standards were used to normalize the data. Another three standards were used to calibrate the data and to check the calibration. These standards contained tropical water, glacier water and regular water. Standards were included in the sampling-set and analysed after every 17 samples. Both the $\delta^{18}O$ and $\delta^{2}H$ were reported relative to the VSMOW in ‰ with an accuracy of <0.1 ‰ and <0.5 ‰ respectively.

5.2 Caffeine sampling

Wells have been sampled for caffeine as a chemical tracer to identify connection between surface water and groundwater in Paradise creek. All sampling has been done at 09-07-13 and 10-07-13 after a dry week. All water samples have been analysed by the Analytical Sciences Lab (ASL) on the University of Idaho campus. The minimum detection limit for caffeine at the ASL is 0.02 ppb. At these levels it is critical to carefully avoid contamination.

5.2.1 Sampling locations

Caffeine has been sampled in 12 wells around the Paradise Creek west of Moscow. These wells were selected based on similar requirements as for the isotopes sampling (§5.1.1): permission of the well-owner to sample, accessibility of the well or a tap connected to the well should be good, information of the well should be known, the location of the well should be around the Paradise Creek and the wells should vary in depth. Because wells were located in Washington State, well information was available from the database of the Department of Ecology from the State of Washington.

Also the effluent of the WWTP was sampled, as well as upstream of Moscow from the Paradise Creek and 100 m downstream of the WWTP-effluent. Additionally three blanks were sampled. See Figure 5.9, Figure 5.10 and Appendix II&VI for the sample locations and properties. All well-owners were informed with a letter including the results (Appendix IV).

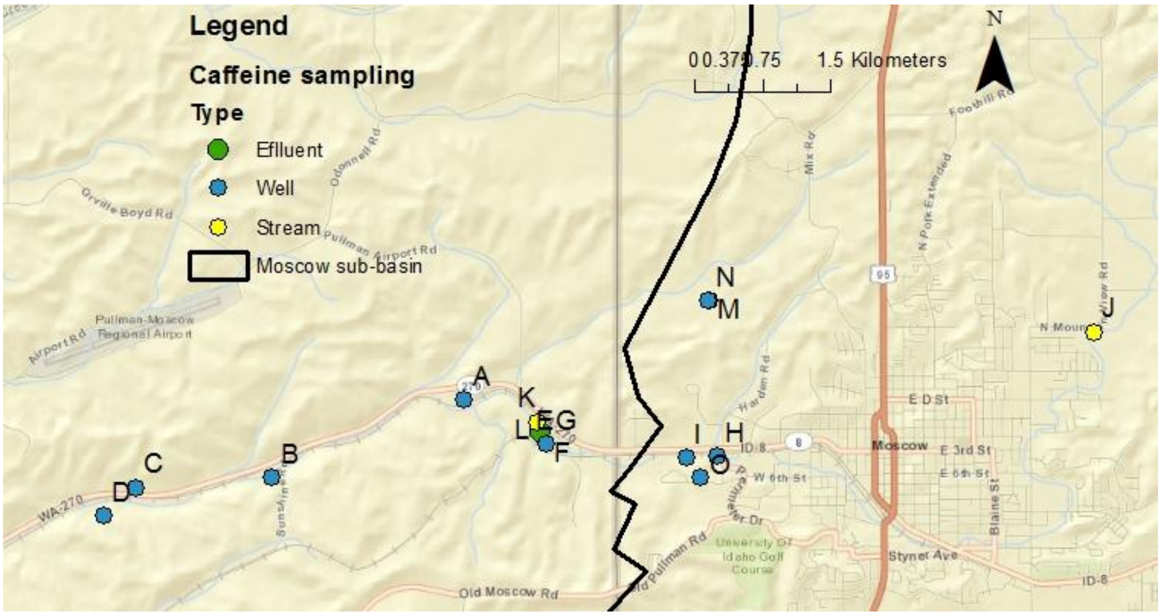


Figure 5.9 showing all sample locations for caffeine in Moscow. Labels correspond to the sampling labels (Appendix VI). The west border of the Moscow sub-basin is included in the figure.

5.2.2 Sampling procedure

The standard protocol is to provide ASL with a 1 L water sample filtered using a 0.7 micron or finer filter. All samples have been delivered to the lab in 1 Liter amber glass bottles (Zaugg et al. 2002). All samples have been sent to the ASL using new amber bottles which have been certified 'Contaminant-free' by the EPA (Cat No: 05-719-91 Fisher-Scientific). Bottles remained closed from the manufacturer until the time of collection. All samples were pre-filtered using Thermo Scientific Nalgene* Rapid-Flow* Sterile Disposable Filter Units with PES Membrane. All the filter units were checked to confirm that the packaging from the manufacturer is air tight before opening the unit. Water samples which could not be sampled directly into the preserved amber bottles (e.g. stream samples and monitoring wells) were collected using 1.5" x 36", weighted, Polyethylene Disposable Bailers (Enviro-Tech). Bailers were not reused or shared between sites. Three blank samples were analysed to test for contamination during data collection. For the blank water which has been certified to be free of caffeine has been used from the ASL. The blanks were carried out to two data collection sites, opened and poured over and/or sampled directly using the disposable bailer before being contained into a new 1 L amber bottle. The blanks were filtered through the disposable filter units following the same procedure as all water samples. All samples were stored at 4˚C and transferred from the field to lab in iced coolers. Water samples were collected both from surface water, effluent from the WWTP, and from wells located both upstream and downstream of the discharge point. These points are described below.

Additionally isotope samples (§5.1.2), temperature and EC has been measured. For wells which were measured with a disposable bailer, the water depth from surface level was measured.

Figure 5.10 Caffeine sampling. Left) the water was filtered in the field; right) a sample was taken from the WWTP effluent with a bailer

5.3 Discharge measurements

Measurements have been repeated over distances up to 1500 meters. Measurements were all done within a period of five hours, to prevent time-effect differences. Locations which have been chosen are the Paradise Creek west of Moscow, Paradise Creek northeast of Moscow and South Fork of Palouse River east of Moscow downstream of the WWTP (Figure 5.11). The discharge of the WWTP-effluent is depending on the water use in Moscow. However, within the time span of five hours these variations can be neglected (Moxley 2012; pers.comm. Kyle Steel 2013). The Paradise Creek runs straight over the basalt west of Moscow. If streams are losing water here, they will recharge the Wanapum. The Paradise Creek northeast of Moscow and the SFPR east of Moscow are running over SOB. If streams are losing water here the water might recharge the basalt by following preferential flow paths like paleo-channels. Measurements have been done at 3-6-13 for the Paradise Creek northeast of Moscow, 17-6-13 for the SFPR and 15-6-13 and 30-6-13 for the Paradise Creek west of Moscow. These last dates are both in the weekend, so the local industry would not affect the discharge in the streams. Additionally, the temperature and EC have been measured at each location.

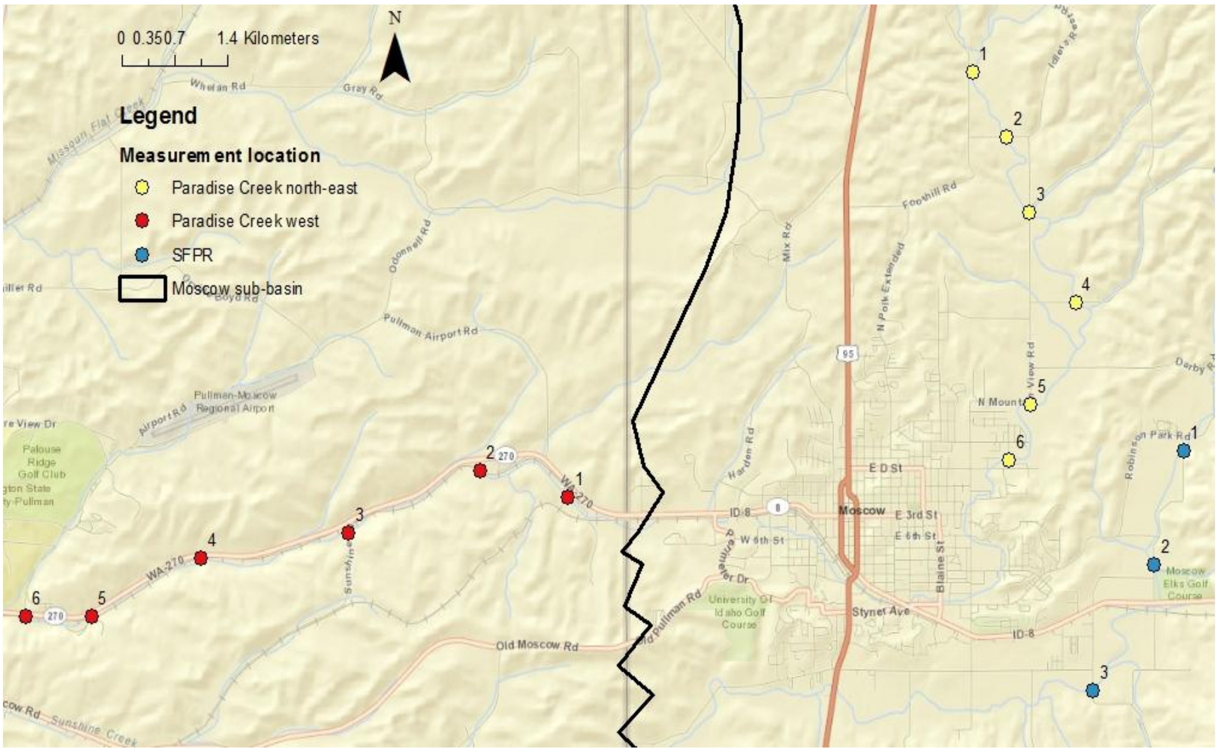


Figure 5.11 showing all sample locations for the discharge measurements. The west boundary of the Moscow sub-basin is included in the figure

6. Model Setup

The use of tracers can be suitable for indicating recharge zones and connections between two water bodies. However, the tracers used in this study are not suitable for quantifying the water fluxes. For this reason, a groundwater model was used.

Several attempts were made in the past to model the Palouse Basin (Barker 1979; Lum et al 1990; Vaccarro 1999; Petie 2007; Woelders 2009; De Graaf 2011, Dijksma et al. 2011). Except from De Graaf (2011) and Dijksma et al. (2011), they all focused on the whole Palouse Basin, which resulted in relatively large grid cells (1x1 km) and thus oversimplification. De Graaf (2011) and Dijksma et al. (2011) were focusing more on the groundwater flow and recharge on a smaller scale of the Paradise Creek watershed. Their scale of interest was the paleo-channel scale, and they concluded paleo-channels play an important role in the aquifer recharge in the Paradise Creek watershed.

In this study the groundwater simulation focused on a larger extent of the Moscow sub-basin, of which the geology, land use, soil-types, climate and hydrological properties are similar to the Paradise Creek watershed. Also unique is the combination of the SMR-model with Modflow. The infiltration calculated by SMR is used as input for the Modflow model (Figure 6.1). This combination makes the groundwater simulation to include both the soil properties as well as the hydrogeological properties. The aim of the groundwater modelling is to identify the aquifer recharge zones and estimate quantities of aquifer recharge. The resolution of these models is too low to include the paleo-channels, so paleo-channels have not been included in these models. However, the indicated aquifer recharge zones might reflect the zones where paleo-channels are present.

The modelling methods have been explained in chapter 4. In this chapter the model setup is described.

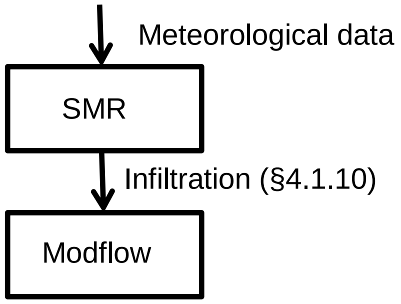


Figure 6.1 Concept of the use of the models in this study. SMR infiltration is used as input for the Modflow model.

6.1 SMR

6.1.1 Flow domain

SMR has been applied to the Moscow sub-basin (Figure 6.2). This area has a size of 150 km^2. The SMR model is based on the SMR model for the Paradise Creek watershed by Dijksma et al. (2011). The flow domain of the Moscow sub-basin is approximately 3 times the size of the Paradise Creek Watershed.

Only the first hypothesis (§1.2) has been tested with the groundwater model. The second hypothesis (§1.2) is located in Washington State, and the required data was mostly only available for the Idaho part of the Moscow sub-basin. For this reason, the models focus on the aquifer recharge from the Moscow Mountain (arrow 3 in Figure 2.25).

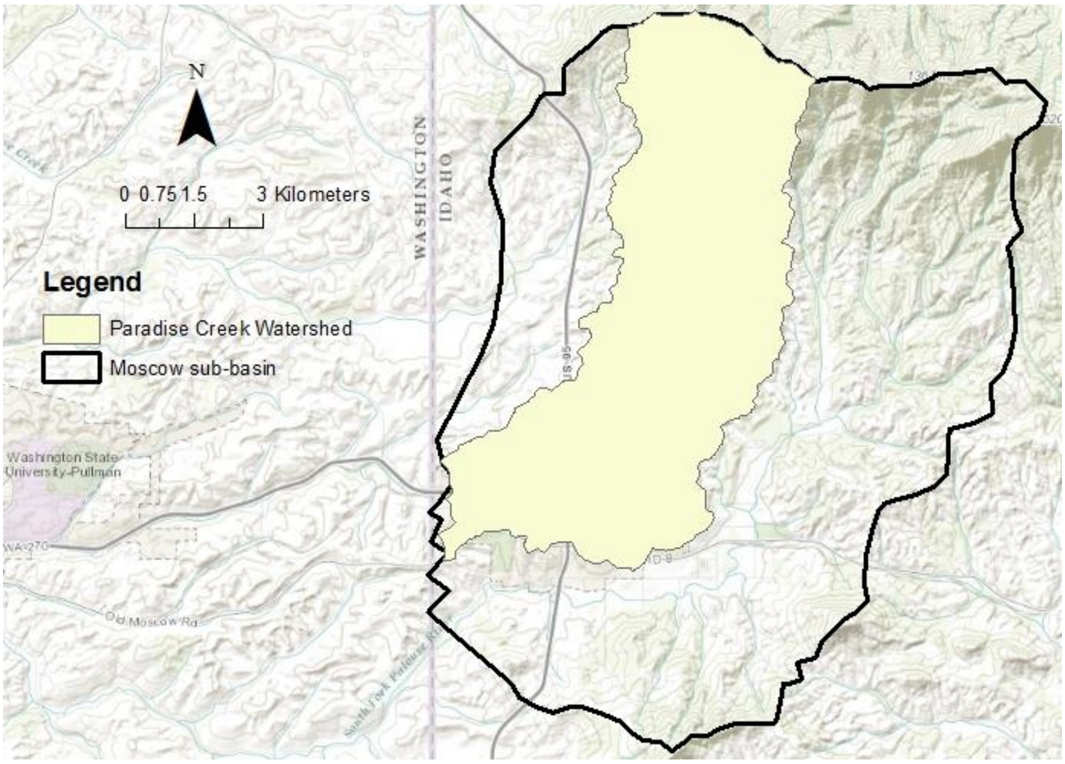


Figure 6.2 Flow domain of the SMR model. The SMR model is based on the SMR model for the Paradise Creek watershed by Dijksma et al. (2011). The flow domain of the Moscow sub-basin is approximately 3 times the size of the Paradise Creek Watershed.

6.1.2 Discretization

In this study the grid has been taken as one layer. The cell-size was taken 30x30m, which is similar to the resolution of the input files. The model was calculated quasi-steady state (equation 9). The chosen time-step was 6 hours with stress-periods of days, over the period of 2001-2008. A similar discretization and period was used by Dijksma et al. (2011) who also focused on aquifer recharge. As input for the Modflow model the total infiltration has been averaged to daily averages over the whole simulation period. All cells were given an initial storage amount of 50% of the saturation amount, which depends on the soil type. This is similar to the Paradise Creek model by Dijksma et al. (2011).

6.1.3 Schematization

SMR needs the input as described in §4.1.3. The soil properties are taken from the soil survey (Barker 1981) and from the calibrated SMR-model used in Dijksma et al. (2011) for the Paradise Creek watershed. The land use consists of five categories: forest, tilled field, grass field, residential and urban. The elevation map is used by SMR to derive the slope and flow direction. Daily temperature, precipitation and ET_{pot} lapse rates were linearly interpolated with elevation using the Moscow Mountain Snotel and Plant Science Farm weather stations. This linear relation with elevation is in line with the climate characteristics of the area (§2.4)

(Frankenberger et al. 1999). The derivation of the ET_{pot} is estimated by using the Hargreaves equation, explained in §2.4.4.1. The input maps were converted into 30x30m grids, covering the total area of the Moscow sub-basin within the defined boundaries (Figure 6.2). Daily weather data from the period of 2001-2008 was used from the Moscow SNOTEL and University of Idaho (§2.4.2). Parameters were used from the calibrated model used by Dijksma et al. (2011) for the Paradise Creek watershed, which covers 1/3 of the Moscow sub-basin.

6.1.4 Calibration

The model has been calibrated for the Paradise Creek watershed area by Dijksma et al. (2011), by using streamflow observations. This calibrated model has been used for the entire Moscow sub-basin. Figure 6.3 shows the simulated and observed streamflow at the outlet of the Paradise Creek watershed over the period 2001-2008. The Nash-Sutcliffe efficiency (NSE) (Nash and Suthcliffe 1970) was 0.57 for the entire Paradise Creek watershed, which is a “good” result according to the qualitative assessment of NSE by Foglia et al. (2009). If the NSE is 1, the agreement is perfect between simulated and observed values. If the NSE is lower than 0.2, the model is insufficient. A good modelled streamflow does not necessarily mean the percolation has been accurately modelled. Infiltration could for example be underestimated when ET_{act} has been overestimated. This counterbalance between ET_{act} and infiltration could still result in an accurately modelled streamflow (Dijksma et al. 2011). However, a detailed study of Brooks et al. (2007) who compared SMR-simulated and observed perched water-table depths recorded every 12 h over a 3-year period at over 100 shallow well locations in a 2-ha catchment showed “very good” model agreement. More information about the SMR modelling results can be found in Brooks et al. (2007) and Dijksma et al. (2011).

In this study, the subsurface lateral flow has been disregarded, since disagreement exists on the existence of subsurface lateral flow. SMR uses the land slope as hydraulic gradient, while these two are unrelated in the unsaturated zone (pers. comm. Bier and Dijksma, 2013). This means that all water flows vertically in the unsaturated zone. The moisture content increases in the cell when the water hits the restrictive layer, until the field capacity is reached. More water in the cell would finally result in surface runoff. Omitting the lateral flow in SMR did not result in a difference in the averaged percolation value over the 8 years, since subsurface lateral flow only occurs after high precipitation peaks.

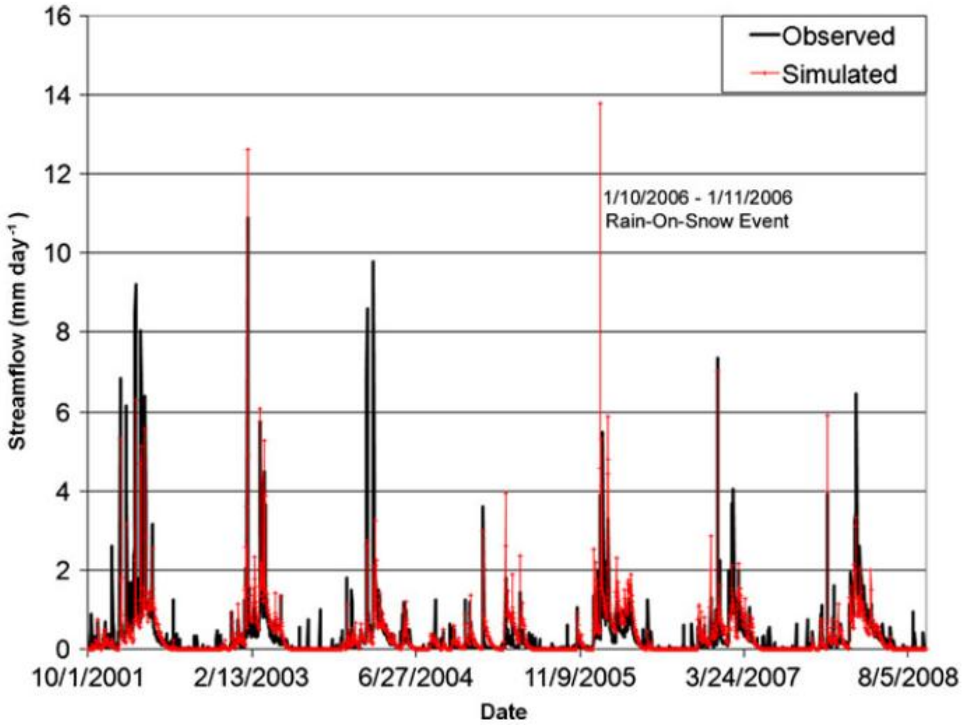


Figure 6.3 Simulated and observed daily streamflow (mm) at the outlet of the Paradise Creek watershed, over the study period (2001-2008) (Dijksma et al. 2011).

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6.1.5 Output

SMR is used to model the infiltration through the soil. The daily average infiltration over the 8 year period is used as input in the Modflow model (Figure 6.1).

6.2 Modflow

6.2.1 Flow domain and boundary conditions

The boundaries are based on the actual boundaries of the Moscow sub-basin defined by the water divide north, east and south of Moscow (§2.6.1) (Figure 6.4). These boundaries are assumed to be Neumann boundaries (no flux), since they consist of the topographical water divides. SMR has not been calculated for the Washington State because of unavailable data. Also the boreholes in the Washington State were documented differently than the boreholes in Idaho. To make the model larger than the Moscow sub-basin and include Pullman would require too much time by using the different well database of Washington State, and would also result in larger cell sizes, so the computer power would not be exceeded. For this reason the west boundary is located within Idaho.

The west boundary is derived from inverse distance weighting of the average groundwater levels of 16 present monitoring wells in the Wanapum Aquifer (Figure 6.4). Figure 6.5 shows an example of the monitored head in the Wanapum by one of the monitoring wells. These wells are located within the Moscow sub-basin. These wells were also used by Leek (2006) (Figure 2.20), but used for a smaller resolution and larger extent. The mean average groundwater level of the available data of each monitoring well was used, which covered the period of 2005-2009 for all wells. The maps of Leek (Figure 2.20) resulted in a similar groundwater isohypse pattern and were eventually used to check the west boundary. A Dirichlet boundary (fixed head) and Neumann boundary has been applied in the west of the model (Figure 6.4). Little monitoring was done on the Grande Ronde within the Moscow sub-basin. So it was assumed, based on Figure 2.20 that the Grande Ronde has a similar stream pattern as the Wanapum. The head for the Grande Ronde boundary has been calculated by using the head of 1990 (Figure 2.20), and subtracting 0.3 m for every year up till 2004. This groundwater decline rate is in line with the groundwater decline of the Grande Ronde (Figure 2.22).

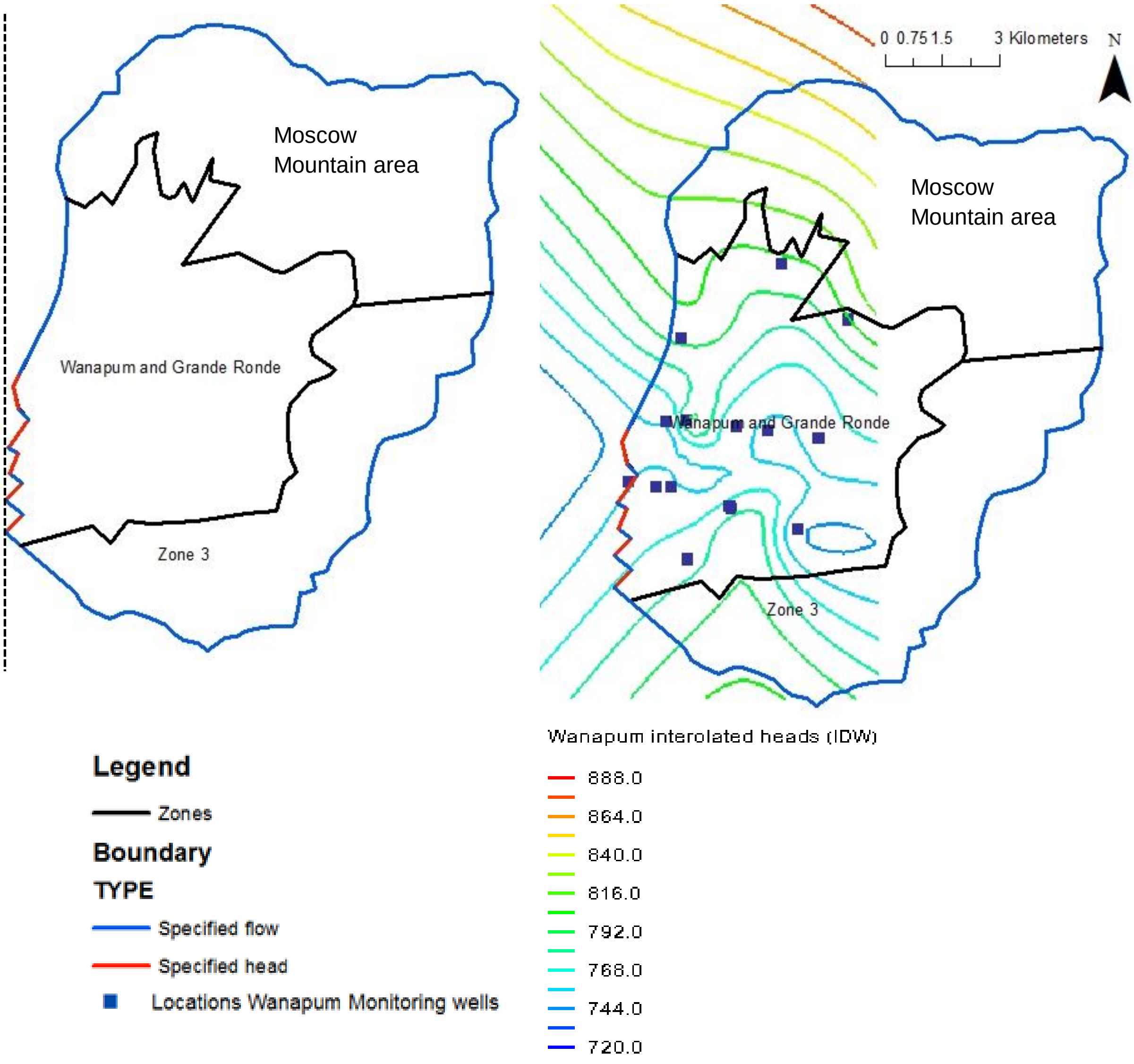

Figure 6.4 Left: Modflow flow domain, boundary types and defined zones. Zone 3 represents the granite/basalt interface southeast of Moscow. Dotted line is the Idaho-Washington State boundary. Right: Boundaries are based on interpolation (IDW) of 16 Wanapum IDWR monitoring wells located in the Moscow sub-basin. This figure shows the generated isohypse lines the west boundary is based on.

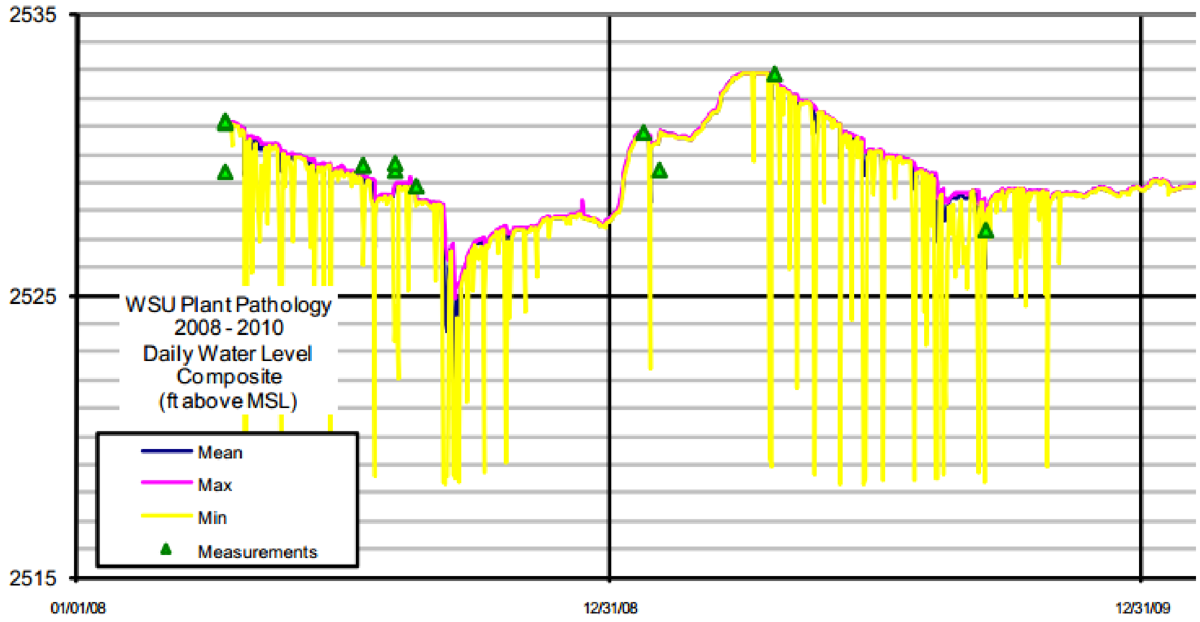

Figure 6.5 Example of the monitored head of the Wanapum aquifer by a monitoring well.

6.2.2 Discretization

6.2.2.1 Space

The total number of cells in the grid is 899760 cells, of which 592620 are active cells. These active cells are the cells within the boundaries of the model. Table 6.1 shows the grid properties, which include the active and non-active cells. Cell sizes are 100x100 m in the x,y -direction. The cell size in the z-direction varies within the model, depending on the surface elevation. These cell sizes make it impossible to study the effect of paleo-channels. However, they are small enough to identify active aquifer recharge zones.

Table 6.1 Grid properties

Dimension	**Number of Cells**	**Length (m)**
X	138	13800
Y	163	16300
Z	40	1000

6.2.2.2 Time

The model was calculated in a stationary time step, as well as in a transient. The stationary model has to give insight in where the aquifer recharge is coming from as well as the flux sizes. Also it is used as an estimation of the parameters. The transient model was used to simulate the groundwater level decline which has been observed over the last decades. The transient time step is one month over the period of 2001-2008. The first month (January 2001) has been calculated stationary. The period of 2001-2008 was repeated twice (called 2009-2016 and 2017-2025), to cover a longer time period.

6.2.2.3 Storage

The specific storage is used in the transient part of the model. The specific storage's physical meaning is described in equation 34. The definition of the specific storage is the amount of water which is released from a certain volume of the aquifer, by remaining fully saturated. The unit of the specific storage is 1/length. For the unsaturated part, the specific yield is used. The specific yield (-) is the volumetric fraction of the aquifer which can be drained out of the aquifer, also called the drainable porosity. However, for this model all layers were set to confined to improve model results (§4.2.3). Modflow assumes the specific yield to be zero, since all layers are confined. In reality the phreatic layers above the groundwater level will have a drainable porosity since the pores are not totally saturated. To correct for this, the specific storage for all cells above the groundwater level were assigned a value which would fit the unconfined properties. The specific storage (m^{-1}) for all cells above the groundwater level was taken as the specific yield (-) divided by the thickness (m), so $S_s = S_y/D$. This formula was applied to correct for the unit differences between specific storage and specific yield. All cells below the groundwater level were assigned a specific storage value which would fit the confined properties (Table 6.2). Which cells were above the groundwater level was derived from the output of the stationary model.

Table 6.2 Specific storage and specific yield used in the model

Hydrogeological Unit	Specific Storage (m^{-1})	Specific Yield (-)
1	0.00001	0.15
2	0.00001	0.15
3	0.00001	0.05
4	0.00001	0.015

The values in Table 6.2 are based on examined values found by Woelders (2009) in her model for the entire Palouse Basin. She based the values on Lum et al. (1990); Johnson and Frederick 2002; Domenico and Schwartz (1998) and Walton (1987).

6.2.3 Schematization

6.2.3.1 Layers

The Moscow sub-basin's geology has been simulated by using 207 boreholes. These boreholes are documented well logs, as described in §5.1.1. Only the boreholes of which the exact coordinates were known have been used. These 207 boreholes are representing the Moscow sub-basin's area of 150 km^2. Since the length of the boreholes varied, some boreholes have been extended in depth. Also 15 borehole copies were added. This was done to get a better coverage of the study area, since e.g. the Moscow Mountain did not contain many boreholes. These additions and extensions were done by using the available knowledge of the area, based on cross-sections of Bush (2005) and Grader (2011). Figure 6.6 shows the coverage of the boreholes in the Moscow sub-basin, as well as the boreholes that have been copied. Figure 6.7 shows the relative depth of the boreholes compared to the digital elevation map. The deepest borehole reaches an elevation of 300 m +amsl. The described borehole layers were simplified to decrease the large diversity of different layer types and to be able to create cross-sections between the different layers. This simplification means that all layers smaller than 2 meter thick were merged with larger thicker layers below or above.

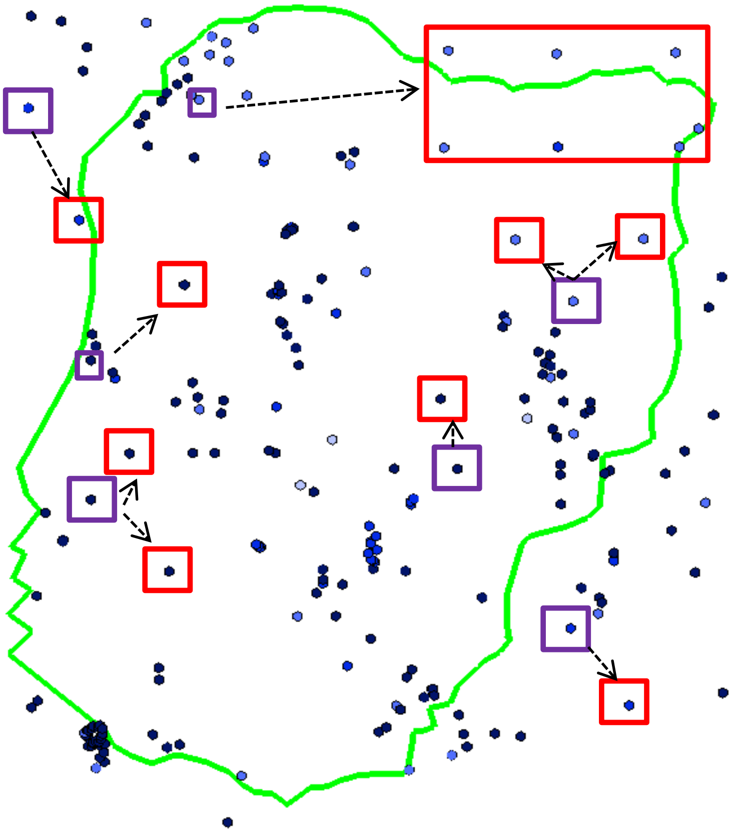

Figure 6.6 Boreholes used for the schematization of the Modflow model. Red squares surround the boreholes which have been copied from other boreholes, surrounded by purple squares. The arrows indicate which copies were made.

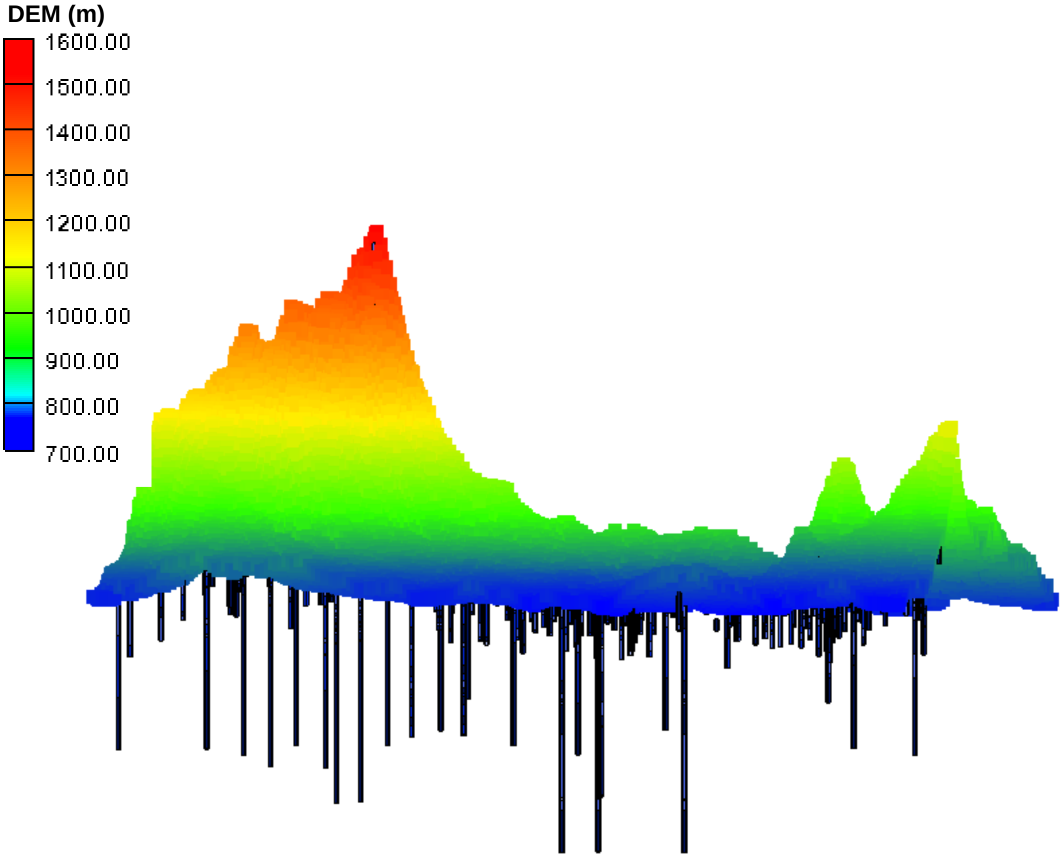

Figure 6.7 Digital Elevation Map (DEM) and boreholes seen from a southwestern angle. Deepest boreholes are up to 300 m +amsl

The borehole-layers were assigned over four different hydrogeological units, categorised by the hydraulic conductivity (Table 6.3 and Table 6.4). Which layer was assigned to which unit was based on hydraulic conductivities known from literature (Table 2.3 & Table 2.4) (Van Lanen and Dijksma 2012; De Graaff 2011; Lum 1990). In Table 2.3 no distinction was made between hard, medium or soft fractured basalt. However, these have been distinguished in this model. Table 6.5 and Figure 6.8 show an example of a borehole that has been subdivided in different hydrogeological units, based on Table 6.3.

Table 6.3 Layer types as described in the well logs, assigned to a hydrogeological unit.

Layer type	**Hydrogeological Unit (HGU)**
Coarse sand	1
Gravel/Sand	1
Soft/Decomposed Granite	2
Soft/Fractured Basalt	2
Cemented sand/silt	3
Medium Basalt	3
Medium Granite	3
Sandy Clay	3
Clay	4
Hard basalt	4
Hard Granite	4
Shale	4

Table 6.4 Hydraulic conductivity for each hydrogeological unit

HGU	**Hydraulic conductivity (m d^{-1})**
1	100
2	10
3	1
4	0.01 horizontal 0.001 vertical

Table 6.5 Example of borehole (Figure 6.8), of which the sediment/rock type have been assigned to a hydrogeological unit.

Elevation (m +amsl)	HGU	Sediment/Rock type
786.7	4	Clay
783.6	4	Hard basalt
778.1	2	Softfractured basalt
775.7	4	Hard basalt
722.0	3	Cemented sand/silt
712.0	4	Clay
697.0	1	Coarse Sand
691.6	2	Soft/Decomposed Granite
670.8	2	Soft/Decomposed Granite
660.8	2	Softfractured basalt
646.8	4	Clay
634.3	4	Hard basalt
605.3	4	Clay
590.1	2	Softfractured basalt
562.0	4	Hard basalt
543.4	2	Softfractured basalt
540.1	4	Clay
500.5	4	Hard basalt
408.1	2	Softfractured basalt
405.7	4	Clay
404.7	4	Clay

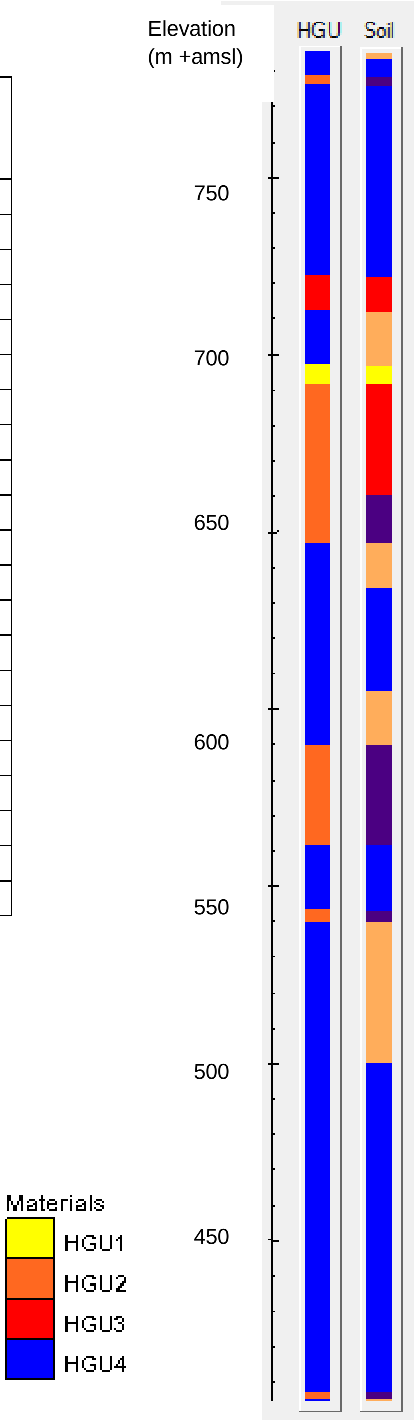

Figure 6.8 Borehole example of which the sediment/rock types are assigned to a HGU (Table 6.5).

Cross-sections were made from the boreholes and converted into solids using the DEM-map as top elevation. These cross-sections have been edited again by using the available knowledge of the area, based on cross-sections of Bush (2005) and Grader (2011). Figure 6.9 shows the cross-sections made for the Moscow sub-basin, and Figure 6.10 the solids that were made from these cross-sections.

Figure 6.11 shows a cross-section made from the solids.

A) At the Moscow Mountain many small layers of decomposed granite are present, as well as some sand layers, alternated with some hard granitic layers.
B) The SOB is present until a large depth, filling up a paleo-valley (described by Grader (unpublished report, 2011). Here the SOB consists of relatively permeable material. Small clay layers are present above the upfilled paleo-valley.
C) An outcrop of the crystalline basement rock is present in the Moscow sub-basin, which could be the boundary of the paleo-valley. This outcrop is also described by Grader (unpublished report, 2011).
D) Granite/basalt interface. The basalt is only present in small volumes at the interface, consisting mostly of fractured basalt (permeable). The basalt is underlain and overlain by sand and clay layers
E) A large unit of medium basalt from the Grande Ronde, with above a permeable layer present with relatively permeable fine sand.
F) Further away from the Moscow Mountain a smaller amount of interbeds are present. Here the Wanapum overlies the Grande Ronde, and is separated by relatively impermeable shale and sandstones.

These solids have been interpolated to a grid (Table 6.1) by grid overlay (Figure 6.12). Modflow interpolates the layers vertically by assigning the highest and lowest point in a specific column of cells, and interpolating the intermediate layers in between those two points. This results in different cell sizes in the vertical for each column, depending on the total thickness of the layers at that location. The material properties of the solid that encloses the cell center are assigned to the cell. This methodology has been used because it was the most practical one. The boundary matching method resulted in very thin, small layers present in the model, and the “grid overlay with K equivalent” made it impossible to easily change the K-values of the HGUs.

All cells in the first layer with the material properties of unit 4 were changed into unit 3. Since the infiltration has to infiltrate in Modflow, a too low hydraulic conductivity in the first layer would result in large unrealistic head gradients at the impermeable surface cells. However, the surface layer is often weathered and fractured, so it can be assumed that the hydraulic conductivity is also higher for these materials when they are exposed at the surface.

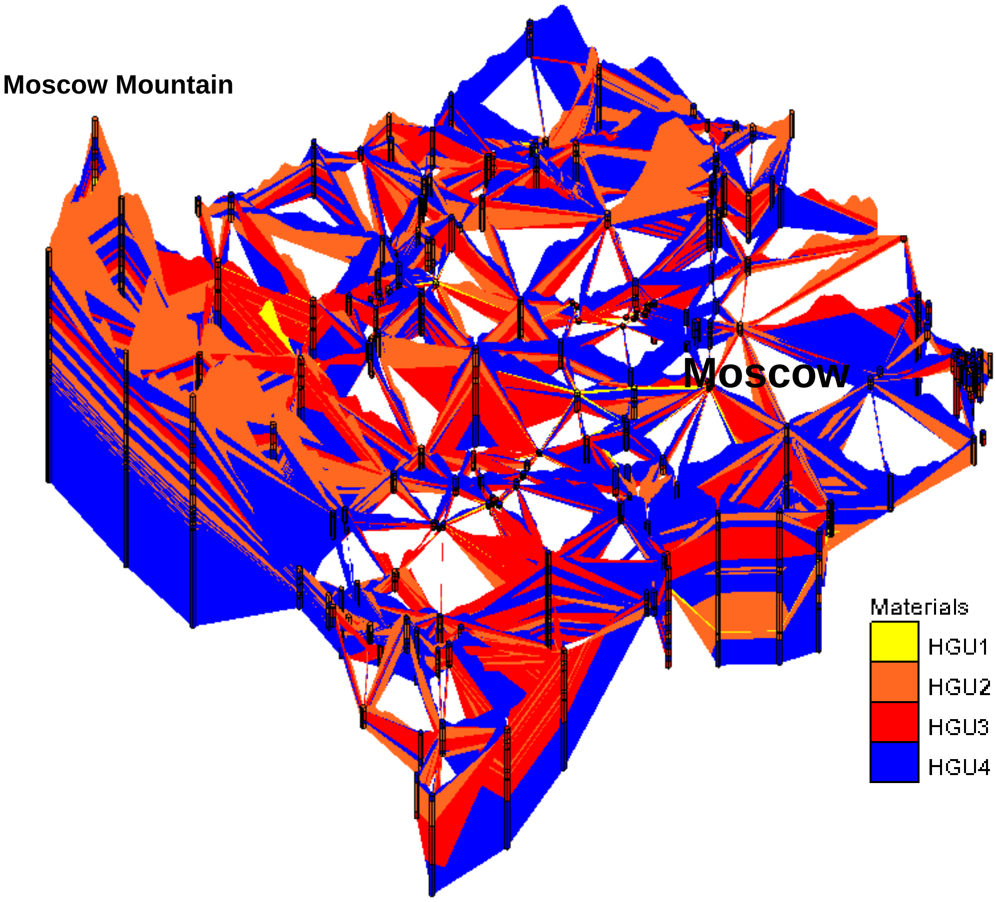

Figure 6.9 Cross-sections made from the boreholes in the Moscow sub-basin, seen from an north-western angle.

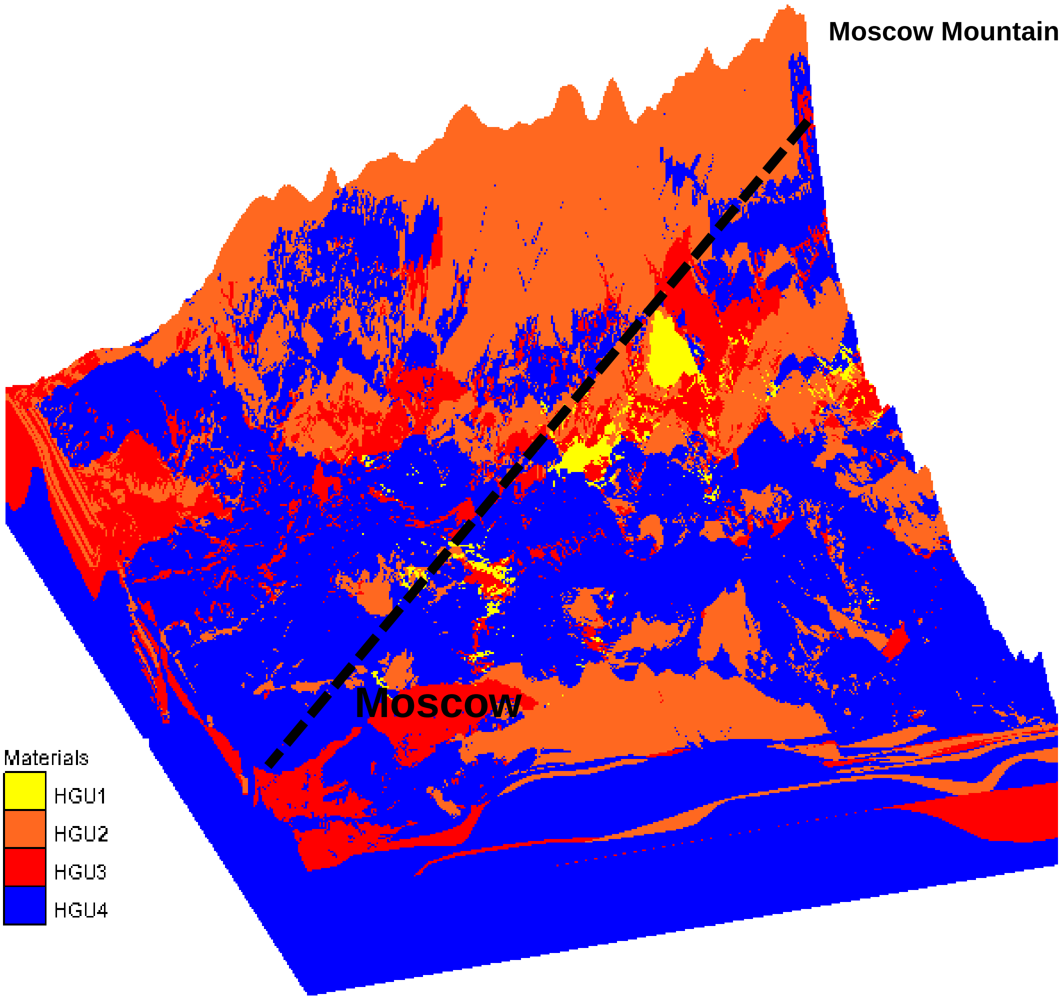

Figure 6.10 Solids designed for the Moscow sub-basin (seen from south-western angle) by the cross-sections (Figure 6.9) and the DEM-map as top elevation. Black dotted line represents a cross-section made from the solids (Figure 6.11).

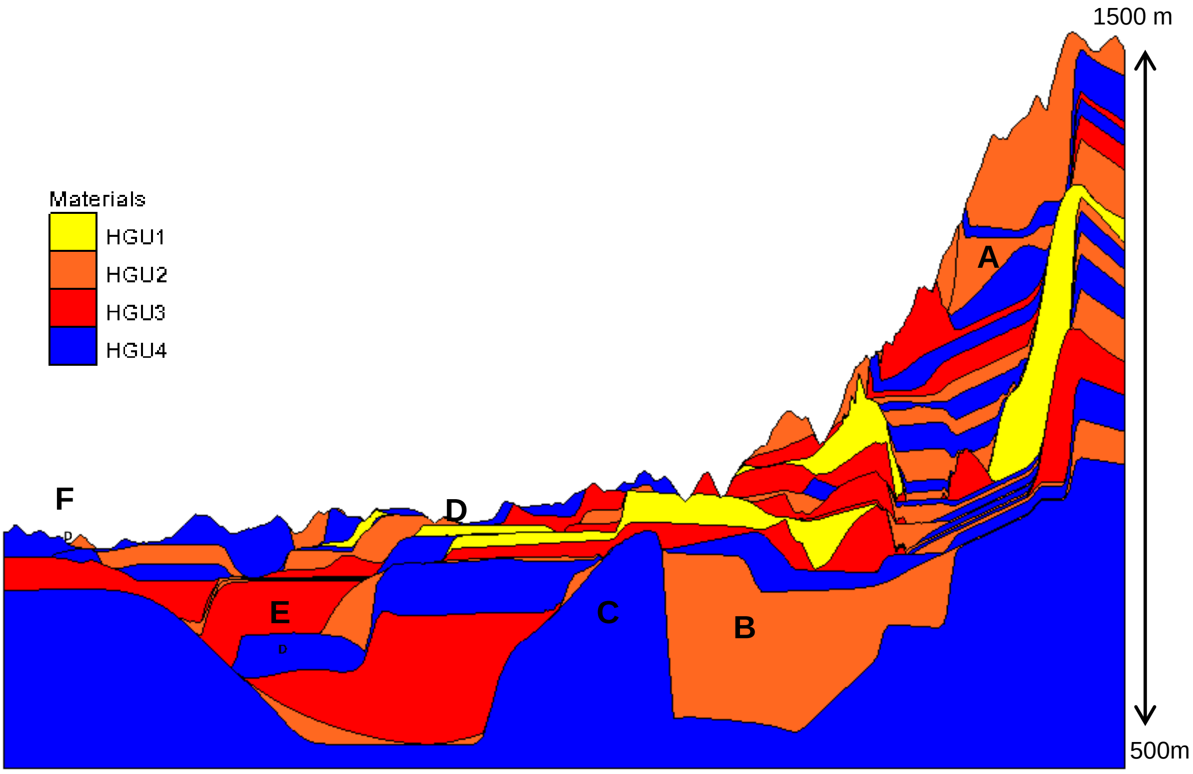

Figure 6.11 Cross-section made from the solids, from Moscow Mountain to Moscow (see Figure 6.10). See explanation of letters above.

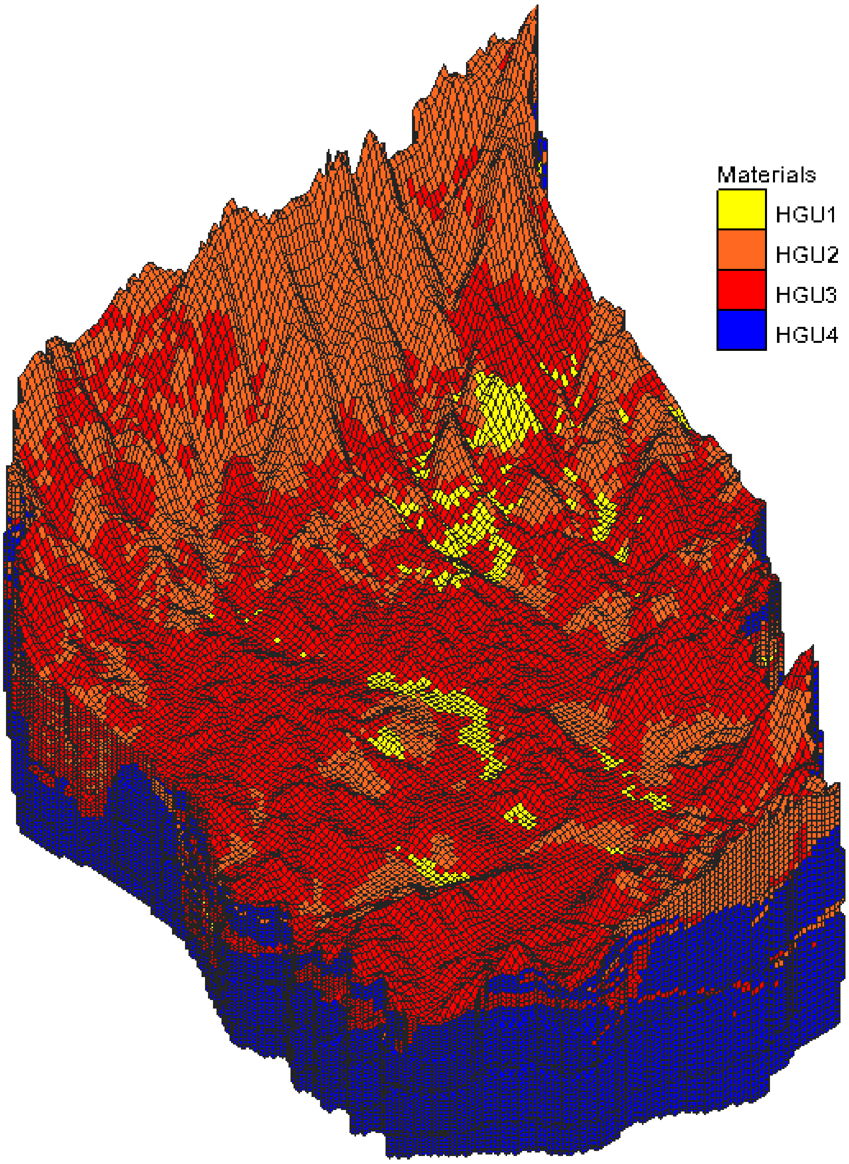

Figure 6.12 Modflow grid made for the Moscow Mountain

6.2.3.2 Top systems

Infiltration

The infiltration output of the SMR model was taken as input for the recharge package. The infiltration output by SMR was calculated for a grid of 30x30m, and was interpolated to the Modflow cells of 100x100m using inverse distance weighting. The SMR cells which overlap the Modflow cells most will have the highest effect on the weighted average by using this interpolation method. For the stationary model, the SMR infiltration was averaged over the period 2001-2008 as daily infiltration in m d^{-1}. Omitting the subsurface lateral flow in SMR did not result in a difference in the averaged percolation value over these 8 years, because subsurface lateral flow only occurs after intense rain events.

For the transient model, each cell was allocated a infiltration group based on its average daily infiltration as in the stationary model (Table 8.1). The number of five groups was chosen, because the chosen interval size of 0.5 mm d^{-1} allowed enough representation of the low infiltration zones and high infiltration zones within the Moscow sub-basin. For each of these groups the SMR model calculated the daily percolation over the period 2001-2008, and calculated a monthly average for each year. The result was used as input infiltration in the transient Modflow model.

Open water

All existing streams were included in the model (Figure 6.14). All streams were assigned a conductance of 0.4 m^2 d^{-1}. This conductance was estimated by using equation 46, as well as by optimizing by trial and error to approximate the yearly averaged discharge as good as possible (§2.5). A hydraulic conductance of 0.4 (m^2 d^{-1}) m^{-1} could mean the average width of all streams is 4 m, and the hydraulic resistance (M/k) is 10 (m^2 d^{-1}) m^{-1}. This hydraulic resistance seems likely, because of the clayey/silty texture in the area. Also springs were included in the model (Figure 6.14), derived from the mapped springs by Dijksma et al. (2011). The conductance assigned to the springs was taken as 1.0 m d^{-1}, similar to the assumption of De Graaf (2011).

Based on the size of the SFPR upstream of the discharge measurement station located in Pullman it is assumed that around 40-50% of the total water measured by the discharge measurement station in Pullman is coming from the SFPR flowing in the Moscow sub-basin. The other discharge is from the Paradise Creek and the part of the SFPR between the Idaho/Washington border and Pullman. The total discharge amount of water in the streams is then estimated to be around 0.7 m^3 s^{-1} (§2.5).

It was assumed that streams were not infiltrating, so the water level height was set equal to the stream bottom elevation. This can also be expected taking into account the silty/clayey texture of the streambed around Moscow. From discharge measurements it also turned out that no streams were losing net water in the Moscow sub-basin (§7.3). In §2.5 it was also described the infiltration rate in the streambed is negligible.

Wells

Hundred wells were added to the model (Figure 6.14), including the top screen and bottom screen elevation of the well and the flow rate. This data was derived from the IDWR database. Since the total amount of wells in the Moscow sub-basin is around 800, all the flow rates were multiplied with the same factor to get the average total flow rate of 8359 m^3 d^{-1} (or 0.056 mm d^{-1}) used in the stationary model. This is the yearly averaged amount of groundwater abstracted by Moscow (§2.7.3). For the transient model the average groundwater extraction of the four winter months (November, December, January and February) and for the rest of the months was calculated, based on the information of Figure 2.23. It was assumed this information is valid for the whole period of 2001-2008.

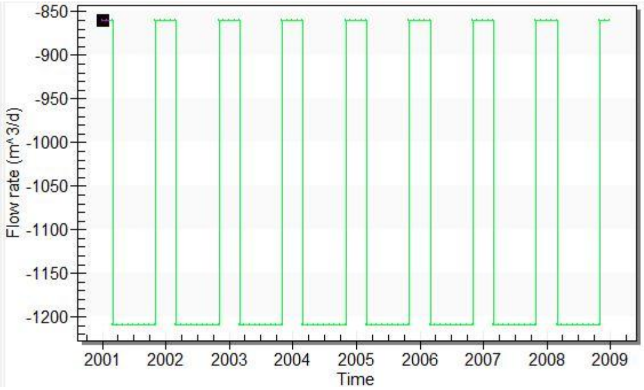

Figure 6.13 Well flow rate of one of the Moscow city wells used in the transient model. In the winter months the flow rate is lower than in the summer months. This is input for the transient Modflow model.

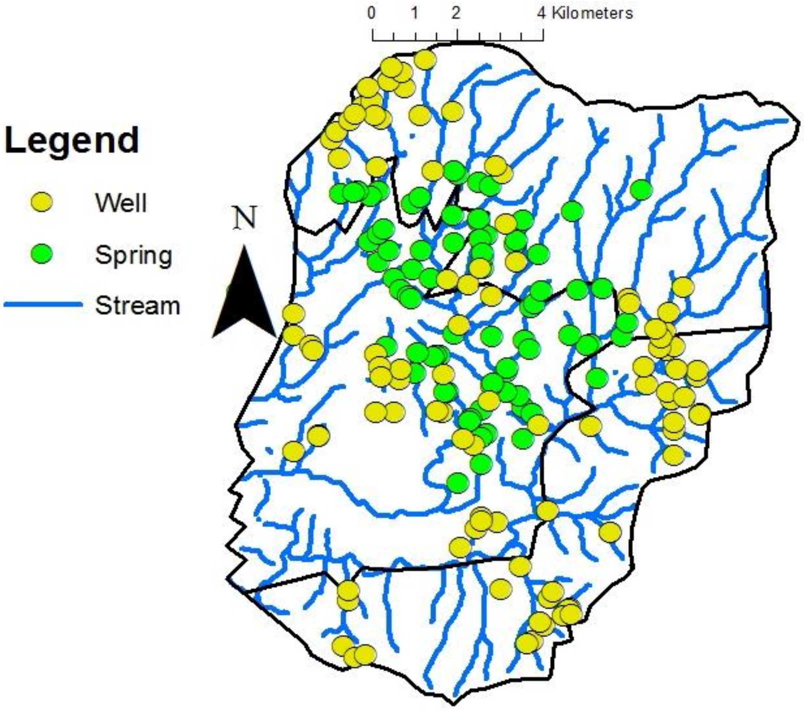

Figure 6.14 Top systems added to the Modflow model

6.2.4 Sensitivity analysis

Table 6.4 shows the hydraulic conductivity per hydrogeological unit used in the model. The hydrogeological units consist of different materials (Table 6.3). Aim of these hydrogeological units was to distinguish the hydraulic conductivities of the materials, which could be done by using 4 categories in total. The division was based on the possible range for the hydraulic conductivity of the material, known from literature (see above). The effect of this range was further tested by sensitivity analyses. Each hydraulic conductivity was raised and lowered by 50%, to investigate the effect on the groundwater flux recharging the aquifers from the northeast. The assigned hydraulic conductivities as in Table 6.3 were checked by simulating the total estimated stream discharge as in §6.2.3.2. So by simulating the estimated stream discharge, the hydraulic conductivities were optimized.

A few monitoring wells are available in the area as well, which could be used for checking the model. However, simulating the total fluxes was seen as a more important way of optimizing than using water levels at single points. Also these monitoring wells were mostly not in the area of interest, which is the granite/basalt interface, but mainly in the city of Moscow. The available monitoring wells show large water level differences between each other (up to 40 m) while having a limited difference in the horizontal (down to 50 m) and vertical distance (within the same geological unit). This is possibly an effect of geological differences and large groundwater extractions in Moscow. This makes the monitoring wells unsuitable for validating the model's performance.

6.2.5 Basemodel

The basemodel includes the following groundwater fluxes:

- The total well extraction, which is known (§6.2.3.2)
- The total infiltration, which was calculated by the SMR model, and has been validated in previous studies for similar areas (§6.1)
- The total stream discharge, which was estimated (§6.2.3.2).
- The groundwater flux over the boundary, which was unknown.

So the groundwater flux over the boundary is left as a rest term. The effect of the west boundary on the aquifer recharge was tested during the sensitivity analysis.

6.2.6 Output

The stationary Modflow model is used to quantify the net groundwater flux from the Moscow Mountain to the Wanapum and Grande Ronde aquifer, as illustrated in Figure 6.4. This represents the aquifer recharge flux 3, shown by Figure 2.25. Also aim was to identify aquifer recharge zones, which might be the locations where paleo-channels are most present.

The transient Modflow model was used to simulate the groundwater level decline of the Wanapum and Grande Ronde aquifer, and to simulate seasonal differences of the storage.

7. Field Results

In this chapter the field results will be presented, which consists of the isotopic sampling, caffeine sampling and discharge measurements. The isotopic sampling also includes the temperature and EC measurements.

7.1 Isotopic Sampling

The isotopic sampling consists of the ^{18}O, temperature and EC results of the 22 selected wells and 2 springs. In total 352 samples have been analysed. For each location the probability of recharge has been derived from these results (§7.1.4). The data analysed in this study consists of the first nine months of the total two years of measurements. The minimum data to compute the residence time for groundwater is two years (McGuire and McDonnell 2006), so only indications of the residence time have been derived in this study.

7.1.1 Stable isotope

In isotopic analysis it is essential that water samples are preserved to avoid evaporation of the water samples. The relationship between ^{18}O and ^{2}H from the different water sources being sampled (LMWL) to the GMWL (Figure 7.1) shows proper preservation has occurred since the data is close to the GMWL. This means little evaporation occurred to the samples. As expected from previous studies in the region (Carey 2011; Moxley 2012; Larson 2000), ^{18}O decreases with depth below the soil surface such that ^{18}O of deep groundwater is often less than -16.0‰ and ^{18}O of shallow water is often greater than -15.0‰ (Figure 7.2).

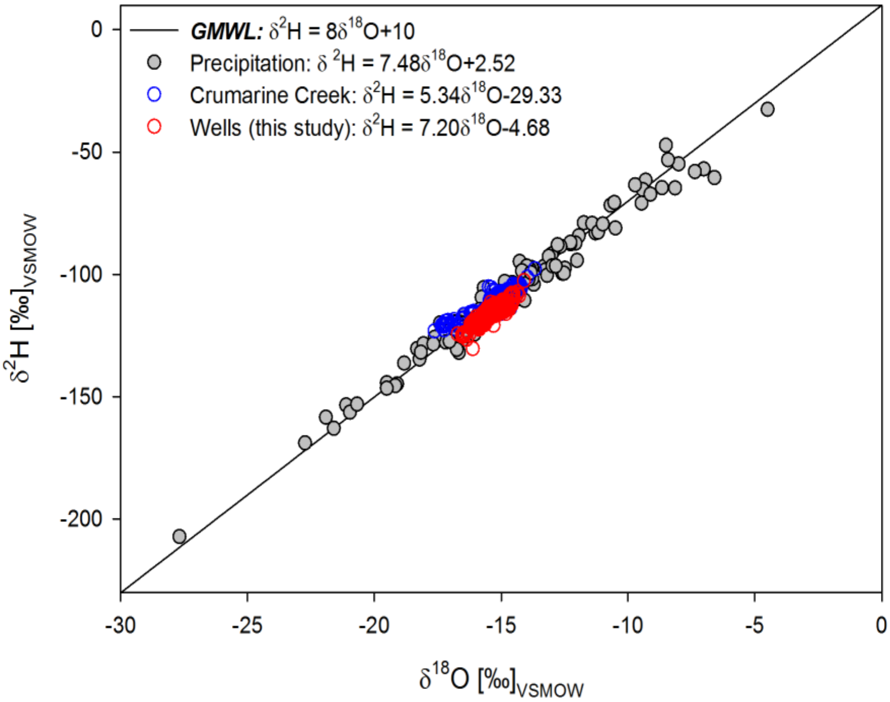

Figure 7.1 Local Meteoric Water Lines (LMWL) for various water sources collected in this study in comparison to the Global Meteoric Water Line (GMWL). Including Sánchez-Murillo unpublished data of Crumarine Creek and precipitation.

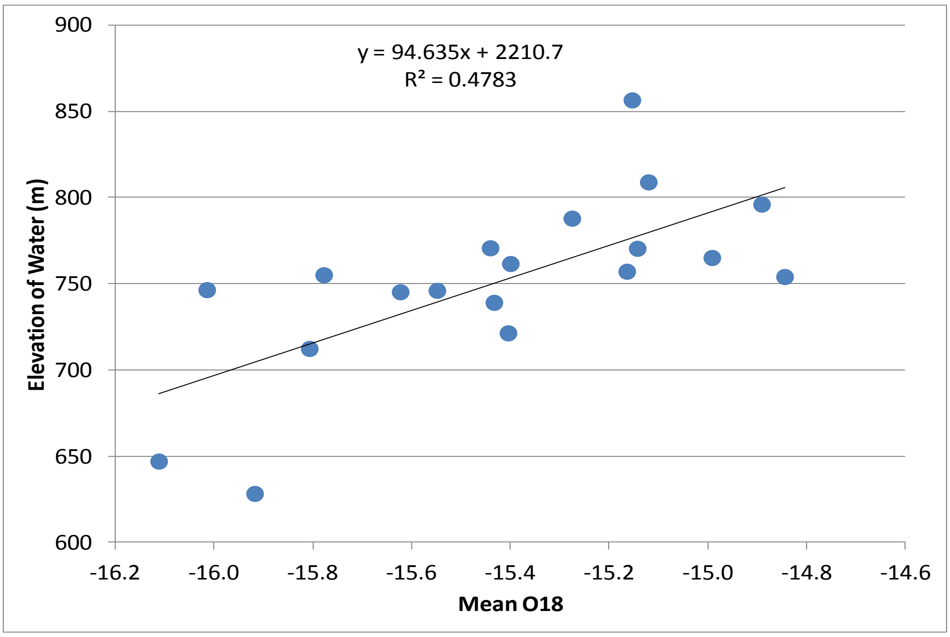

Figure 7.2 Relationship between average ^{18}O and elevation of the bottom of the well

Variability in the ^{18}O signature with time suggests that groundwater recharge is occurring in some of the wells. The variability in ^{18}O is significant and consistent across many of the locations. Figure 7.3 shows highly dynamic ^{18}O fluctuations at four well locations in the study (see Figure 5.4 for these well locations). These four wells are showing the largest fluctuations. The Picarro instrument is accurate to ±0.1‰ and therefore fluctuations of greater than 0.1‰ are significant (§5.1.3). In contrast, ^{18}O in other wells are relatively stable (Figure 7.4). If the fluctuations in ^{18}O are occurring due to recharge, then the precipitation should have a similar peak which occurs earlier in time. It can be seen in Figure 7.3, that the peak in ^{18}O in the dynamic wells often occurs two to five weeks after a peak in ^{18}O in the precipitation. Remarkable is that wells which have the greatest fluctuations in ^{18}O normally have a much more depleted ^{18}O signature between recharge events (Figure 7.3) in comparison to the ^{18}O signature of more stable wells (Figure 7.4). This could suggest deep recharge pathways, since depleted ^{18}O signatures are often related to deeper groundwater (Figure 7.2). It is also interesting to see the wells which do not show strong fluctuations still have a dampened signal suggesting a slower connection or smaller amount of recharge may be occurring in these wells. Figure 7.5 shows the precipitation events in relation to the ^{18}O signature of the precipitation.

As expected with surface water, the ^{18}O signal from Crumarine Creek is much more closely related to the signal in precipitation (Figure 5.2). However, the fluctuations in ^{18}O in the surface water appear to be lagged further behind the precipitation signal than observed in the well data.

The differences in LMWL slopes of the different water sources can also be used to determine surface and groundwater connectivity (§3.1.3). The slopes of the precipitation and groundwater samples are very similar (7.48 and 7.20, respectively) which indicate that infiltration may occur fast, preventing the water from evaporation. The Crumarine Creek has a slope of 5.34, which clearly shows the surface water has been subjected to evaporation. This also means the amount of infiltration in the Crumarine Creek can be neglected as mentioned earlier in §2.5, since no signs of evaporation were found in the groundwater samples.

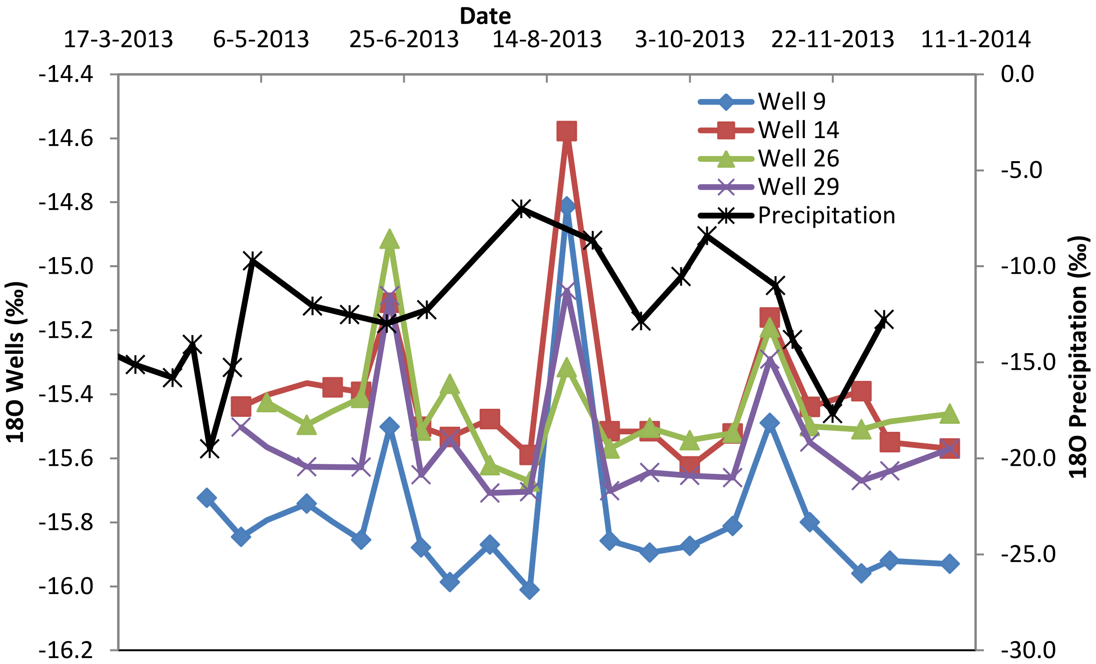

Figure 7.3 ^{18}O results for the four most dynamic wells in the study with the precipitation results. See Figure 5.4 for these well locations

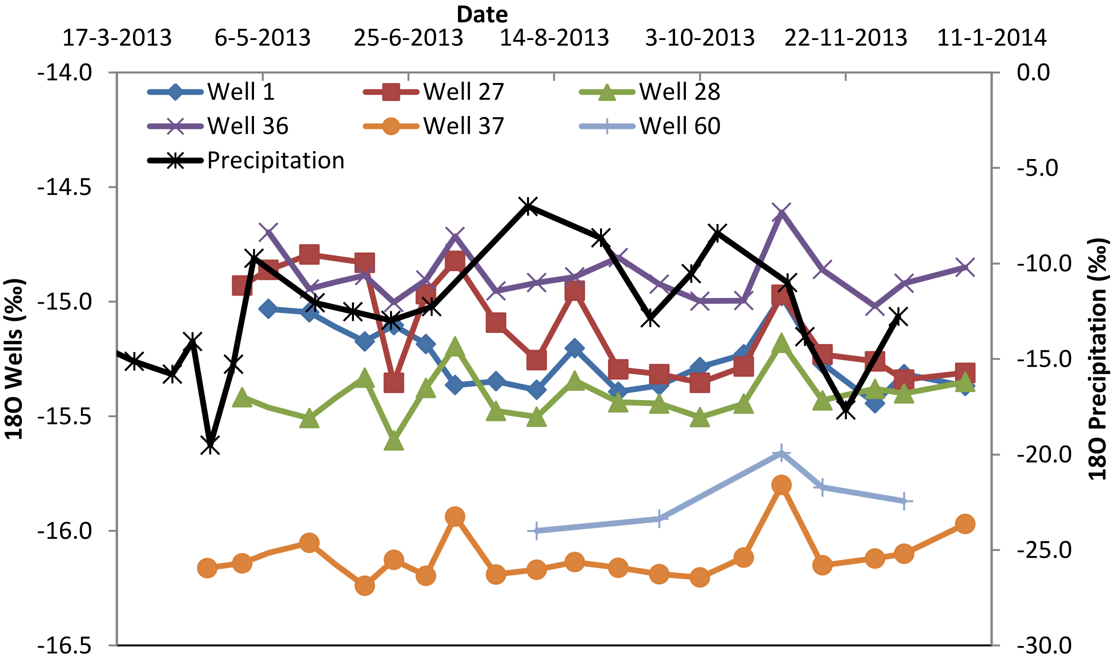

Figure 7.4 ^{18}O results for the six most stable wells in the study with the precipitation results. See Figure 5.4 for these well locations

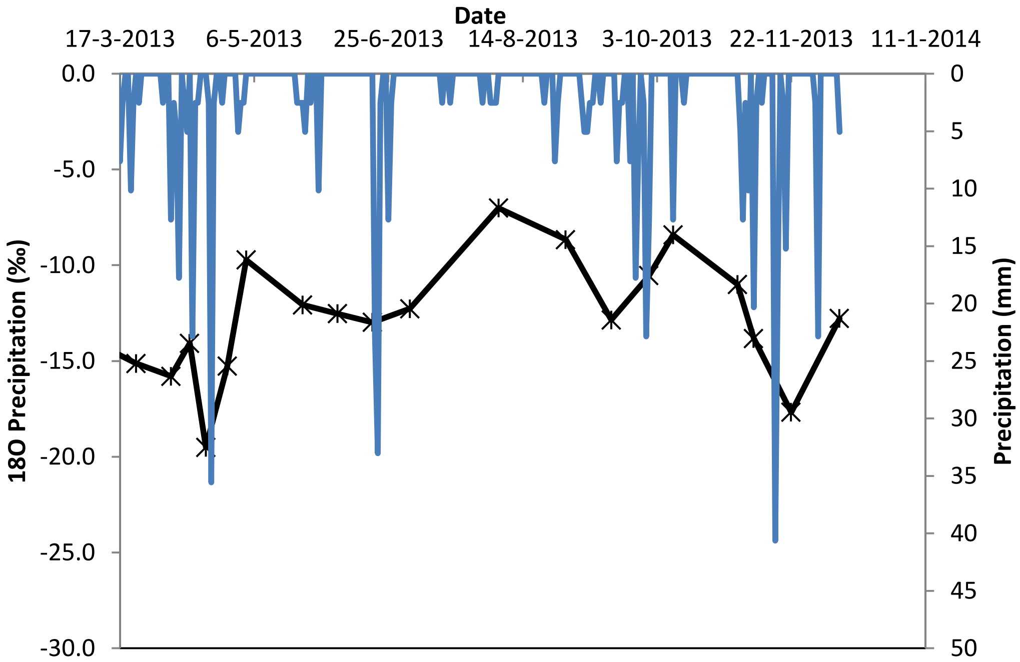

Figure 7.5 ^{18}O for the precipitation, including the precipitation intensity.

Figure 7.6 shows there is a high variability in ^{18}O signatures in the Moscow sub-basin. Since Figure 7.2 showed there is a clear relation with depth, it is hard to interpret the absolute ^{18}O signatures on a 2D-map. As described in §3.1.3 the d-excess can be used to correct for the abssolute differences, and derive the relation of the water source to the precipitation (Figure 7.7). A small deviation from the GMWL means more evaporation occurred. The smallest difference in d-excess was found near the Moscow Mountain. Closer to Moscow the d-excess difference to the GMWL was larger.

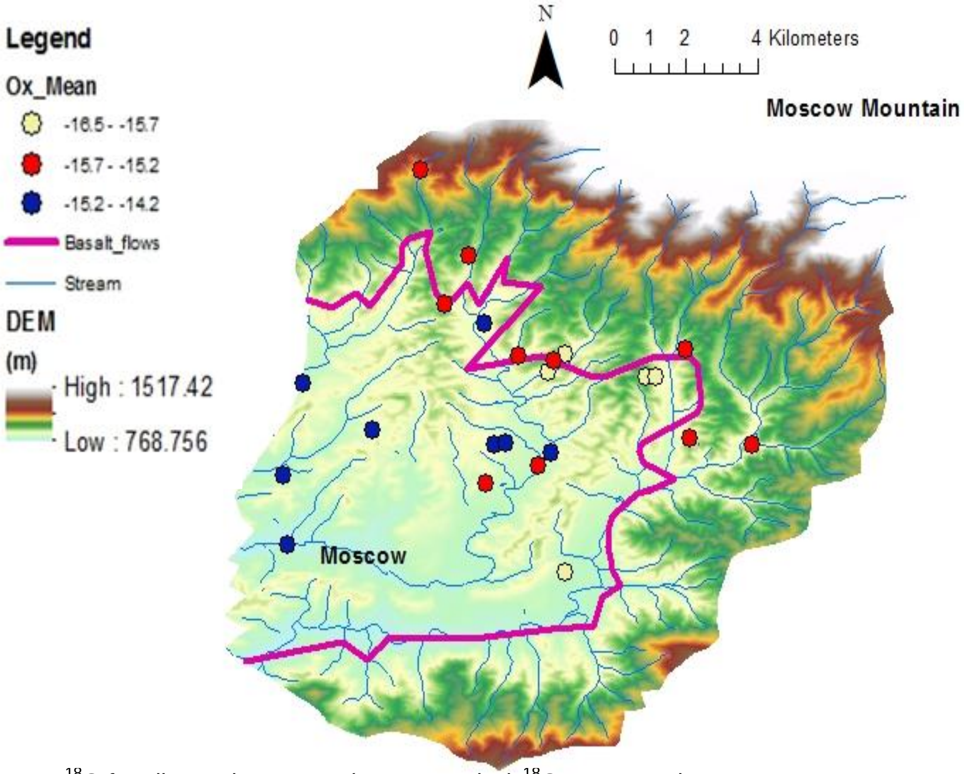

Figure 7.6 Average ^{18}O for all samples. Lower (more negative) ^{18}O concentrations suggest water was recharged during relatively cooler conditions with relatively little enrichment due to evaporation. Concentration depends partly on the depth.

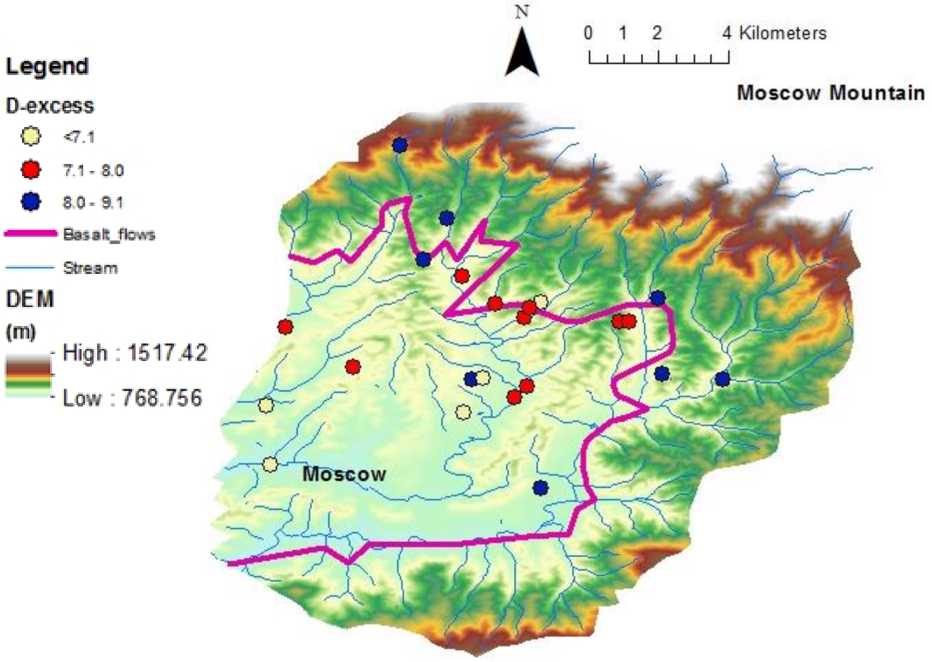

Figure 7.7 Average d-excess for all samples. D-excess close to 10 is closely related to the GMWL and indicates little evaporation has occurred to the well water before it infiltrated.

7.1.2 Temperature

Figure 7.8 shows the results of the average temperature measurements from the wells and springs. These temperatures are measured after the tap was running for a long time (several minutes) until the temperature was stabilizing (§5.1.2). The stream temperature was fluctuating similar to the average air temperature. The well temperature is fluctuating less. For groundwater it was expected the temperature would be constant over time, being the average annual air temperature (§3.5). This temperature decline in the wells and springs could mean the recharge occurs relatively fast, and infiltrated water is pressing down the older groundwater, which is also a result of an in general low porosity in the area. It could also be an indication of the preferential flow paths in the subsurface, which were called paleo-channels earlier in this report. These preferential flow paths could result in a fast recharge.

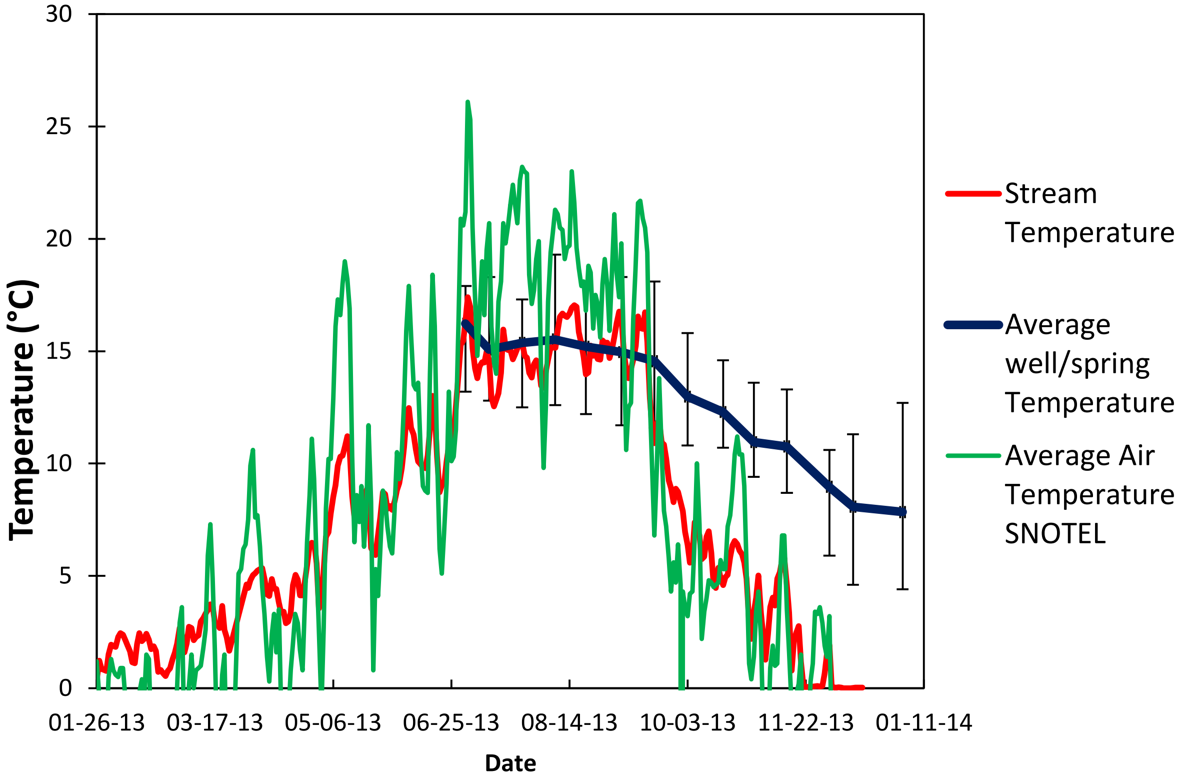

Figure 7.8 Average measured temperature of the wells and springs compared to the measured temperature of the streams by Sánchez-Murillo and the air temperature measured at the SNOTEL weather station. The boxplots are the total range of temperatures measured of all the measured wells and springs.

7.1.3 EC

Figure 7.9 shows the results of the measured average EC for every well and spring. A high EC suggests water high in solute or ion concentrations (§3.4), which might mean the water has been in the ground for a relatively long time. In general the EC's are relatively constant over time for most of the wells/springs, but some wells show significant fluctuations being larger than 20% of the average EC (well #35) (Figure 7.10). Larger fluctuations could mean a strong interaction with surface water and fast recharge pathways.

The lowest average EC was 126 µS cm^{-1} measured for well #17, and the highest EC was 609 µS cm^{-1} for well #39. Well #39 is a shallow well at the UIGWRS which could be water subjected to pollutants from the city.

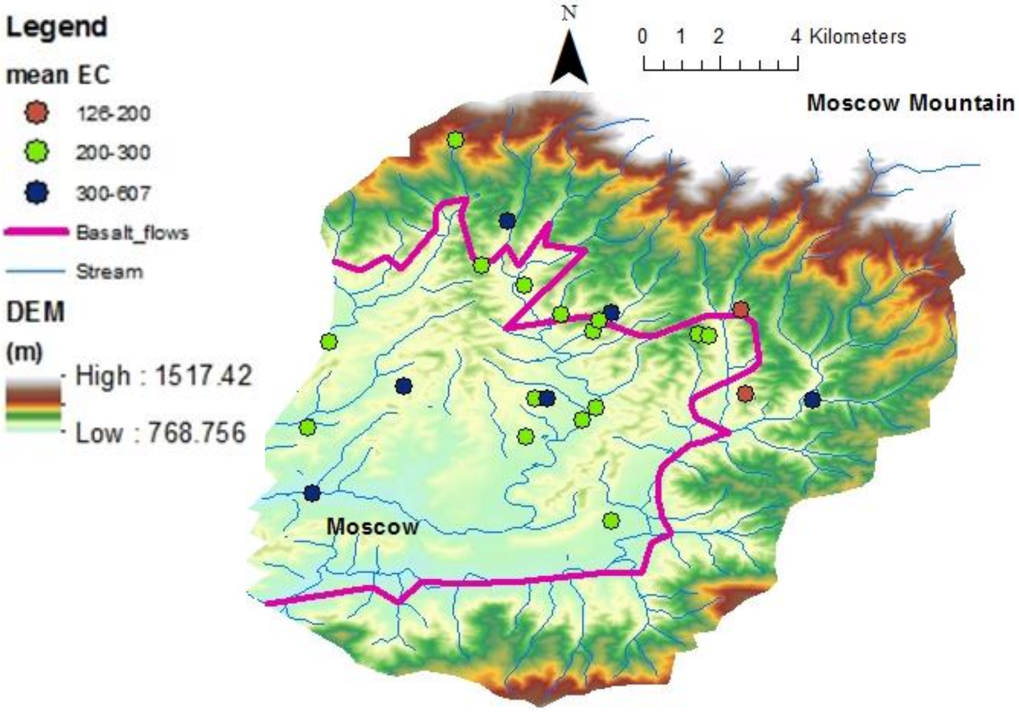

Figure 7.9 EC values found in wells and springs. Higher EC suggest water high in solute or ion concentrations.

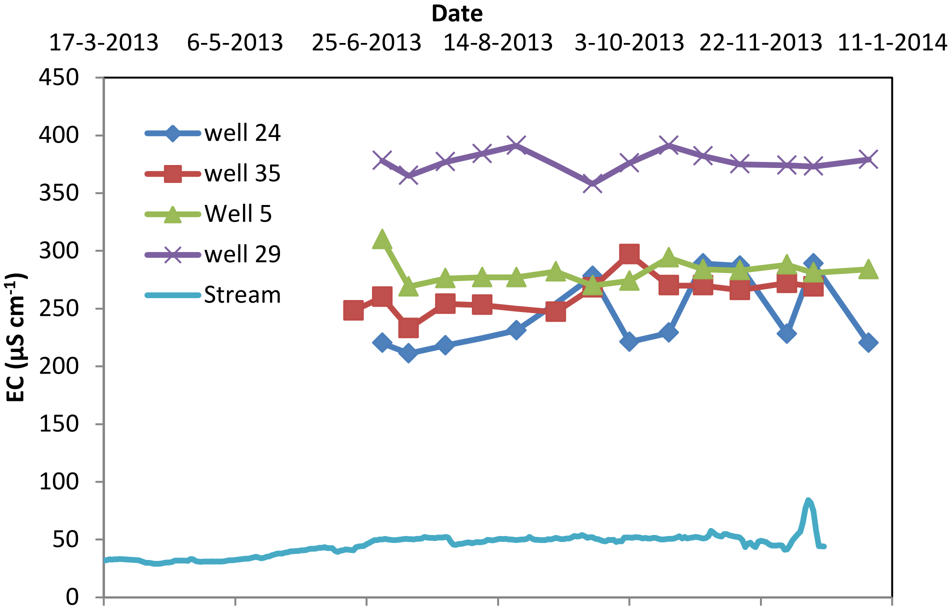

Figure 7.10 EC fluctuations found in some wells and the Crumarine Creek.

7.1.4 Recharge indications

The above results all include indications of recharge for each sampled location. Some of these locations have more indications of recharge than others. The sampling points have been assigned a number ranging from 1, meaning little indications of recharge, to 4, meaning strong indications of recharge (Figure 7.11). These indications were assigned based on the methodology as discussed in chapter 3. Summarizing; strong indications for recharge are:

- A relatively large isotopic signature fluctuation
- A relatively low EC
- A relatively large EC fluctuation
- A relatively large temperature fluctuation
- A D-excess close to 10

Figure 7.11 shows the assigned indications of recharge for all sampling locations. The properties of the wells are found back in Appendix I&V. Strongest indications of recharge are found in the proximity of the Moscow Mountain, Well #5, #26 and #37 are wells running in the basalt with strong indications of recharge (3-4). Well #20, #39, #41 and #60 are also wells running in the basalt, but these have little indications of recharge (1-2).

The strong indications of recharge below impermeable layers also suggest the recharge occurs in lateral flow paths instead of vertical infiltration. Strong proof for lateral flow paths in the granite is well #11, #17, #29 and #35. These are all wells in the granite and show strong indications of recharge in decomposed granite below hard impermeable granite (according to well logs). The same proof exists for lateral flow paths in the Sediments of Bovill and at the granite/basalt interface. Well #5, #9, #14, #26 and #27 are all wells getting water from below

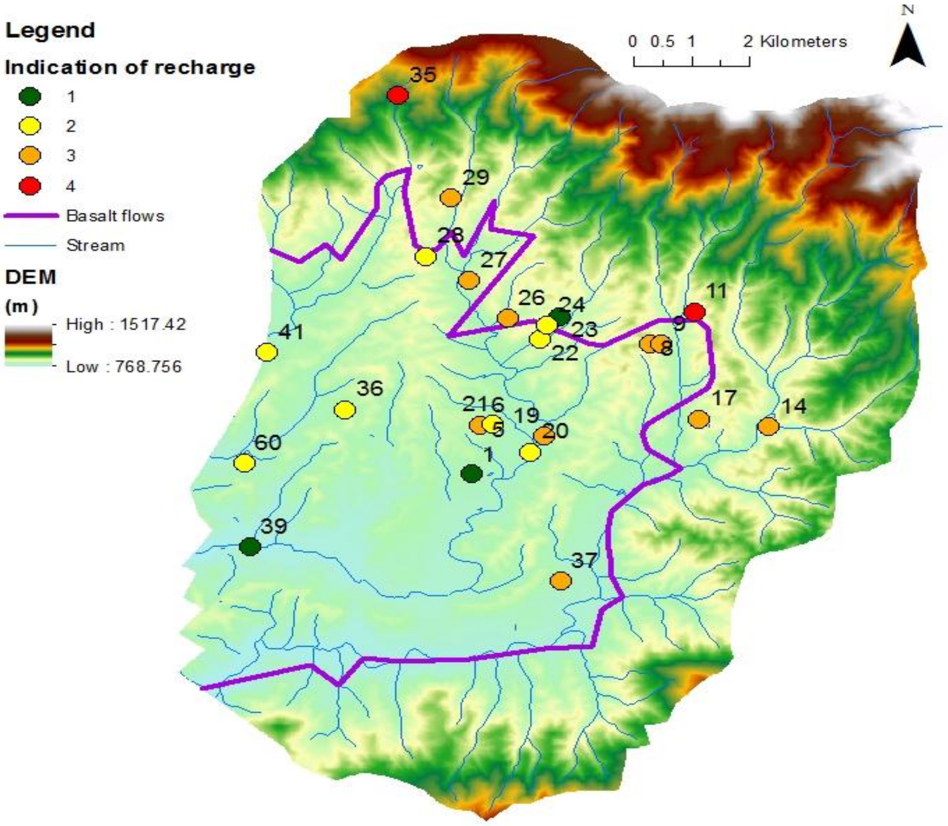

Figure 7.11 # of all recharge indications for the sample wells and springs. Label for each point is the well number. Results have been plotted on a digital elevation map of the area.

impermeable clay layers and show strong indications of recharge.

Remarkable are well #8, #9 and #11 which are very close together and all have strong indications of recharge. However, all these wells with a depth of 213 m, 77 m and 27 m respectively have their screen-level at different depths; 655, 757 and 824 m amsl respectively. This means they are either connected or recharge occurs at different depths via different lateral flow paths.

7.2 Caffeine Sampling

The caffeine sampling results are shown in Figure 7.12 & Table 7.1. Caffeine has only been detected in sample H and K, with the detection level of 0.02 µg L^{-1}. Respectively these samples are located at the University of Idaho Groundwater Research Site (UIGRS), and the downstream part of the effluent in the Paradise Creek (Figure 7.12, Appendix II&VI)). No caffeine has been detected in the effluent itself, which is surprising looking to similar studies (§3.2). Since the discharge of the Paradise Creek upstream of the WWTP was very small (less than 1 l s^{-1}) compared to the effluent (22 l s^{-1}), most of the downstream water was originating from the effluent. This is also confirmed by the comparable EC values from the effluent and the downstream part of the Paradise Creek. This would suggest that the caffeine found in the downstream part of the Paradise Creek is originating from the Paradise Creek flowing through Moscow. If that is the case, then the caffeine concentrations would have been approximately 22 times higher in that part of the Paradise Creek because of smaller discharges, so approximately 1,2 µg L^{-1}.

Since caffeine has been traced in sample H and the Paradise Creek, a recharge connection might exist between the Paradise Creek and the upper basalt layer at the UIGRS, which has a depth of approximately 25m. Whether other recharge pathways exist West of Moscow cannot be derived from the rest of the caffeine measurements, since no caffeine has been detected in the other samples. The well H was also included in the isotope measurements (labelled as well 39) (§7.1). However, the indications of recharge occurring at well H were low according to Figure 7.11.

Also isotope samples have been taken during the caffeine sampling (§5.2.2). The isotope results of sample A (93 m deep), E, F and G (all 6-7 m deep) (Figure 7.12) would suggest recharge pathways could exist, because of the enriched isotopic values. The wells E, F and G are not reaching the basalt but only a clay layer, so it would only indicate infiltration in the first meters. The well A reaches the basalt. However, without the caffeine results, long term isotopic measurements are needed to be able to detect whether recharge pathways are present, like is done for the east of Moscow.

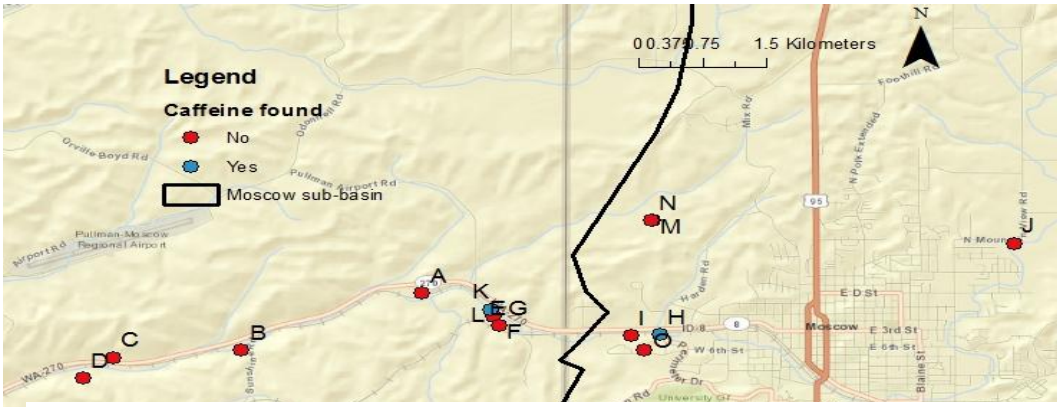

Figure 7.12 Caffeine results.

Table 7.1 Caffeine results

nr	Well name	Caffeine concentration ($\mu g\ L^{-1}$)	Ox18 (‰)	H2 (‰)	EC ($\mu S\ cm^{-1}$)	Temp (°C)	pH
A	Toyota Garage	-	-14.63	-110.40	333	17.2	7
B	Motley & Motley	-	-16.53	-124.30	368	16.5	7.37
C	Thonney	-	-16.60	-125.40	428	16.5	7.36
D	Poe Asphalt	-	-17.17	-129.75	361	15.8	7.52
E	Busch distributors	-	-14.24	-107.59	1560	15.3	6.46
F	Busch distributors	-	-14.39	-107.04	878	14.2	6.55
G	Busch distributors	-	-15.06	-112.34	1307	15.1	6.52
H	T16D	0.045	-14.96	-113.03	607	14.7	6.68
I	D19D	-	-15.53	-117.59	337	14.3	7.33
J	Paradise Creek Upstream	-	NT	NT	283	17.4	6.72
K	Paradise Creek Downstream	0.057	NT	NT	731	22.4	7.48
L	Effluent	-	NT	NT	742	22.2	7.5
M	IDWR 3	-	-15.95	-119.73	258	17.8	6.64
N	IDWR 4	-	-17.28	-131.78	294	16.3	8.28
O	Aquaculture #7	-	-15.86	-118.96	312	14.7	6.79
P	blank with filter+bailer	-	NT	NT	NT	NT	NT
Q	Blank with filter	-	NT	NT	NT	NT	NT
R	Blank without	-	NT	NT	NT	NT	NT

The caffeine turned out to be an unsuitable tracer in this area, since the effluent of the WWTP contained an undetectable amount of caffeine. Only in 1 well and at 1 location in the Paradise Creek the caffeine has been detected. Since the lab needed a minimum of 10 samples, and the sampling had to be done for all wells at the same time to prevent time differences, the effluent was not checked beforehand on the presence of detectable caffeine. As described in §3.2, it was very likely caffeine could be traced in the WWTP-effluent with the accuracy of 0.02 µg L^{-1} based on previous studies at different locations. Also the timing could have played a role, since rainwater could have diluted the water sources. Now a period of one week of dry weather was chosen before caffeine was sampled. It could be that a longer period of dry weather is needed to be able to detect caffeine in the different water sources.

7.3 Discharge Measurements

Discharge measurements of the Paradise Creek northeast of Moscow, and the SFPR east of Moscow (Figure 7.14) are indications that the streams are gaining water (Appendix VII). These flow measurements show there is net stream gaining, instead of net stream loss.

For the Paradise Creek west of Moscow the results are different (Figure 7.13). Here the stream runs over the basalt. These measurements show there is net stream loss west of Moscow. The largest loss measured is 70% and almost 50% at respectively 15-06-13 and 30-06-13. The volume of losses is 50 l s^{-1} (or $4.3*10^3$ m^3 d^{-1}) and 60 l s^{-1} (or $5.2*10^3$ m^3 d^{-1}) respectively. Remarkable is the difference between the measurements done at 15-06-13 and 30-06-13. A large gain of water (almost four times as much) was measured at the last measurement point at 15-06-13, while this gain of water has not been measured at 30-06-13. Also the loss of water which has been measured at the third location at 30-06-13 was measured one location further downstream at 15-06-13. The stream seems to lose its water at different sections over time depending on the discharge of the stream. Similar differences as in the flow discharges are not found in the EC and temperature measurements.

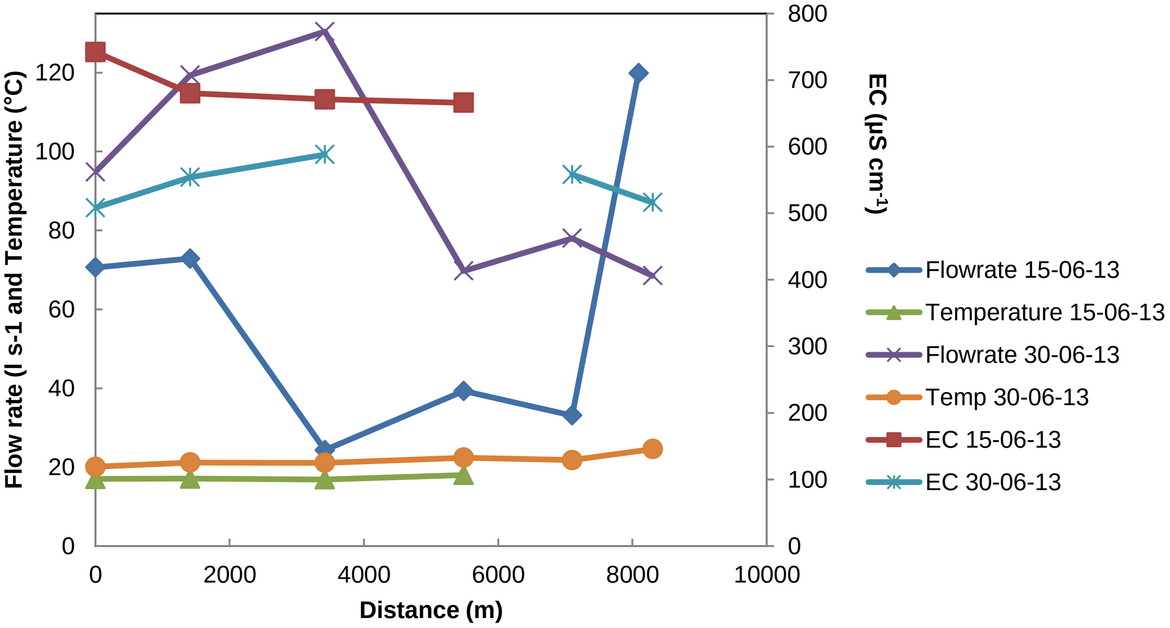

Figure 7.13 Discharge, temperature and EC measurements for the Paradise Creek west of Moscow done at 15-06-13 and 30-06-13 (Figure 5.11). At both days the EC and temperature probe stopped functioning during the day, but the EC and temperature are relatively stable.

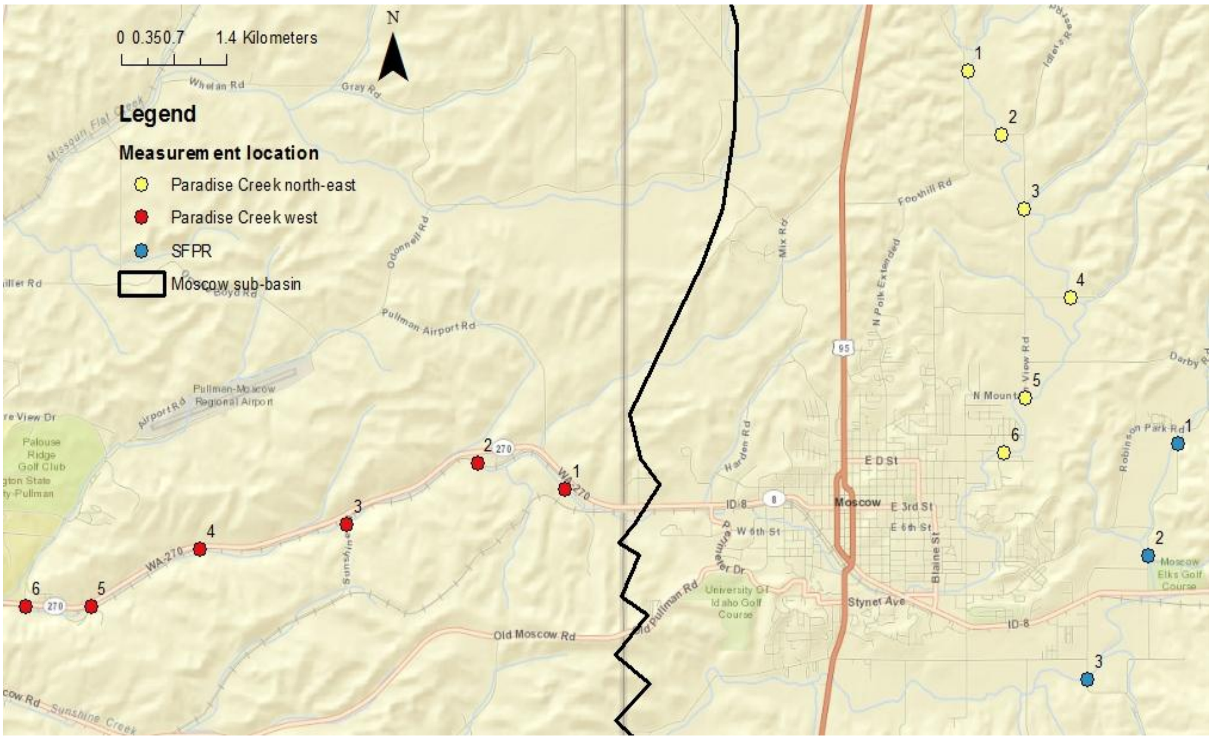

Figure 7.14 showing all sample locations for the discharge measurements. The west boundary of the Moscow sub-basin is included in the figure

8. Modelling results

In this chapter the model results will be presented. First the SMR result is presented, which has been used as infiltration input in the Modflow model. First the stationary model will be presented, secondly the transient Modflow model.

8.1 SMR

Figure 8.1 shows the result of the SMR model. The daily average infiltration over the period 2001-2008 was calculated for each 30x30 m cell in the Moscow sub-basin. The average daily infiltration over the Moscow sub-basin was 0.50 mm d^{-1}. The highest average percolation was approximately 2 mm d^{-1}, the lowest average percolation was zero. These areas with a percolation of zero are the areas with steep slopes and argillic properties, where surface runoff occurs (Figure 2.5). The largest percolation occurs at the Moscow Mountain, in the northern part of the area. Lower percolation rates are found in Moscow, where urbanized landscape limits the infiltration. These results have been used as infiltration input for the stationary Modflow model, as described earlier, and are the source of the simulated aquifer recharge.

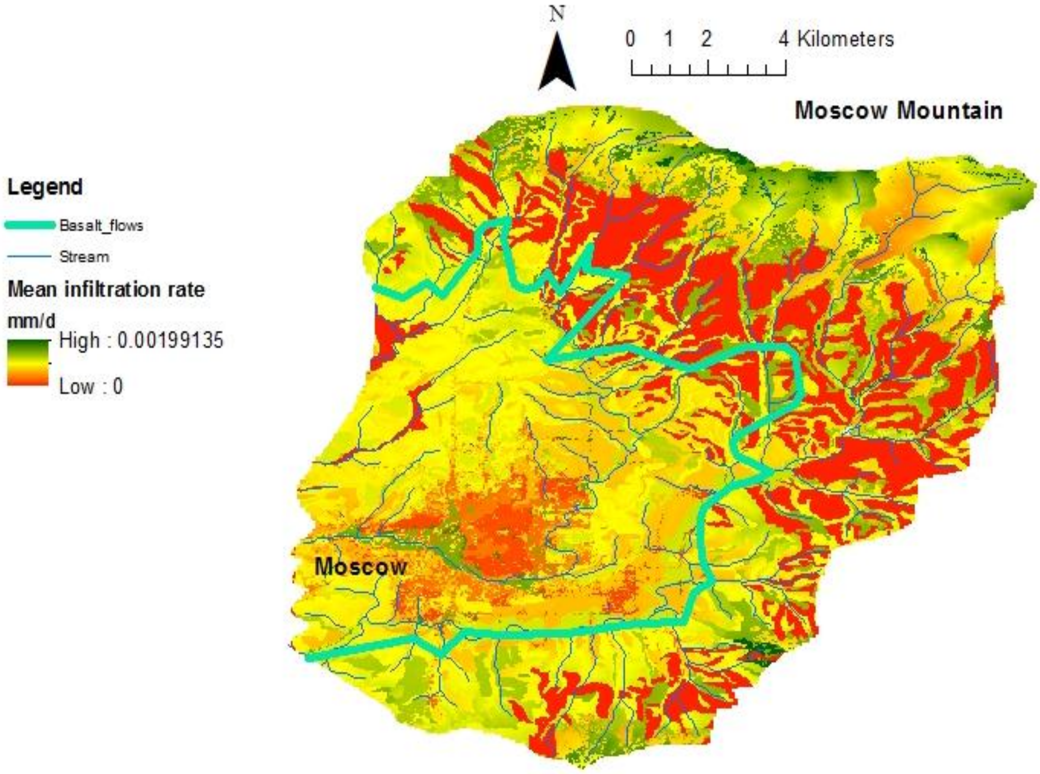

Figure 8.1 Daily average percolation in the Moscow sub-basin in m d^{-1}. A result from the SMR model.

For the transient model, five percolation groups were identified and constructed (Table 8.1). The number of five groups was chosen, because the chosen interval size of 0.5 mm d^{-1} allowed enough representation of the low infiltration zones and high infiltration zones within the Moscow sub-basin. Figure 8.2 shows the infiltration groups. For each of these groups the SMR model calculated the daily infiltration over the period 2001-2008, and calculated a monthly average for each year. Figure 8.3 shows the monthly average infiltration rates for each infiltration group. This result has been used as input infiltration in transient Modflow model.

Table 8.1 Infiltration groups used in the transient model, derived from the stationary model

Infiltration Group	**Infiltration rate in stationary model (mm d^{-1})**
1	0
2	0-0.5
3	0.5-1.0
4	1.0-1.5
5	1.5-2.0

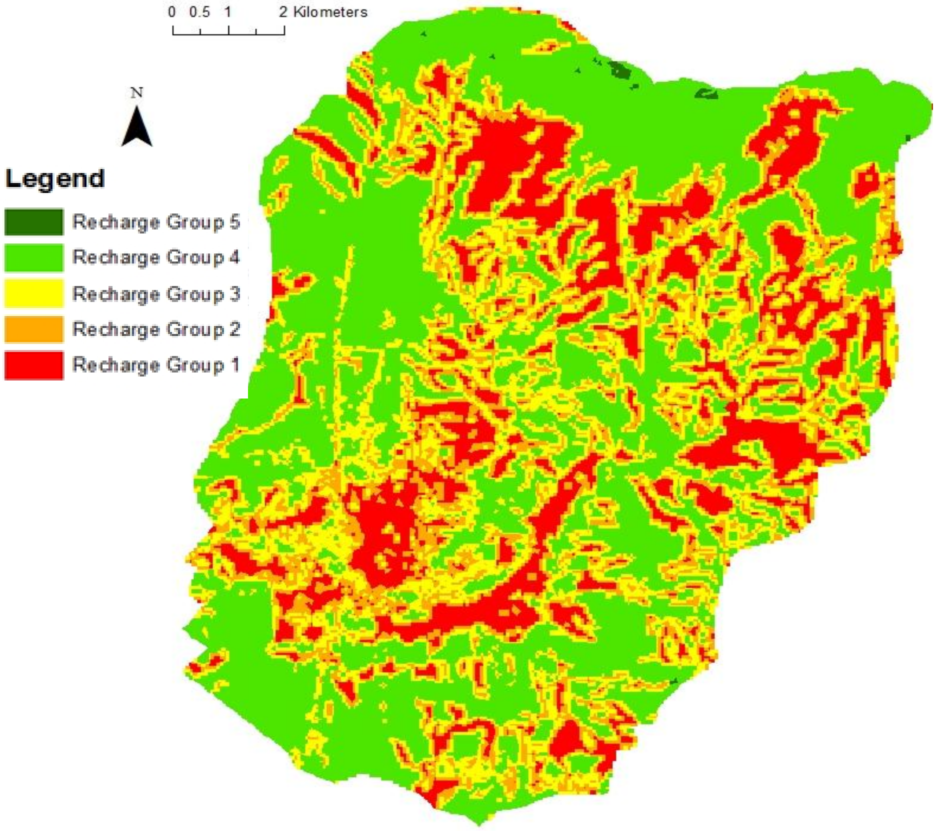

Figure 8.2 Infiltration groups constructed for the transient Modflow model. Infiltration rates are presented in Table 8.1.

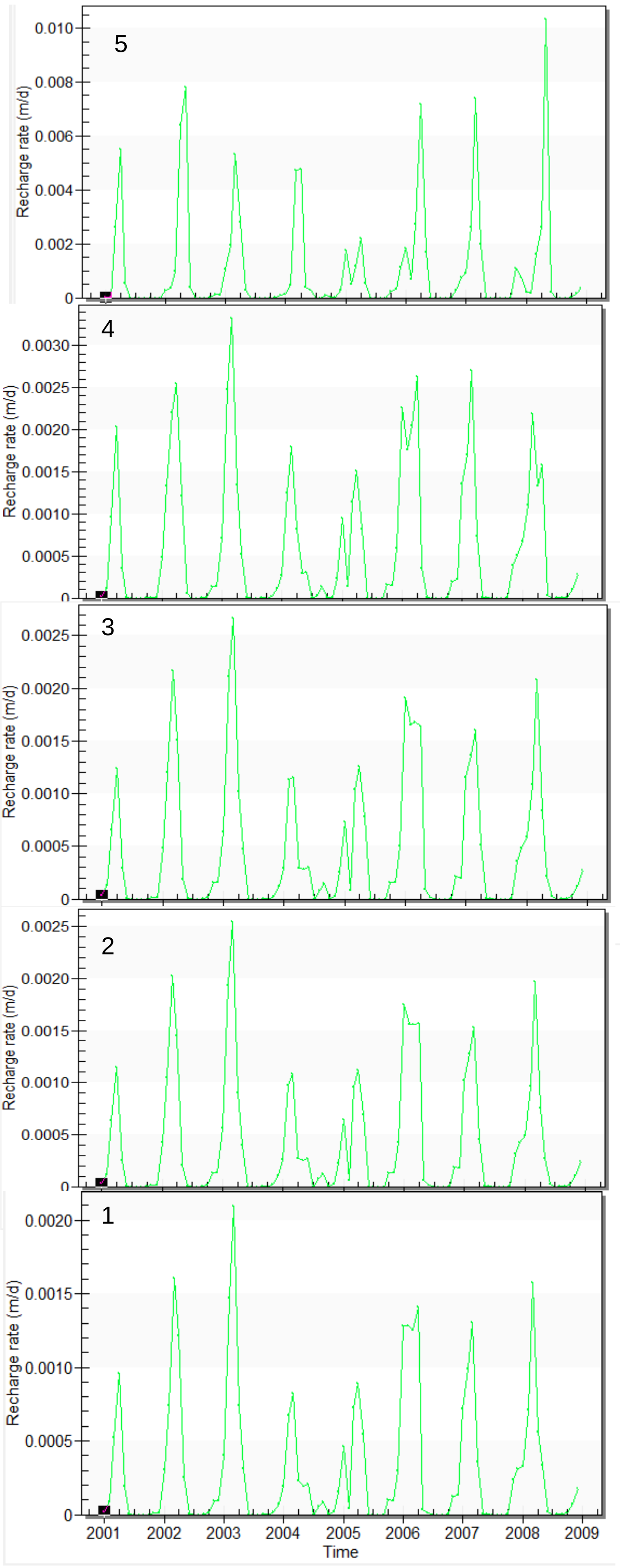

Figure 8.3 Monthly averaged infiltration rate for infiltration group 1-5, calculated by SMR. This has been used as infiltration input for the transient Modflow model.

8.2 Stationary Modflow Model

Field results have identified recharge zones in the Sediments of Bovill in the proximity of the Moscow Mountain (Figure 7.11). The aim of the stationary model was to estimate the quantity of aquifer recharge from the Moscow Mountain into the Wanapum and Grande Ronde (Figure 8.4 and Figure 8.5).

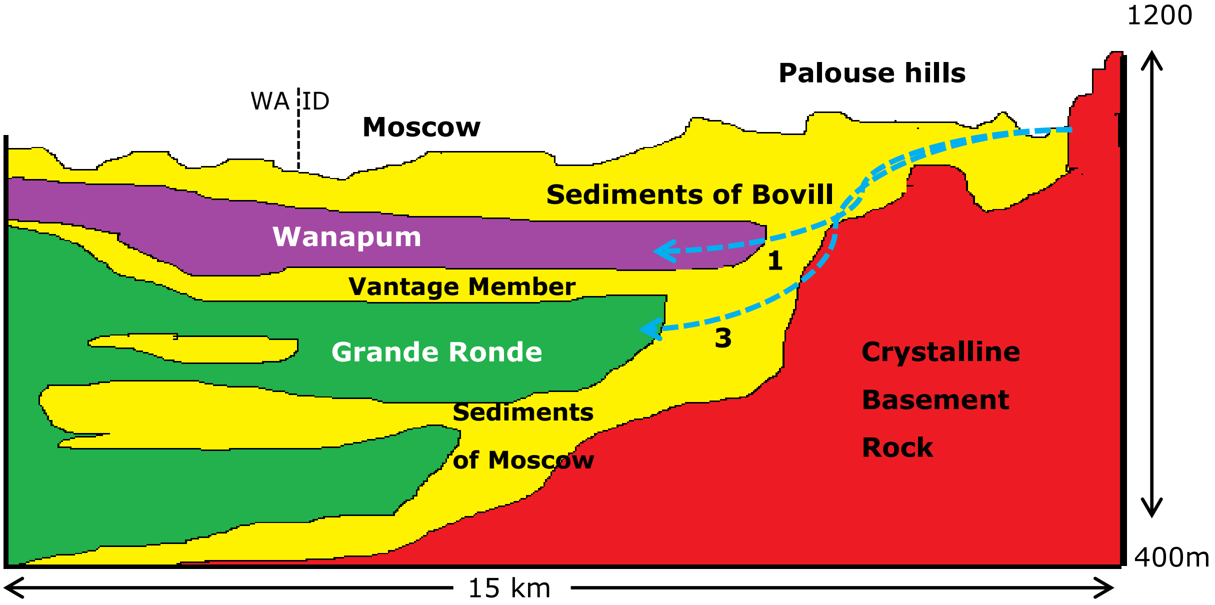

Figure 8.4 Geological cross-section of the Moscow sub-basin from west to east as has been presented earlier in chapter 2. Blue arrows correspond to the aquifer recharge quantified by the Modflow model, of which the numbers correspond to the numbers in Figure 8.7. Same arrows are also shown in Figure 8.5.

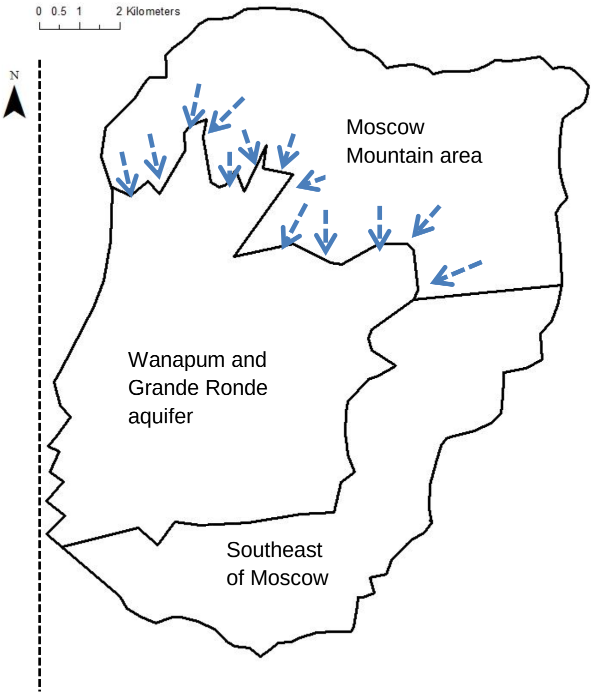

Figure 8.5 The aquifer recharge from Moscow Mountain to the Wanapum and Grande Ronde aquifer at the granite/basalt interface, as also has been illustrated in Figure 8.4. The other groundwater fluxes from the water balance (Figure 8.7) have not been printed here. Dotted line is the Idaho-Washington State boundary.

8.2.1 Model performance

The total aquifer recharge from the Moscow Mountain into the Wanapum and Grande Ronde aquifer, at the granite/basalt interface (Figure 8.5) has been calculated by the Modflow model. All fluxes from/to the Wanapum and Grande Ronde are further elaborated in §8.2.2. In this paragraph the model performance will be discussed.

8.2.1.1 Observations versus simulation

Simulated heads have been compared with the observed heads. Figure 8.6 shows the contour map of the simulated heads in the Moscow sub-basin at the depth of the Wanapum Aquifer. The contour-lines show a similar stream-pattern as the maps of Leek (Figure 2.20), which were made for a larger area with a lower resolution. The plots bars represent the declination to the observed heads. The acceptable range was taken as 10 m for this model, because of the large head differences known within the area (± 100 m) due to the complex geological structures, which was also described in §6.2.4. These large head differences at a

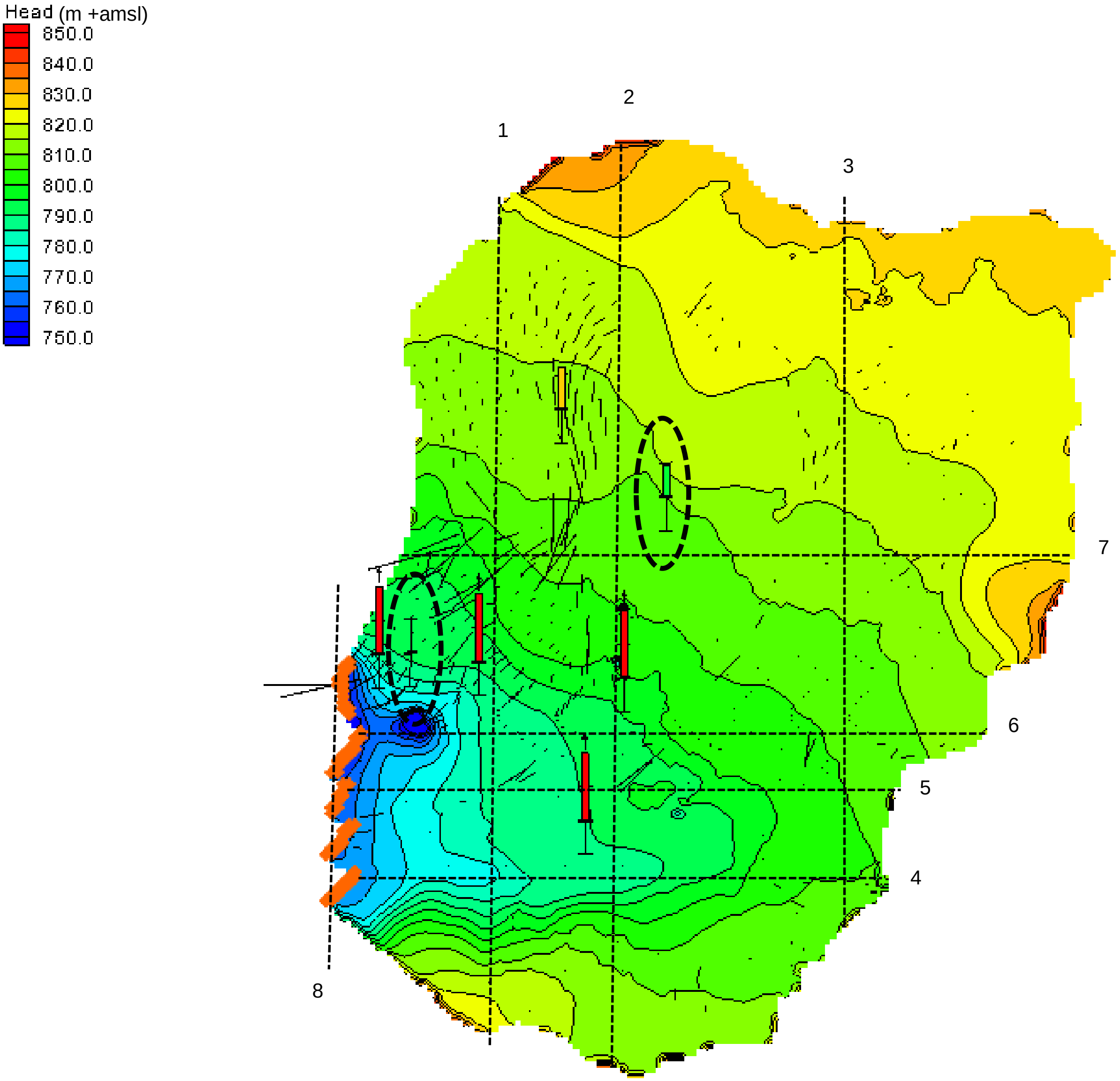

Figure 8.6 Potentiometric head at the depth of the upper part of the Wanapum Aquifer. Orange cells in the west represent the constant head boundary. Plots bars represent the declination to the observed heads, of which the green plot bars were simulated within an acceptable range (10 m) from the observed head. Arrows represent flow vectors. Dotted lines are cross-sections made from the simulated heads, in Appendix VIII.

short horizontal distance can also be seen in Figure 8.6. Near the west boundary, 2 observation wells are shown of which 1 has been simulated within the acceptable range ($\Delta H = H_{obs} - H_{sim} = -0.42$ m) and the other well was far off from this range ($\Delta H = -33.3$ m). All simulated heads were larger than the observed heads ($\Delta H = 25.5$, n =7). This can be explained by the simulated stream discharge. The model was able to simulate the estimated stream discharge of 0.7 m^3 s^-, by which the model has been optimized using trial and error. This optimization has been done using the sensitivity properties of the parameters (see §8.2.1.3). To be able to get enough stream discharge, the heads had to be higher than the observed heads. This was a choice made during the optimization. Because of the large local head differences in the area, simulating the total fluxes was seen as a more important way of optimizing than using water levels at single points.

8.2.1.2 Head distributions

Figure 8.6 shows the head distribution for the Wanapum, simulated by Modflow. More cross-sections of the simulated head in the Moscow sub-basin can be found in Appendix VIII.

8.2.1.3 Sensitivity Analysis

For the sensitivity of the model the most important parameters were chosen. These include the hydraulic conductivity of all hydrogeological units (HGU) (Table 6.4), the stream conductance, the boundary and the infiltration. Considering the research question of this study, the most important groundwater flux is the aquifer recharge coming from the Moscow Mountain, going into the Wanapum and Grande Ronde. So the effect of the parameters has been calculated on the aquifer recharge (Table 8.2). The sensitivity analysis was used in this study as a method to understand the system, to understand the possible ranges of the aquifer recharge from the Moscow Mountain and to use for the optimization as described above (calculated in §8.2.2).

The total aquifer recharge was calculated as 0.063 mm d^{-1} or $9.5*10^2$ m^3 d^{-1}. More about the aquifer recharge and other groundwater fluxes will be discussed in §8.2.2. Here the 0.063 mm d^{-1} is used as the aquifer recharge value for the basemodel. Table 8.2 shows the effect of changing the above mentioned parameters on the aquifer recharge. The aquifer recharge is mostly sensitive to the hydraulic conductivity of HGU 2. HGU 2 consists of decomposed, weathered granite and soft, fractured basalt (Table 6.3). A decrease in hydraulic conductivity of 50% results in smaller aquifer recharge of 20.1% flowing from the north of Moscow into the aquifers. Apparently, the hydraulic conductivity of HGU 2 plays an important role in the aquifer recharge shown by the relative high sensitivity.

An increase in the hydraulic conductivity does not necessarily mean a higher aquifer recharge. Table 8.2 shows that aquifer recharge can also decrease when the hydraulic conductivity is raised. This can be explained by more groundwater entering the streams due to higher hydraulic conductivities, which is not available anymore for aquifer recharge.

Also the infiltration calculated by SMR affects the aquifer recharge from the Moscow Mountain into the Wanapum and Grande Ronde. A 10% change in infiltration results in a similar change of approximately 9% in the aquifer recharge, so aquifer recharge is very much depending on the infiltration rate calculated by SMR.

As explained in §6.2.1 the west boundary was hard to derive from the available data. Table 8.2 shows the aquifer recharge is very insensitive to a change in the boundary. A rise or decrease of the western boundary with 5 m had almost a zero effect on the groundwater flux.

This can be explained by a low hydraulic conductivity at the western boundary, which is present there. These low hydraulic conductivities are present because the amount of permeable sediments and fractures in between the basalt layers decreases to the west, as explained in chapter 2. This is also represented in the model, which can be seen in Figure 6.11.

Table 8.2 Sensitivity analysis of the most important parameters to the net groundwater flux from the Moscow Mountain to the Wanapum and Grande Ronde.

Parameter	**Change**	**Aquifer recharge (mm d^{-1})**	**Change aquifer recharge compared to basemodel (%)**
Basemodel	**-**	0.063	0
HGU1	**+50%**	0.059	-6.1
	-50%	0.070	10.5
HGU2	**+50%**	0.071	11.7
	-50%	0.050	-20.1
HGU3	**+50%**	0.062	-2.0
	-50%	0.065	2.8
HGU4	**+50%**	0.063	-0.4
	-50%	0.064	0.4
Conductance Streams	**+25%**	0.063	0.4
	-25%	0.063	-0.6
SMR infiltration	**+10%**	0.069	8.8
	-10%	0.057	-9.1
Boundary	**+5m**	0.063	0.0
	-5m	0.063	-0.3

8.2.2 Water balance

The water balance has been derived for the Wanapum and Grande Ronde aquifer, which includes the aquifer recharge component (§8.2.2.1). The water balance has also been derived for the entire Moscow sub-basin, which includes the stream discharge for which the model has been optimized.

8.2.2.1 Wanapum and Grande Ronde aquifer

Figure 8.7 and Table 8.1 show the calculated net fluxes to the Wanapum and Grande Ronde. The model results show that the aquifer recharge to the Wanapum is all originating from the Moscow Mountain area. This flux is 0.035 mm d^{-1}. The Grande Ronde receives almost 2/3th of the total aquifer recharge from the Moscow Mountain (0.028 mm d^{-1}). The rest is originating from the overlying Vantage Member (0.017 mm d^{-1}), which includes leakage from the Wanapum (0.01 mm d^{-1}).

To compare the calculated aquifer recharge with the total well extraction: the wells extract in total 0.055 mm d^{-1} in the Moscow sub-basin from the aquifers, which is less than the total calculated aquifer recharge from the Moscow Mountain area (0.063 mm d^{-1}). Almost half of the well extraction amount was directly extracted from the Wanapum and Grande Ronde in the model. The rest of the well extraction occurred above or in between both aquifers, or outside the granite/basalt interface in the SOB.

The groundwater flux flowing across the western boundary from the Wanapum and Grande Ronde is in total 0.017 mm d^{-1} (Table 8.3). Water is also lost from the Wanapum to the overlying sediments, ending in the streams as discharge where impermeable layers are absent. The property of streams gaining water in this part of the Moscow sub-basin was also found by the discharge measurements done in this research (§7.3).

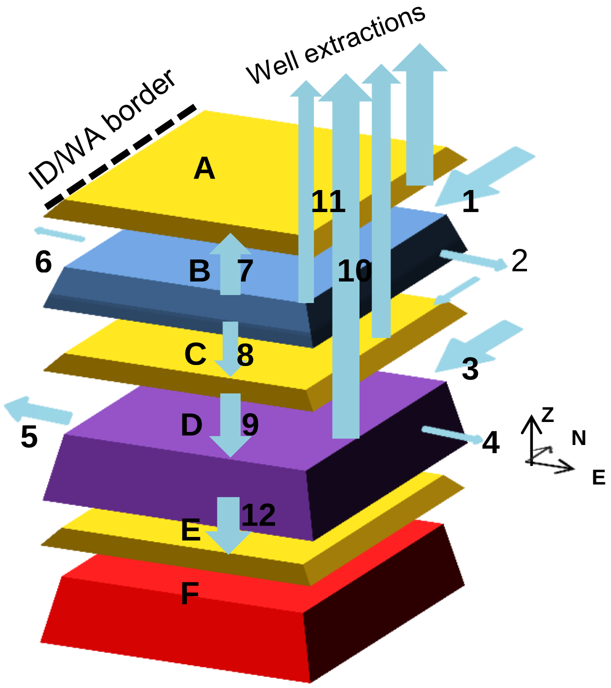

Figure 8.7 Schematic sketch of the stationary net fluxes calculated by Modflow. A = overlying sediments, B = Wanapum, C = Sediments in between aquifers called Vantage Member, D = Grande Ronde, E = Underlying sediments, F = Basement Rock. Fluxes are only drawn for the Wanapum (B) and Grande Gronde (D) . The thickness of the arrows indicates the approximate flux size. For the numbers , see Table 8.3

Table 8.3 Net fluxes to/from Wanapum and Grande Ronde, calculated from the stationary model by GMS Modflow. See fluxes in Figure 8.7. Negative flux means the flux leaves the Wanapum or Grande Ronde

Flux from/to	**Net fluxes to/from Wanapum (B)**			**Net fluxes to/from Grande Ronde (D)**		
	Flux nr.	Flux size		Flux nr.	Flux size	
		(mm d^{-1})	(m^3 d^{-1})		(mm d^{-1})	(m^3 d^{-1})
Moscow Mountain	1	0.035	$5.3*10^3$	3	0.028	$4.2*10^3$
Southeast of Moscow	2	-0.0016	$-2.4*10^2$	4	0.00	0
West Boundary	6	-0.0025	$-3.8*10^2$	5	-0.014	$-2.1*10^3$
Overlying sediments	7	-0.017	$-2.6*10^3$	9	0.017	$2.6*10^3$
Underlying sediments	8	-0.01	$-1.5*10^3$	12	-0.014	$-2.1*10^3$
Wells	11	-0.007	$-1.1*10^3$	10	-0.018	$-2.7*10^3$

8.2.2.2 Moscow sub-basin

Table 8.4 shows the flow budget for the entire stationary model of the Moscow sub-basin. Each simulated groundwater flow is explained below:

- The total simulated yearly averaged extraction from the wells is 8359 m^3 d^{-1} or 0.055 mm d^{-1}(§6.2.3.2).
- The drains have zero flow in the stationary model. Most of the drains run dry in summer and are running during winter. However, this cannot be simulated in the steady-state model.
- The total discharge in the rivers was estimated around 0.7 m^3 s^{-1} (§6.2.3.2), which is 0.40 mm d^{-1}. This flux has been used for the optimization of the model.
- The SMR infiltration has been calibrated for the Paradise Creek watershed (§6.1.4).
- The unknown fluxes are the western boundary fluxes (constant head), which close the water balance. Water flows into the model (0.009 mm d^{-1}), because a large city well extraction is located close to the boundary which gets water from the lower part in the Grande Ronde and also affects the boundary in these lower layers. This can also be seen in the cross-sections in Appendix VIII. The total flow out over the boundary is small (12%) compared to the total river leakage. The total river leakage is 80.7% of the total recharge.

Table 8.4 Water balance for the entire stationary model

Sources and Sinks	**Flow in (mm d^{-1})**	**Flow out (mm d^{-1})**
Wells	0	0.056
Drains	0	0
River Leakage	0	-0.40
SMR infiltration	0.50	0
Constant Head (west)	0.009	0.050
Total	0.51	-0.51

8.2.3 Preferential flow

Figure 8.8 and Appendix IX show the aquifer recharge occurs in certain zones. The scale of the Modflow model was not meant to include small sized paleo-channels, since the cell sizes in this model were chosen larger than the size of paleo-channels (chapter 6). However, zones with a relative high rate of aquifer recharge can represent zones where paleo-channels are present in large densities. The vectors shown in Figure 8.8 represent large groundwater fluxes of aquifer recharge.

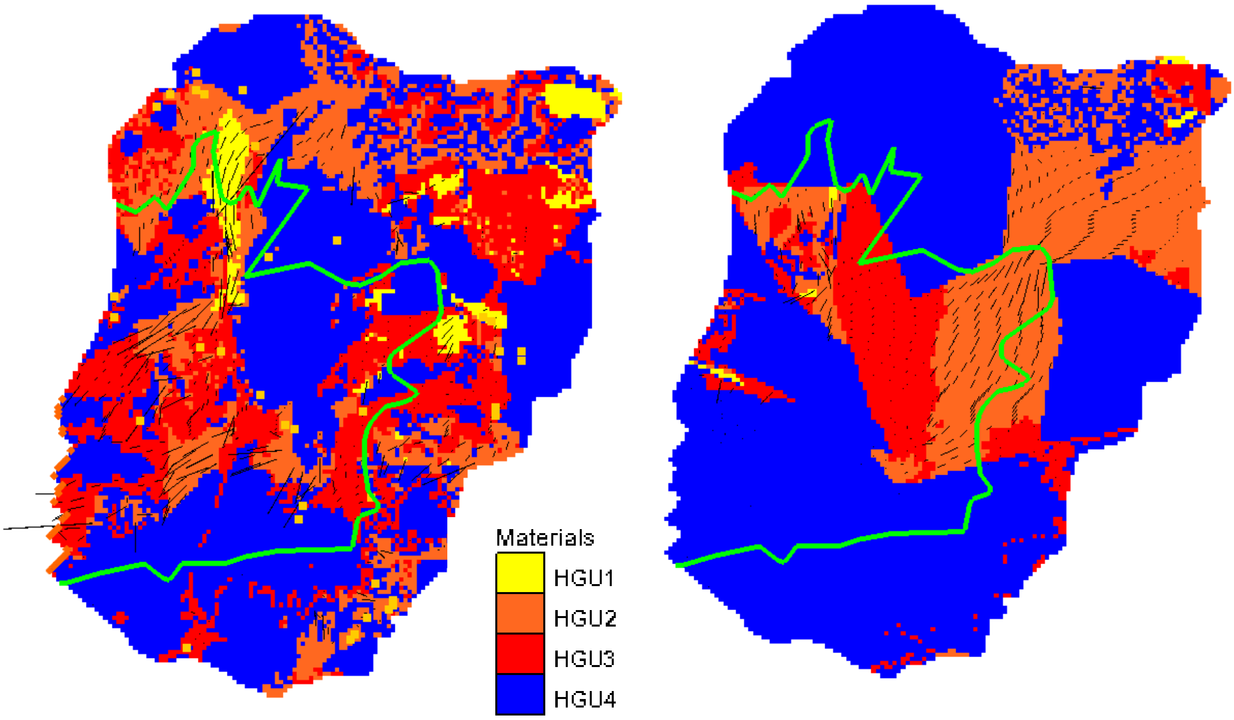

Figure 8.8 Top view on the upper part of the Wanapum (left) and the upper part of the Grande Ronde (right). Vectors are the groundwater fluxes. Green line forms the area covered by the Wanapum Formation. More cross-sections can be seen in Appendix IX.

8.3 Transient Modflow model

This study also included the first development of a transient model to model the seasonal differences in storage and groundwater levels. In §6.2.2.3 the input of the storage to Modflow has been explained. Since the transient model is only a first try out, it will only be described shortly here. No observation values have been added yet to the model and the model has not been calibrated. The transient model has only been compared by simulated stream discharge.

In the stationary model, all surplus of water would flow over the boundary, representing the extraction of Pullman. However, in the transient model the main surplus of water goes into the storage, resulting in increasing groundwater levels. Lowering the constant head boundary to represent the extraction of Pullman, did not result in a larger boundary flow, as could be expected based on the results of the stationary model (§8.2.1.3). For this reason, Pullman has been represented as an extraction point in Moscow. Pullman is located 8 km west of Moscow and extracts a similar amount of groundwater to Moscow. The extraction amount was assumed to be half the amount of the total extraction in the Moscow sub-basin. This is a rough guess, and it assumes that Pullman derives the other half from other directions than Moscow.

Appendix X shows the total out- and inflow of sources and sinks to the Wanapum and Grande Ronde aquifer, respectively. Almost all of the SMR simulated infiltration goes into the storage (Figure 8.9). The “Storage OUT – Storage IN” is the amount of flow that contributes to the change in head in the Moscow sub-basin. Figure 8.9 shows the “Storage OUT” (flow into the storage, out of the model) is larger than the “Storage IN” (flow out of the storage, into the model). This means the groundwater levels are increasing for the Moscow sub-basin, which is also shown by Figure 8.10 and Figure 8.11. Both the Wanapum and Grande Ronde groundwater levels increase with rates of approximately 0.2 - 0.3 m yr^{-1}, which is opposite of what has been observed (groundwater level declines of 0.3 m yr^{-1}) (Figure 2.22). Both graphs Figure 8.10 and Figure 8.11 show a decreasing slope over the year, meaning the groundwater levels stabilize after 25-30 years. This could mean a longer simulation run was needed to get the groundwater levels and storage in equilibrium. The groundwater level increase is the result of a too low outflow to the streams. Figure 8.12 shows the stream and drain discharge increases over time, following the increase of the groundwater levels. The drains start to get perennial flow at the end of the simulation period, which is in line with the discharge observations of these springs (De Graaf 2011). The average simulated stream discharge was a factor 3-4 too low due to water stored in the ground instead of entering the streams (an average yearly stream discharge of 60480 m^3 d^{-1} has been estimated before).

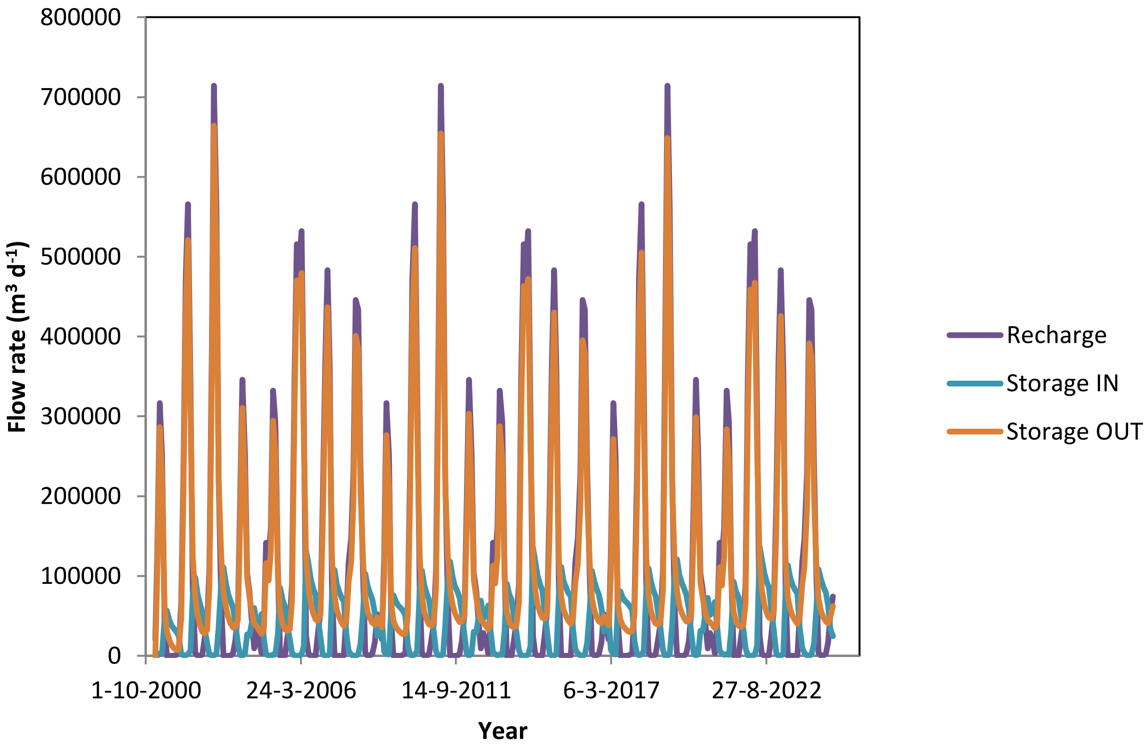

Figure 8.9 Transient model result for entire model. Storage out is the total flow rate which is stored. The storage out – storage in is the amount that contributes to increasing heads in the Moscow sub-basin. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).

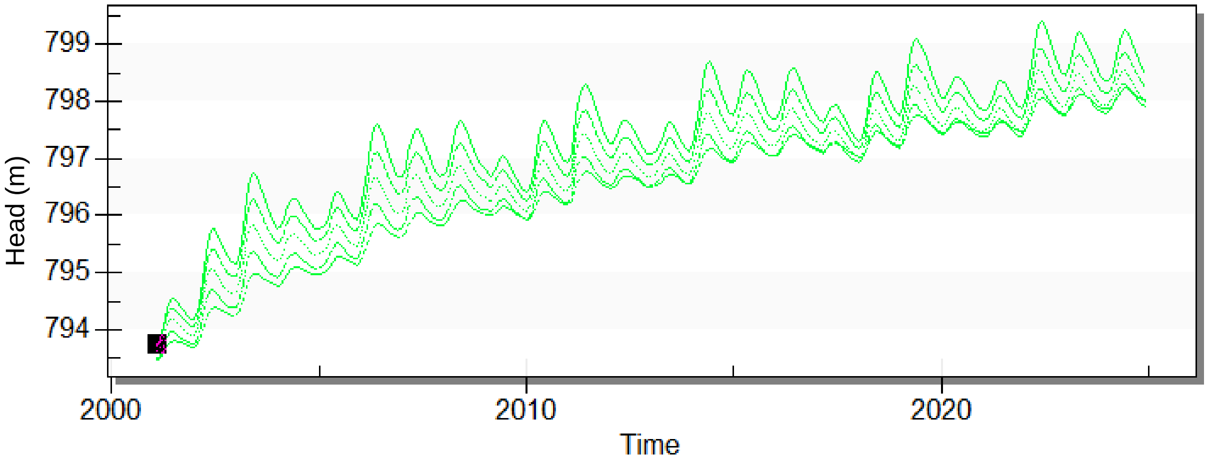

Figure 8.10 Head increase for the cells in the middle layer (layer 16) of the Wanapum Aquifer. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).

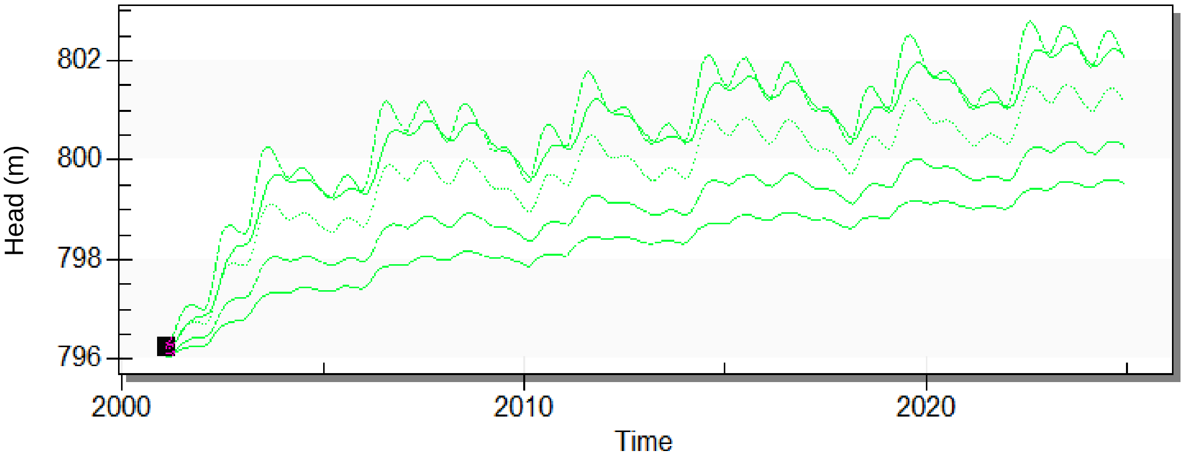

Figure 8.11 Head increase for the cells in the middle layer (layer 26) of the Grande Ronde Aquifer. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).

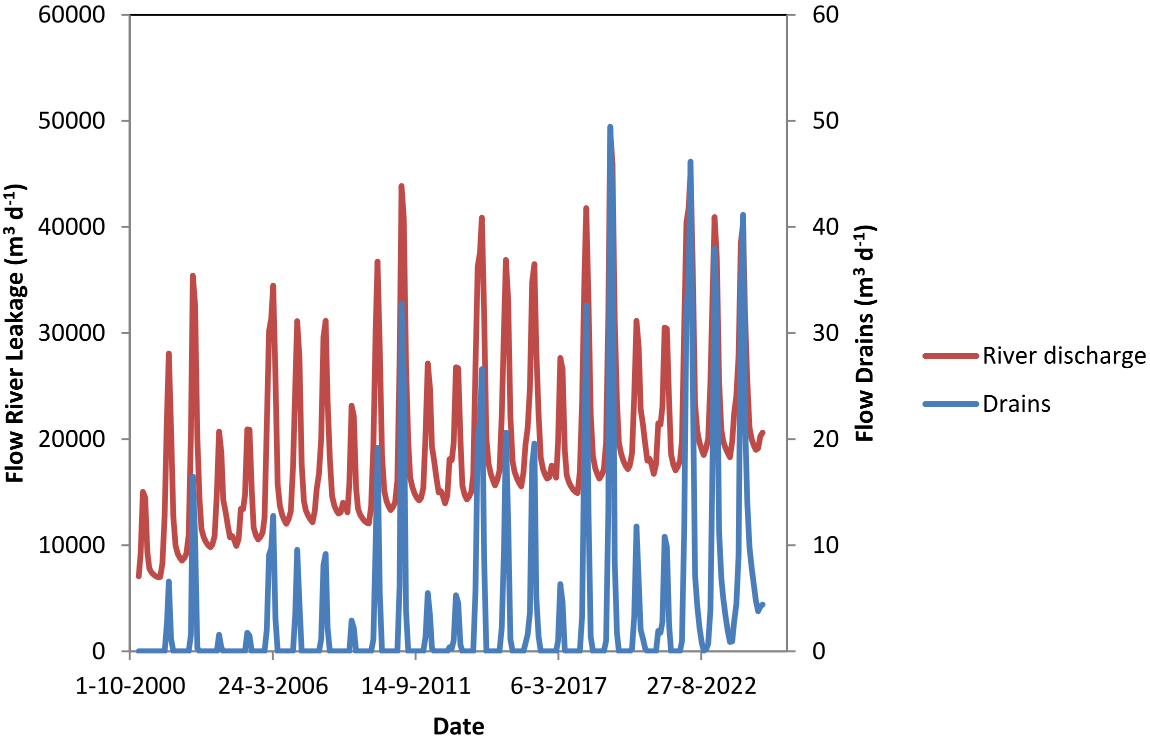

Figure 8.12 Transient model result of the river discharge and drain discharge for entire model. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).

9. Discussion

This study consisted of several field methods and modelling methods to determine recharge zones in the Moscow sub-basin. Some field methods clearly showed recharge occurs at certain locations. These methods include isotope, EC and temperature measurements done in the proximity of the granite/basalt interface, as well as discharge measurements done downstream of the WWTP. The stationary Modflow model in combination with the SMR model was able to quantify the aquifer recharge occurring in the Moscow sub-basin. Other methods like the caffeine sampling and the transient Modflow model were less able to show recharge connections. These methods will not be included in this chapter, but included in the recommendations in chapter 10. In this chapter both the field work and modelling will be discusses, in addition to what has already been discussed in the previous chapters. Previous findings and new findings will be combined in a synthesis at the end of this chapter.

9.1 Fieldwork

The fieldwork conducted in this study has been very depending on the wells in the study area. The existence of these wells was very valuable for this research, but it also causes some issues to deal with. Many of these wells were hard to track back in the well log database of IDWR, and just a small amount of these wells were getting water from just one geological layer, which was a requirement in this study. Together with the willingness of the well-owners, these factors limited the possibility of well locations that could be used for sampling. The preliminary, isotopic sampling with a large amount of sampled wells helped in selecting the wells of interest for this study (§5.1).

9.1.1 Isotopic, EC and temperature sampling

Remarkable of the field results is that indications for recharge in wells are not always consistent. A well showing a large isotopic fluctuation indicating recharge did not always resulted in a similar signature for recharge in the EC or temperature, and vice versa. This also shows the importance of measuring multiple factors that could indicate recharge as was done in this study, to come to an overall recharge indication.

The temperature drop measured in this study is hard to explain. Well #28 has a data logger installed in the well, measuring the temperature. The temperature data of the data logger shows fluctuations from summer to winter with a range of 1.5-2 ºC in 2006-2008, with an average temperature around 10.5 ºC. In this study the temperature range for the groundwater in this well was 6.4 ºC, so much larger. Similar results are found for well #60, which has been sampled with a bailer in this study. A data logger installed in this well showed a relatively stable temperature with very small (up to 1 ºC) fluctuations. Data loggers in other wells which were not sampled in this study also showed smaller seasonal, temperature differences than have been found in this study, of maximum 2 ºC. Apparently the data loggers and the well samples from this study are representing different water coming out of the same well. It could be that the data loggers are located halfway the well-pipe above the pumping level. In that case the data loggers might measure water which is not replaced by new water, since newer water comes in lower in the well pipe below the pump. So then the water measured by the data loggers represents the temperature at that specific depth. The water which has been sampled in this study might be newer water, coming in at the bottom of the well by pumping. However, the water from above the pumping level might drop down due to the pumping, and mix with the newer water coming in from the sides. In this study the sampling was done when the temperature of the water coming out of the tap had stabilized. However, it is still unclear what the relative amounts of old and new water is in the samples taken.

A small test was done to compare water which has been sampled according to the sampling protocol in this study (until temperature stabilizes), and water that has been sampled after leaving the tap open for 10-11 minutes. This test was done for 5 different wells, and resulted in similar isotopic and EC signatures for both methods. For 3 of the 5 wells the temperatures were similar after 10 minutes compared to the current applied method. However, for 2 of the 5 wells the temperature varied every minute within the 10 minutes the tap was running. The water temperature of well #26 stabilized in the 2nd minute to 6.7 ºC, dropped again to 5.3 ºC in the 5th minute, increased to 6.2 ºC in the 8th minute and dropped again to 5.6 ºC in the last minute. For well #27 a similar result was found. The temperature increased from 5.2 ºC to 10 ºC in the 4th minute, increased to 11.3 ºC in the 9th minute, and dropped again to 8.5 ºC in the 11th minute. No explanation was found for these temperature fluctuations. However, the relatively large temperature fluctuations from summer to winter found in this study might still be a proof of fast recharge occurring at those locations.

Although the wells were selected based on several requirements, the distance from the tap to the well was varying between the well locations. Ideally, the well tap would be connected straight to the well itself, which was the case for several wells. However, at some locations the tap could be up to 100 m away from the actual well. At these locations the water had to flow for a longer time until the temperature would stabilize and the sample could be taken. As described above, well #27 showed the fluctuating temperature in the 10 minutes sampling interval. This cannot be explained by the distance to the well, since the tap of well #27 is connected to the well itself.

9.1.2 Discharge Measurements

The discharge measurements downstream of the WWTP could have been affected by the difference in effluent discharge from the WWTP. However, measurements were done in a time interval of 3-5 hours, so the effect was expected to be negligible (§5.3). The difference between the two discharge measurements at 15th of June and 30th of June is probably not explained by the WWTP's effluent (§7.3). The results seem to indicate the infiltration area in the Paradise Creek depends on the amount of discharge in the Paradise Creek. A low discharge will shift the infiltration location upstream. It might also mean the location of the stream gaining water at the last measured location will shift upstream as well, which would explain why the gain of water was not found at the other time of sampling when there was a higher discharge.

9.2 Modelling

Although a groundwater decline has been observed in the Moscow sub-basin for the past decades (Figure 2.22), the stationary groundwater model simulated a relatively large aquifer recharge. The assumptions and uncertainties of several components in the model will be discussed here, in addition to what already has been discussed in previous chapters.

9.2.1 SMR

Several assumptions have been made in SMR which are discussed here.

- As explained in §6.1.4, the SMR model is an extension of the SMR model which was calibrated by Dijksma et al. (2011). This calibrated model covered 1/3 of the Moscow sub-basin and has been applied to the whole Moscow sub-basin (Figure 6.2). Since there was a lack of time to calibrate the SMR model again for the entire Moscow sub-basin, it was assumed the calibrated model would still apply for the entire Moscow sub-basin. This assumption could be made because of similar geological and hydrological characteristics of the Moscow sub-basin to the Paradise Creek watershed.
- The subsurface lateral flow that was included in the SMR model was deactivated, since discussion existed on the existence of lateral flow in an unsaturated zone (§4.1.8). SMR uses the land slope to determine the gradient of the lateral flow flux, which is a debatable assumption (pers. comment. G. Bier, 2013). The SMR was run both with and without the lateral flow. Since SMR has been averaged over the whole period 2001-2008, it resulted in a relatively small difference in the average percolation. The lateral flow is mainly occurring during the high precipitation peaks, which occur just a few months a year. The deactivated lateral flow has now been mainly present as surface runoff.
- SMR interpolates the weather data linear with the elevation between the two weather stations. This simple assumption is very useful to include spatial differences in precipitation and ET_{pot} in the SMR model, but it might result in a under- or overestimated precipitation and ET_{pot}. However, it is the same method as used by the calibrated SMR model of Dijksma et al. (2011) which had similar elevation differences as the Moscow sub-basin.
- SMR is very much depending on the soil map. A mistake made in the soil map could result in a different infiltration. However, all the SMR-input had cell sizes of 30x30 m which was used again in the groundwater model which had cell sizes of 100x100 m, so mistakes in the input data such as the soil map will be averaged out.

The sensitivity analysis showed that the aquifer recharge is relatively sensitive to the SMR infiltration. If the SMR infiltration would be 13% lower, the aquifer recharge from the Moscow Mountain would be lower than the total well extraction in Moscow. However, this would still mean the Moscow Mountain is the most important and significant recharge area, since all net aquifer recharge to the Wanapum came from this area (Table 8.3).

9.2.2 Stationary Modflow model

9.2.2.1 Western boundary

In §8.2.1.3 the western boundary has been discussed. However, it has not been discussed yet what the boundary flow represents. Since the well extraction of Pullman has not been included in the model, it is now represented by the western boundary. The well extraction by Pullman is almost similar to the well extraction by Moscow (Figure 2.21). The calculated groundwater flux over the boundary is also almost equal to the total well extraction of the Moscow sub-basin (Table 8.4). Although the aquifer recharge from the Moscow Mountain turned out to be insensitive for the boundary, the boundary still results in large uncertainties in the final water balance (§8.2.2). Unknown is the effect of Pullman's well extraction on the groundwater levels in Moscow. The potentiometric maps made by Leek (2006) in Figure 2.20 suggest a major part of the groundwater in Pullman originates from the Moscow sub-basin. However, these potentiometric maps are based on a relative small amount of observation wells.

9.2.2.2 Schematization of Modflow

The Modflow model used 4 hydrogeological units, which is relatively coarse. All sediment types or geological units were assigned to one of these hydrogeological units. The spatial variability of the impermeable and permeable units was based on 207 well logs from the IDWR database (§6.2.3.1). However, these well logs are made by well drillers from many different companies. They will probably interpret the geology different, and use a different level of detail. The difference between hard and medium basalt might be different for each driller, and it might result in a different hydrogeological unit (HGU3 or HGU4). For this reason, the schematization of Modflow has also been checked based on the geological descriptions by Grader (2011). The cross-section in Figure 6.11 shows the hydrogeological units present which are representing the geological units as described by Grader (2011). For the aim of this research the choice of 4 hydrogeological units was good enough to determine what the significant recharge area is in the Moscow sub-basin. However, more hydrogeological units might result in a model with more detail.

As was described in this study, the aquifer recharge might occur via meter scale paleo-channels. Paleo-channels were not included in the Modflow model, because the used cell sizes were too large and modelling the paleo-channels did not belong to the aim of this research. De Graaf (2011) was able to simulate aquifer recharge through paleo-channels and concluded a relatively large aquifer recharge might occur through these paleo-channels in the Paradise Creek watershed. However, it is still unknown where these paleo-channels are located and what their density is. These paleo-channels might be present in the aquifer recharge zones which have been identified in this study.

9.3 Synthesis

9.3.1 Introduction

This research consisted of several approaches to identify recharge connections in the Moscow sub-basin. Knowing the source locations of recharge to the basalt aquifers in the Moscow sub-basin is vital for understanding the long-term sustainability of its water resources and for developing solutions which enhance recharge and protect the drinking water sources for future generations. The results of these approaches have been elaborated in chapter 7 and 8. In this synthesis the results will be combined together and interpreted from the general context as described in chapter 2.

Dijksma et al. (2011) showed that it is possible recharge occurs only in certain landscape positions. They suggested two regions of the Moscow sub-basin with the greatest potential for recharge:

1.) Paleo-channels draining from high elevation forested regions on the Moscow Mountain range
2.) Direct vertical recharge from streams run directly over basalt (e.g., Paradise Creek near the state line).

These hypotheses will be discussed again based on the results found in this research.

9.3.2 Hypothesis: Paleo-channels

The hypothesis of recharge occurring through paleo-channels was already mentioned in §2.7.4. Additionally, the results of this study will be used to reconstruct the recharge pathways according to this hypothesis.

The SMR model calculated that the highest infiltration (up to 2.0 mm d^{-1}) occurs at the Moscow Mountain (Figure 8.1). At the Moscow Mountain paleo-channels consist of fractures and weathered, decomposed granite. At the interface of the Moscow Mountain and the Sediments of Bovill the water can reach permeable layers below or in between impermeable layers located in the Sediments of Bovill. These permeable layers consist of weathered, decomposed granite, known as paleo-channels (§2.6.4.3). Some of these flow paths which are running close to the surface level hit the surface and end up as a spring (example Willard spring). Signs of recharge at a lower elevation were found by temperature, EC and $\delta^{18}O$ measurements of wells and springs throughout the Moscow sub-basin (Figure 7.11). Several evidences of recharge were found in wells running in permeable sand/gravel layers below impermeable layers. The evidences of recharge increase in the proximity of the Moscow Mountain. Fairley et al. (2006) indicated vertical recharge in the Moscow sub-basin is very limited due to the argillic soil-properties in the area, so the main source of the recharge seems to be the Moscow Mountain. This advocates that recharge occurs laterally from the Moscow Mountain infiltration area through the subsurface via prefential flow paths. These preferential flow paths running through the Sediments of Bovill seem to reach the interbeds of the Wanapum Aquifer, since recharge indications were also found in wells running in the basalt and its interbeds (§7.1.4).

Especially remarkable is the temperature drop found in the wells and springs. Groundwater often shows a smoothened and lagged signal in temperature (Figure 3.2); unless recharge occurs relatively fast and the signal of the air temperature is preserved in the groundwater temperature. This seems to be the case and also advocates for a relatively fast recharge occurring in the area.

Results of Modflow also indicated all aquifer recharge to the Wanapum is coming from the Moscow Mountain. Similar results of recahrge were found for the Grande Ronde, except from some additional interaction between overlying sediments and the Wanapum (§8.2.2). Sensitivity analyses of the parameters also showed the importance of weathered granite layers and fractured basalt layers to the aquifer recharge coming from the Moscow Mountain (§8.2.1.3). The aquifer recharge has been identified in certain zones in the subsurface (Figure 8.8). Preferential flow path locations (Figure 7.11) seem to correspond with the aquifer recharge zones identified in Figure 8.8. This means the modelling results are in line with the field results, both showing indications of aquifer recharge with the Moscow Mountain being the source.

9.3.3 Hypothesis: Streams running over basalt

The hypothesis of vertical recharge by streams running over the basalt west of Moscow was tested by sampling wells for caffeine, as well as discharge measurements in the Paradise Creek west of Moscow.

The caffeine sampling indicated a recharge connection to a 25 m deep well at the UIGRS, which runs into the Wanapum. The water in the well is probably originating from the Paradise Creek, in which caffeine has been detected upstream of the WWTP.

Figure 7.13 underlines the hypothesis, since a significant amount of water is lost downstream of Moscow, similar to the findings of Rosenberry (2008) who found water infiltration through the streambed near this location. The location of recharge seems to depend on the total amount of water being discharged in the stream, which is an indication of a surface water / groundwater interaction. Figure 7.13 shows that between 30-50 l s^{-1} is lost downstream of Moscow at the two measurement days in June, which is 2600 – 4300 m^3 d^{-1}. This is a large amount compared to the well extraction of 8359 m^3 d^{-1}. Figure 7.13 also shows that the stream also gained water near Pullman, but it is unknown whether this is the same water which has infiltrated earlier upstream. More research is needed to quantify the net loss of the Paradise Creek below the WWTP.

10. Conclusions & Recommendations

10.1 Conclusions

The main research question of this study was:

Where does recharge of the aquifers occur in the Moscow sub-basin?

The aim of this study was to test two hypotheses of where recharge might occur in the Moscow sub-basin; the granite/basalt interface and the Paradise Creek running directly over basalt near the state line. The conclusions are:

Does recharge occur at the granite/basalt interface?

1. Biweekly isotope, temperature and EC measurements of 24 wells showed strong indications of recharge in the proximity of the Moscow Mountain. The first indications show a response time of 2-5 weeks.
2. These indications have also been found in wells which reach below impermeable layers, suggesting recharge occurs in lateral flow paths from the Moscow Mountain.
3. Similar indications were found at several wells in the Wanapum Aquifer suggesting the recharge reaches the aquifer system from the Moscow Mountain through the Sediments of Bovill, entering the aquifer at the granite/basalt interface.
4. A Soil Moisture Routing model indicated the Moscow sub-basin has an average infiltration rate of 0.5 mm d^{-1}, of which the Moscow Mountain has the highest average infiltration rates of up to 2.0 mm d^{-1}. These infiltration rates are the source of aquifer recharge.
5. The aquifer recharge was most sensitive to the hydraulic conductivity of weathered, decomposed granite and soft, fractured basalt. This is an indication that the aquifer recharge mainly occurs through these geological units.
6. The stationary groundwater model showed similarly to the field results that the aquifer recharge occurs in certain zones at the granite/basalt interface.

Does recharge occur vertically from streams running directly over basalt?

1. Caffeine was found in 1 well (25 m deep in Wanapum basalt) at the University of Idaho Groundwater Research Site, which is an indication of a recharge connection with the Paradise Creek running through Moscow, in which caffeine has been detected as well.
2. An enriched ^{18}O signature was found in a deep well (93 m in basalt) near the Paradise Creek, which might suggest recharge occurs.
3. Relatively large discharge losses are found in the Paradise Creek between Moscow and Pullman. At certain stretches the discharge loss was 50-70% measured in June 2013.

How large are these recharge fluxes?

1. A stationary GMS Modflow model, indicated the Wanapum and Grande Ronde receive a relatively large amount of aquifer recharge from the granite/basalt interface, respectively 0.035 mm d^{-1} ($5.3*10^3$ m^3 d^{-1}) and 0.028 mm d^{-1} ($4.2*10^3$ m^3 d^{-1}) versus an average well extraction of 0.055 mm d^{-1} ($8.4*10^3$ m^3 d^{-1}) in the Moscow sub-basin.
2. Relatively large stream losses up to $4.3*10^3$ m^3 d^{-1} were measured in the Paradise Creek, which runs directly over basalt downstream the WWTP.

10.2 Recommendations

This research has led to the following recommendations:

- The isotopic field study northeast of Moscow should continue, so a dataset of at least 2 years is available to be able to derive the response times of the groundwater. This should include the precipitation and stream measurements done by Sánchez-Murillo, to be able to interpret the groundwater results.
- Increase of understanding in the temperature drop is needed which has been found in the field measurements.
- Besides caffeine, other tracers should be investigated on their suitability for the waste water treatment plant. Examples are hormones like oestrogen which might be present in the effluent of the waste water treatment plant. For this, samples of the effluent should be taken and analysed on all possible tracers
- GeoRadar or electrical resistivity tomography could be used to determine the densities of the paleo-channels between the Moscow Mountain and the aquifer. This will also help in improving the quantification in the modelling.
- Pullman should be included in the groundwater model to be able to include the effect of a similar extraction 8 km west of Moscow.
- A continuation with the transient groundwater model is needed to be able to include the seasonal effects, to increase the understanding of the quantities and to model and understand the groundwater decline in the Moscow sub-basin. Better estimations are needed for the specific storage.
- More well logs can be added to the groundwater model. There are around 800 wells in the Moscow sub-basin, of which 207 have been added to this groundwater model. Also the ones without an exact known coordinate can be included to improve the model.
- Statistics should be applied to all well logs in the Moscow sub-basin to determine the relative amounts of sand/gravel layers compared to clay layers. This will also help in determining the amount of paleo-channels/preferential flow paths.
- A combination of the groundwater model made in this study and the model of De Graaf (2011) should be made to be able to include the small scale paleo-channels in the Moscow sub-basin. This can also include the above mentioned GeoRadar results.
- More discharge measurements stations are needed in the creeks in the Moscow sub-basin to be able to calibrate the groundwater models.
- Exploration to use the Moscow Mountain and/or the Paradise Creek as a recharge area is needed, with the ideas of Managed Aquifer Recharge concept (MAR).

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Appendix I: Well logs used for isotopic sampling

Below all the well logs are included of the wells used during the isotopic sampling. Also descriptions of the wells without a well log and the springs have been included here.

Descriptions:

The spring #6 is from the same owners as well #5. The spring consists of a hose attached to a hole in the ground. Water flows out of the hose with intervals of a few minutes. It seems that pressure is building up below the surface, and water is released when the pressure reaches a certain level. The spring is flowing continuous over the year.

The well # 14 is from the Robinson Park. The well pumps up water from 335 feet deep (102m) (pers. comm. Andrew Grant, supervision of Latah County Parks; 2013)

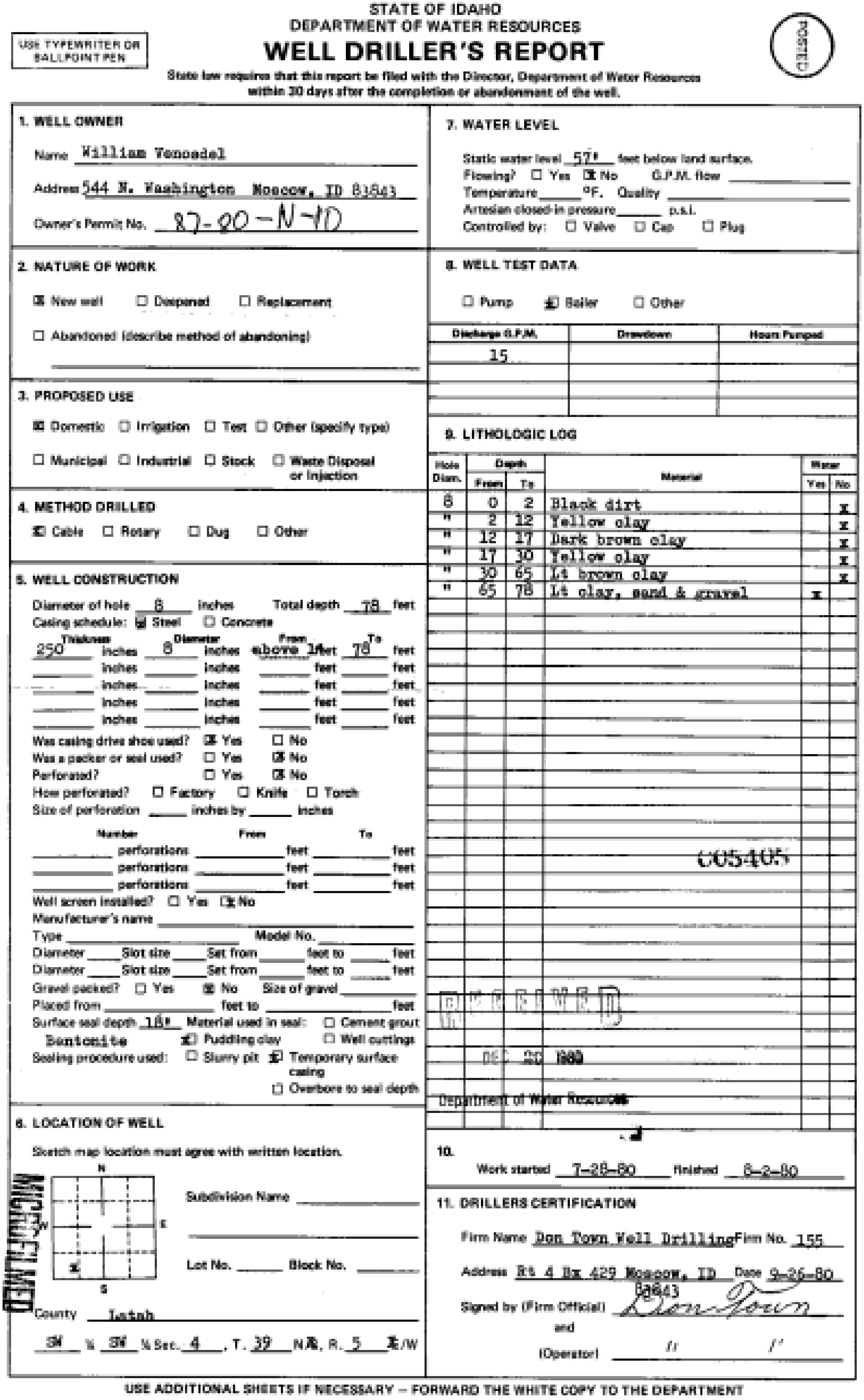
The spring #19 is from Jenis Willard. More research on this spring was done by Woelders (2009). This spring is unique in the area since water runs below a thick clay layer in a sandy, gravel layer. Probably this spring is the end of a paleo-channel. The spring is flowing continuous over the year.

Well #35 is the well from George Grader. The well is 307 feet deep.

Plant Science Farm

Well #39 or T16D is a well of 25 m depth, running in the Wanapum Basalt

Well #41 is a very old well which does not have a well log. The well is an artesian well, and except from one month in the summer, the well is flowing continuously year-round. The well is getting water from the Wanapum.



USE TYPEWRITER OR BALLPOINT PEN

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

POSTED

1. WELL OWNER

Name William Venosdel

Address 544 N. Washington Moscow, ID 83843

Owner's Permit No. 87-00-N-ID

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement

☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Other (specify type)

☐ Municipal ☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

4. METHOD DRILLED

☒ Cable ☐ Rotary ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Diameter of hole 8 inches Total depth 78 feet

Casing schedule: ☒ Steel ☐ Concrete

Thickness		Diameter		From		To	
250	inches	8	inches	above 1	feet	78	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type Model No.
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☒ No Size of gravel
Placed from ____ feet to ____ feet
Surface seal depth 18' Material used in seal: ☐ Cement grout
Bentonite ☒ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☒ Temporary surface casing ☐ Overbore to seal depth

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

MICROFILMED

Subdivision Name
Lot No. ____ Block No. ____
County Latah
SW ¼ SW ¼ Sec. 4 , T. 39 N/S, R. 5 E/W

7. WATER LEVEL

Static water level 57' feet below land surface.
Flowing? ☐ Yes ☒ No G.P.M. flow
Temperature ____ °F. Quality
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug

8. WELL TEST DATA

☐ Pump ☒ Bailer ☐ Other

Discharge G.P.M.	Drawdown	Hours Pumped
15		

9. LITHOLOGIC LOG

Hole Diam.	Depth		Material	Water	
	From	To		Yes	No
8	0	2	Black dirt		x
"	2	12	Yellow clay		x
"	12	17	Dark brown clay		x
"	17	30	Yellow clay		x
"	30	65	Lt brown clay		x
"	65	78	Lt clay, sand & gravel	x	

C05405

RECEIVED
DEC 30 1980
Department of Water Resources

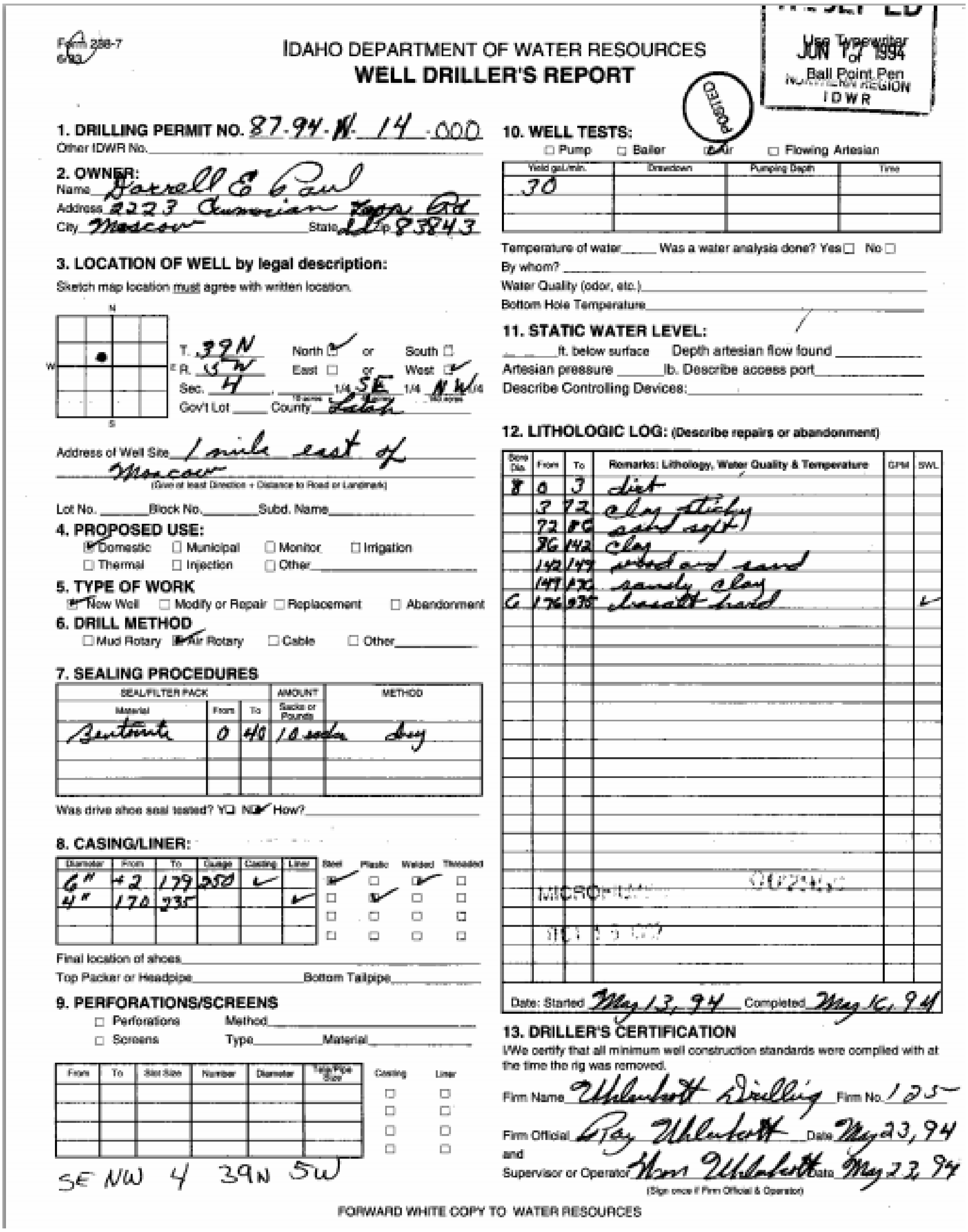
10. Work started 7-28-80 finished 8-2-80

11. DRILLERS CERTIFICATION

Firm Name Don Town Well Drilling Firm No. 155
Address Rt 4 Bx 429 Moscow, ID 83843 Date 9-26-80
Signed by (Firm Official) Don Town
and
(Operator) " "

USE ADDITIONAL SHEETS IF NECESSARY – FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #1



Form 238-7
6/93

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

Use Typewriter or Ball Point Pen

JUN 17 1994
NORTHERN REGION
IDWR

POSTED

1. DRILLING PERMIT NO. 87-94-W-14-000
Other IDWR No. ____

2. OWNER:
Name Darrell E Paul
Address 2223 [illegible] Rd
City Moscow State ID Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

T. 39N North ☑ or South ☐
R. 5W East ☐ or West ☑
Sec. 4, ____ 1/4 SE 1/4 NW 1/4
Gov't Lot ____ County Latah

Address of Well Site 1 mile east of Moscow
(Give at least Direction + Distance to Road or Landmark)

Lot No. ____ Block No. ____ Subd. Name ____

4. PROPOSED USE:
☑ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ____

5. TYPE OF WORK
☑ New Well ☐ Modify or Repair ☐ Replacement ☐ Abandonment

6. DRILL METHOD
☐ Mud Rotary ☑ Air Rotary ☐ Cable ☐ Other ____

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
Bentonite	0	40	10 sacks	dry

Was drive shoe seal tested? Y☐ N☑ How? ____

8. CASING/LINER:

Diameter	From	To	Gauge	Casing	Liner	Steel	Plastic	Welded	Threaded
6"	+2	179	.250	✓		☑	☐	☑	☐
4"	170	235			✓	☐	☑	☐	☐
						☐	☐	☐	☐
						☐	☐	☐	☐

Final location of shoes ____
Top Packer or Headpipe ____ Bottom Tailpipe ____

9. PERFORATIONS/SCREENS
☐ Perforations Method ____
☐ Screens Type ____ Material ____

From	To	Slot Size	Number	Diameter	Tele/Pipe Size	Casing	Liner
						☐	☐
						☐	☐
						☐	☐
						☐	☐

SE NW 4 39N 5W

10. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Depth	Time
30			

Temperature of water ____ Was a water analysis done? Yes ☐ No ☐
By whom? ____
Water Quality (odor, etc.) ____
Bottom Hole Temperature ____

11. STATIC WATER LEVEL:
____ ft. below surface Depth artesian flow found ____
Artesian pressure ____ lb. Describe access port ____
Describe Controlling Devices: ____

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	GPM	SWL
8	0	3	dirt		
	3	72	clay sticky		
	72	86	sand soft		
	86	142	clay		
	142	149	[illegible] and sand		
	149	176	sandy clay		
6	176	235	basalt hard		✓

MICROFILMED

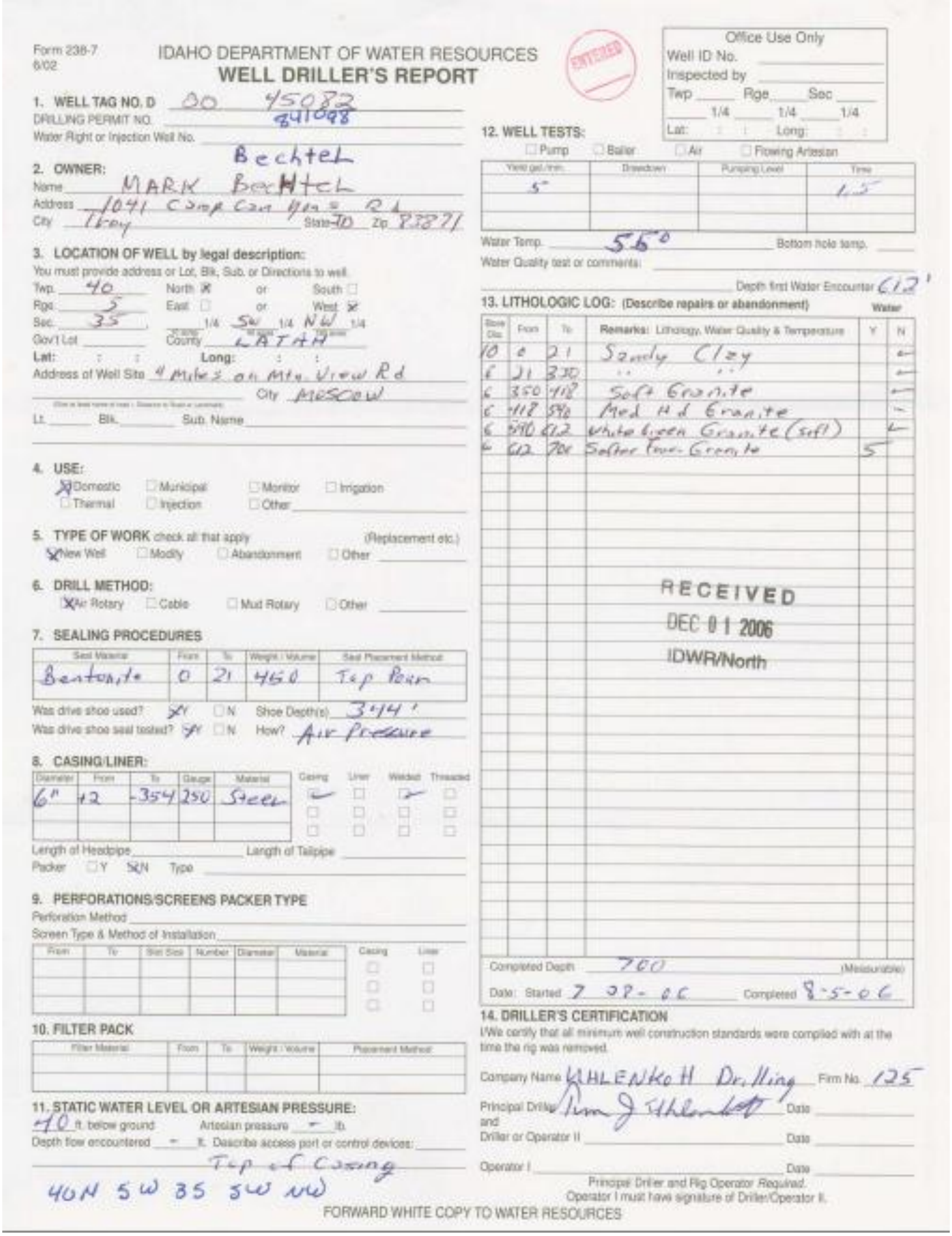
Date: Started May 13, 94 Completed May 16, 94

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Uhlenkott Drilling Firm No. 125
Firm Official Ray Uhlenkott Date May 23, 94
and
Supervisor or Operator Tom Uhlenkott Date May 23, 94
(Sign once if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Well log of well #5



Form 238-7
6/02

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

ENTERED

Office Use Only
Well ID No. ______
Inspected by ______
Twp ____ Rge ____ Sec ____
____ 1/4 ____ 1/4 ____ 1/4
Lat: : : Long: : :

1. WELL TAG NO. D 00 45082
DRILLING PERMIT NO. 841098
Water Right or Injection Well No. ______

2. OWNER:
Bechtel
Name MARK BecHtel
Address 1041 Camp Can Yon Rd
City Troy State ID Zip 83871

3. LOCATION OF WELL by legal description:
You must provide address or Lot, Blk, Sub. or Directions to well.
Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 35 , ____ 1/4 SW 1/4 NW 1/4
Gov't Lot ______ County LATAH
Lat: : : Long: : :
Address of Well Site 4 Miles on Mtn View Rd
City MOSCOW
Lt. ____ Blk. ____ Sub. Name ______

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ______

5. TYPE OF WORK check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other ______

6. DRILL METHOD:
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other ______

7. SEALING PROCEDURES

Seal Material	From	To	Weight / Volume	Seal Placement Method
Bentonite	0	21	460	Top Pour

Was drive shoe used? ☒ Y ☐ N Shoe Depth(s) 344'
Was drive shoe seal tested? ☒ Y ☐ N How? Air Pressure

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
6"	+2	-354	250	Steel	☑	☐	☑	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe ______ Length of Tailpipe ______
Packer ☐ Y ☒ N Type ______

9. PERFORATIONS/SCREENS PACKER TYPE
Perforation Method ______
Screen Type & Method of Installation ______

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. FILTER PACK

Filter Material	From	To	Weight / Volume	Placement Method

11. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
40 ft. below ground Artesian pressure - lb.
Depth flow encountered - ft. Describe access port or control devices: ______
Top of Casing

40N 5W 35 SW NW

12. WELL TESTS:
☐ Pump ☐ Bailer ☐ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
5			1.5

Water Temp. 55° Bottom hole temp. ______
Water Quality test or comments: ______
Depth first Water Encounter 612'

13. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	21	Sandy Clay		—
6	21	330	" "		—
6	350	418	Soft Granite		—
6	418	590	Med Hd Granite		—
6	590	612	white Green Granite (soft)		—
6	612	700	Softer Fine Granite	5	

RECEIVED
DEC 01 2006
IDWR/North

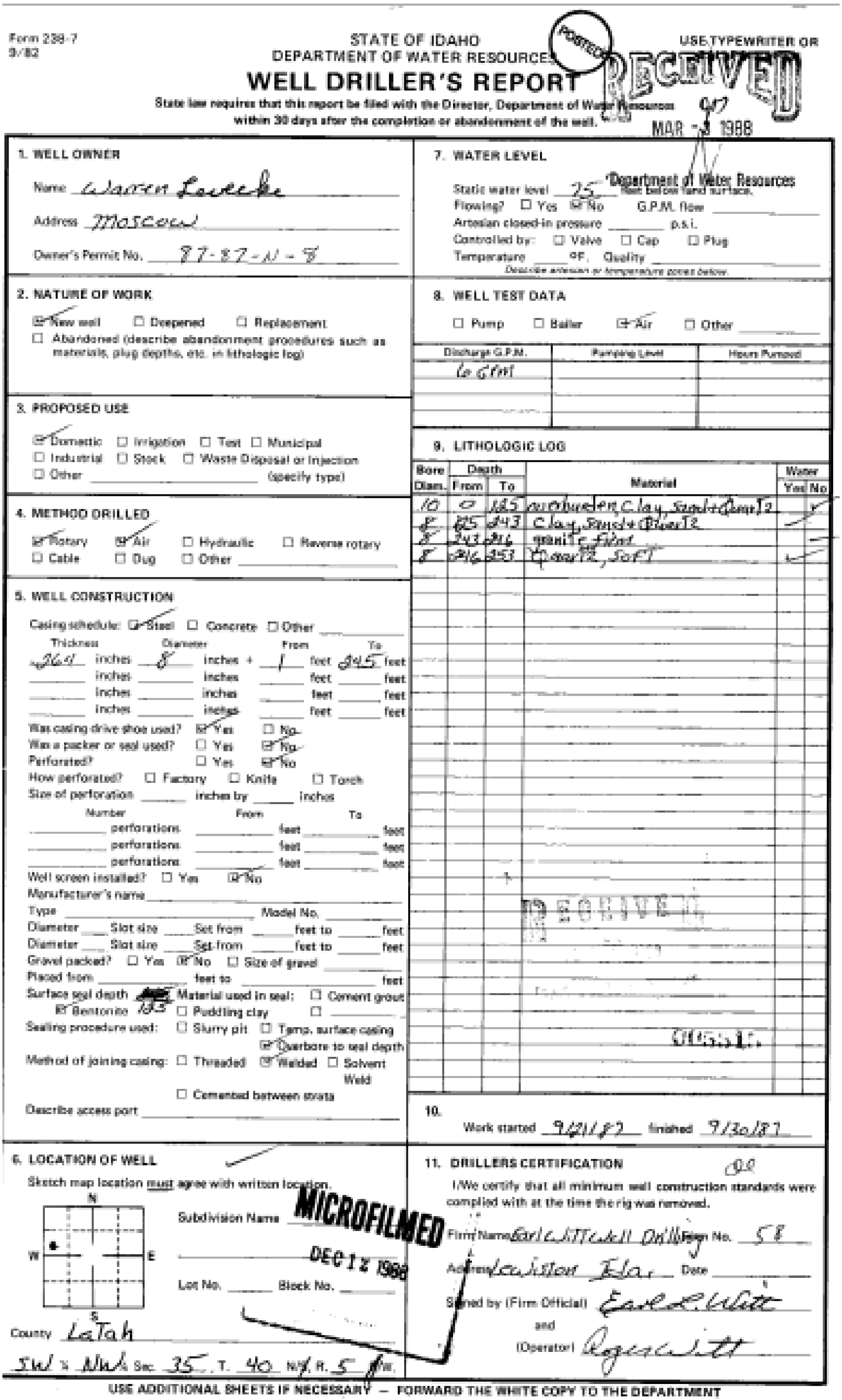
Completed Depth 700 (Measurable)
Date: Started 7 28-06 Completed 8-5-06

14. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Company Name UHLENKOTT Drilling Firm No. 125
Principal Driller Tim J Uhlenkott Date ______
and
Driller or Operator II ______ Date ______
Operator I ______ Date ______
Principal Driller and Rig Operator Required.
Operator I must have signature of Driller/Operator II.

FORWARD WHITE COPY TO WATER RESOURCES

Well log of well #8



Form 238-7
9/82

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR

POSTED

RECEIVED
MAR -3 1988
Department of Water Resources

1. WELL OWNER

Name Warren Loecke
Address Moscow
Owner's Permit No. 87-87-N-8

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☑ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ____ (specify type)

4. METHOD DRILLED

☑ Rotary ☑ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ____

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other ____

Thickness		Diameter		From		To	
.264	inches	8	inches +	1	feet	245	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☑ Yes ☐ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name ____
Type ____ Model No. ____
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel ____
Placed from ____ feet to ____ feet
Surface seal depth 185 Material used in seal: ☐ Cement grout ☑ Bentonite ☐ Puddling clay ☐ ____
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☑ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ____

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name ____
Lot No. ____ Block No. ____

MICROFILMED
DEC 12 1988

County Latah
SW ¼ NW ¼ Sec. 35, T. 40 N, R. 5 W.

7. WATER LEVEL

Static water level 75 feet below land surface.
Flowing? ☐ Yes ☑ No G.P.M. flow ____
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality ____
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☑ Air ☐ Other ____

Discharge G.P.M.	Pumping Level	Hours Pumped
6 GPM		

9. LITHOLOGIC LOG

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
10	0	185	overburden, Clay, Sand+Quartz		✓
8	185	243	Clay, Sand+Quartz	✓	
8	243	246	granite firm		✓
8	246	353	Quartz, soft	✓	

10.

Work started 9/21/87 finished 9/30/87

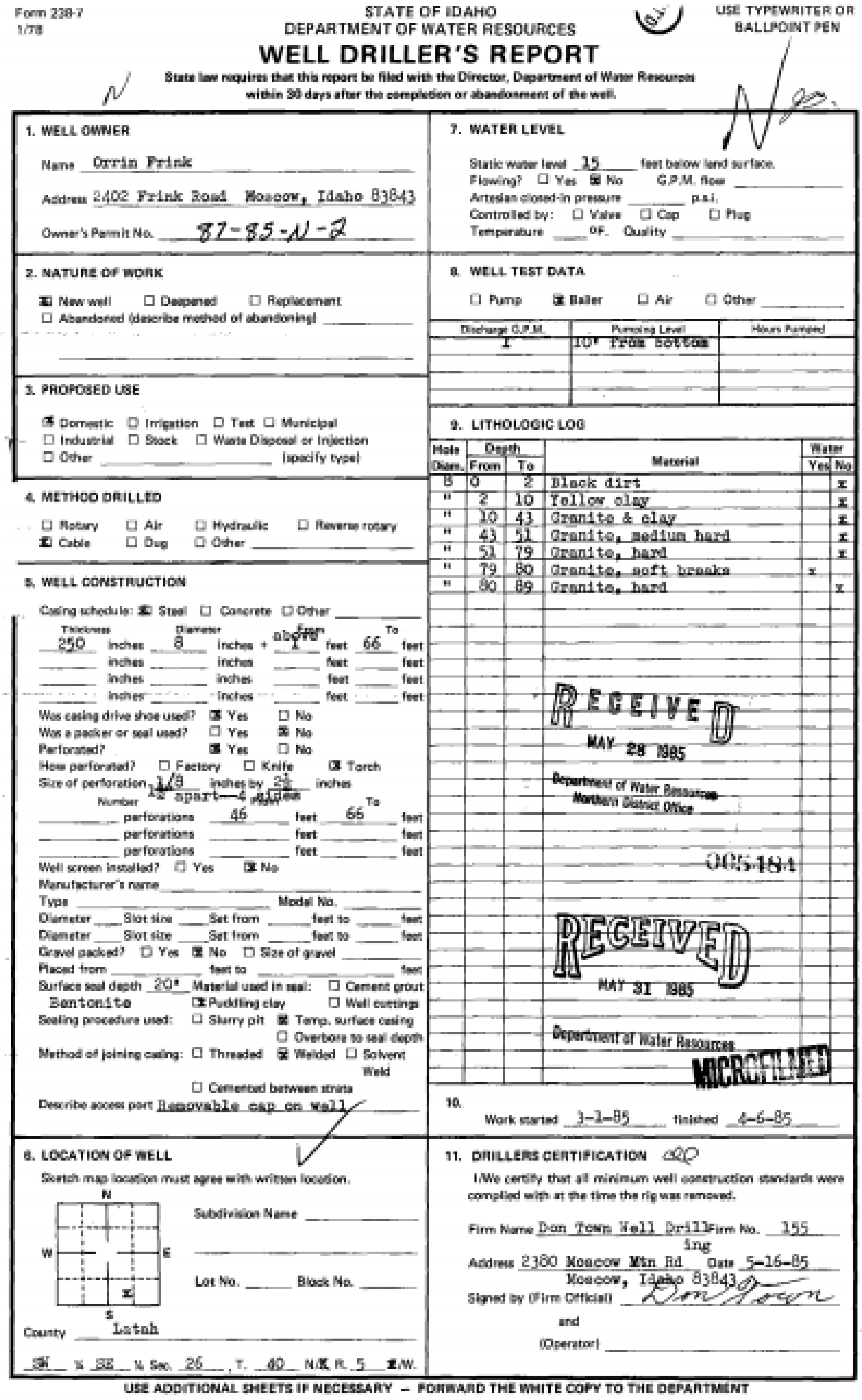
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Earl L. Witt Well Drilling Firm No. 58
Address Lewiston Ida. Date ____
Signed by (Firm Official) Earl L. Witt
and
(Operator) Roger Witt

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #9



Form 238-7
1/78

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

USE TYPEWRITER OR BALLPOINT PEN

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Orrin Frink
Address 2402 Frink Road Moscow, Idaho 83843
Owner's Permit No. 87-85-N-2

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☒ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other

Thickness		Diameter		From		To	
250	inches	8	inches +	above 1	feet	66	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☒ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☒ Torch
Size of perforation 1/8 inches by 2½ inches
12 apart—4 sides

Number		From		To	
	perforations	46	feet	66	feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type Model No.
Diameter Slot size Set from feet to feet
Diameter Slot size Set from feet to feet
Gravel packed? ☐ Yes ☒ No ☐ Size of gravel
Placed from feet to feet
Surface seal depth 20' Material used in seal: ☐ Cement grout
Bentonite ☒ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☒ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port Removable cap on well

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
x
S

Subdivision Name
Lot No. Block No.
County Latah
SW ¼ SE ¼ Sec. 26 , T. 40 N/~~S~~, R. 5 ~~E~~/W.

7. WATER LEVEL

Static water level 15 feet below land surface.
Flowing? ☐ Yes ☒ No G.P.M. flow
Artesian closed-in pressure p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature °F. Quality

8. WELL TEST DATA

☐ Pump ☒ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped
1	10' from bottom	

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	0	2	Black dirt		x
"	2	10	Yellow clay		x
"	10	43	Granite & clay		x
"	43	51	Granite, medium hard		x
"	51	79	Granite, hard		x
"	79	80	Granite, soft breaks	x	
"	80	89	Granite, hard		x

RECEIVED
MAY 28 1985
Department of Water Resources
Northern District Office

005484

RECEIVED
MAY 31 1985
Department of Water Resources

MICROFILMED

10.

Work started 3-1-85 finished 4-6-85

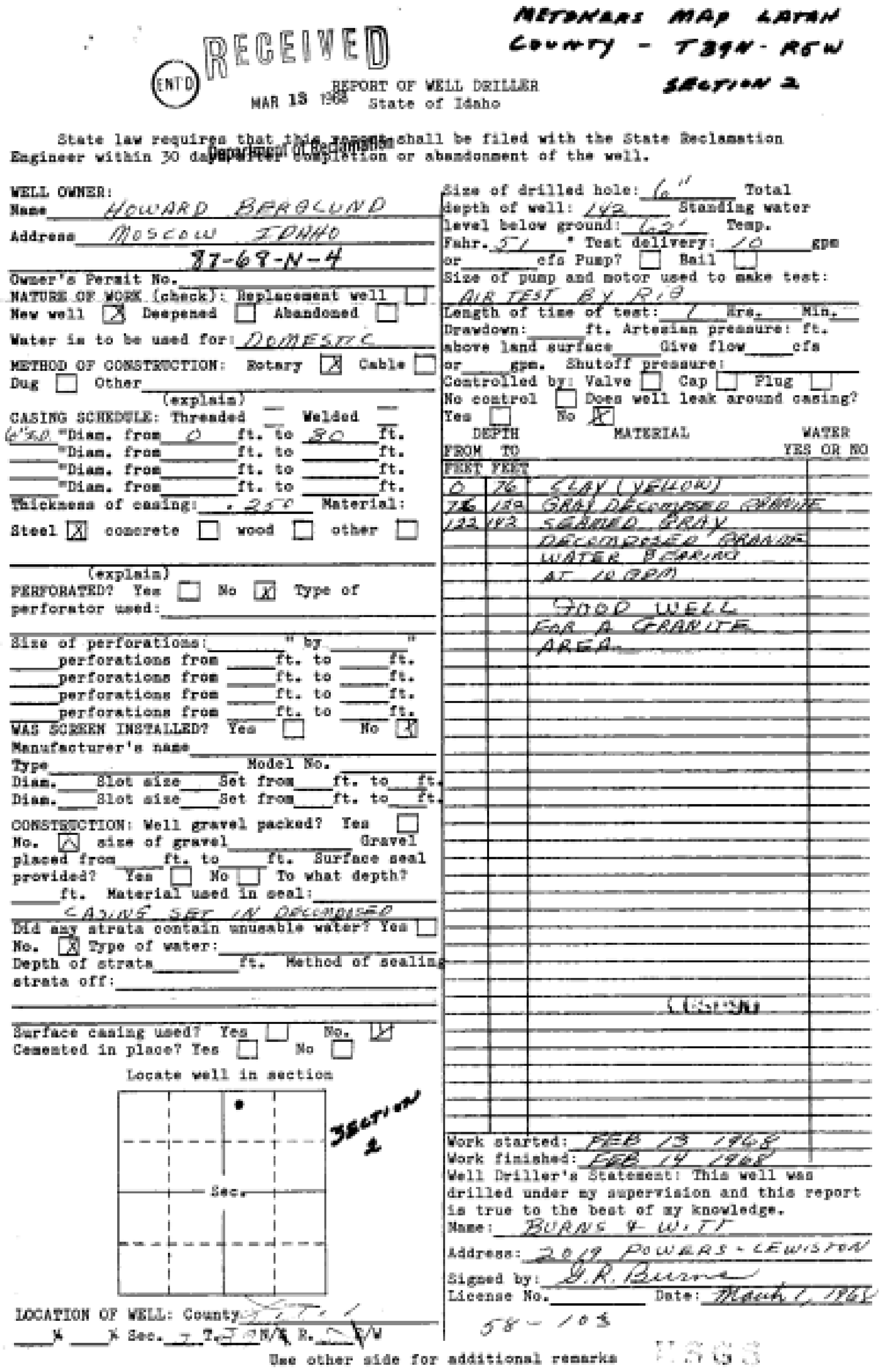
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Don Town Well Drilling Firm No. 155
Address 2380 Moscow Mtn Rd Moscow, Idaho 83843 Date 5-16-85
Signed by (Firm Official) Don Town
and
(Operator)

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #11



METSKERS MAP LATAH COUNTY - T39N - R6W SECTION 2

RECEIVED
ENT'D
MAR 13 1968
Department of Reclamation

REPORT OF WELL DRILLER
State of Idaho

State law requires that this report shall be filed with the State Reclamation Engineer within 30 days after completion or abandonment of the well.

WELL OWNER:
Name HOWARD BERGLUND
Address MOSCOW IDAHO
37-69-N-4
Owner's Permit No.
NATURE OF WORK (check): Replacement well ☐ New well ☒ Deepened ☐ Abandoned ☐
Water is to be used for: DOMESTIC
METHOD OF CONSTRUCTION: Rotary ☒ Cable ☐ Dug ☐ Other ______ (explain)
CASING SCHEDULE: Threaded __ Welded __
6"x20 "Diam. from 0 ft. to 80 ft.
"Diam. from ___ ft. to ___ ft.
"Diam. from ___ ft. to ___ ft.
"Diam. from ___ ft. to ___ ft.
Thickness of casing: .250 Material: Steel ☒ concrete ☐ wood ☐ other ☐ ______ (explain)
PERFORATED? Yes ☐ No ☒ Type of perforator used: ______
Size of perforations: ___" by ___"
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.
___ perforations from ___ ft. to ___ ft.
WAS SCREEN INSTALLED? Yes ☐ No ☒
Manufacturer's name ______
Type ______ Model No. ______
Diam. ___ Slot size ___ Set from ___ ft. to ___ ft.
Diam. ___ Slot size ___ Set from ___ ft. to ___ ft.
CONSTRUCTION: Well gravel packed? Yes ☐ No. ☒ size of gravel ______ Gravel placed from ___ ft. to ___ ft. Surface seal provided? Yes ☐ No ☐ To what depth? ___ ft. Material used in seal: CASING SET IN DECOMPOSED
Did any strata contain unusable water? Yes ☐ No. ☒ Type of water: ______
Depth of strata ___ ft. Method of sealing strata off: ______
Surface casing used? Yes ☐ No. ☒
Cemented in place? Yes ☐ No ☐
Locate well in section
Sec.
SECTION 2
LOCATION OF WELL: County LATAH
___ ¼ ___ ¼ Sec. 2 T. 39 N/S R. 5 E/W

Size of drilled hole: 6" Total depth of well: 142 Standing water level below ground: 62' Temp. Fahr. 51 ° Test delivery: 10 gpm or ___ cfs Pump? ☐ Bail ☐
Size of pump and motor used to make test: AIR TEST BY RIG
Length of time of test: 1 Hrs. ___ Min.
Drawdown: ___ ft. Artesian pressure: ft. above land surface ___ Give flow ___ cfs or ___ gpm. Shutoff pressure: ______
Controlled by: Valve ☐ Cap ☐ Plug ☐ No control ☐ Does well leak around casing? Yes ☐ No ☒

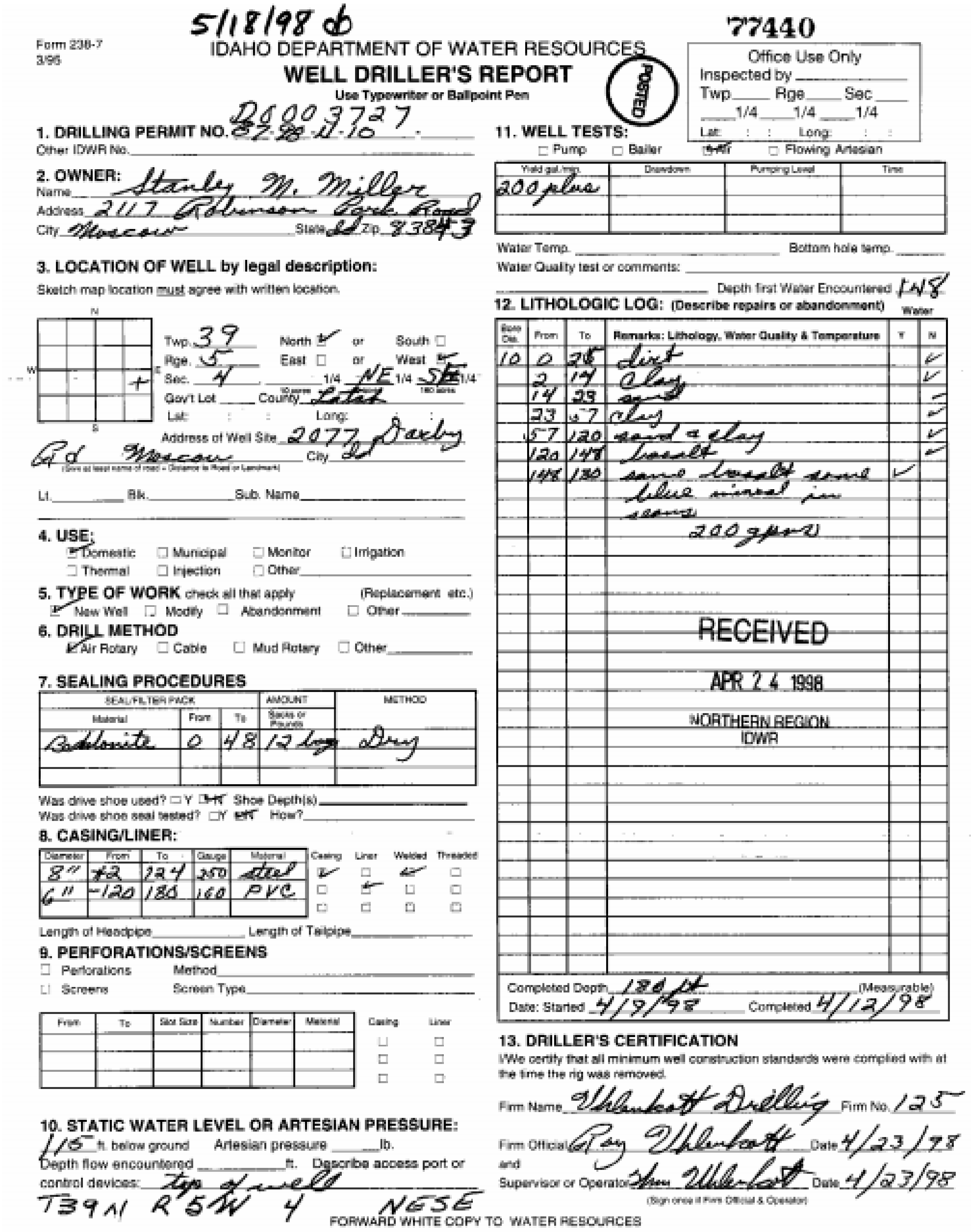
DEPTH FROM FEET	DEPTH TO FEET	MATERIAL	WATER YES OR NO
0	76	CLAY (YELLOW)	
76	122	GRAY DECOMPOSED GRANITE	
122	142	SEAMED GRAY DECOMPOSED GRANITE WATER BEARING AT 10 GPM	
		GOOD WELL FOR A GRANITE AREA.	

Work started: FEB 13 1968
Work finished: FEB 14 1968
Well Driller's Statement: This well was drilled under my supervision and this report is true to the best of my knowledge.
Name: BURNS & WITT
Address: 2019 POWERS - LEWISTON
Signed by: G.R. Burns
License No. ______ Date: March 1, 1968
58-108

Use other side for additional remarks

USGS

Well log of well #17



5/18/98 ob

Form 238-7
3/95

77440

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Use Typewriter or Ballpoint Pen

POSTED

Office Use Only
Inspected by ______
Twp.____ Rge____ Sec ____
____1/4 ____1/4 ____1/4
Lat: : : Long: : :

1. DRILLING PERMIT NO. D0003727 82-98-11-10
Other IDWR No. ______

2. OWNER:
Name Stanley M. Miller
Address 2117 Robinson Park Road
City Moscow State Id Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp. 39 North ☑ or South ☐
Rge. 5 East ☐ or West ☑
Sec. 4, ______ 1/4 NE 1/4 SE 1/4
Gov't Lot ____ County Latah
Lat: : : Long: : :
Address of Well Site 2077 Darby Rd Moscow City Id
(Give at least name of road + Distance to Road or Landmark)
Lt.______ Blk.______ Sub. Name______

4. USE:
☑ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other______

5. TYPE OF WORK check all that apply (Replacement etc.)
☑ New Well ☐ Modify ☐ Abandonment ☐ Other______

6. DRILL METHOD
☑ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other______

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
Bentonite	0	48	12 bags	Dry

Was drive shoe used? ☐ Y ☑ N Shoe Depth(s)______
Was drive shoe seal tested? ☐ Y ☑ N How?______

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8"	+2	124	250	steel	☑	☐	☑	☐
6"	-120	180	160	PVC	☐	☑	☐	☐
					☐	☐	☐	☐

Length of Headpipe______ Length of Tailpipe______

9. PERFORATIONS/SCREENS
☐ Perforations Method______
☐ Screens Screen Type______

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
115 ft. below ground Artesian pressure ______lb.
Depth flow encountered ______ft. Describe access port or control devices: top of well

T39N R5W 4 NESE

FORWARD WHITE COPY TO WATER RESOURCES

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
200 plus			

Water Temp. ______ Bottom hole temp. ______
Water Quality test or comments: ______
Depth first Water Encountered 148

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	25	dirt		✓
	2	14	clay		✓
	14	23	sand		✓
	23	57	clay		✓
	57	120	sand & clay		✓
	120	148	basalt		✓
	148	180	same basalt some blue mineral in seams	✓	
			200 gpm		

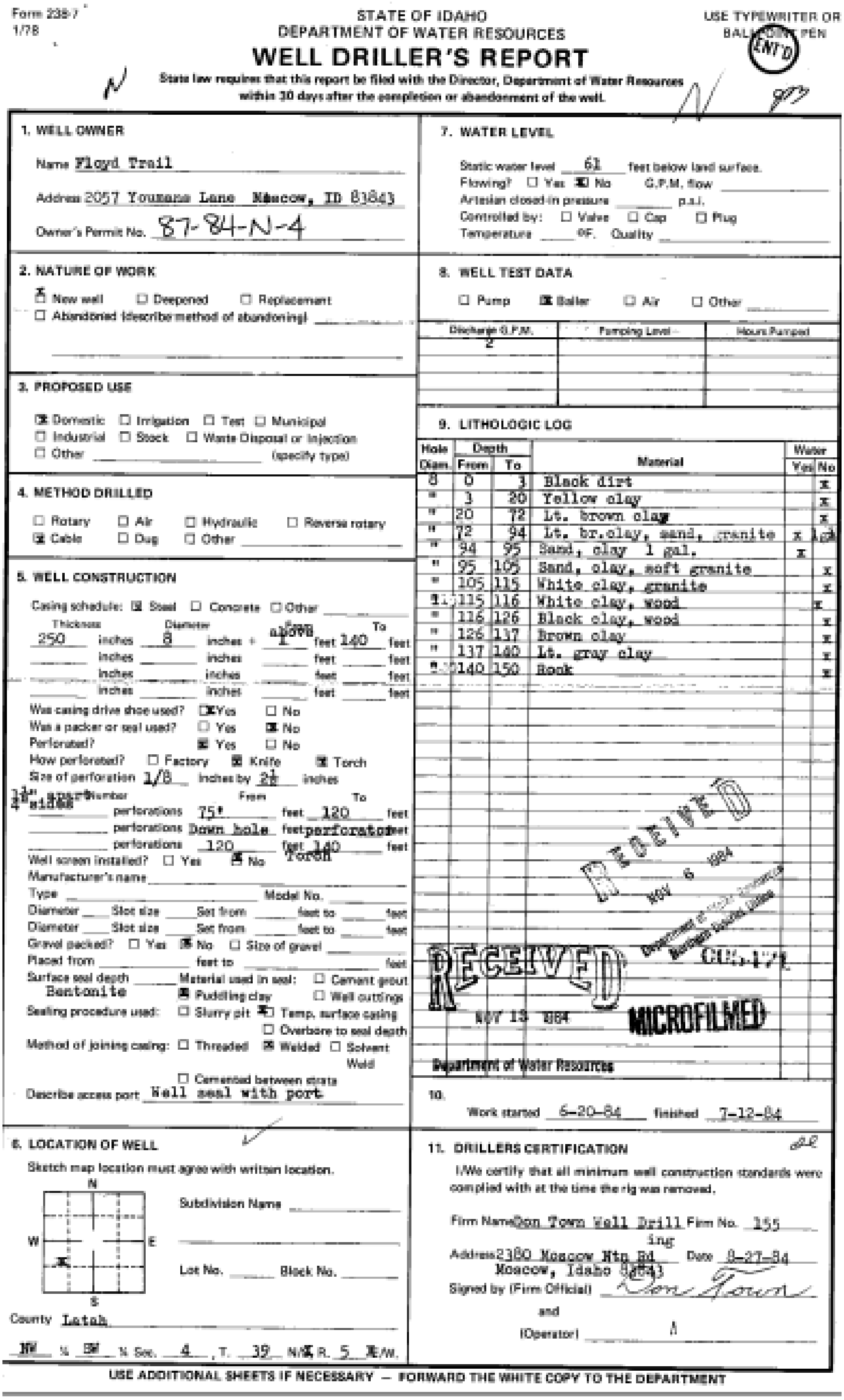
RECEIVED
APR 2 4 1998
NORTHERN REGION
IDWR

Completed Depth 180 ft (Measurable)
Date: Started 4/9/98 Completed 4/12/98

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Uhlenkott Drilling Firm No. 125
Firm Official Ray Uhlenkott Date 4/23/98
and
Supervisor or Operator Tom Uhlenkott Date 4/23/98
(Sign once if Firm Official & Operator)

Well log of well #20



Form 238-7
1/78

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

USE TYPEWRITER OR BALLPOINT PEN

ENT'D

N

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

N 977

1. WELL OWNER

Name Floyd Trail

Address 2057 Youmans Lane Moscow, ID 83843

Owner's Permit No. 87-84-N-4

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other (specify type)

4. METHOD DRILLED

☐ Rotary ☐ Air ☐ Hydraulic ☐ Reverse rotary
☒ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other

Thickness		Diameter		From		To	
250	inches	8	inches +	1 above	feet	140	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☒ Yes ☐ No
How perforated? ☐ Factory ☒ Knife ☒ Torch
Size of perforation 1/8 inches by 2½ inches

Number		From		To	
1½" apart 4 sides	perforations	75'	feet	120	feet
	perforations	Down hole	feet	perforator	feet
	perforations	120	feet	140 Torch	feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type Model No.
Diameter Slot size Set from feet to feet
Diameter Slot size Set from feet to feet
Gravel packed? ☐ Yes ☒ No ☐ Size of gravel
Placed from feet to feet
Surface seal depth Bentonite Material used in seal: ☐ Cement grout ☒ Puddling clay ☐ Well cuttings
Sealing procedure used: ☐ Slurry pit ☒ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld
☐ Cemented between strata
Describe access port Well seal with port

6. LOCATION OF WELL

Sketch map location must agree with written location.

N / W / E / S — X

Subdivision Name
Lot No. Block No.

County Latah

NW ¼ SW ¼ Sec. 4, T. 39 N/S, R. 5 E/W.

7. WATER LEVEL

Static water level 61 feet below land surface.
Flowing? ☐ Yes ☒ No G.P.M. flow
Artesian closed-in pressure p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature °F. Quality

8. WELL TEST DATA

☐ Pump ☒ Bailer ☐ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped
2		

9. LITHOLOGIC LOG

Hole Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	0	3	Black dirt		x
"	3	20	Yellow clay		x
"	20	72	Lt. brown clay		x
"	72	94	Lt. br.clay, sand, granite	x	1[illegible]
"	94	95	Sand, clay 1 gal.	x	
"	95	105	Sand, clay, soft granite		x
"	105	115	White clay, granite		x
[illegible]	115	116	White clay, wood		x
"	116	126	Black clay, wood		x
"	126	137	Brown clay		x
"	137	140	Lt. gray clay		x
[illegible]	140	150	Rock		x

RECEIVED
NOV 6 1984
Department of Water Resources
Northern District Office

CC5-171

RECEIVED
NOV 13 1984
Department of Water Resources

MICROFILMED

10.
Work started 6-20-84 finished 7-12-84

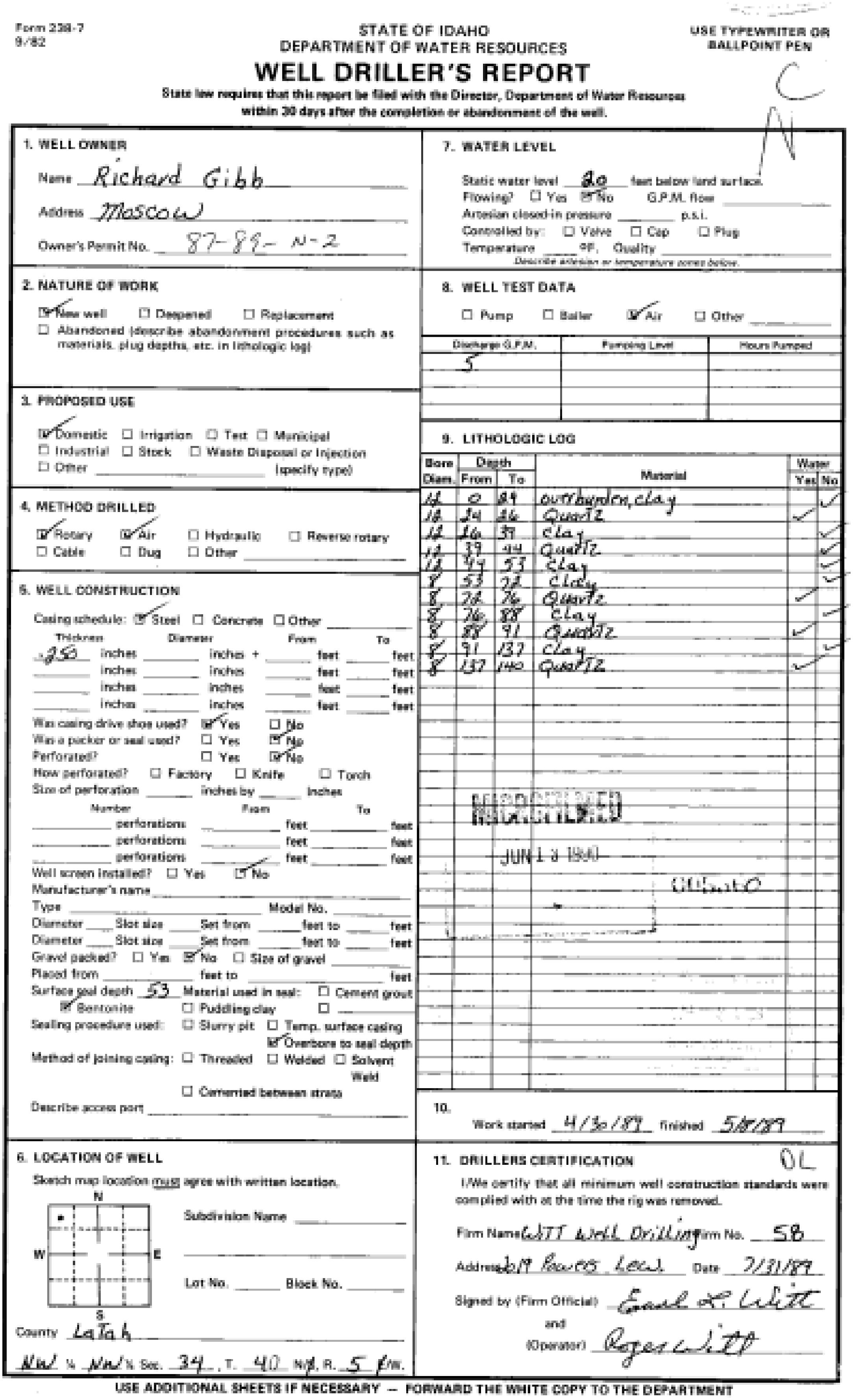
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Don Town Well Drilling Firm No. 155
Address 2380 Moscow Mtn Rd
Moscow, Idaho 83843
Date 8-27-84
Signed by (Firm Official) Don Town
and
(Operator)

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #21



Form 238-7
9/82

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

USE TYPEWRITER OR BALLPOINT PEN

C
N

1. WELL OWNER

Name Richard Gibb
Address Moscow
Owner's Permit No. 87-89- N-2

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☑ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ________ (specify type)

4. METHOD DRILLED

☑ Rotary ☑ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ________

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☐ Other ________

Thickness		Diameter		From		To	
.250	inches		inches +		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☑ Yes ☐ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☐ Yes ☑ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ____ inches by ____ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name ________
Type ________ Model No. ________
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel ________
Placed from ____ feet to ____ feet
Surface seal depth 53 Material used in seal: ☐ Cement grout ☑ Bentonite ☐ Puddling clay ☐ ________
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☐ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ________

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
W E
S

Subdivision Name ________
Lot No. ____ Block No. ____
County LaTah
NW ¼ NW ¼ Sec. 34, T. 40 [✓ N]/S, R. 5 [✓ E]/W.

7. WATER LEVEL

Static water level 20 feet below land surface.
Flowing? ☐ Yes ☑ No G.P.M. flow ________
Artesian closed-in pressure ____ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality ________
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☑ Air ☐ Other ________

Discharge G.P.M.	Pumping Level	Hours Pumped
5		

9. LITHOLOGIC LOG

Bore Diam.	Depth		Material	Water	
	From	To		Yes	No
12	0	24	overburden, clay		✓
12	24	26	Quartz	✓	
12	26	39	clay		✓
12	39	44	Quartz		✓
12	44	53	clay		✓
8	53	72	clay		✓
8	72	76	Quartz	✓	
8	76	88	clay		✓
8	88	91	Quartz	✓	
8	91	137	clay		✓
8	137	140	Quartz	✓	

MICROFILMED
JUN 1 3 1990

10.

Work started 4/30/89 finished 5/8/89

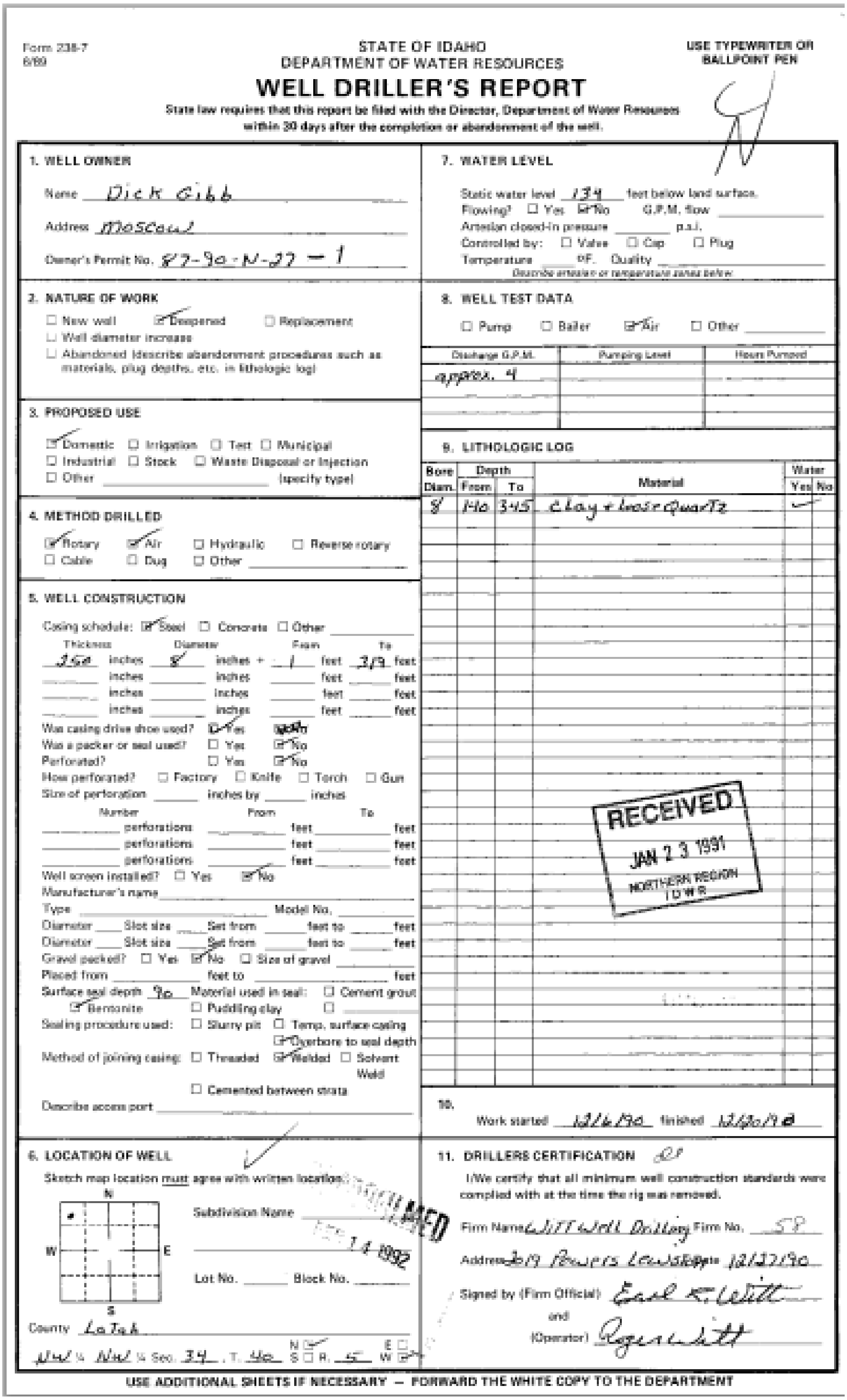
11. DRILLERS CERTIFICATION OL

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name WITT Well Drilling Firm No. 58
Address 619 Powers Loop Date 7/31/89
Signed by (Firm Official) Earl L. Witt
and
(Operator) Roger Witt

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log part 1 of well #22



Form 238-7
6/89

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name Dick Gibb
Address Moscow
Owner's Permit No. 87-90-N-27 — 1

2. NATURE OF WORK

☐ New well ☒ Deepened ☐ Replacement
☐ Well diameter increase
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ______ (specify type)

4. METHOD DRILLED

☒ Rotary ☒ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other

Thickness	Diameter	From	To
.250 inches	8 inches	+ 1 feet	319 feet
inches	inches	feet	feet
inches	inches	feet	feet
inches	inches	feet	feet

Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch ☐ Gun
Size of perforation ______ inches by ______ inches

Number	From	To
perforations	feet	feet
perforations	feet	feet
perforations	feet	feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name
Type ______ Model No.
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Diameter ____ Slot size ____ Set from ______ feet to ______ feet
Gravel packed? ☐ Yes ☒ No ☐ Size of gravel
Placed from ______ feet to ______ feet
Surface seal depth 90 Material used in seal: ☐ Cement grout ☒ Bentonite ☐ Puddling clay ☐
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☒ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port

6. LOCATION OF WELL

Sketch map location must agree with written location.

Subdivision Name
Lot No. ______ Block No. ______

[illegible] 14 1992

County Latah
NW ¼ NW ¼ Sec. 34, T. 40 N ☒ S ☐, R. 5 E ☐ W ☒

7. WATER LEVEL

Static water level 134 feet below land surface.
Flowing? ☐ Yes ☒ No G.P.M. flow
Artesian closed-in pressure ______ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ______ °F. Quality
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☒ Air ☐ Other

Discharge G.P.M.	Pumping Level	Hours Pumped
approx. 4		

9. LITHOLOGIC LOG

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	140	345	clay + loose quartz	✓	

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NORTHERN REGION
IDWR

10.

Work started 12/6/90 finished 12/20/90

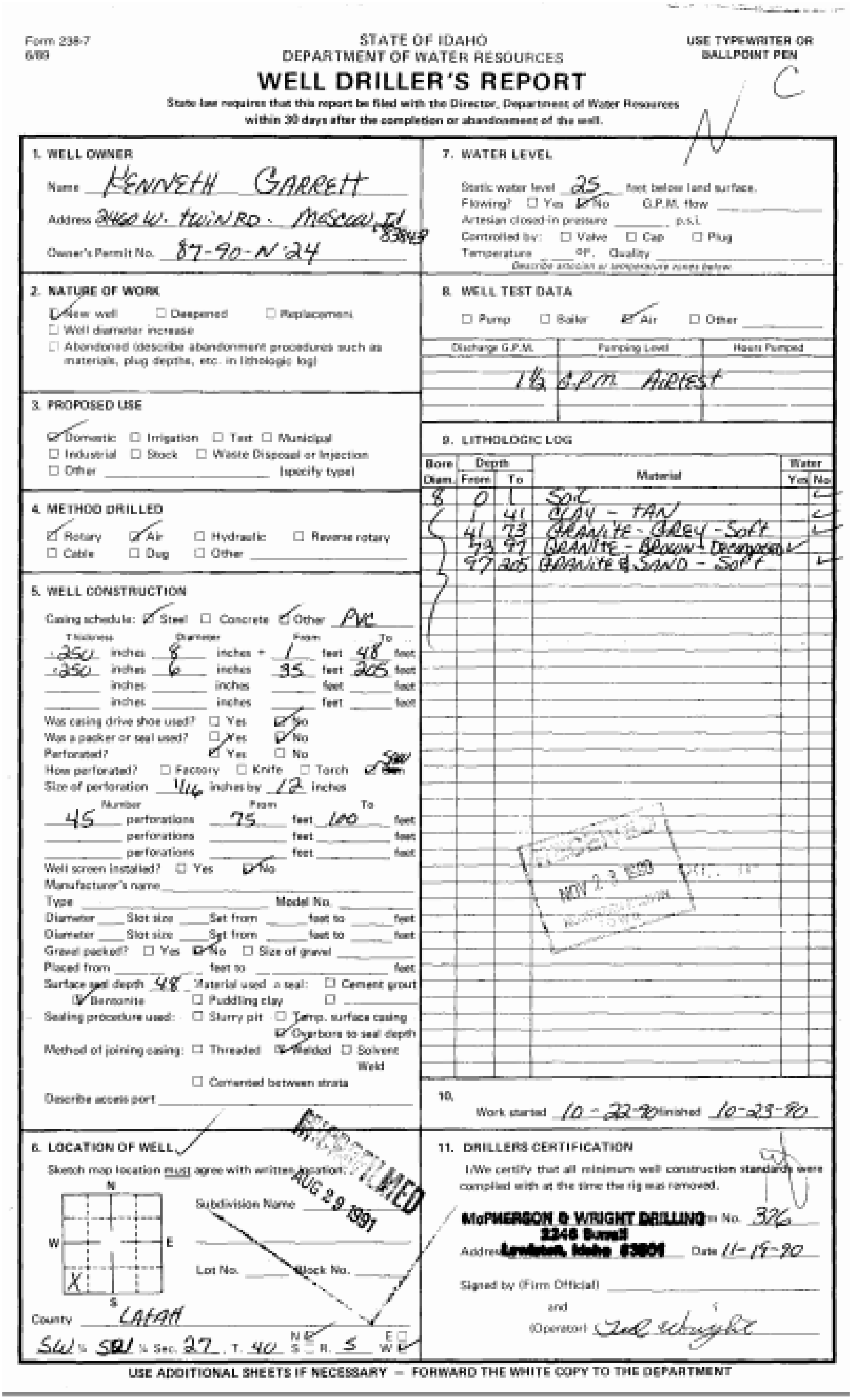
11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Witt Well Drilling Firm No. 58
Address 2019 Powers Lewiston Date 12/22/90
Signed by (Firm Official) Earl K. Witt
and
(Operator) Roger Witt

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log part 2 of well #22



Form 238-7
6/89

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

C

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

N

1. WELL OWNER

Name KENNETH GARRETT
Address 2460 W. TWIN RD. MOSCOW, ID 83843
Owner's Permit No. 87-90-N-24

2. NATURE OF WORK

☑ New well ☐ Deepened ☐ Replacement
☐ Well diameter increase
☐ Abandoned (describe abandonment procedures such as materials, plug depths, etc. in lithologic log)

3. PROPOSED USE

☑ Domestic ☐ Irrigation ☐ Test ☐ Municipal
☐ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ______ (specify type)

4. METHOD DRILLED

☑ Rotary ☑ Air ☐ Hydraulic ☐ Reverse rotary
☐ Cable ☐ Dug ☐ Other ______

5. WELL CONSTRUCTION

Casing schedule: ☑ Steel ☐ Concrete ☑ Other PVC

Thickness		Diameter		From		To	
.250	inches	8	inches +	1	feet	48	feet
.250	inches	6	inches	95	feet	205	feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was casing drive shoe used? ☐ Yes ☑ No
Was a packer or seal used? ☐ Yes ☑ No
Perforated? ☑ Yes ☐ No
How perforated? ☐ Factory ☐ Knife ☐ Torch ☑ Saw
Size of perforation 1/16 inches by 12 inches

Number		From		To	
45	perforations	75	feet	100	feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☑ No
Manufacturer's name ______
Type ______ Model No. ______
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Diameter ____ Slot size ____ Set from ____ feet to ____ feet
Gravel packed? ☐ Yes ☑ No ☐ Size of gravel ______
Placed from ______ feet to ______ feet
Surface seal depth 48 Material used in seal: ☐ Cement grout ☑ Bentonite ☐ Puddling clay ☐ ______
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☑ Overbore to seal depth
Method of joining casing: ☐ Threaded ☑ Welded ☐ Solvent Weld ☐ Cemented between strata
Describe access port ______

6. LOCATION OF WELL

Sketch map location must agree with written location.

N / W / E / S — X

Subdivision Name ______
Lot No. ______ Block No. ______
County LATAH
SW ¼ SW ¼ Sec. 27, T. 40 N ☑ S ☐ R. 5 E ☐ W ☑

7. WATER LEVEL

Static water level 25 feet below land surface.
Flowing? ☐ Yes ☑ No G.P.M. flow ______
Artesian closed-in pressure ______ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ____ °F. Quality ______
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☑ Air ☐ Other ______

Discharge G.P.M.	Pumping Level	Hours Pumped
1½ G.P.M.	AIRTEST	

9. LITHOLOGIC LOG

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
8	0	1	SOIL		✓
	1	41	CLAY - TAN		✓
	41	73	GRANITE - GREY - SOFT		✓
	73	97	GRANITE - BROWN - DECOMPOSED		✓
	97	205	GRANITE & SAND - SOFT		✓

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NOV 2 3 1990
DEPARTMENT OF WATER RESOURCES

10.

Work started 10-22-90 finished 10-23-90

11. DRILLERS CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

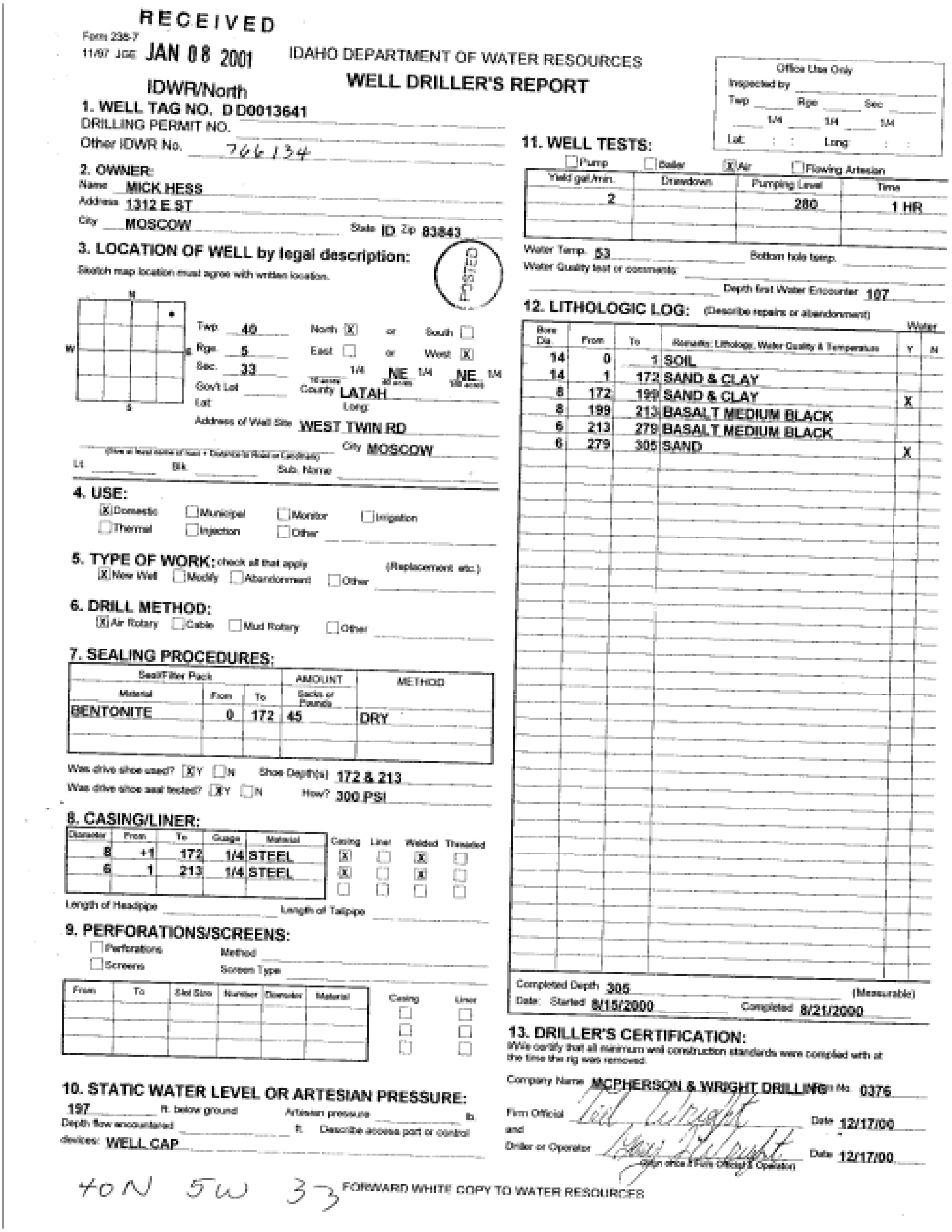
Firm Name McPHERSON & WRIGHT DRILLING Firm No. 326
2246 Burrell
Address Lewiston, Idaho 83501 Date 11-19-90

Signed by (Firm Official) ______
and
(Operator)

MICROFILMED
AUG 29 1991

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #23



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Form 238-7
11/97 JGE JAN 08 2001

IDWR/North

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Office Use Only
Inspected by
Twp Rge Sec
1/4 1/4 1/4
Lat : : Long : :

1. WELL TAG NO. D D0013641
DRILLING PERMIT NO.
Other IDWR No. 766134

2. OWNER:
Name MICK HESS
Address 1312 E ST
City MOSCOW State ID Zip 83843

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3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 33 1/4 NE 1/4 NE 1/4
Gov't Lot County LATAH
Lat Long
Address of Well Site WEST TWIN RD
City MOSCOW
Lt. Blk. Sub. Name

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other

5. TYPE OF WORK: check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other

6. DRILL METHOD:
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other

7. SEALING PROCEDURES:

Seal/Filter Pack			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
BENTONITE	0	172	45	DRY

Was drive shoe used? ☒Y ☐N Shoe Depth(s) 172 & 213
Was drive shoe seal tested? ☒Y ☐N How? 300 PSI

8. CASING/LINER:

Diameter	From	To	Guage	Material	Casing	Liner	Welded	Threaded
8	+1	172	1/4	STEEL	☒	☐	☒	☐
6	1	213	1/4	STEEL	☒	☐	☒	☐
					☐	☐	☐	☐

Length of Headpipe Length of Tailpipe

9. PERFORATIONS/SCREENS:
☐ Perforations Method
☐ Screens Screen Type

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
197 ft. below ground Artesian pressure lb.
Depth flow encountered ft. Describe access port or control devices: WELL CAP

11. WELL TESTS:
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
2		280	1 HR

Water Temp. 53 Bottom hole temp.
Water Quality test or comments:
Depth first Water Encounter 107

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
14	0	1	SOIL		
14	1	172	SAND & CLAY		
8	172	199	SAND & CLAY	X	
8	199	213	BASALT MEDIUM BLACK		
6	213	279	BASALT MEDIUM BLACK		
6	279	305	SAND	X	

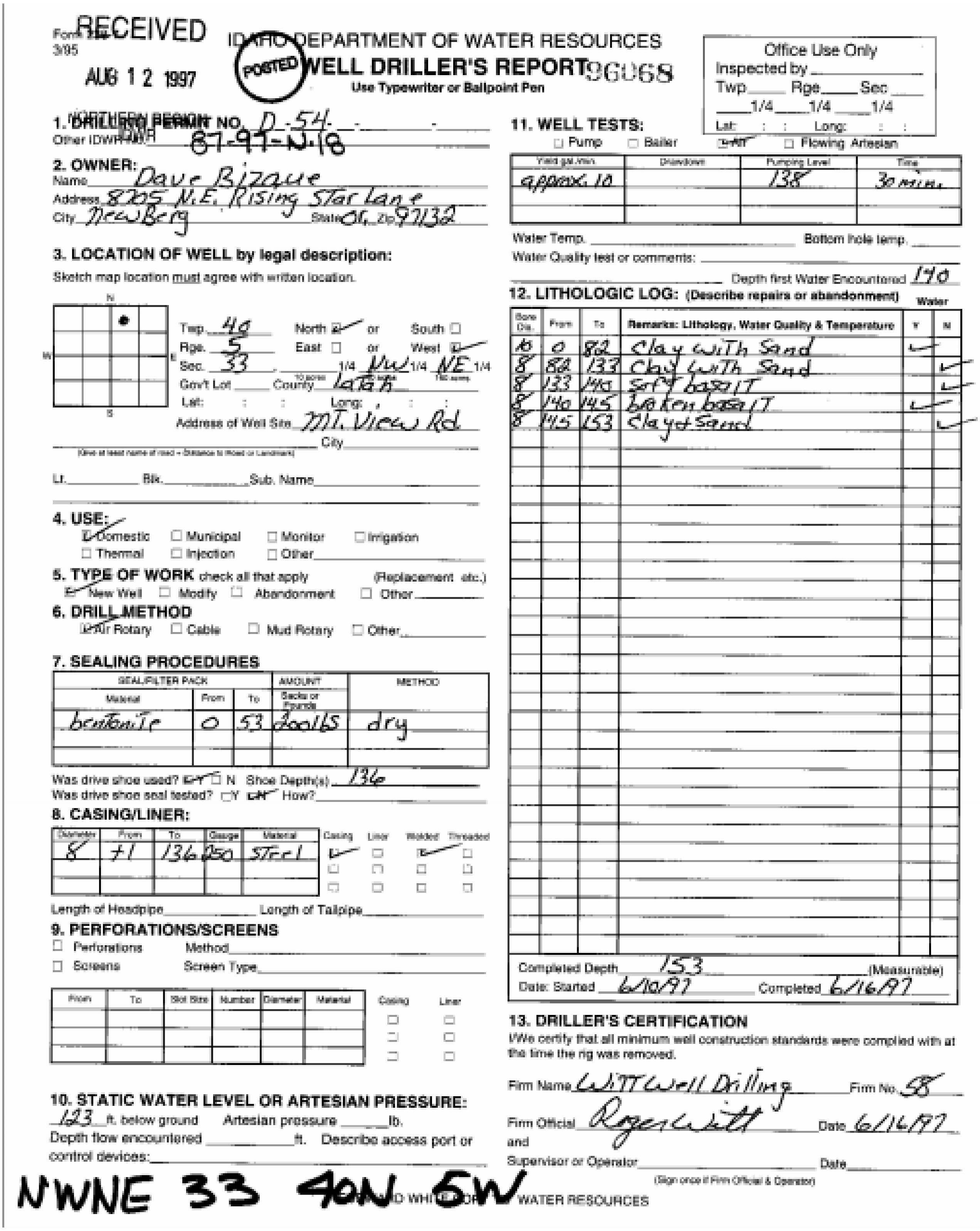
Completed Depth 305 (Measurable)
Date: Started 8/15/2000 Completed 8/21/2000

13. DRILLER'S CERTIFICATION:
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Company Name MCPHERSON & WRIGHT DRILLING No. 0376
Firm Official Date 12/17/00
and
Driller or Operator Date 12/17/00
(Sign once if Firm Official & Operator)

40N 5W 33 FORWARD WHITE COPY TO WATER RESOURCES

Well log of well #24



Form 238-7 3/95

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NORTHERN REGION IDWR

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IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT 96068

Use Typewriter or Ballpoint Pen

Office Use Only
Inspected by ______
Twp ____ Rge ____ Sec ____
____1/4 ____1/4 ____1/4
Lat: : : Long: : :

1. DRILLING PERMIT NO. D-54-____-____
Other IDWR No. 87-97-N-18

2. OWNER:
Name Dave Bizaue
Address 8705 N.E. Rising Star Lane
City NewBerg State OR Zip 97132

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp. 40 North ☑ or South ☐
Rge. 5 East ☐ or West ☑
Sec. 33, ____1/4 NW 1/4 NE 1/4
Gov't Lot ____ County Latah
Lat: : : Long: : :
Address of Well Site MT. View Rd.
____ City ____
(Give at least name of road + Distance to Road or Landmark)
Lt. ____ Blk. ____ Sub. Name ____

4. USE:
☑ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ____

5. TYPE OF WORK check all that apply (Replacement etc.)
☑ New Well ☐ Modify ☐ Abandonment ☐ Other ____

6. DRILL METHOD
☑ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other ____

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
bentonite	0	53	200 lbs	dry

Was drive shoe used? ☑ Y ☐ N Shoe Depth(s) 136
Was drive shoe seal tested? ☐ Y ☑ N How? ____

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+1	136	.250	Steel	☑	☐	☑	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe ____ Length of Tailpipe ____

9. PERFORATIONS/SCREENS
☐ Perforations Method ____
☐ Screens Screen Type ____

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
123 ft. below ground Artesian pressure ____ lb.
Depth flow encountered ____ ft. Describe access port or control devices: ____

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
approx. 10		138	30 min.

Water Temp. ____ Bottom hole temp. ____
Water Quality test or comments: ____
Depth first Water Encountered 140

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	82	Clay with Sand	✓	
8	82	133	Clay with Sand		✓
8	133	140	soft basalT		✓
8	140	145	broken basalT	✓	
8	145	153	Clay & Sand		✓

Completed Depth 153 (Measurable)
Date: Started 6/10/97 Completed 6/16/97

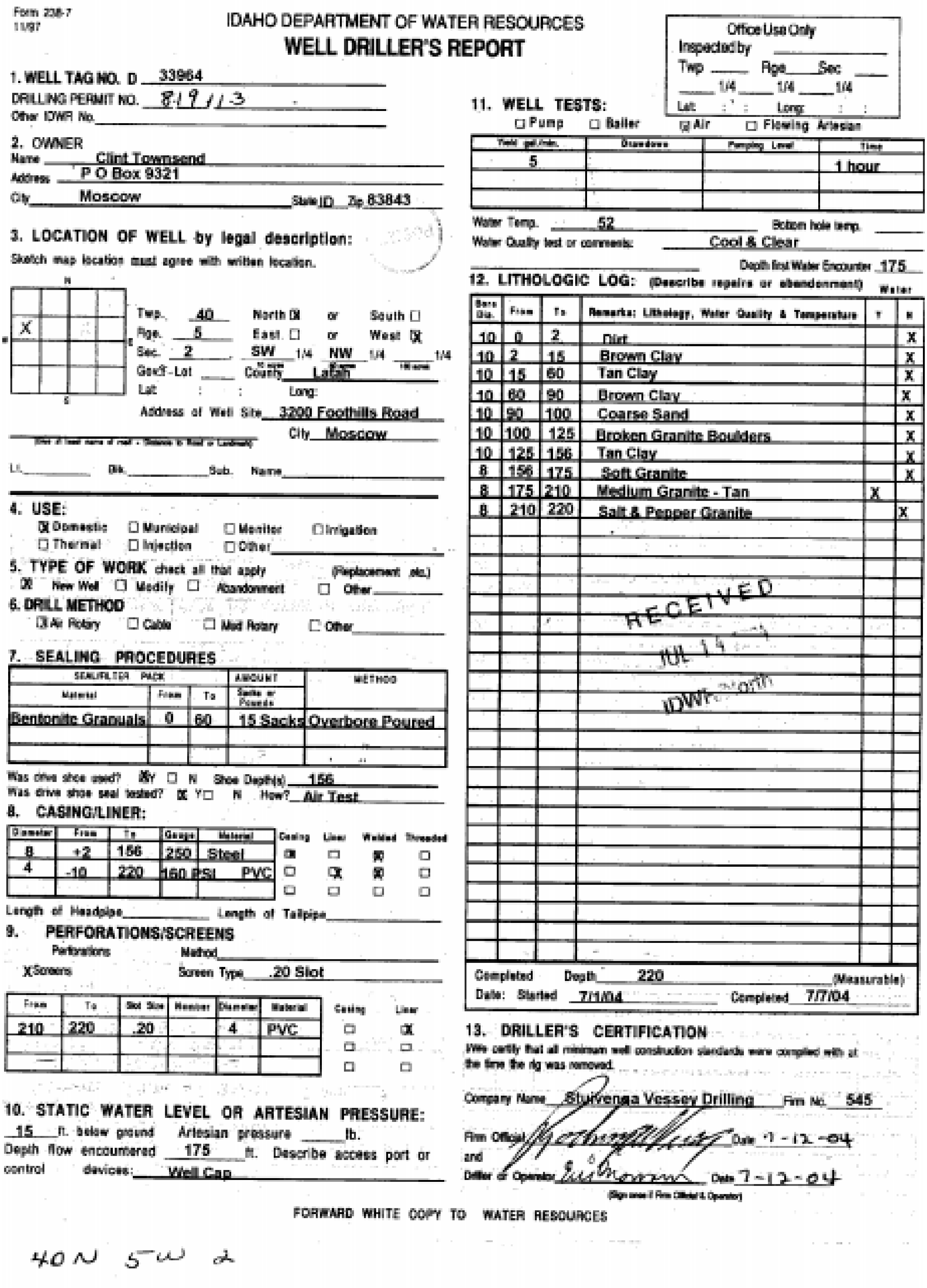
13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name Witt Well Drilling Firm No. 58
Firm Official Roger Witt Date 6/16/97
and
Supervisor or Operator ____ Date ____
(Sign once if Firm Official & Operator)

NWNE 33 40N 5W

...D WHITE... WATER RESOURCES

Well log of well #26



Form 238-7
11/97

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Office Use Only
Inspected by ______
Twp ____ Rge ____ Sec ____
____ 1/4 ____ 1/4 ____ 1/4
Lat: : : Long: : :

1. WELL TAG NO. D 33964
DRILLING PERMIT NO. 819113
Other IDWR No. ______

2. OWNER
Name Clint Townsend
Address P O Box 9321
City Moscow State ID Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

X			

N W E S

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 2, SW 1/4 NW 1/4 ____ 1/4
Gov't Lot ____ County Latah
Lat : : Long:
Address of Well Site 3200 Foothills Road
City Moscow
Lt. ____ Blk. ____ Sub. Name ____

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ____

5. TYPE OF WORK check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other ____

6. DRILL METHOD
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other ____

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
Bentonite Granuals	0	60	15 Sacks	Overbore Poured

Was drive shoe used? ☒ Y ☐ N Shoe Depth(s) 156
Was drive shoe seal tested? ☒ Y ☐ N How? Air Test

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+2	156	250	Steel	☒	☐	☒	☐
4	-10	220	160 PSI	PVC	☐	☒	☒	☐
					☐	☐	☐	☐

Length of Headpipe ____ Length of Tailpipe ____

9. PERFORATIONS/SCREENS
Perforations Method ____
X Screens Screen Type .20 Slot

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
210	220	.20		4	PVC	☐	☒
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
15 ft. below ground Artesian pressure ____ lb.
Depth flow encountered 175 ft. Describe access port or control devices: Well Cap

11. WELL TESTS:
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
5			1 hour

Water Temp. 52 Bottom hole temp. ____
Water Quality test or comments: Cool & Clear
Depth first Water Encounter 175

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	2	Dirt		X
10	2	15	Brown Clay		X
10	15	60	Tan Clay		X
10	60	90	Brown Clay		X
10	90	100	Coarse Sand		X
10	100	125	Broken Granite Boulders		X
10	125	156	Tan Clay		X
8	156	175	Soft Granite		X
8	175	210	Medium Granite - Tan	X	
8	210	220	Salt & Pepper Granite		X

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IDWR-North

Completed Depth 220 (Measurable)
Date: Started 7/1/04 Completed 7/7/04

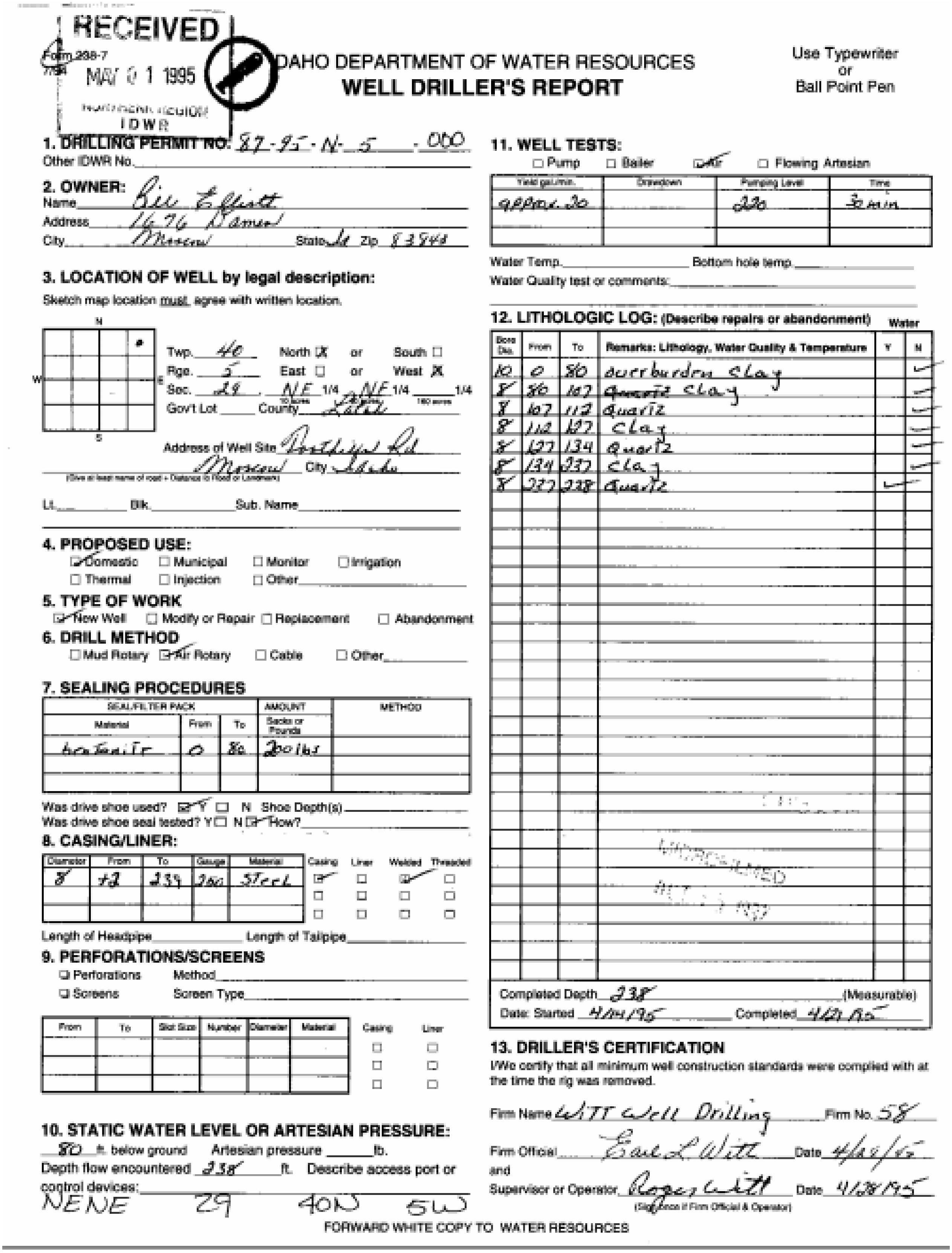
13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Company Name Stuivenga Vessey Drilling Firm No. 545
Firm Official ____ Date 7-12-04
and
Driller or Operator ____ Date 7-12-04
(Sign once if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

40N 5W 2

Well log of well #27



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IDWR

Form 238-7
7/93

IDAHO DEPARTMENT OF WATER RESOURCES
WELL DRILLER'S REPORT

Use Typewriter
or
Ball Point Pen

1. DRILLING PERMIT NO. 87-95-N-5-000
Other IDWR No.

2. OWNER:
Name Bill Elliott
Address 1676 Damen
City Moscow State Id Zip 83843

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 29, NE 1/4 NE 1/4 ___ 1/4
Gov't Lot ___ County Latah
Address of Well Site [illegible] Rd
Moscow City Idaho
(Give at least name of road + Distance to Road or Landmark)
Lt. ___ Blk. ___ Sub. Name ___

4. PROPOSED USE:
☑ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other ___

5. TYPE OF WORK
☑ New Well ☐ Modify or Repair ☐ Replacement ☐ Abandonment

6. DRILL METHOD
☐ Mud Rotary ☑ Air Rotary ☐ Cable ☐ Other ___

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
bentonite	0	80	200 lbs	

Was drive shoe used? ☑ Y ☐ N Shoe Depth(s) ___
Was drive shoe seal tested? Y ☐ N ☑ How? ___

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8"	+2	239	250	Steel	☑	☐	☑	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe ___ Length of Tailpipe ___

9. PERFORATIONS/SCREENS
☐ Perforations Method ___
☐ Screens Screen Type ___

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
80 ft. below ground Artesian pressure ___ lb.
Depth flow encountered 238 ft. Describe access port or control devices: ___

NENE 29 40N 5W

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal/min.	Drawdown	Pumping Level	Time
approx. 30		220	30 min

Water Temp. ___ Bottom hole temp. ___
Water Quality test or comments: ___

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
10	0	80	overburden clay		✓
8	80	107	~~quartz~~ clay		✓
8	107	112	quartz		✓
8	112	127	clay		✓
8	127	134	quartz		✓
8	134	237	clay		✓
8	237	238	quartz	✓	

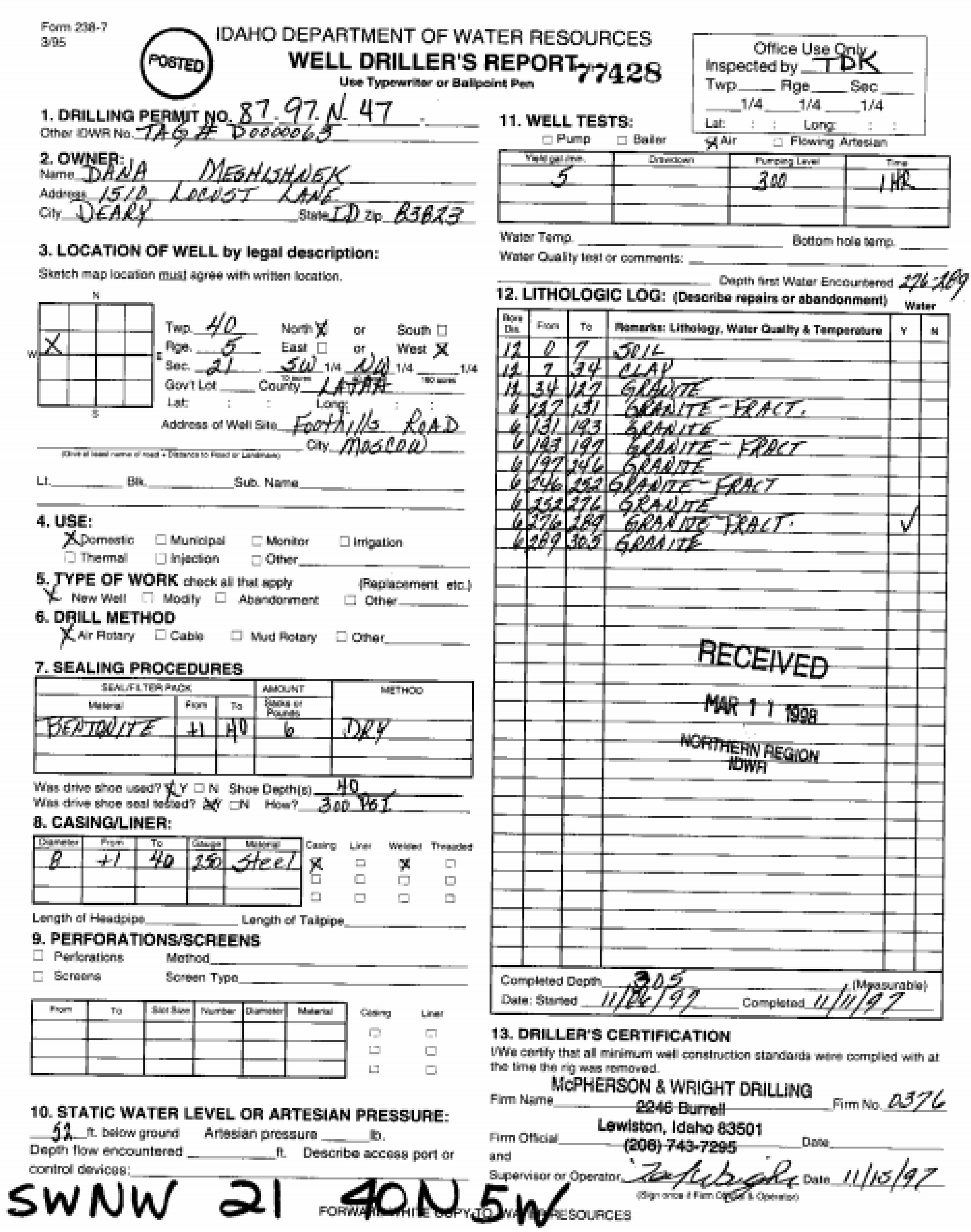
Completed Depth 238 (Measurable)
Date: Started 4/14/95 Completed 4/21/95

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name WITT Well Drilling Firm No. 58
Firm Official Earl L Witt Date 4/28/95
and
Supervisor or Operator Roger Witt Date 4/28/95
(Signature if Firm Official & Operator)

FORWARD WHITE COPY TO WATER RESOURCES

Well log of well #28



Form 238-7
3/95

POSTED

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT 77428

Use Typewriter or Ballpoint Pen

Office Use Only
Inspected by TDK
Twp____ Rge____ Sec____
____1/4____1/4____1/4
Lat: : : Long: : :

1. DRILLING PERMIT NO. 87.97.N.47
Other IDWR No. TAG # D0000063

2. OWNER:
Name DANA MESHISHNEK
Address 1510 LOCUST LANE
City DEARY State ID Zip 83823

3. LOCATION OF WELL by legal description:
Sketch map location must agree with written location.

	N		
W X			E
	S		

Twp. 40 North ☒ or South ☐
Rge. 5 East ☐ or West ☒
Sec. 21, SW 1/4 NW 1/4 ____ 1/4 (10 acres, 40 acres, 160 acres)
Gov't Lot ____ County LATAH
Lat: : : Long: : :
Address of Well Site Foothills ROAD City MOSCOW
(Give at least name of road + Distance to Road or Landmark)
Lt.________ Blk.________ Sub. Name________

4. USE:
☒ Domestic ☐ Municipal ☐ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other________

5. TYPE OF WORK check all that apply (Replacement etc.)
☒ New Well ☐ Modify ☐ Abandonment ☐ Other________

6. DRILL METHOD
☒ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other________

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
BENTONITE	+1	40	6	DRY

Was drive shoe used? ☒ Y ☐ N Shoe Depth(s) 40
Was drive shoe seal tested? ☒ Y ☐ N How? 300 PSI

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+1	40	250	Steel	☒	☐	☒	☐
					☐	☐	☐	☐
					☐	☐	☐	☐

Length of Headpipe________ Length of Tailpipe________

9. PERFORATIONS/SCREENS
☐ Perforations Method________
☐ Screens Screen Type________

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
						☐	☐
						☐	☐
						☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
52 ft. below ground Artesian pressure ____ lb.
Depth flow encountered ________ ft. Describe access port or control devices:________

11. WELL TESTS:
☐ Pump ☐ Bailer ☒ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
5		300	1 HR

Water Temp.________ Bottom hole temp.________
Water Quality test or comments:________
Depth first Water Encountered 276-289

12. LITHOLOGIC LOG: (Describe repairs or abandonment)

Bore Dia.	From	To	Remarks: Lithology, Water Quality & Temperature	Water Y	Water N
12	0	7	SOIL		
12	7	34	CLAY		
12	34	127	GRANITE		
6	127	131	GRANITE-FRACT.		
6	131	193	GRANITE		
6	193	197	GRANITE- FRACT		
6	197	246	GRANITE		
6	246	252	GRANITE-FRACT		
6	252	276	GRANITE		
6	276	289	GRANITE FRACT.	✓	
6	289	305	GRANITE		

RECEIVED
MAR 11 1998
NORTHERN REGION
IDWR

Completed Depth 305 (Measurable)
Date: Started 11/[illegible]/97 Completed 11/11/97

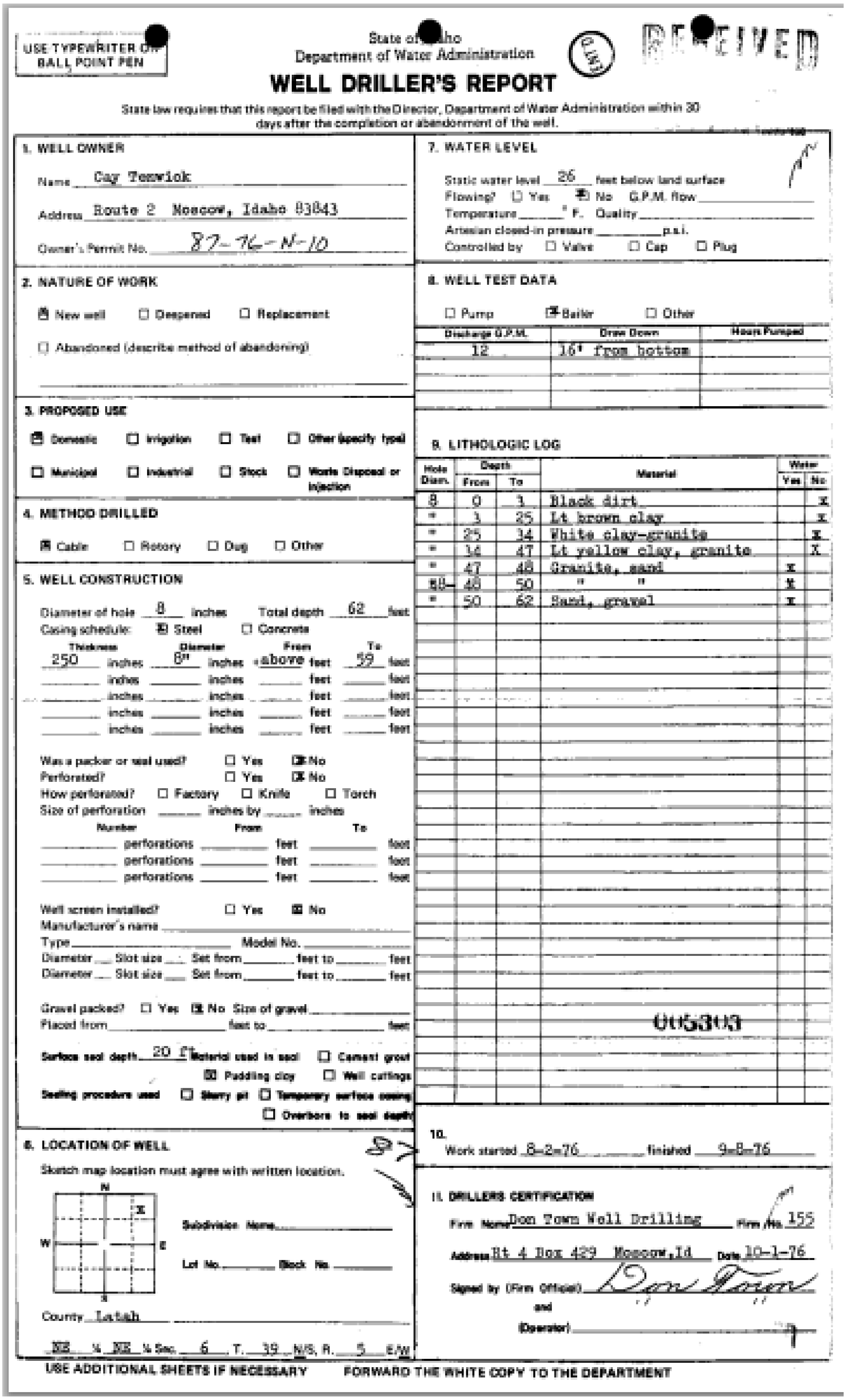
13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name McPHERSON & WRIGHT DRILLING
2246 Burrell
Lewiston, Idaho 83501
(208) 743-7295
Firm No. 0376
Firm Official________ Date________
and
Supervisor or Operator Date 11/15/97
(Sign once if Firm Official & Operator)

SWNW 21 40N 5W

FORWARD WHITE COPY TO WATER RESOURCES

Well log of well #29



USE TYPEWRITER OR
BALL POINT PEN

State of Idaho
Department of Water Administration

RECEIVED

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Administration within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name: Cay Tenwick

Address: Route 2 Moscow, Idaho 83843

Owner's Permit No. 87-76-N-10

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement

☐ Abandoned (describe method of abandoning)

3. PROPOSED USE

☒ Domestic ☐ Irrigation ☐ Test ☐ Other (specify type)

☐ Municipal ☐ Industrial ☐ Stock ☐ Waste Disposal or Injection

4. METHOD DRILLED

☒ Cable ☐ Rotary ☐ Dug ☐ Other

5. WELL CONSTRUCTION

Diameter of hole 8 inches Total depth 62 feet

Casing schedule: ☒ Steel ☐ Concrete

Thickness		Diameter		From		To	
250	inches	8"	inches	above	feet	59	feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet
	inches		inches		feet		feet

Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch
Size of perforation ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☐ Yes ☒ No
Manufacturer's name ______
Type ______ Model No. ______
Diameter ___ Slot size ___ Set from ______ feet to ______ feet
Diameter ___ Slot size ___ Set from ______ feet to ______ feet

Gravel packed? ☐ Yes ☒ No Size of gravel ______
Placed from ______ feet to ______ feet

Surface seal depth 20 ft Material used in seal ☐ Cement grout ☒ Puddling clay ☐ Well cuttings
Sealing procedure used ☐ Slurry pit ☐ Temporary surface casing ☐ Overbore to seal depth

6. LOCATION OF WELL

Sketch map location must agree with written location.

N
X
W E
S

Subdivision Name ______

Lot No. ______ Block No. ______

County Latah

NE ¼ NE ¼ Sec. 6, T. 39 N/S, R. 5 E/W

87

7. WATER LEVEL

Static water level 26 feet below land surface
Flowing? ☐ Yes ☒ No G.P.M. flow ______
Temperature ______ °F. Quality ______
Artesian closed-in pressure ______ p.s.i.
Controlled by ☐ Valve ☐ Cap ☐ Plug

8. WELL TEST DATA

☐ Pump ☒ Bailer ☐ Other

Discharge G.P.M.	Draw Down	Hours Pumped
12	16' from bottom	

9. LITHOLOGIC LOG

Hole Diam.	Depth		Material	Water	
	From	To		Yes	No
8	0	3	Black dirt		X
"	3	25	Lt brown clay		X
"	25	34	White clay-granite		X
"	34	47	Lt yellow clay, granite		X
"	47	48	Granite, sand	X	
88–	48	50	" "	X	
"	50	62	Sand, gravel	X	

005303

10.

Work started 8-2-76 finished 9-8-76

11. DRILLERS CERTIFICATION

Firm Name Don Town Well Drilling Firm No. 155

Address Rt 4 Box 429 Moscow, Id Date 10-1-76

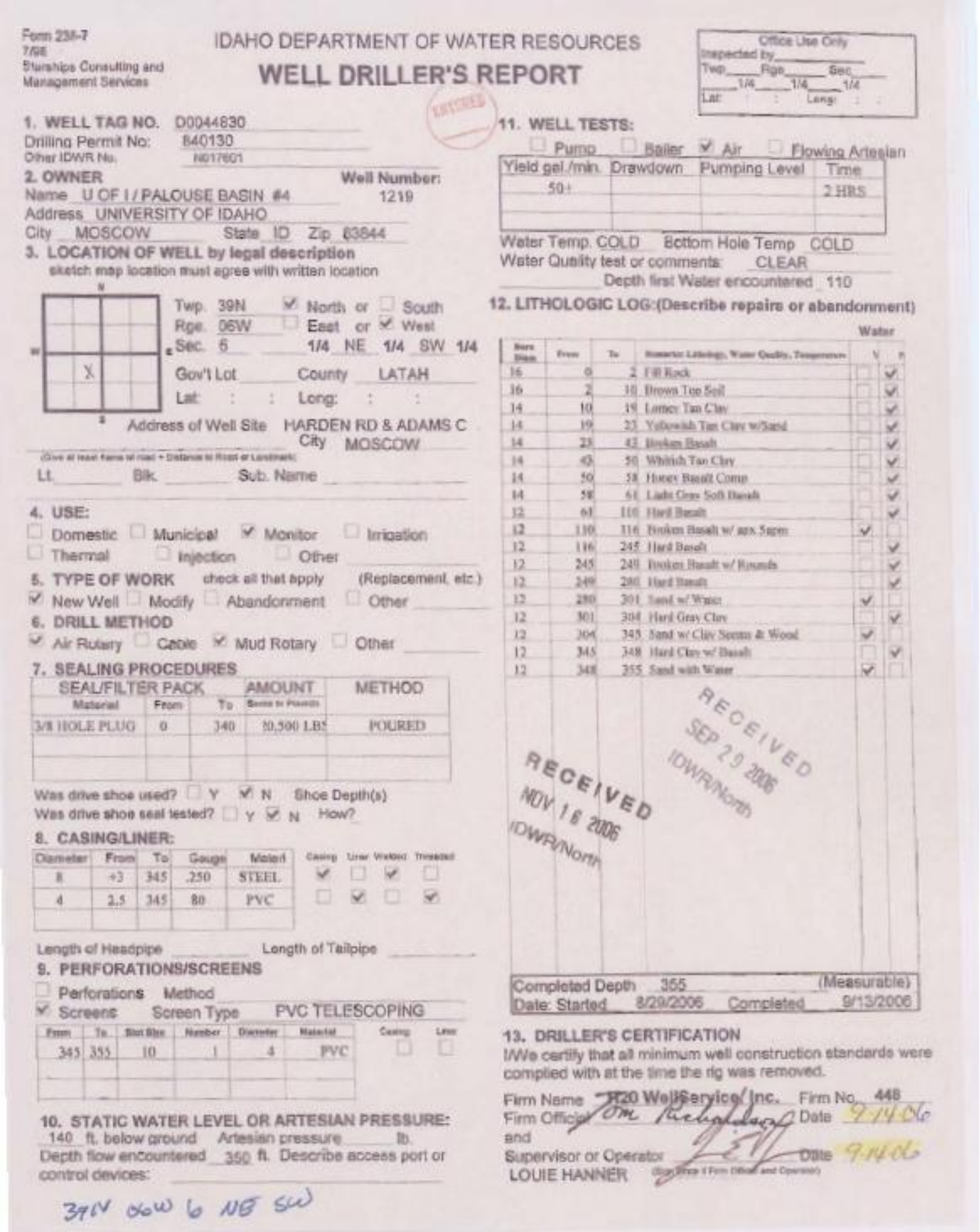
Signed by (Firm Official) Don Town

and

(Operator) ______

USE ADDITIONAL SHEETS IF NECESSARY FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well #36



Form 238-7
7/98
Starships Consulting and
Management Services

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

ENTERED

Office Use Only
Inspected by______
Twp____ Rge____ Sec____
____1/4____1/4____1/4
Lat: : : Long: : :

1. WELL TAG NO. D0044830
Drilling Permit No: 840130
Other IDWR No. N017601

2. OWNER **Well Number:** 1219
Name U OF I / PALOUSE BASIN #4
Address UNIVERSITY OF IDAHO
City MOSCOW State ID Zip 83844

3. LOCATION OF WELL by legal description
sketch map location must agree with written location

N W E S X

Twp. 39N ☑ North or ☐ South
Rge. 06W ☐ East or ☑ West
Sec. 6 1/4 NE 1/4 SW 1/4
Gov't Lot County LATAH
Lat: : : Long: : :
Address of Well Site HARDEN RD & ADAMS C City MOSCOW
(Give at least Name of road + Distance to Road or Landmark)
Lt. Blk. Sub. Name

4. USE:
☐ Domestic ☐ Municipal ☑ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other

5. TYPE OF WORK check all that apply (Replacement, etc.)
☑ New Well ☐ Modify ☐ Abandonment ☐ Other

6. DRILL METHOD
☑ Air Rotary ☐ Cable ☑ Mud Rotary ☐ Other

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
3/8 HOLE PLUG	0	340	80,500 LBS	POURED

Was drive shoe used? ☐ Y ☑ N Shoe Depth(s)
Was drive shoe seal tested? ☐ Y ☑ N How?

8. CASING/LINER:

Diameter	From	To	Gauge	Material	Casing	Liner	Welded	Threaded
8	+3	345	.250	STEEL	☑	☐	☑	☐
4	2.5	345	80	PVC	☐	☑	☐	☑

Length of Headpipe Length of Tailpipe

9. PERFORATIONS/SCREENS
☐ Perforations Method
☑ Screens Screen Type PVC TELESCOPING

From	To	Slot Size	Number	Diameter	Material	Casing	Liner
345	355	10	1	4	PVC	☐	☐

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
140 ft. below ground Artesian pressure ____ lb.
Depth flow encountered 350 ft. Describe access port or control devices:

39N 06W 6 NE SW

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
50+			2 HRS

Water Temp. COLD Bottom Hole Temp COLD
Water Quality test or comments: CLEAR
Depth first Water encountered 110

12. LITHOLOGIC LOG:(Describe repairs or abandonment)

Bore Diam.	From	To	Remarks: Lithology, Water Quality, Temperature	Water Y	N
16	0	2	Fill Rock	☐	☑
16	2	10	Brown Top Soil	☐	☑
14	10	19	Lomey Tan Clay	☐	☑
14	19	23	Yellowish Tan Clay w/Sand	☐	☑
14	23	43	Broken Basalt	☐	☑
14	43	50	Whitish Tan Clay	☐	☑
14	50	58	Honey Basalt Comp	☐	☑
14	58	61	Light Gray Soft Basalt	☐	☑
12	61	110	Hard Basalt	☐	☑
12	110	116	Broken Basalt w/ apx 5gpm	☑	☐
12	116	245	Hard Basalt	☐	☑
12	245	249	Broken Basalt w/ Rounds	☐	☑
12	249	280	Hard Basalt	☐	☑
12	280	301	Sand w/ Water	☑	☐
12	301	304	Hard Gray Clay	☐	☑
12	304	345	Sand w/ Clay Seams & Wood	☑	☐
12	345	348	Hard Clay w/ Basalt	☐	☑
12	348	355	Sand with Water	☑	☐

RECEIVED
SEP 29 2006
IDWR/North

RECEIVED
NOV 16 2006
IDWR/North

Completed Depth 355 (Measurable)
Date: Started 8/29/2006 Completed 9/13/2006

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name H20 Well Service, Inc. Firm No. 448
Firm Official Tom Richardson Date 9-14-06
and
Supervisor or Operator Date 9-14-06
LOUIE HANNER (Sign once if Firm Official and Operator)

Well log of well #60

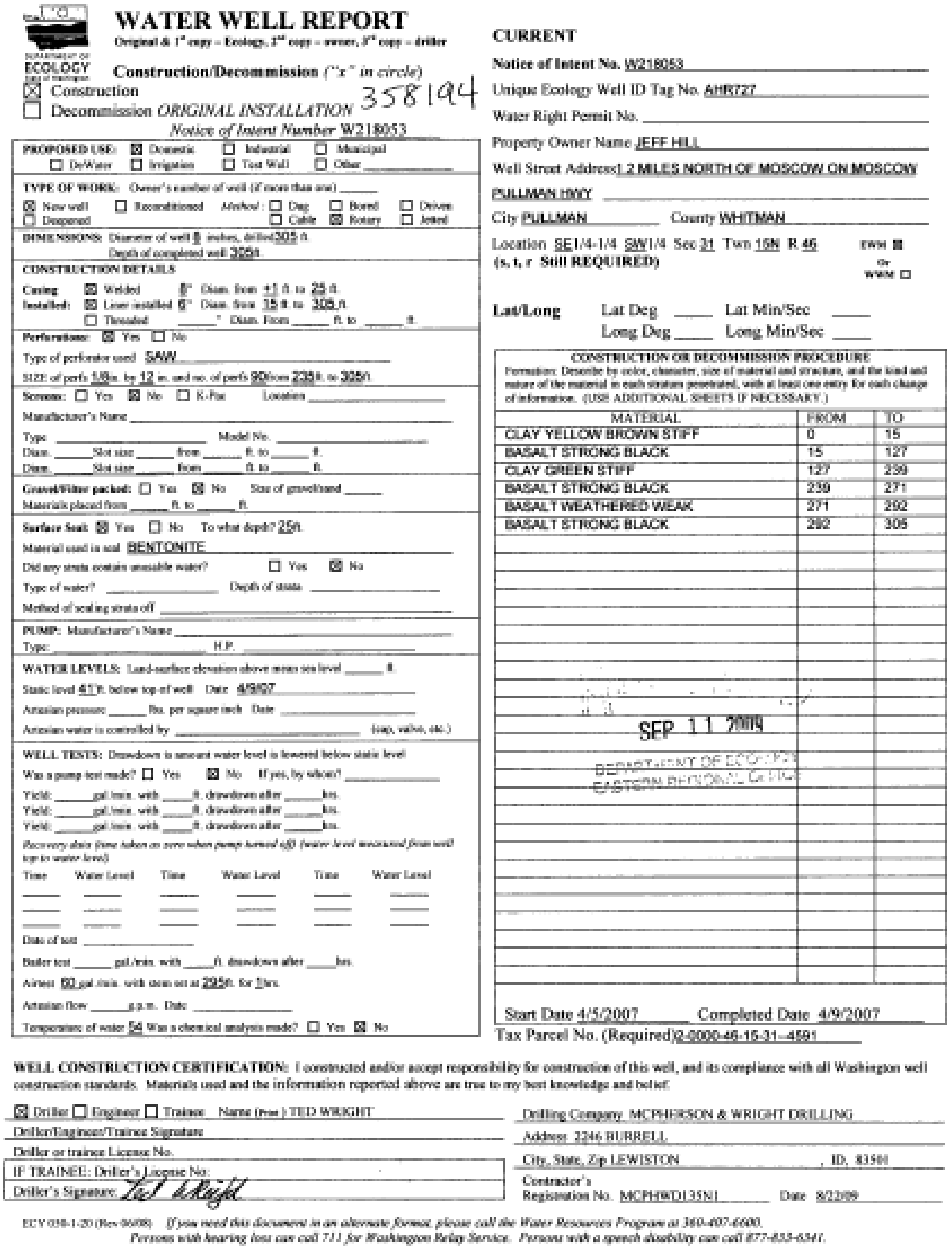
Appendix II: Well logs used for caffeine sampling

Below all the well logs are included of the wells used during the caffeine sampling. Also descriptions of the wells without a well log have been included here.

Descriptions:

Well T16D (H) is described in Appendix I, since it was also included in the isotopic sampling.

Well D19D (I) is at the similar location as T16D, which is at the UIGWRS. D19D is 43 m, and gets its water from a deeper basalt layer than T16D.



WATER WELL REPORT

Original & 1st copy – Ecology, 2nd copy – owner, 3rd copy – driller

DEPARTMENT OF ECOLOGY State of Washington

Construction/Decommission *("x" in circle)*
☒ Construction
☐ Decommission *ORIGINAL INSTALLATION* 358194
Notice of Intent Number W218053

PROPOSED USE: ☒ Domestic ☐ Industrial ☐ Municipal ☐ DeWater ☐ Irrigation ☐ Test Well ☐ Other ________

TYPE OF WORK: Owner's number of well (if more than one) ______
☒ New well ☐ Reconditioned *Method:* ☐ Dug ☐ Bored ☐ Driven
☐ Deepened ☐ Cable ☒ Rotary ☐ Jetted

DIMENSIONS: Diameter of well 8 inches, drilled 305 ft.
Depth of completed well 305 ft.

CONSTRUCTION DETAILS
Casing Installed: ☒ Welded 8" Diam. from +1 ft. to 25 ft.
☒ Liner installed 6" Diam. from 15 ft. to 305 ft.
☐ Threaded ______" Diam. From ______ ft. to ______ ft.

Perforations: ☒ Yes ☐ No
Type of perforator used SAW
SIZE of perfs 1/8 in. by 12 in. and no. of perfs 90 from 235 ft. to 305 ft.

Screens: ☐ Yes ☒ No ☐ K-Pac Location ______________
Manufacturer's Name ______________
Type ______________ Model No. ______________
Diam. ______ Slot size ______ from ______ ft. to ______ ft.
Diam. ______ Slot size ______ from ______ ft. to ______ ft.

Gravel/Filter packed: ☐ Yes ☒ No Size of gravel/sand ______
Materials placed from ______ ft. to ______ ft.

Surface Seal: ☒ Yes ☐ No To what depth? 25 ft.
Material used in seal BENTONITE
Did any strata contain unusable water? ☐ Yes ☒ No
Type of water? ______________ Depth of strata ______________
Method of sealing strata off ______________

PUMP: Manufacturer's Name ______________
Type: ______________ H.P. ______________

WATER LEVELS: Land-surface elevation above mean sea level ______ ft.
Static level 41 ft. below top of well Date 4/9/07
Artesian pressure ______ lbs. per square inch Date ______________
Artesian water is controlled by ______________ (cap, valve, etc.)

WELL TESTS: Drawdown is amount water level is lowered below static level
Was a pump test made? ☐ Yes ☒ No If yes, by whom? ______________
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.
Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______________
Bailer test ______ gal./min. with ______ ft. drawdown after ______ hrs.
Airtest 60 gal./min. with stem set at 295 ft. for 1 hrs.
Artesian flow ______ g.p.m. Date ______________
Temperature of water 54 Was a chemical analysis made? ☐ Yes ☒ No

CURRENT
Notice of Intent No. W218053
Unique Ecology Well ID Tag No. AHR727
Water Right Permit No. ______________
Property Owner Name JEFF HILL
Well Street Address 1.2 MILES NORTH OF MOSCOW ON MOSCOW PULLMAN HWY
City PULLMAN County WHITMAN
Location SE1/4-1/4 SW1/4 Sec 31 Twn 15N R 46 EWM ☒ or WWM ☐
(s, t, r Still REQUIRED)

Lat/Long Lat Deg ____ Lat Min/Sec ____
Long Deg ____ Long Min/Sec ____

CONSTRUCTION OR DECOMMISSION PROCEDURE
Formation: Describe by color, character, size of material and structure, and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information. (USE ADDITIONAL SHEETS IF NECESSARY.)

MATERIAL	FROM	TO
CLAY YELLOW BROWN STIFF	0	15
BASALT STRONG BLACK	15	127
CLAY GREEN STIFF	127	239
BASALT STRONG BLACK	239	271
BASALT WEATHERED WEAK	271	292
BASALT STRONG BLACK	292	305

SEP 11 2009
DEPARTMENT OF ECOLOGY
EASTERN REGIONAL OFFICE

Start Date 4/5/2007 Completed Date 4/9/2007
Tax Parcel No. (Required) 2-0000-46-15-31-4591

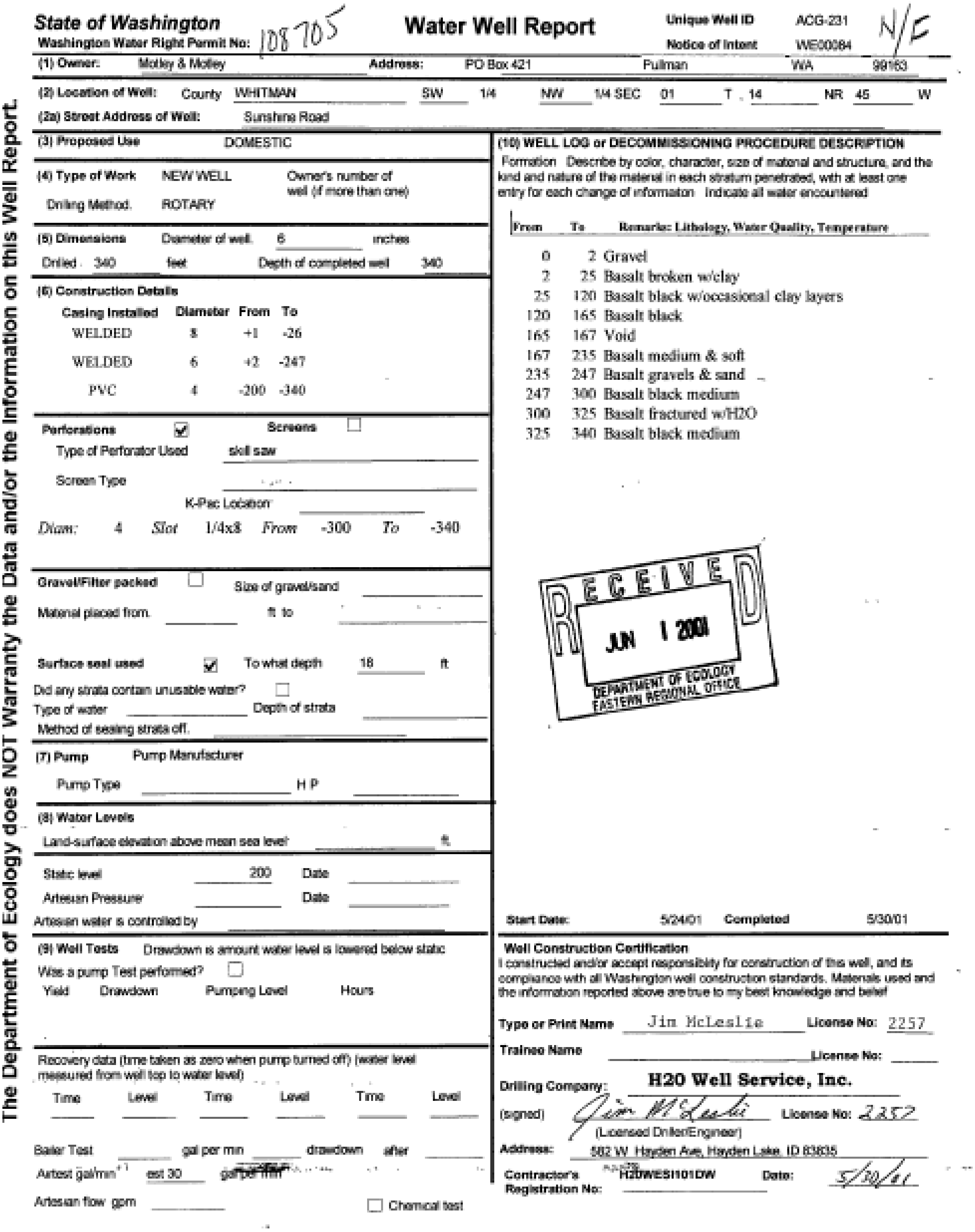
WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

☒ Driller ☐ Engineer ☐ Trainee Name (Print) TED WRIGHT
Driller/Engineer/Trainee Signature
Driller or trainee License No.
IF TRAINEE: Driller's License No:
Driller's Signature: Ted Wright

Drilling Company MCPHERSON & WRIGHT DRILLING
Address 3246 BURRELL
City, State, Zip LEWISTON , ID, 83501
Contractor's Registration No. MCPHWD135NI Date 8/22/09

ECY 050-1-20 (Rev 06/08) *If you need this document in an alternate format, please call the Water Resources Program at 360-407-6600. Persons with hearing loss can call 711 for Washington Relay Service. Persons with a speech disability can call 877-833-6341.*

Well log of well A



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

State of Washington **Water Well Report**

Washington Water Right Permit No: 108705

Unique Well ID ACG-231

Notice of Intent WE00084

N/E

(1) Owner: Motley & Motley **Address:** PO Box 421 Pullman WA 99163

(2) Location of Well: County WHITMAN SW 1/4 NW 1/4 SEC 01 T 14 NR 45 W

(2a) Street Address of Well: Sunshine Road

(3) Proposed Use DOMESTIC

(4) Type of Work NEW WELL Owner's number of well (if more than one)

Drilling Method. ROTARY

(5) Dimensions Diameter of well. 6 inches

Drilled . 340 feet Depth of completed well 340

(6) Construction Details

Casing Installed	Diameter	From	To
WELDED	8	+1	-26
WELDED	6	+2	-247
PVC	4	-200	-340

Perforations ☑ **Screens** ☐

Type of Perforator Used skill saw

Screen Type

K-Pac Location

Diam: 4 *Slot* 1/4x8 *From* -300 *To* -340

Gravel/Filter packed ☐ Size of gravel/sand

Material placed from. ft to

Surface seal used ☑ To what depth 18 ft

Did any strata contain unusable water? ☐

Type of water Depth of strata

Method of sealing strata off.

(7) Pump Pump Manufacturer

Pump Type H P

(8) Water Levels

Land-surface elevation above mean sea level ft.

Static level 200 Date

Artesian Pressure Date

Artesian water is controlled by

(9) Well Tests Drawdown is amount water level is lowered below static

Was a pump Test performed? ☐

Yield Drawdown Pumping Level Hours

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time Level Time Level Time Level

Bailer Test gal per min drawdown after

Airtest gal/min est 30 gal per min

Artesian flow gpm ☐ Chemical test

(10) WELL LOG or DECOMMISSIONING PROCEDURE DESCRIPTION

Formation Describe by color, character, size of material and structure, and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information Indicate all water encountered

From	To	Remarks: Lithology, Water Quality, Temperature
0	2	Gravel
2	25	Basalt broken w/clay
25	120	Basalt black w/occasional clay layers
120	165	Basalt black
165	167	Void
167	235	Basalt medium & soft
235	247	Basalt gravels & sand
247	300	Basalt black medium
300	325	Basalt fractured w/H2O
325	340	Basalt black medium

RECEIVED JUN 1 2001 DEPARTMENT OF ECOLOGY EASTERN REGIONAL OFFICE

Start Date: 5/24/01 **Completed** 5/30/01

Well Construction Certification

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief

Type or Print Name Jim McLeslie **License No:** 2257

Trainee Name **License No:**

Drilling Company: **H20 Well Service, Inc.**

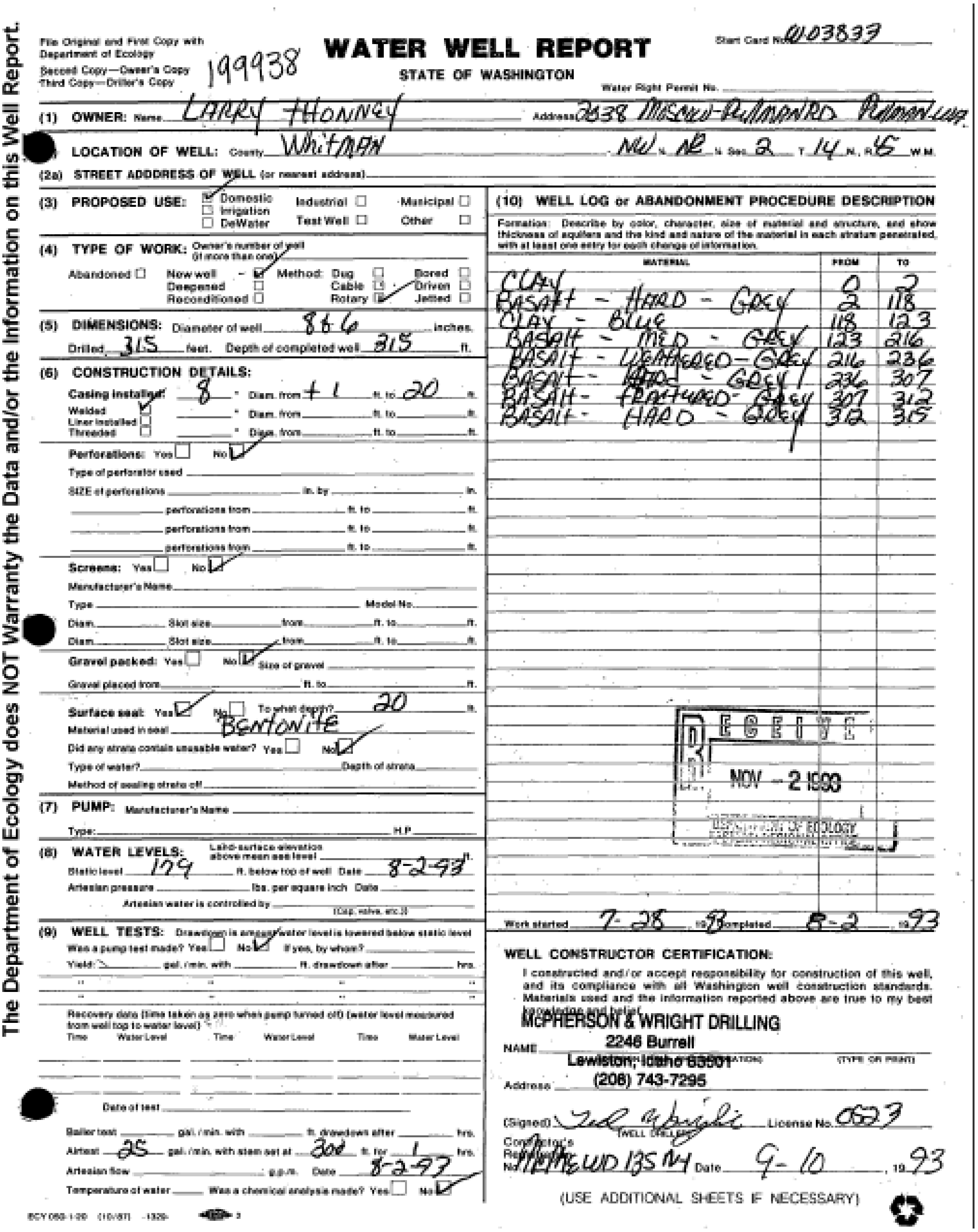
(signed) Jim McLeslie **License No:** 2257

(Licensed Driller/Engineer)

Address: 582 W. Hayden Ave, Hayden Lake, ID 83835

Contractor's Registration No: H20WESI101DW **Date:** 5/30/01

Well log of well B



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

File Original and First Copy with Department of Ecology
Second Copy—Owner's Copy
Third Copy—Driller's Copy

199938

WATER WELL REPORT

STATE OF WASHINGTON

Start Card No. W03837
Water Right Permit No. ______

(1) **OWNER:** Name LARRY HONNEY Address 2638 MOSCOW-PULLMAN RD PULLMAN WA

LOCATION OF WELL: County Whitman NW ¼ NE ¼ Sec. 2 T. 14 N., R. 45 W.M.

(2a) **STREET ADDRESS OF WELL** (or nearest address) ______

(3) **PROPOSED USE:** ☑ Domestic ☐ Irrigation ☐ DeWater Industrial ☐ Test Well ☐ Municipal ☐ Other ☐

(4) **TYPE OF WORK:** Owner's number of well (if more than one) ______
Abandoned ☐ New well ☑ Deepened ☐ Reconditioned ☐
Method: Dug ☐ Cable ☐ Rotary ☑ Bored ☐ Driven ☐ Jetted ☐

(5) **DIMENSIONS:** Diameter of well 8 & 6 inches.
Drilled 315 feet. Depth of completed well 315 ft.

(6) **CONSTRUCTION DETAILS:**
Casing installed: 8 " Diam. from +1 ft. to 20 ft.
Welded ☑ ______ " Diam. from ______ ft. to ______ ft.
Liner installed ☐
Threaded ☐ ______ " Diam. from ______ ft. to ______ ft.

Perforations: Yes ☐ No ☑
Type of perforator used ______
SIZE of perforations ______ in. by ______ in.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.
______ perforations from ______ ft. to ______ ft.

Screens: Yes ☐ No ☑
Manufacturer's Name ______
Type ______ Model No. ______
Diam. ______ Slot size ______ from ______ ft. to ______ ft.
Diam. ______ Slot size ______ from ______ ft. to ______ ft.

Gravel packed: Yes ☐ No ☑ Size of gravel ______
Gravel placed from ______ ft. to ______ ft.

Surface seal: Yes ☑ No ☐ To what depth? 20 ft.
Material used in seal BENTONITE
Did any strata contain unusable water? Yes ☐ No ☑
Type of water? ______ Depth of strata ______
Method of sealing strata off ______

(7) **PUMP:** Manufacturer's Name ______
Type: ______ H.P. ______

(8) **WATER LEVELS:** Land-surface elevation above mean sea level ______ ft.
Static level 179 ft. below top of well Date 8-2-93
Artesian pressure ______ lbs. per square inch Date ______
Artesian water is controlled by ______ (Cap, valve, etc.)

(9) **WELL TESTS:** Drawdown is amount water level is lowered below static level
Was a pump test made? Yes ☐ No ☑ If yes, by whom? ______
Yield: ______ gal./min. with ______ ft. drawdown after ______ hrs.

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time	Water Level	Time	Water Level	Time	Water Level

Date of test ______
Bailer test ______ gal./min. with ______ ft. drawdown after ______ hrs.
Airtest 25 gal./min. with stem set at 300 ft. for 1 hrs.
Artesian flow ______ g.p.m. Date 8-2-93
Temperature of water ______ Was a chemical analysis made? Yes ☐ No ☑

(10) **WELL LOG or ABANDONMENT PROCEDURE DESCRIPTION**

Formation: Describe by color, character, size of material and structure, and show thickness of aquifers and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information.

MATERIAL	FROM	TO
CLAY	0	2
BASALT - HARD - GREY	2	118
CLAY - BLUE	118	123
BASALT - MED - GREY	123	216
BASALT - WEATHERED - GREY	216	236
BASALT - HARD - GREY	236	307
BASALT - FRACTURED - GREY	307	312
BASALT - HARD - GREY	312	315

RECEIVED
NOV - 2 1993
DEPARTMENT OF ECOLOGY

Work started 7-28 1993 Completed 8-2 1993

WELL CONSTRUCTOR CERTIFICATION:

I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

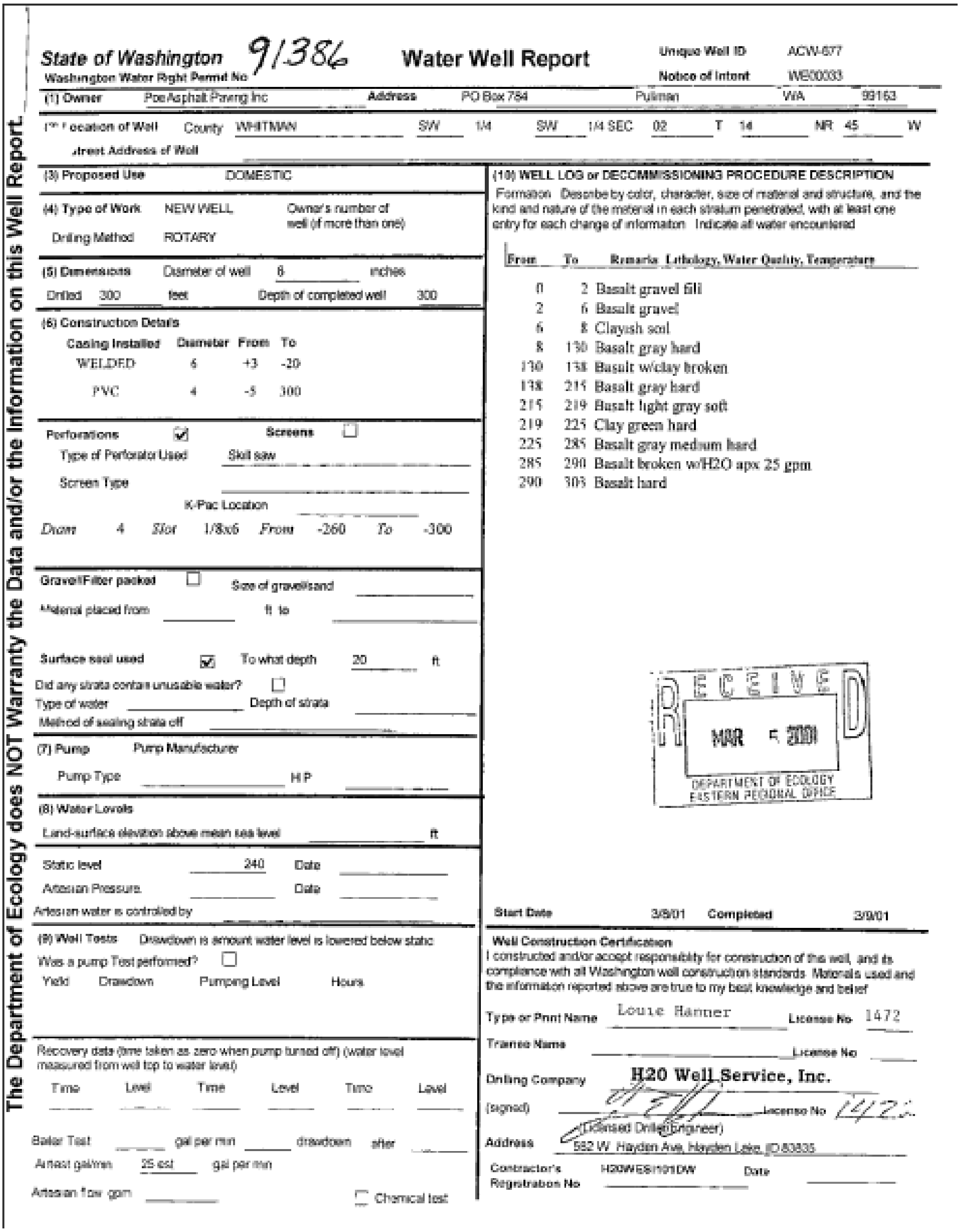
NAME McPHERSON & WRIGHT DRILLING (PERSON, FIRM, OR CORPORATION) (TYPE OR PRINT)
Address 2246 Burrell
Lewiston, Idaho 83501
(208) 743-7295

(Signed) (WELL DRILLER) License No. 0527
Contractor's Registration No. MCPHEWD135NY Date 9-10, 1993

(USE ADDITIONAL SHEETS IF NECESSARY)

ECY 050-1-20 (10/87) -1329-

Well log of well C



The Department of Ecology does NOT Warranty the Data and/or the Information on this Well Report.

State of Washington Washington Water Right Permit No 91386

Water Well Report

Unique Well ID ACW-677
Notice of Intent WE00033

(1) Owner Poe Asphalt Paving Inc Address PO Box 784 Pullman WA 99163

(2) Location of Well County WHITMAN SW 1/4 SW 1/4 SEC 02 T 14 NR 45 W

Street Address of Well

(3) Proposed Use DOMESTIC

(4) Type of Work NEW WELL Owner's number of well (if more than one)

Drilling Method ROTARY

(5) Dimensions Diameter of well 8 inches

Drilled 300 feet Depth of completed well 300

(6) Construction Details

Casing Installed	Diameter	From	To
WELDED	6	+3	-20
PVC	4	-5	300

Perforations ☑ Screens ☐

Type of Perforator Used Skil saw

Screen Type

K-Pac Location

Diam 4 *Slot* 1/8x6 *From* -260 *To* -300

Gravel/Filter packed ☐ Size of gravel/sand

Material placed from ft to

Surface seal used ☑ To what depth 20 ft

Did any strata contain unusable water? ☐

Type of water Depth of strata

Method of sealing strata off

(7) Pump Pump Manufacturer

Pump Type H P

(8) Water Levels

Land-surface elevation above mean sea level ft

Static level 240 Date

Artesian Pressure Date

Artesian water is controlled by

(9) Well Tests Drawdown is amount water level is lowered below static

Was a pump Test performed? ☐

Yield Drawdown Pumping Level Hours

Recovery data (time taken as zero when pump turned off) (water level measured from well top to water level)

Time Level Time Level Time Level

Bailer Test gal per min drawdown after

Airtest gal/min 25 est gal per min

Artesian flow gpm ☐ Chemical test

(10) WELL LOG or DECOMMISSIONING PROCEDURE DESCRIPTION

Formation Describe by color, character, size of material and structure, and the kind and nature of the material in each stratum penetrated, with at least one entry for each change of information Indicate all water encountered

From	To	Remarks Lithology, Water Quality, Temperature
0	2	Basalt gravel fill
2	6	Basalt gravel
6	8	Clayish soil
8	130	Basalt gray hard
130	138	Basalt w/clay broken
138	215	Basalt gray hard
215	219	Basalt light gray soft
219	225	Clay green hard
225	285	Basalt gray medium hard
285	290	Basalt broken w/H2O apx 25 gpm
290	303	Basalt hard

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EASTERN REGIONAL OFFICE

Start Date 3/5/01 Completed 3/9/01

Well Construction Certification
I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief

Type or Print Name Louie Hanner License No 1472

Trainee Name License No

Drilling Company H20 Well Service, Inc.

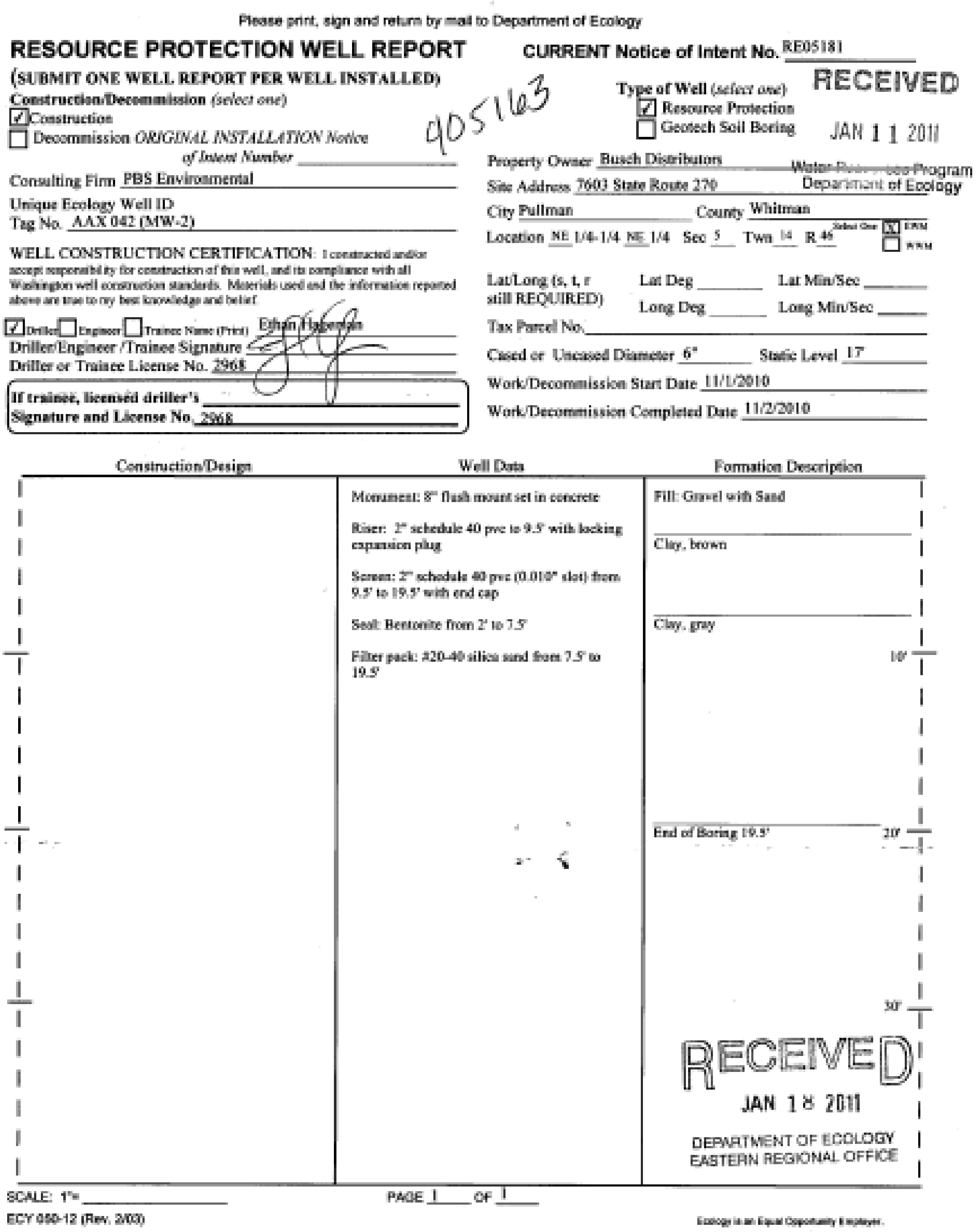
(signed) License No 1472

(Licensed Driller/Engineer)

Address 582 W Hayden Ave, Hayden Lake, ID 83835

Contractor's Registration No H20WESI101DW Date

Well log of well D



Please print, sign and return by mail to Department of Ecology

RESOURCE PROTECTION WELL REPORT

CURRENT Notice of Intent No. RE05181

(SUBMIT ONE WELL REPORT PER WELL INSTALLED)

Construction/Decommission *(select one)*

☑ Construction

☐ Decommission *ORIGINAL INSTALLATION Notice of Intent Number* ____

905163

Type of Well *(select one)*

☑ Resource Protection

☐ Geotech Soil Boring

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JAN 11 2011

Water ~~Resources~~ Program
Department of Ecology

Consulting Firm PBS Environmental

Unique Ecology Well ID Tag No. AAX 042 (MW-2)

Property Owner Busch Distributors

Site Address 7603 State Route 270

City Pullman County Whitman

Location NE 1/4-1/4 NE 1/4 Sec 5 Twn 14 R 46 Select One ☒ EWM ☐ WWM

Lat/Long (s, t, r still REQUIRED) Lat Deg ____ Lat Min/Sec ____ Long Deg ____ Long Min/Sec ____

Tax Parcel No. ____

Cased or Uncased Diameter 6" Static Level 17'

Work/Decommission Start Date 11/1/2010

Work/Decommission Completed Date 11/2/2010

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

☑ Driller ☐ Engineer ☐ Trainee Name (Print) Ethan Haberman

Driller/Engineer /Trainee Signature

Driller or Trainee License No. 2968

If trainee, licensed driller's Signature and License No. 2968

Construction/Design	Well Data	Formation Description
	Monument: 8" flush mount set in concrete Riser: 2" schedule 40 pvc to 9.5' with locking expansion plug Screen: 2" schedule 40 pvc (0.010" slot) from 9.5' to 19.5' with end cap Seal: Bentonite from 2' to 7.5' Filter pack: #20-40 silica sand from 7.5' to 19.5'	Fill: Gravel with Sand Clay, brown Clay, gray 10' End of Boring 19.5' 20' 30'

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EASTERN REGIONAL OFFICE

SCALE: 1"= ____ PAGE 1 OF 1

ECY 050-12 (Rev. 2/03)

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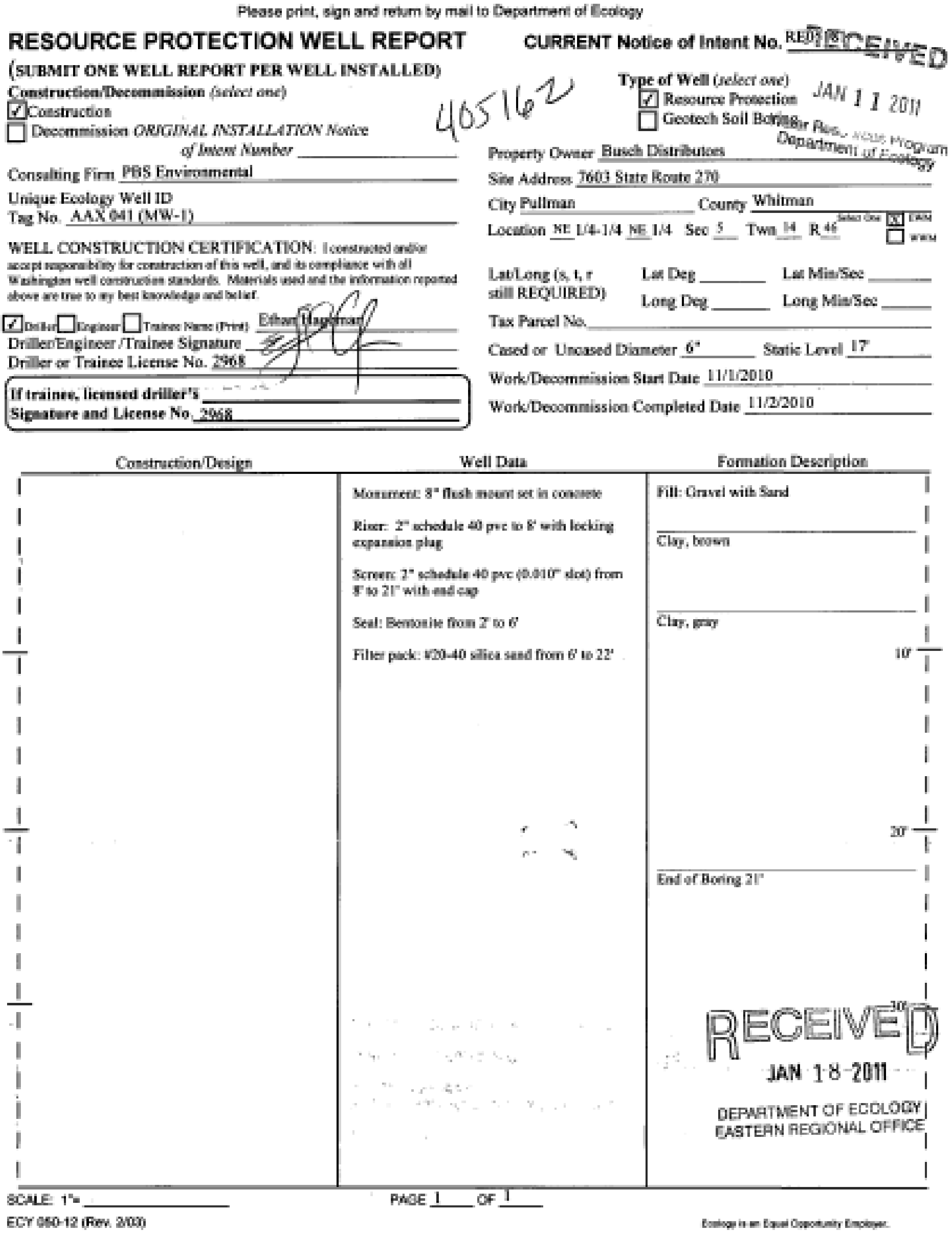
Well log of well E



Please print, sign and return by mail to Department of Ecology

RESOURCE PROTECTION WELL REPORT

(SUBMIT ONE WELL REPORT PER WELL INSTALLED)

CURRENT Notice of Intent No. [illegible]

405162

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Water Resources Program
Department of Ecology

Construction/Decommission *(select one)*
☑ Construction
☐ Decommission *ORIGINAL INSTALLATION Notice of Intent Number* ______

Type of Well *(select one)*
☑ Resource Protection
☐ Geotech Soil Boring

Property Owner Busch Distributors
Site Address 7603 State Route 270
City Pullman County Whitman
Location NE 1/4-1/4 NE 1/4 Sec 5 Twn 14 R 46 Select One ☒ EWM ☐ WWM
Lat/Long (s, t, r still REQUIRED) Lat Deg ______ Lat Min/Sec ______ Long Deg ______ Long Min/Sec ______
Tax Parcel No. ______
Cased or Uncased Diameter 6" Static Level 17'
Work/Decommission Start Date 11/1/2010
Work/Decommission Completed Date 11/2/2010

Consulting Firm PBS Environmental
Unique Ecology Well ID Tag No. AAX 041 (MW-1)

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

☑ Driller ☐ Engineer ☐ Trainee Name (Print) Ethan Hagerman
Driller/Engineer /Trainee Signature
Driller or Trainee License No. 2968

If trainee, licensed driller's Signature and License No. 2968

Construction/Design	Well Data	Formation Description
	Monument: 8" flush mount set in concrete Riser: 2" schedule 40 pvc to 8' with locking expansion plug Screen: 2" schedule 40 pvc (0.010" slot) from 8' to 21' with end cap Seal: Bentonite from 2' to 6' Filter pack: #20-40 silica sand from 6' to 22'	Fill: Gravel with Sand Clay, brown Clay, gray 10' 20' End of Boring 21' 30'

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EASTERN REGIONAL OFFICE

SCALE: 1"= ______ PAGE 1 OF 1

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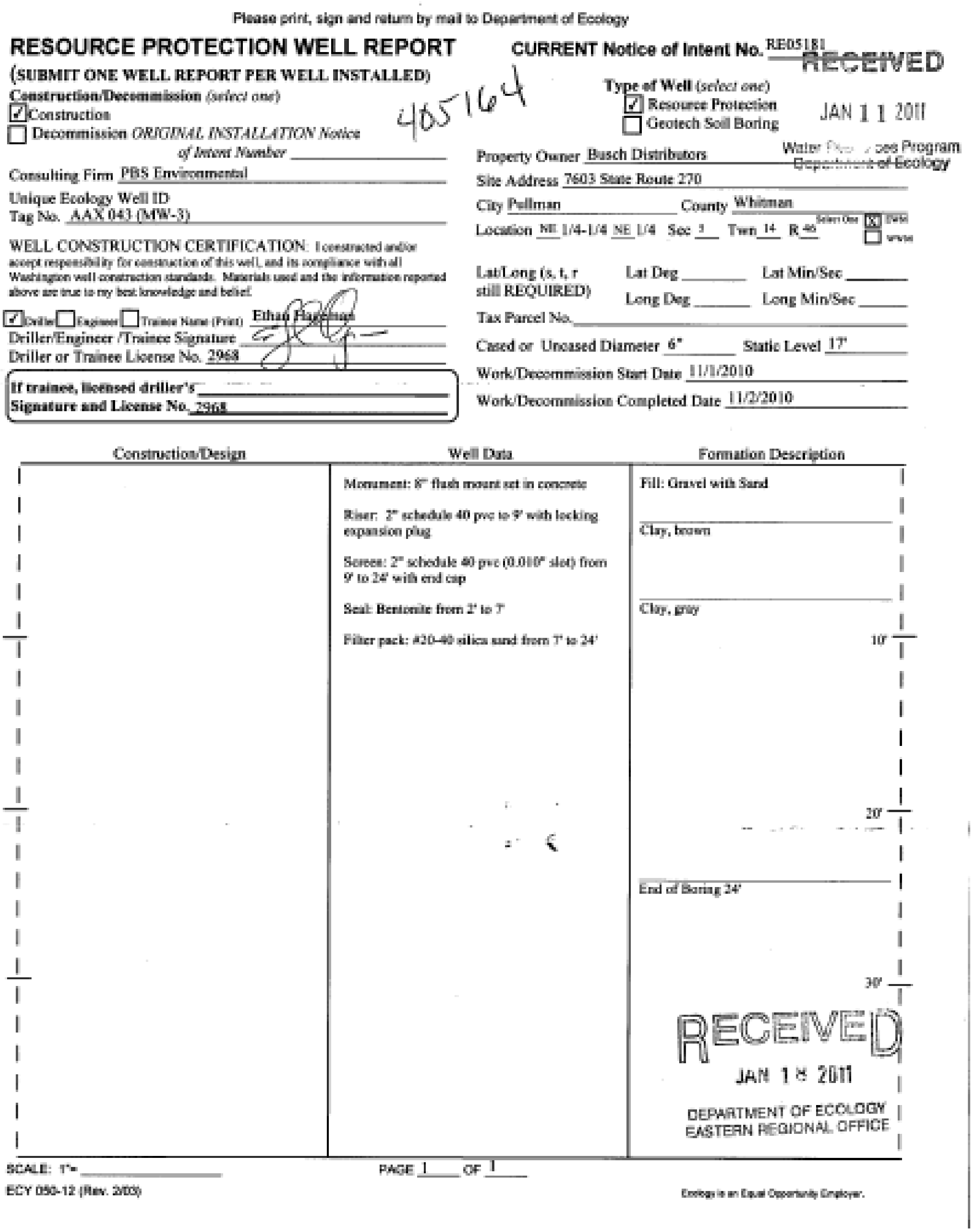
Well log of well F



Please print, sign and return by mail to Department of Ecology

RESOURCE PROTECTION WELL REPORT

(SUBMIT ONE WELL REPORT PER WELL INSTALLED)

CURRENT Notice of Intent No. RE05181

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Water Resources Program
Department of Ecology

405164

Construction/Decommission *(select one)*
☑ Construction
☐ Decommission *ORIGINAL INSTALLATION Notice of Intent Number* ______

Type of Well *(select one)*
☑ Resource Protection
☐ Geotech Soil Boring

Consulting Firm PBS Environmental

Unique Ecology Well ID Tag No. AAX 043 (MW-3)

Property Owner Busch Distributors

Site Address 7603 State Route 270

City Pullman County Whitman

Location NE 1/4-1/4 NE 1/4 Sec 3 Twn 14 R 46 Select One ☒ EWM ☐ WWM

Lat/Long (s, t, r still REQUIRED) Lat Deg ______ Lat Min/Sec ______ Long Deg ______ Long Min/Sec ______

Tax Parcel No. ______

Cased or Uncased Diameter 6" Static Level 17'

Work/Decommission Start Date 11/1/2010

Work/Decommission Completed Date 11/2/2010

WELL CONSTRUCTION CERTIFICATION: I constructed and/or accept responsibility for construction of this well, and its compliance with all Washington well construction standards. Materials used and the information reported above are true to my best knowledge and belief.

☑ Driller ☐ Engineer ☐ Trainee Name (Print) Ethan Hageman

Driller/Engineer /Trainee Signature

Driller or Trainee License No. 2968

If trainee, licensed driller's Signature and License No. 2968

Construction/Design	Well Data	Formation Description
	Monument: 8" flush mount set in concrete Riser: 2" schedule 40 pvc to 9' with locking expansion plug Screen: 2" schedule 40 pvc (0.010" slot) from 9' to 24' with end cap Seal: Bentonite from 2' to 7' Filter pack: #20-40 silica sand from 7' to 24'	Fill: Gravel with Sand Clay, brown Clay, gray 10' 20' End of Boring 24' 30'

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SCALE: 1"= ______ PAGE 1 OF 1

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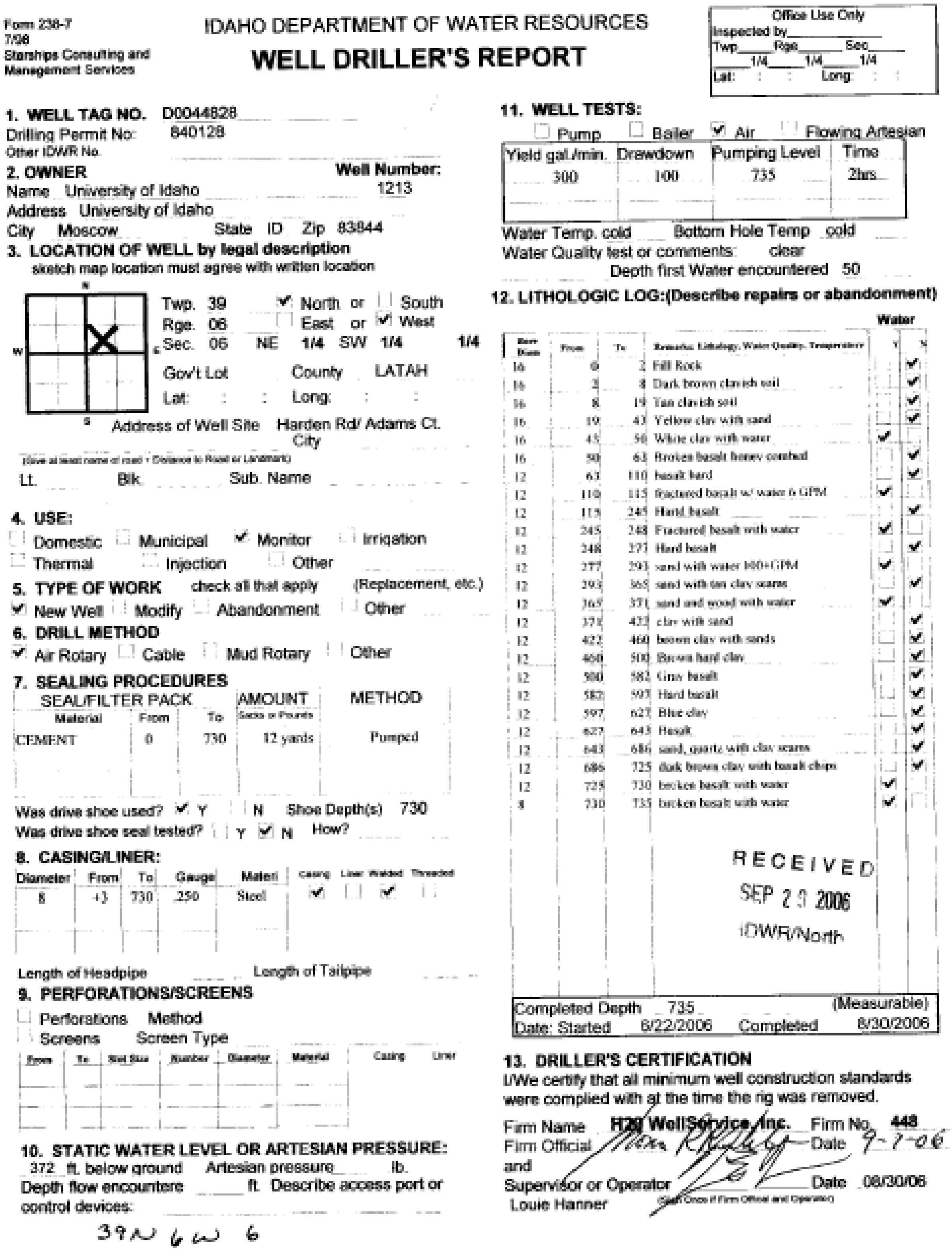
Well log of well G



Form 238-7
7/98
Starships Consulting and
Management Services

IDAHO DEPARTMENT OF WATER RESOURCES

WELL DRILLER'S REPORT

Office Use Only
Inspected by__________
Twp____ Rge____ Sec____
____1/4____1/4____1/4
Lat: : : Long: : :

1. WELL TAG NO. D0044828
Drilling Permit No: 840128
Other IDWR No.

2. OWNER **Well Number:** 1213
Name University of Idaho
Address University of Idaho
City Moscow State ID Zip 83844

3. LOCATION OF WELL by legal description
sketch map location must agree with written location

Twp. 39 ☑ North or ☐ South
Rge. 06 ☐ East or ☑ West
Sec. 06 NE 1/4 SW 1/4 1/4
Gov't Lot County LATAH
Lat: : : Long: : :
Address of Well Site Harden Rd/ Adams Ct.
City
(Give at least name of road + Distance to Road or Landmark)
Lt. Blk. Sub. Name

4. USE:
☐ Domestic ☐ Municipal ☑ Monitor ☐ Irrigation
☐ Thermal ☐ Injection ☐ Other

5. TYPE OF WORK check all that apply (Replacement, etc.)
☑ New Well ☐ Modify ☐ Abandonment ☐ Other

6. DRILL METHOD
☑ Air Rotary ☐ Cable ☐ Mud Rotary ☐ Other

7. SEALING PROCEDURES

SEAL/FILTER PACK			AMOUNT	METHOD
Material	From	To	Sacks or Pounds	
CEMENT	0	730	12 yards	Pumped

Was drive shoe used? ☑ Y ☐ N Shoe Depth(s) 730
Was drive shoe seal tested? ☐ Y ☑ N How?

8. CASING/LINER:

Diameter	From	To	Gauge	Materi	Casing	Liner	Welded	Threaded
8	+3	730	.250	Steel	☑	☐	☑	☐

Length of Headpipe ____ Length of Tailpipe ____

9. PERFORATIONS/SCREENS
☐ Perforations Method
☐ Screens Screen Type

From	To	Slot Size	Number	Diameter	Material	Casing	Liner

10. STATIC WATER LEVEL OR ARTESIAN PRESSURE:
372 ft. below ground Artesian pressure____ lb.
Depth flow encountere ____ ft. Describe access port or control devices:

39N 6W 6

11. WELL TESTS:
☐ Pump ☐ Bailer ☑ Air ☐ Flowing Artesian

Yield gal./min.	Drawdown	Pumping Level	Time
300	100	735	2hrs

Water Temp. cold Bottom Hole Temp cold
Water Quality test or comments: clear
Depth first Water encountered 50

12. LITHOLOGIC LOG:(Describe repairs or abandonment)

Bore Diam	From	To	Remarks: Lithology, Water Quality, Temperature	Water Y	Water N
16	0	2	Fill Rock	☐	☑
16	2	8	Dark brown clayish soil	☐	☑
16	8	19	Tan clayish soil	☐	☑
16	19	43	Yellow clay with sand	☐	☑
16	45	50	White clay with water	☑	☐
16	50	63	Broken basalt honey combed	☐	☑
12	63	110	basalt hard	☐	☑
12	110	115	fractured basalt w/ water 6 GPM	☑	☐
12	115	245	Hard basalt	☐	☑
12	245	248	Fractured basalt with water	☑	☐
12	248	277	Hard basalt	☐	☑
12	277	293	sand with water 100+GPM	☑	☐
12	293	365	sand with tan clay seams	☐	☑
12	365	371	sand and wood with water	☑	☐
12	371	422	clay with sand	☐	☑
12	422	460	brown clay with sands	☐	☑
12	460	500	Brown hard clay	☐	☑
12	500	582	Gray basalt	☐	☑
12	582	597	Hard basalt	☐	☑
12	597	627	Blue clay	☐	☑
12	627	643	Basalt	☐	☑
12	643	686	sand, quartz with clay seams	☐	☑
12	686	725	dark brown clay with basalt chips	☐	☑
12	725	730	broken basalt with water	☑	☐
8	730	735	broken basalt with water	☑	☐

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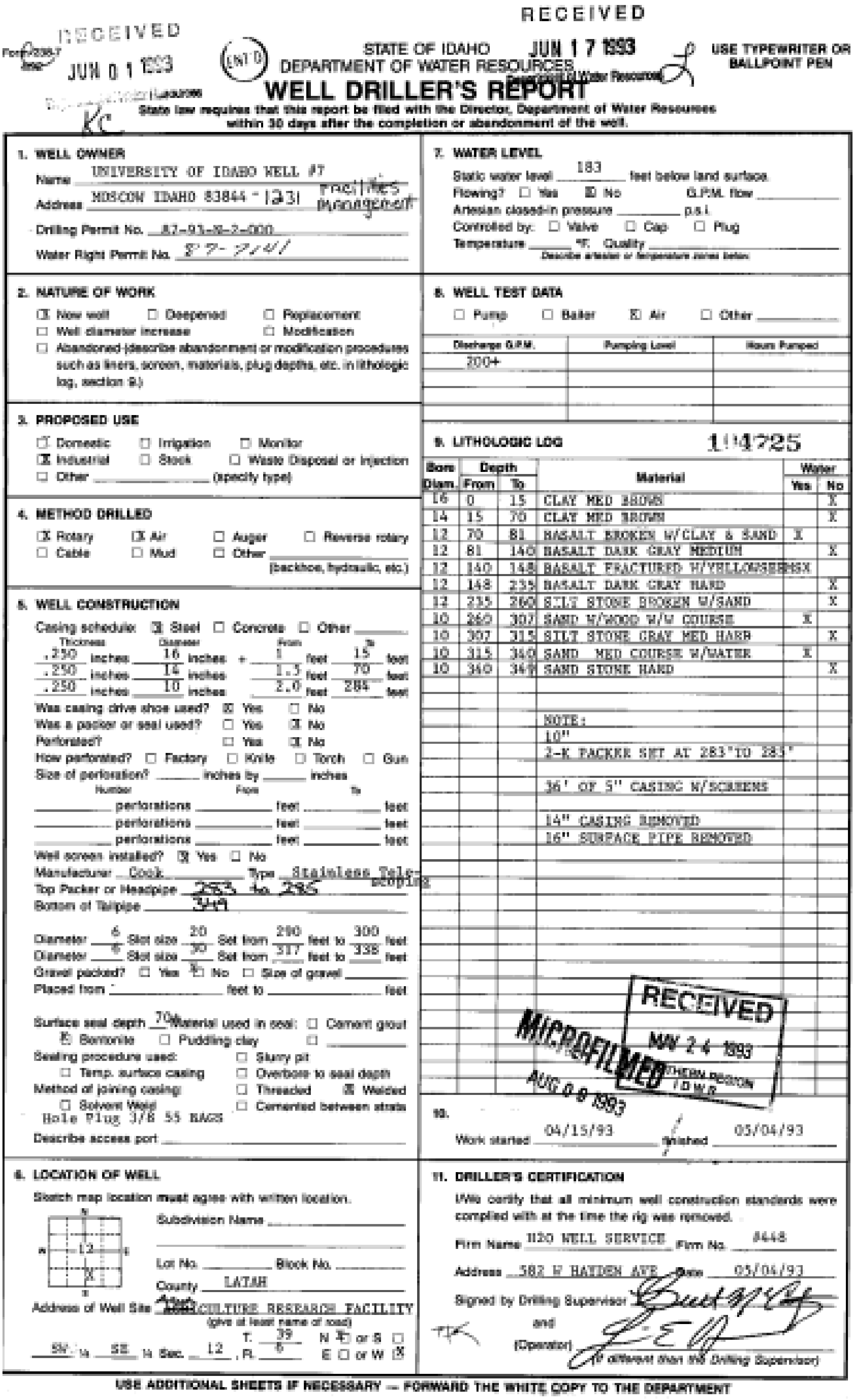
IDWR/North

Completed Depth 735 (Measurable)
Date: Started 6/22/2006 Completed 8/30/2006

13. DRILLER'S CERTIFICATION
I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name H2O Well Service, Inc. Firm No. 448
Firm Official Date 9-7-06
and
Supervisor or Operator Date 08/30/06
Louie Hanner
(Sign Once if Firm Official and Operator)

Well log of well N



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Department of Water Resources
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JUN 1 7 1993
Department of Water Resources

Form 238-7

ENT'D

STATE OF IDAHO
DEPARTMENT OF WATER RESOURCES

USE TYPEWRITER OR BALLPOINT PEN

WELL DRILLER'S REPORT

State law requires that this report be filed with the Director, Department of Water Resources within 30 days after the completion or abandonment of the well.

1. WELL OWNER

Name UNIVERSITY OF IDAHO WELL #7
Address MOSCOW IDAHO 83844 - 1231 Facilities Management
Drilling Permit No. 87-93-N-2-000
Water Right Permit No. 87-7141

2. NATURE OF WORK

☒ New well ☐ Deepened ☐ Replacement
☐ Well diameter increase ☐ Modification
☐ Abandoned (describe abandonment or modification procedures such as liners, screen, materials, plug depths, etc. in lithologic log, section 9.)

3. PROPOSED USE

☐ Domestic ☐ Irrigation ☐ Monitor
☒ Industrial ☐ Stock ☐ Waste Disposal or Injection
☐ Other ________ (specify type)

4. METHOD DRILLED

☒ Rotary ☒ Air ☐ Auger ☐ Reverse rotary
☐ Cable ☐ Mud ☐ Other ________ (backhoe, hydraulic, etc.)

5. WELL CONSTRUCTION

Casing schedule: ☒ Steel ☐ Concrete ☐ Other ________

Thickness		Diameter			From		To	
.250	inches	16	inches	+	1	feet	15	feet
.250	inches	14	inches		1.5	feet	70	feet
.250	inches	10	inches		2.0	feet	284	feet

Was casing drive shoe used? ☒ Yes ☐ No
Was a packer or seal used? ☐ Yes ☒ No
Perforated? ☐ Yes ☒ No
How perforated? ☐ Factory ☐ Knife ☐ Torch ☐ Gun
Size of perforation? ______ inches by ______ inches

Number		From		To	
	perforations		feet		feet
	perforations		feet		feet
	perforations		feet		feet

Well screen installed? ☒ Yes ☐ No
Manufacturer Cook Type Stainless Telescoping
Top Packer or Headpipe 283 to 285
Bottom of Tailpipe 349

Diameter 6 Slot size 20 Set from 290 feet to 300 feet
Diameter 6 Slot size 30 Set from 317 feet to 338 feet
Gravel packed? ☐ Yes ☒ No ☐ Size of gravel ________
Placed from ________ feet to ________ feet

Surface seal depth 70 Material used in seal: ☐ Cement grout ☒ Bentonite ☐ Puddling clay ☐ ________
Sealing procedure used: ☐ Slurry pit ☐ Temp. surface casing ☐ Overbore to seal depth
Method of joining casing: ☐ Threaded ☒ Welded ☐ Solvent Weld ☐ Cemented between strata
Hole Plug 3/8 55 BAGS
Describe access port ________

6. LOCATION OF WELL

Sketch map location must agree with written location.

N, W, E, S
12
X

Subdivision Name ________
Lot No. ______ Block No. ______
County LATAH
Address of Well Site Agriculture ~~AGRI~~CULTURE RESEARCH FACILITY (give at least name of road)
SW ¼ SE ¼ Sec. 12, T. 39 N ☒ or S ☐, R. 6 E ☐ or W ☒

7. WATER LEVEL

Static water level 183 feet below land surface.
Flowing? ☐ Yes ☒ No G.P.M. flow ________
Artesian closed-in pressure ________ p.s.i.
Controlled by: ☐ Valve ☐ Cap ☐ Plug
Temperature ______ °F. Quality ________
Describe artesian or temperature zones below.

8. WELL TEST DATA

☐ Pump ☐ Bailer ☒ Air ☐ Other ________

Discharge G.P.M.	Pumping Level	Hours Pumped
200+		

9. LITHOLOGIC LOG 104725

Bore Diam.	Depth From	Depth To	Material	Water Yes	Water No
16	0	15	CLAY MED BROWN		X
14	15	70	CLAY MED BROWN		X
12	70	81	BASALT BROKEN W/CLAY & SAND	X	
12	81	140	BASALT DARK GRAY MEDIUM		X
12	140	148	BASALT FRACTURED W/YELLOWSEE	MSX	
12	148	235	BASALT DARK GRAY HARD		X
12	235	260	SILT STONE BROKEN W/SAND		X
10	260	307	SAND W/WOOD W/W COURSE	X	
10	307	315	SILT STONE GRAY MED HARD		X
10	315	340	SAND MED COURSE W/WATER	X	
10	340	349	SAND STONE HARD		X
			NOTE:		
			10"		
			2-K PACKER SET AT 283'TO 285'		
			36' OF 5" CASING W/SCREENS		
			14" CASING REMOVED		
			16" SURFACE PIPE REMOVED		

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MICROFILMED
AUG 0 9 1993

10.

Work started 04/15/93 finished 05/04/93

11. DRILLER'S CERTIFICATION

I/We certify that all minimum well construction standards were complied with at the time the rig was removed.

Firm Name H2O WELL SERVICE Firm No. #448
Address 582 W HAYDEN AVE Date 05/04/93
Signed by Drilling Supervisor
and
(Operator) (if different than the Drilling Supervisor)

USE ADDITIONAL SHEETS IF NECESSARY — FORWARD THE WHITE COPY TO THE DEPARTMENT

Well log of well O

Appendix III: Letter to well-owners isotopic sampling

Thanks for your contribution to my graduate research by having me sampling your well. By this way I would like to inform you about the topic of my research and some preliminary results, which includes the results of your well.

Introduction

Despite curtailed groundwater pumping in the Pullman-Moscow region since 1992, aquifer levels have continued to decline at 12 inches/yr or more. Pullman-Moscow groundwater systems are fairly complex with multiple basalt flows underlain by protruding basement metamorphic/granitic ridges, paleo-valleys and interwoven with sand/gravel inter-beds; see Figure 1. Knowing the source locations of recharge to the basalt aquifers in the Moscow sub-basin is vital for understanding the long-term sustainability of our water resources and for developing solutions which enhance recharge and protect the quality of our drinking water sources for future generations.From reduced pumping of the Wanapum aquifer (the most shallow aquifer in the Moscow sub-basin) we know that recharge of the aquifer is occurring, since the water levels recovered. However there is no clear evidence indicating *where* recharge is occurring in the Moscow sub-basin.

The "Sediments of Bovill" is a known geological layer in this area, which is basically granitic weathered material. They are known to contain large amounts of clays, gravels and sands. We expect the Moscow Mountain to be a region with the greatest potential for recharge. Figure 1 shows these potential recharge pathways in the Moscow sub-basin. Water infiltrating at the granitic Moscow Mountains is expected to find its way through the Sediments of Bovill, recharging the Wanapum and Grande Ronde aquifer.

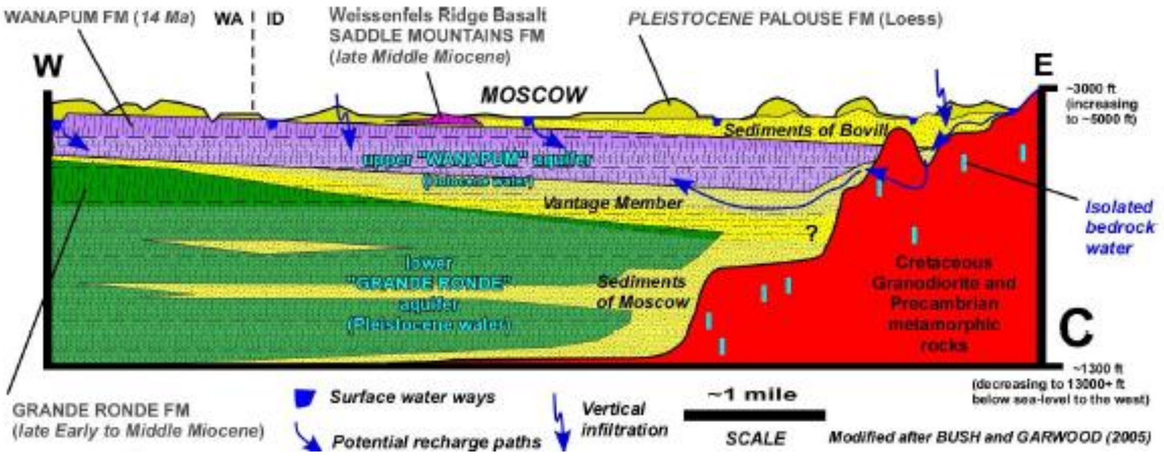


Fig.1 Geology of the Moscow sub-basin

Isotopes

One of the primary approaches to determine whether a hydrologic connection exists between two water bodies is to use tracers. The tracer technique that we will use to investigate recharge flow pathways in the Moscow sub-basin are isotopic tracers. The oxygen and hydrogen isotopic signature of water is a unique attribute largely defined by the changes of phase which occur from the point of evaporation/condensation in the storm cloud to the point where the water infiltrates through the soil. In general the isotopic signature varies with elevation, phase of water (i.e. snow vs rain), and season with enriched values in the summer and depleted values in the winter. The isotope signal in wells is expected to show similar, but lagged variations as the precipitation and surface water in the creeks.

Objectives

In this study we propose to investigate one of the primary ground water recharge hypotheses through the use of isotopic tracers. Specifically we will:

11. Establish long-term, high-frequency isotopic sampling to investigate the hypothesis that surface waters are hydrologically connected to groundwater systems.
12. Examine spatial patterns in the isotopic response of wells to determine if large paleo-channels or paleo-valleys can be identified and related to well log data.

Preliminary Results

The graph shows the first results of the isotope analysis. An overview of all the wells and springs can be seen in figure 3. The wells cover a wide range of the isotope signal, from very depleted values (left side) to very enriched values (right side). A depleted value means the water has been infiltrated long time ago or infiltrated at high elevation or is water from snow melt peaks. Often these values are found in deep wells. The enriched values mean that before the water infiltrated into the soil the water has been evaporating. These values are often found in springs and very shallow wells. The values in the middle of the graph have a similar signal as the surface water.

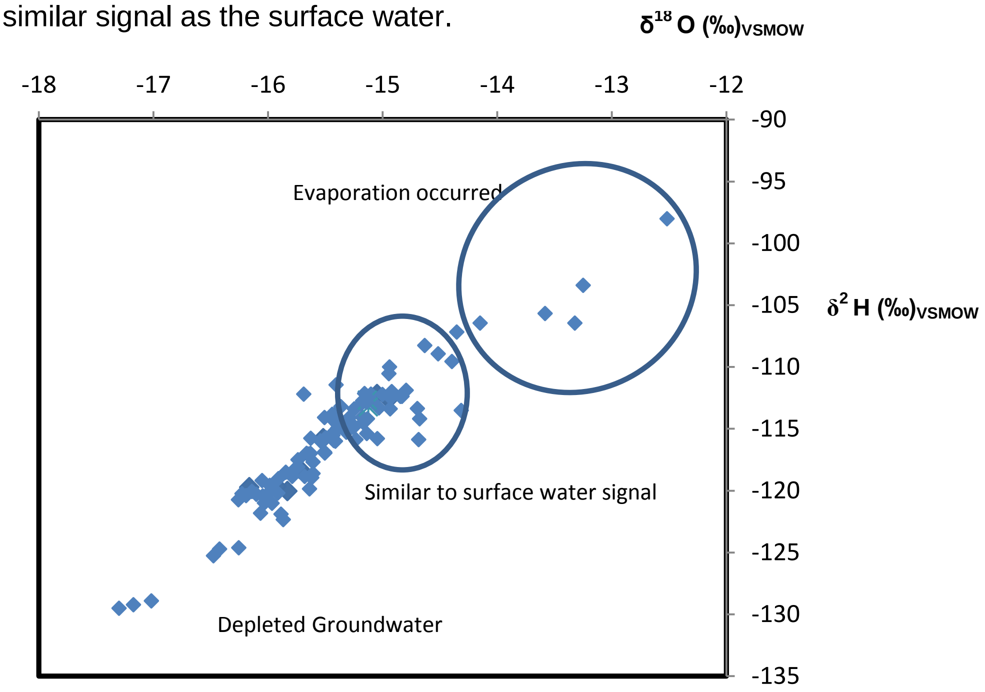


Fig2. Isotope results for wells in the Moscow sub-basin

By sampling a selection of these wells for two years we hope to see how the isotope signal of the water in the wells of these 3 groups is changing and whether it changes similar (but lagged) as the isotopic signal of the creek water.

Your well results

Isotope value:

Oxygen-18 (‰)	-15.03
Hydrogen-2 (‰)	-113.3

Geology and depth well: 78ft in Sediments of Bovill

Selected for 2-year sampling: Yes, interesting to see long-term fluctuations

Contact:

If you have questions about this project, feel free to contact me or my supervisor Erin Brooks.

- Jasper Candel, jasper.candel@wur.nl; 2085961946 (valid until 08-28-13)
- Erin Brooks, ebrooks@uidaho.edu, Dept. Bio. and Ag. Eng., PO Box 442060, University of Idaho, Moscow, ID 83844-2060; 208-885-6562

From the 13th of July, Hydrology student Craig Woodruff will take over the sampling for the selected wells for 2 years, with a frequency of once every 2 weeks. So you will see him around.

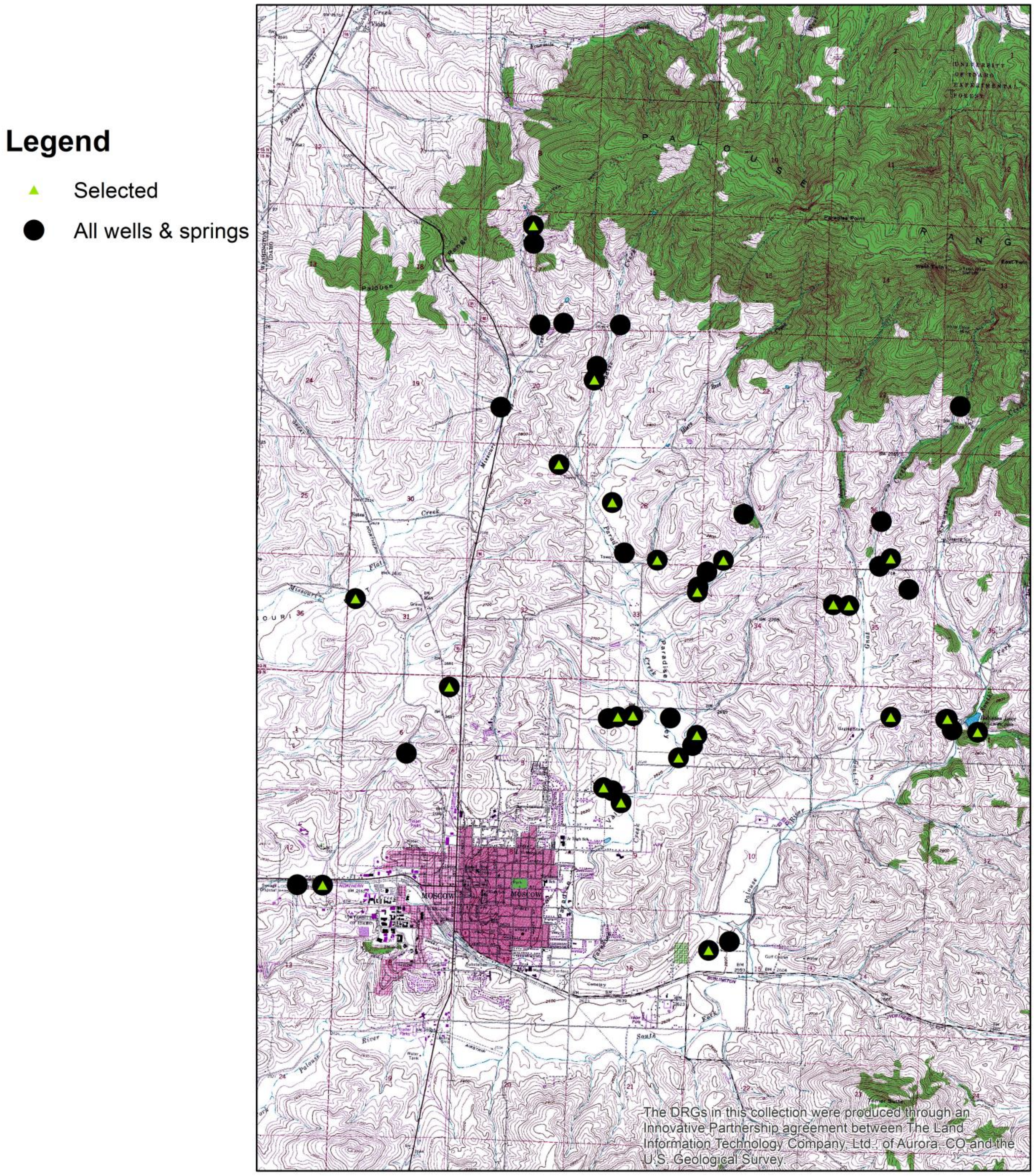
Craig's contact info is:

- Craig Woodruff. Phone (360) 463-1011 and email wood3615@vandals.uidaho.edu

Jasper

Thanks a lot for your contribution!

Craig



The DRGs in this collection were produced through an Innovative Partnership agreement between The Land Information Technology Company, Ltd., of Aurora, CO and the U.S. Geological Survey.

Fig3. Map of all the wells and springs, showing which wells & springs have been selected for the 2 year sampling

Appendix IV: Letter to well-owners caffeine sampling

Thanks for your contribution to my graduate research by having me sampling your well for caffeine. By this way I would like to inform you about the topic of my research and some preliminary results, which includes the results of your well.

Introduction

Despite curtailed groundwater pumping in the Pullman-Moscow region since 1992, aquifer levels have continued to decline at 12 inches/yr or more. Pullman-Moscow groundwater systems are fairly complex with multiple basalt flows underlain by protruding basement metamorphic/granitic ridges, paleo-valleys and interwoven with sand/gravel inter-beds; see Figure 1. Knowing the source locations of recharge to the basalt aquifers in the Moscow sub-basin is vital for understanding the long-term sustainability of our water resources and for developing solutions which enhance recharge and protect the quality of our drinking water sources for future generations. From reduced pumping of the Wanapum aquifer (the most shallow aquifer in the Moscow sub-basin) we know that recharge of the aquifer is occurring, since the water levels recovered. However there is no clear evidence indicating *where* recharge is occurring in the Moscow sub-basin. Since the Moscow sub-basin has a lot of soils which are impermeable, we do not know from where the surface water could reach the groundwater systems.

Hypothesis: Recharge occurs as stream loss over basalt (western Moscow sub-basin)

The hypothesis that recharge occurs in areas where the basalt is near the surface can also be justified by preliminary evidence. The Paradise Creek runs directly above basalt downstream from the University of Idaho campus. There are no thick clay layers to impede vertical flow. In addition, the city of Moscow waste water treatment plant sustains perennial flow downstream of the discharge point and therefore there is a greater opportunity for water to infiltrate than further upstream in the creek where the flow is intermittent in the summer. The precipitation near the state line exceeds crop uptake in this region and therefore there is a high potential for vertical leaching. Moxley (2012) recently provided strong evidence indicating that the South Fork of the Palouse River downstream of Pullman provides local recharge. Carey (2011) also suggested that wells closer to streams were more likely to show a connection with the surface water. However, in many cases these streams dry up during the summer and therefore may not provide the magnitude of recharge observed in the Wanapum aquifer.

One of the primary approaches to determine whether a hydrologic connection exists between two water bodies is to use tracers. One tracer technique that we will use to investigate recharge flow pathways in the Moscow sub-basin is a caffeine tracer.

Caffeine Tracers

Caffeine has been used to detect a hydrologic connection to groundwater primarily in urban landscapes. In North America the source of caffeine is almost exclusively related to sewage sources. Since most waste water treatment plants are not required to treat effluent for caffeine the concentrations released to a stream through the effluent can be relatively large. Also the Paradise Creek which is flowing through Moscow could contain caffeine, because of leaching from the urban landscape. Caffeine has been measured in surface waters and aquifers all around the world, and is found in ranges of 1-300 µg/L. Upon reaching a groundwater system, caffeine is a conservative tracer.

Objectives

In this study we propose to investigate one of the primary ground water recharge hypotheses through the use of caffeine tracers. Specifically we will test wells near the city of Moscow waste water treatment plant for caffeine to determine whether the surface water downstream of the waste water treatment plant is a source of recharge to the aquifer.

Preliminary Results

Only in the well at the Groundwater Research Site at the University of Idaho campus a small amount of 0,045 µg/ was found. Also in the surface water downstream of the effluent a small amount of 0,057 µg/l was found. All the other samples had no caffeine or no concentrations of caffeine which were above the detection limit of 0,02 µg/l. Remarkably also the effluent didn't contain enough caffeine to detect.

Figure showing all sample locations for caffeine in Moscow. In yellow the wells, blue the Paradise Creek and green the effluent.

Conclusion

Since the surface water upstream of Moscow didn't contain caffeine, the caffeine probably came into the Paradise Creek while flowing through Moscow. Since the concentration is already close to the detection limit it is very unlikely that we could have detected caffeine in the wells. However, there seems to be a hydrologic connection between the Paradise Creek and the shallow aquifer at the Groundwater Research Site.

Since the concentrations of caffeine in the surface water and well water are very low (mostly below our detection limit) other tracers like for example oestrogen could be used in future research. The tracer should be present in a much higher concentration in the surface water to be able to detect the tracer in the wells.

Contact:

If you have questions about this project, feel free to contact me or my supervisor Erin Brooks.

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- Erin Brooks, ebrooks@uidaho.edu, Dept. Bio. and Ag. Eng., PO Box 442060, University of Idaho, Moscow, ID 83844-2060; 208-885-6562

Appendix V: Selected wells for the isotopic sampling

Sample nr.	Name	WellID	Bed-rock	Surface elevation (m amsl)	D well (m)	Elevation water (m amsl)	Long	Lat
1	1275 MV-road	279844	SOB	811,7	23,8	792	-116,975467	46,745203
5	Darrel, Dawn Paul	279433	Basalt	818,1	71,6	764	-116,973363	46,754049
6	Darrel, Dawn Paul	spring	Spring	818,1	0,0	818	-116,973363	46,754049
8	Mark Bechtel	411379	Granite	841,6	213,4	655	-116,935307	46,76893
9	Warren Levecke	279954	SOB	832,2	77,1	757	-116,932524	46,768905
11	Orrin Frink	279918	Granite	848,6	27,1	824	-116,925279	46,774895
14	Latah countys department	unknown	unknown	823,5	102,1	823	-116,908495	46,753806
17	Howard Berglund	280306	Granite	828,9	43,3	792	-116,924215	46,755273
19	Jenis Willard	spring	Spring	809,0	0,0	809	-116,95898	46,752131
20	Stanley	279727	Basal	800,1	54,9	755	-116,962	46,7492

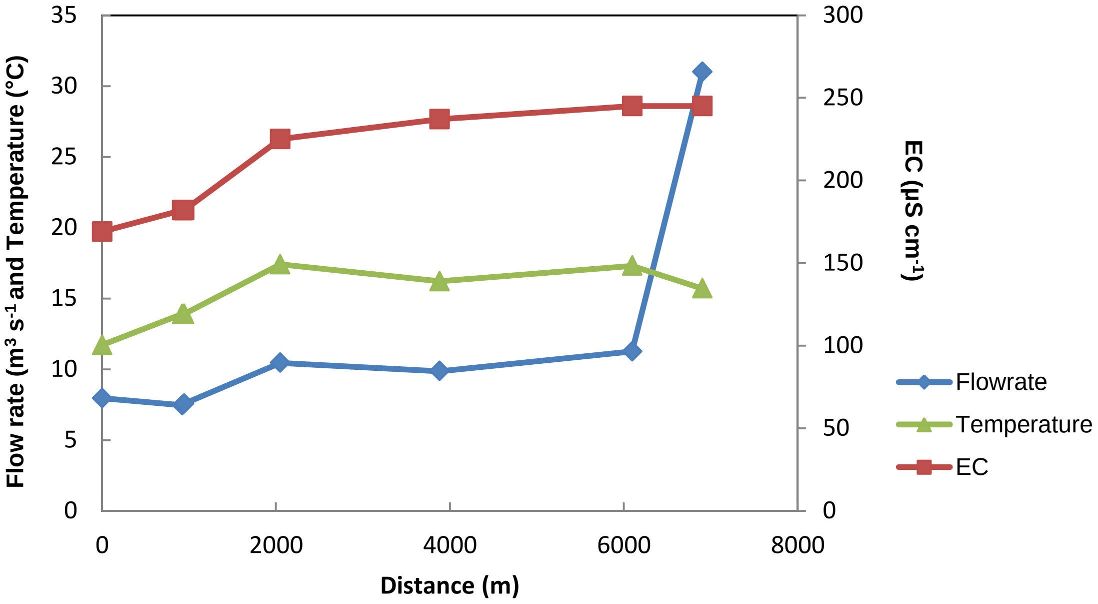
	Miller		t				16	62
21	Floyd Trail	279905	SOB	810,8	45,7	789	-116,970663	46,754251
22	Gang	280057 & 280008	SOB	817,5	105,2	775	-116,959883	46,769872
23	Kenneth Garretz	280053	SOB	827,4	62,5	814	-116,95542	46,773923
24	Mick Hess	338130	SOB	832,1	93,0	747	-116,958287	46,77242
26	Bizeau	279678	Basalt	817,4	46,6	775	-116,967314	46,773636
27	Fouchachon	389781	Granite	824,2	67,1	771	-116,975827	46,780564
28	Elliot	279492	SOB	834,1	72,5	762	-116,985709	46,785009
29		279708	Granite	839,0	93,0	755	-116,979895	46,795657
35	George Grader	unknown	Granite	950,1	93,6	945	-116,991942	46,814497
41	Carson	-	Basalt	797,9	27,4	770	-117,021437	46,76746
36	Caw Tenwick	280524	SOB	815,0	18,9	801	-117,003918	46,756973
37	Plant Science	unknown	Basalt	797,0	150,0	765	-116,955	46,725566

	Farm						45	
39	T16D	unknown	Basalt		21,0	754	-117,02535	46,731821
60	IDWR 3	unknown	Vantage	800,1	108,2	692	-117,0265894	46,7472020

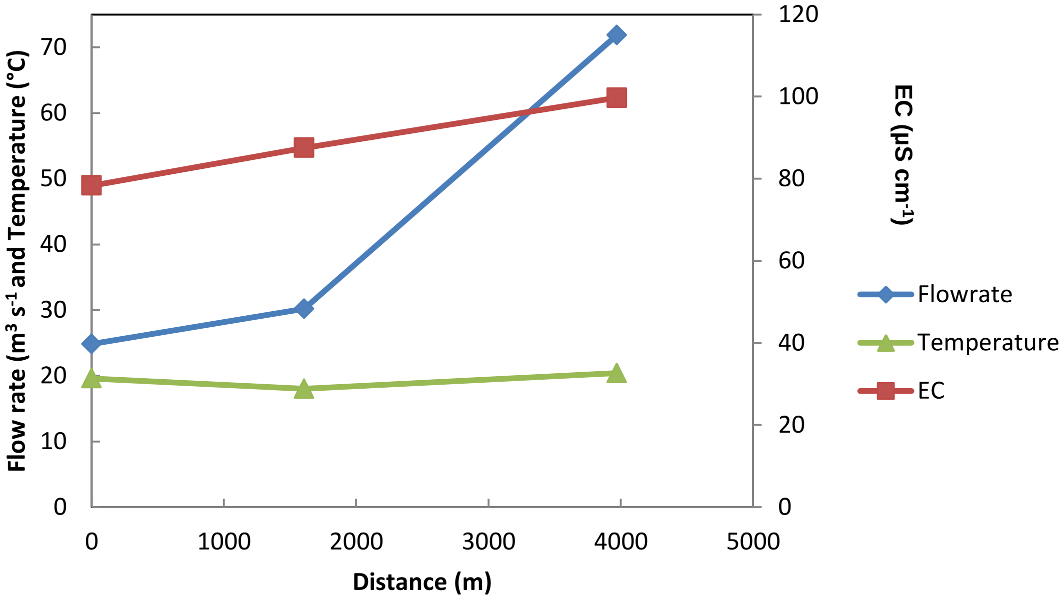
Appendix VI: Selected wells for the caffeine sampling

Sample	Well	Depth well (m)	Geology	Lat	Long
A	Toyota Garage	93	Basalt	46.737441°	-117.061779°
B	Motley & Motley	104	Basalt	46.729754°	-117.089533°
C	Thonney	96	Basalt	46.728688°	-117.109162°
D	Poe Asphalt	92	basalt	46.725957°	-117.113708°
E	Busch distributors	6	Clay	46,733078	-117,049982
F	Busch distributors	6	Clay	46,733078	-117,049982
G	Busch distributors	7	Clay	46,733078	-117,049982
H	T16D	25	Basalt	46,731821	-117,02535
I	D19D	43	Basalt	46,731748	-117,029873
J	Paradise Creek Upstream	.	-	46,744152	-116,971144
K	Paradise Creek Downstream	.	-	46,735242	-117,05134
L	Effluent	.	-	46,734297	-117,050919
M	IDWR 3	108	Vantage Member	46,7472020	-117,026589
N	IDWR 4	224	Grande Rhonde	46,7472213	-117,026753
O	Aquaculture #7	.	Basalt and Latah Formation	46.729800°	-117.027836
P	blank with filter+bailer	.	-	.	.
Q	Blank with filter	.	-	.	.
R	Blank without	.	-	.	.

Appendix VII: Stream measurements



Discharge, temperature and EC measurements for the Paradise Creek northeast of Moscow done at 03-06-13 (Figure 5.11).

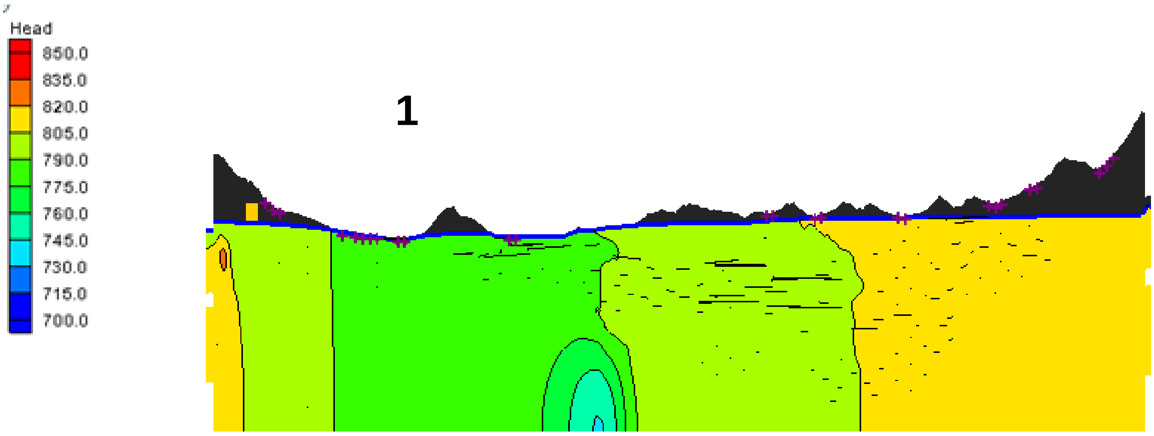


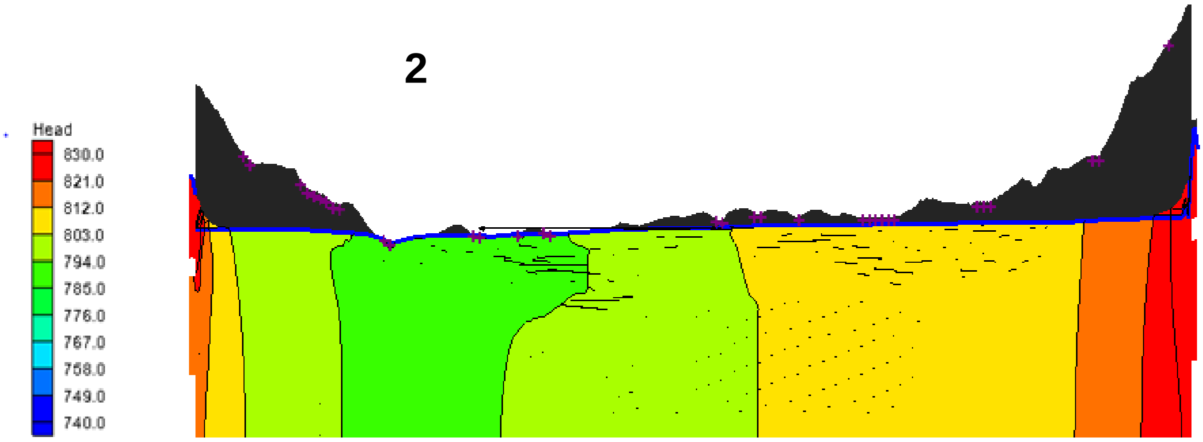
Discharge, temperature and EC measurements for the SFPR east of Moscow done at 17-06-13 (Figure 5.11).

Appendix VIII: Head distributions Steady-State Modflow model

The cross-sections correspond to the numbered dotted lines in Figure 8.6. All heads displayed at each cross-section is in m +amsl. A general legend for all cross-sections is is illustrated below. All black cells in the cross-sections are dry cells.

—	Groundwater level
■	Well
+	Stream
◆	Constant head





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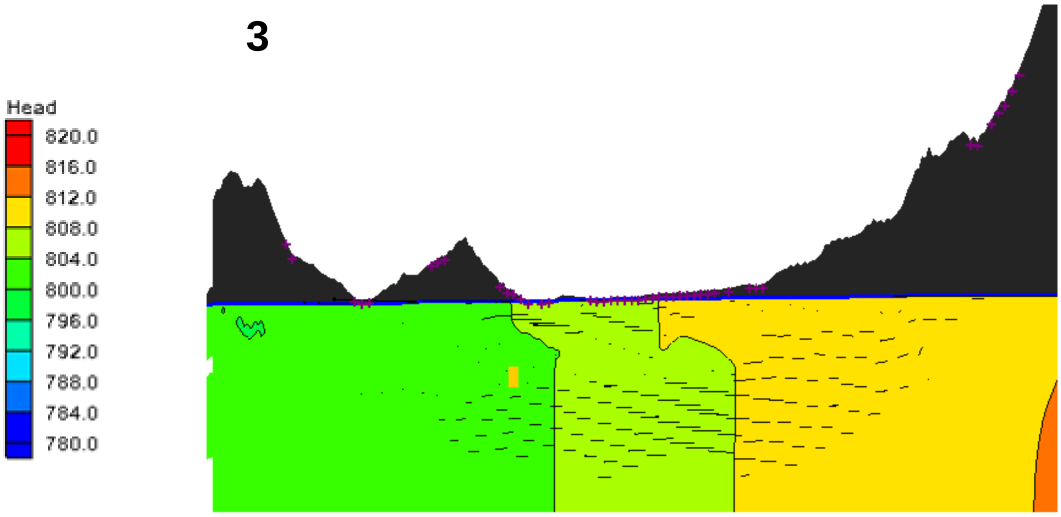
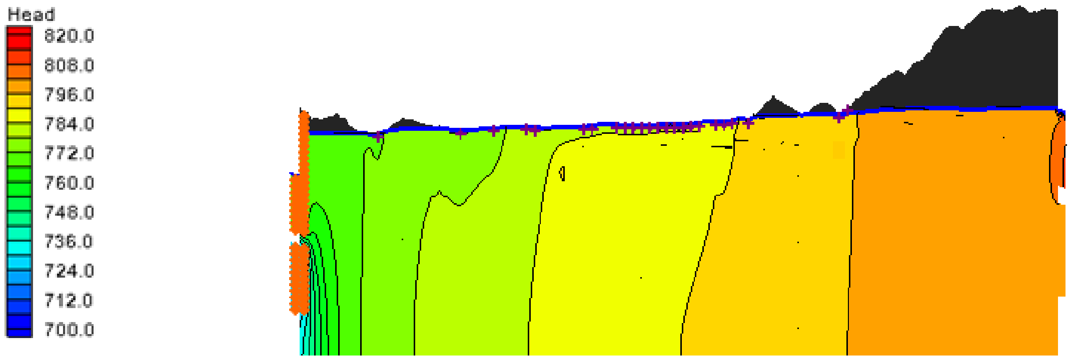
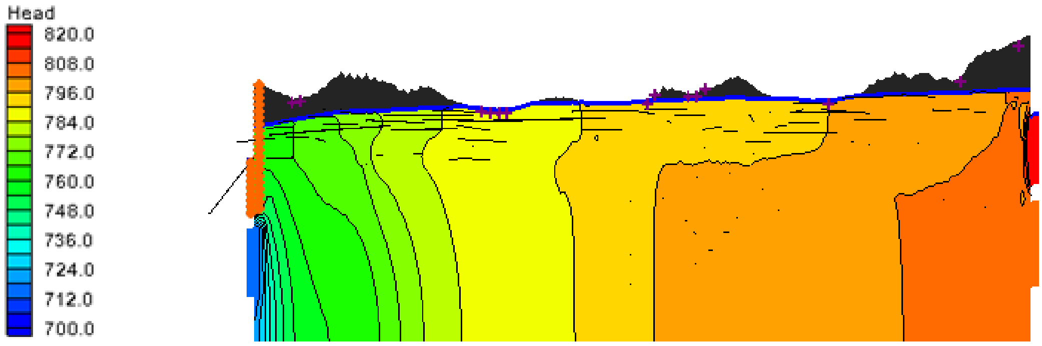

Head
820.0
816.0
812.0
808.0
804.0
800.0
796.0
792.0
788.0
784.0
780.0

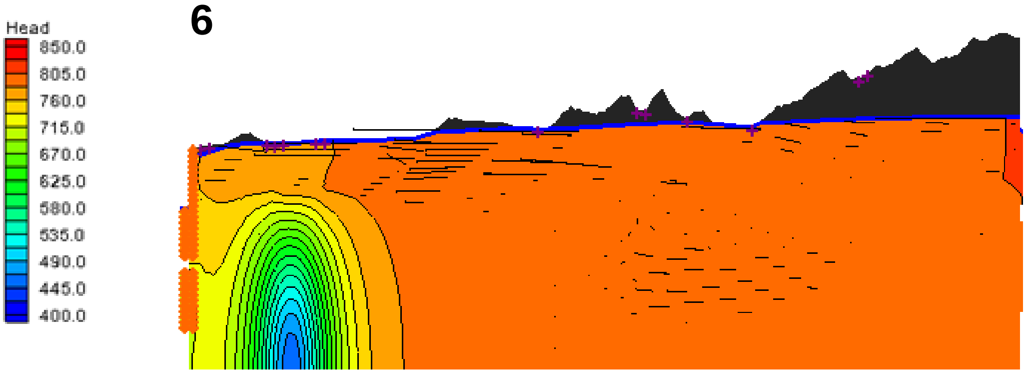
4


Head
820.0
808.0
796.0
784.0
772.0
760.0
748.0
736.0
724.0
712.0
700.0

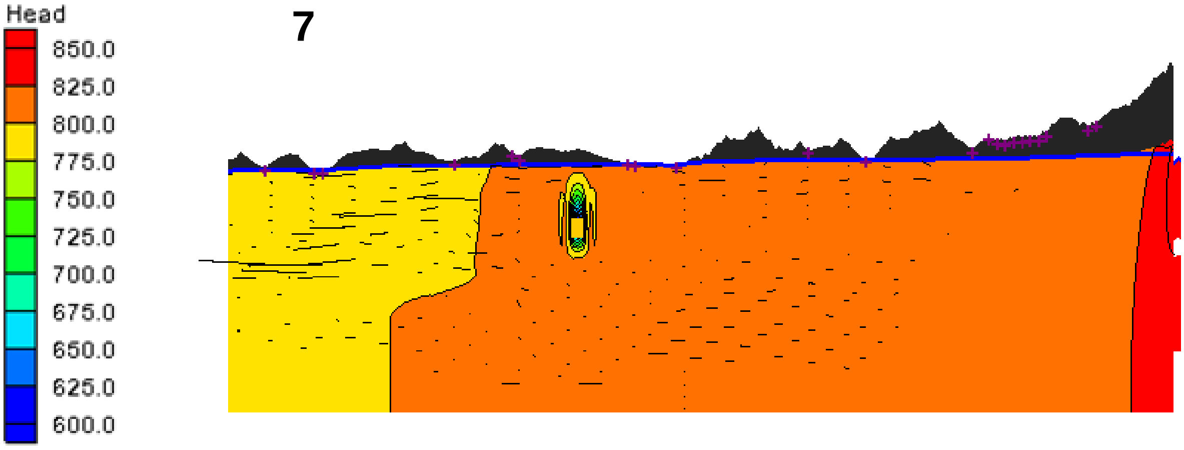
5


Head
820.0
808.0
796.0
784.0
772.0
760.0
748.0
736.0
724.0
712.0
700.0

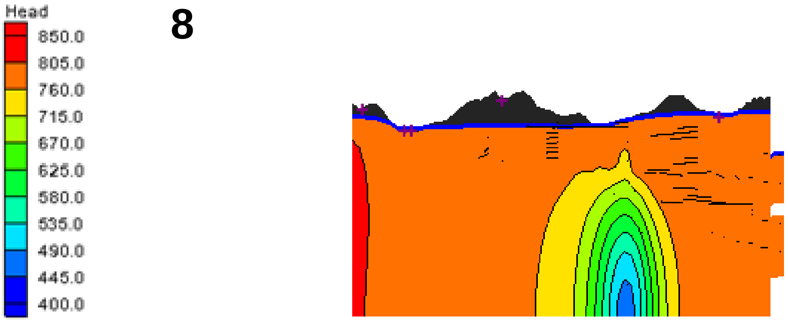
6


Head
850.0
805.0
760.0
715.0
670.0
625.0
580.0
535.0
490.0
445.0
400.0

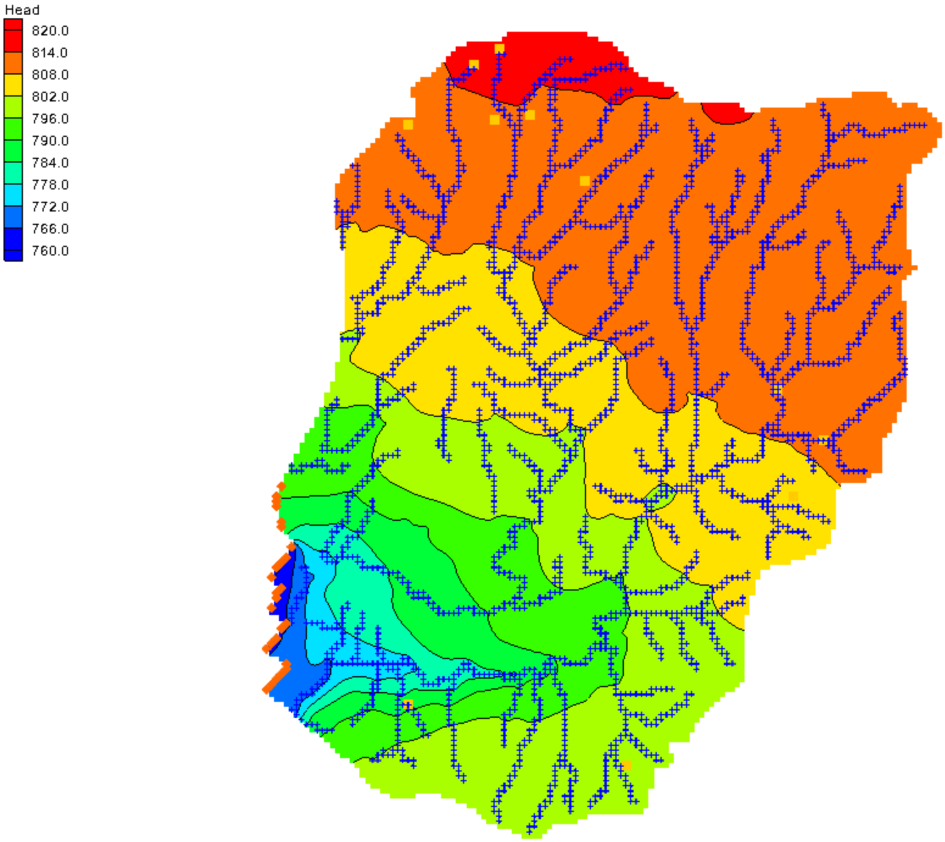
7


Head
850.0
825.0
800.0
775.0
750.0
725.0
700.0
675.0
650.0
625.0
600.0

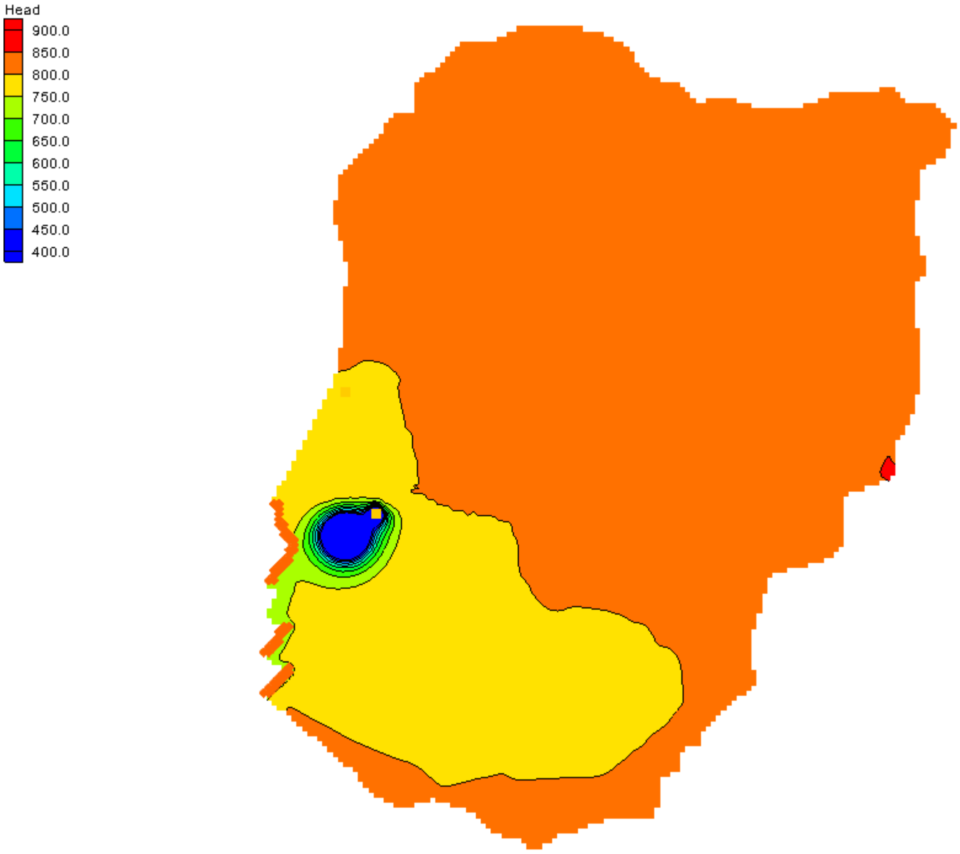
8

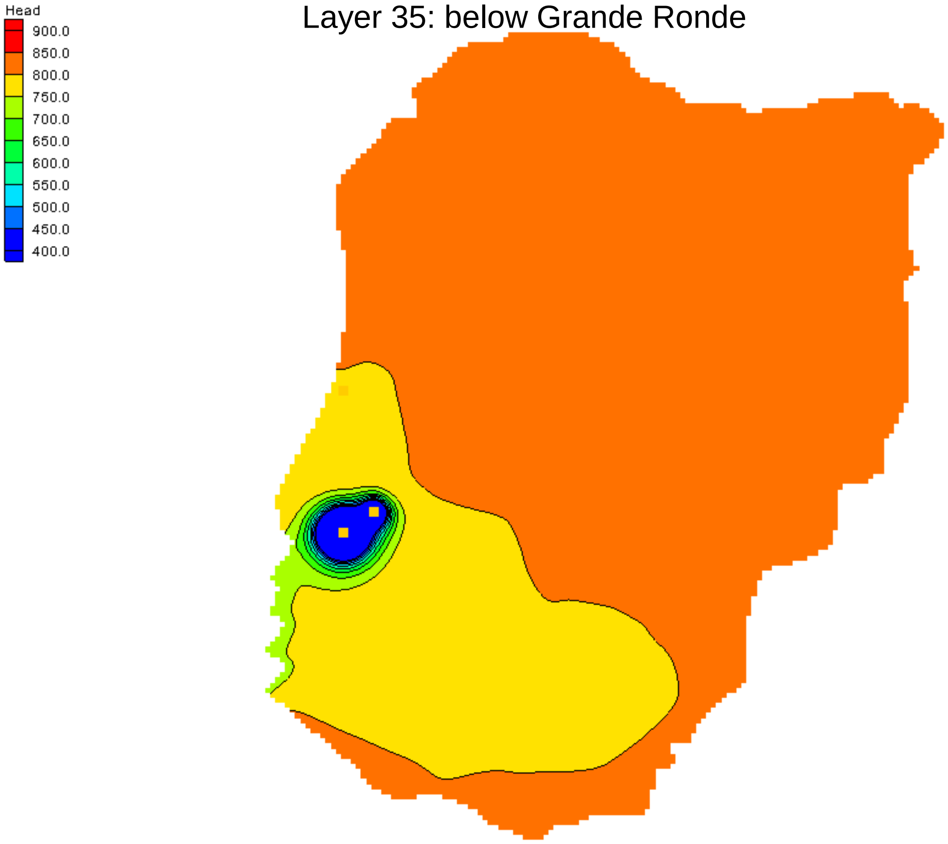

Head
850.0
805.0
760.0
715.0
670.0
625.0
580.0
535.0
490.0
445.0
400.0

Surface level



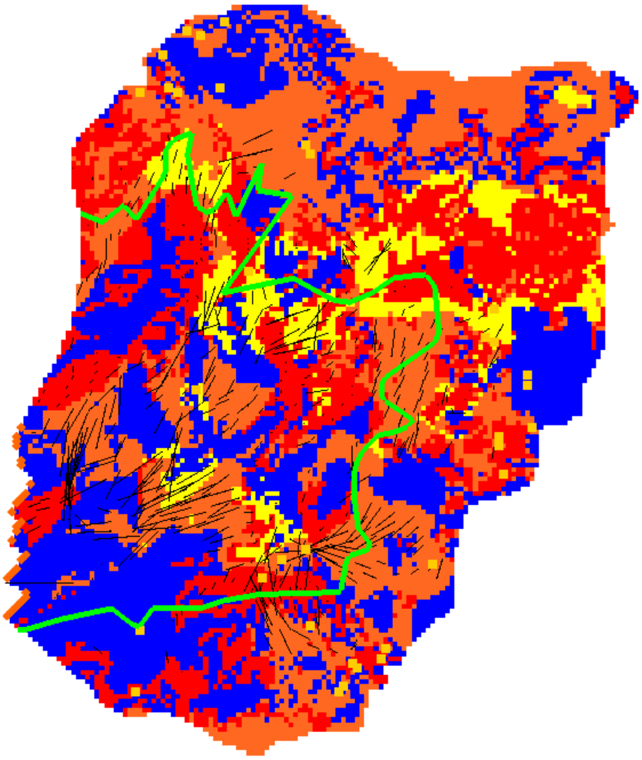
Layer 25: Upper Grande Ronde





Layer 35: below Grande Ronde

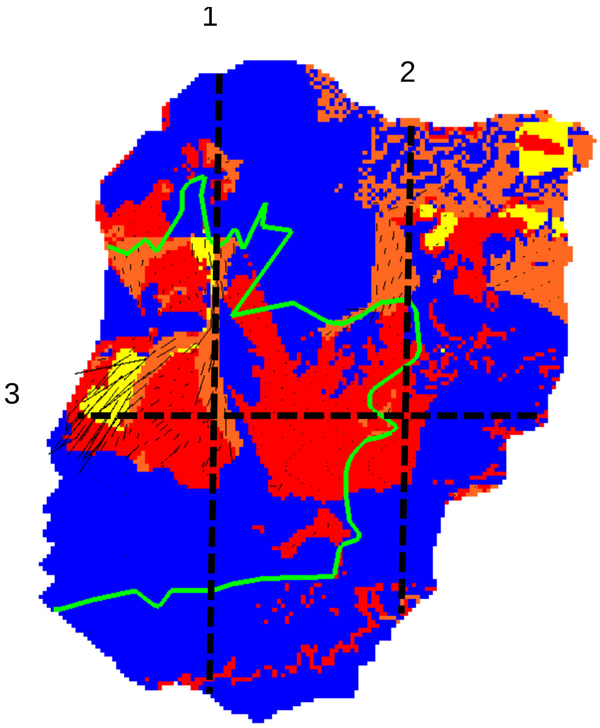
Appendix IX Groundwater flow paths



Layer 5. Sediments overlying the Wanapum.

Materials

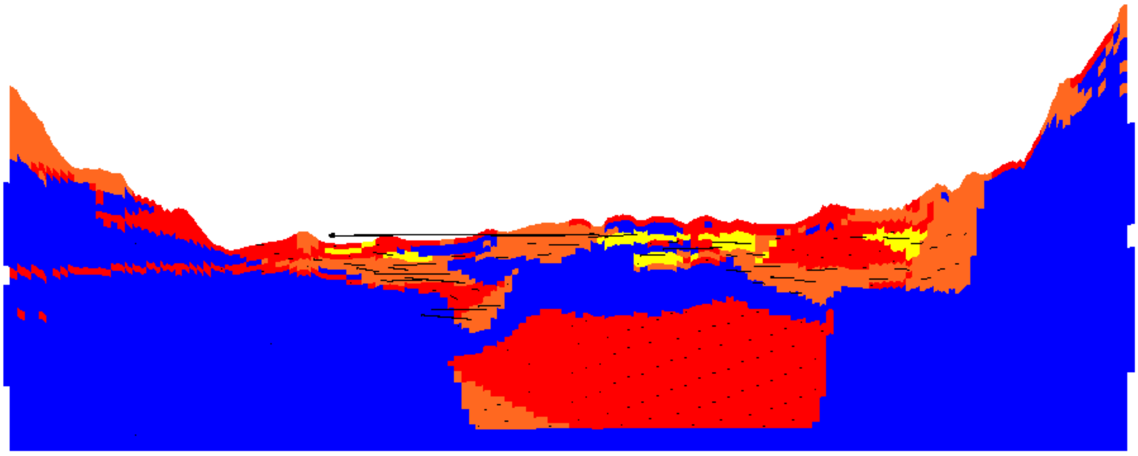
🟨	HGU1
🟧	HGU2
🟥	HGU3
🟦	HGU4



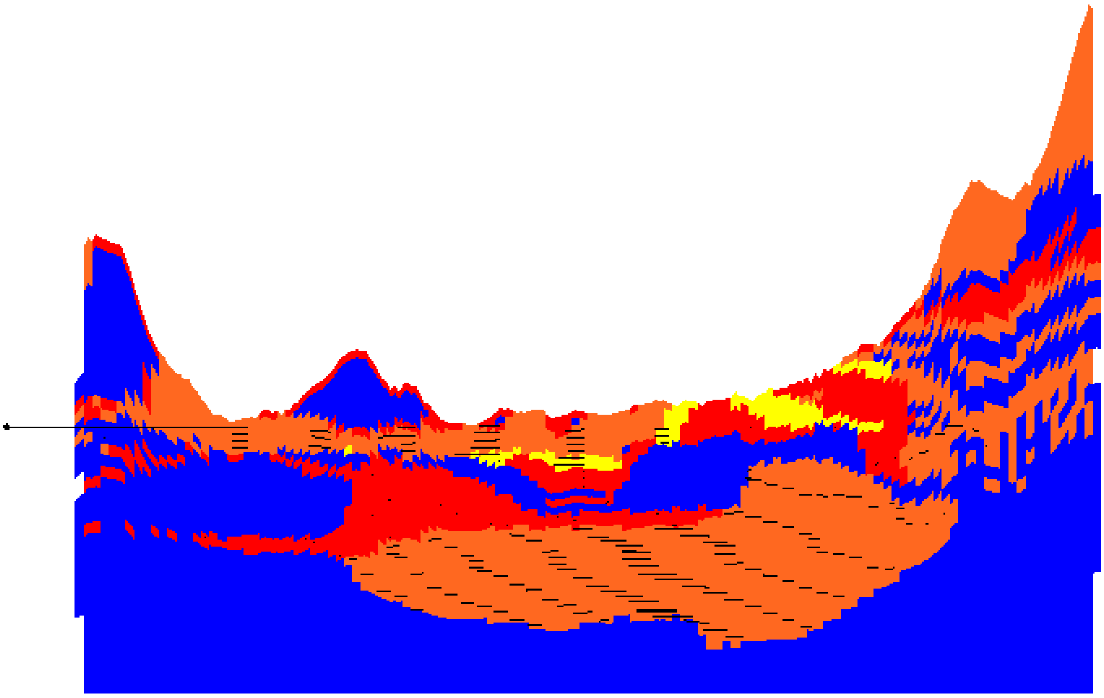
Layer 16. Middle of the Wanapum

.

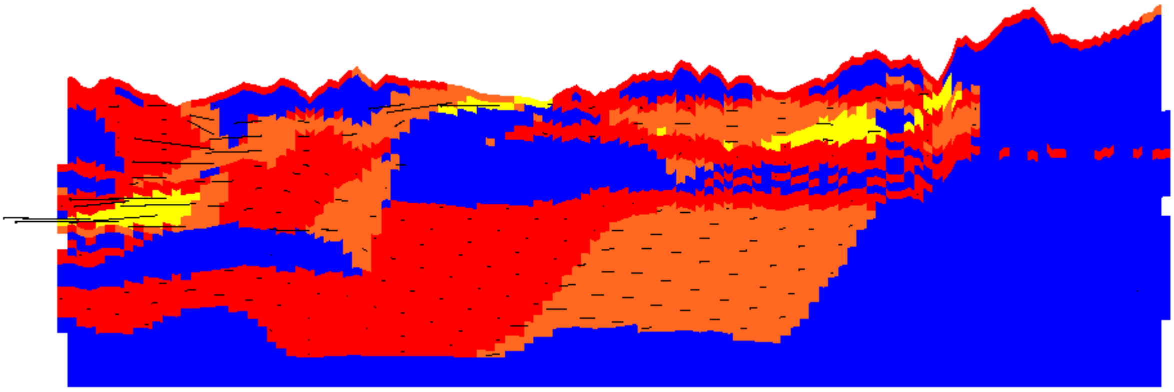
Dotted lines represent the cross-sections below



N-S cross-section. Nr. 1

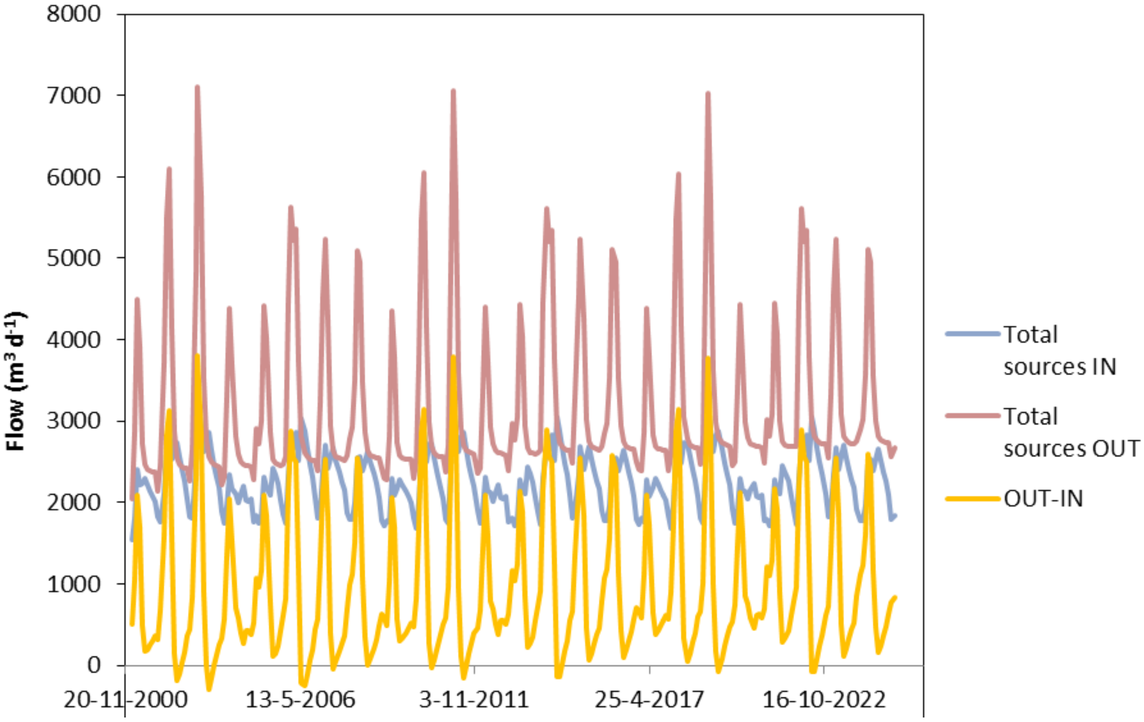


N-S cross-section. Nr.2

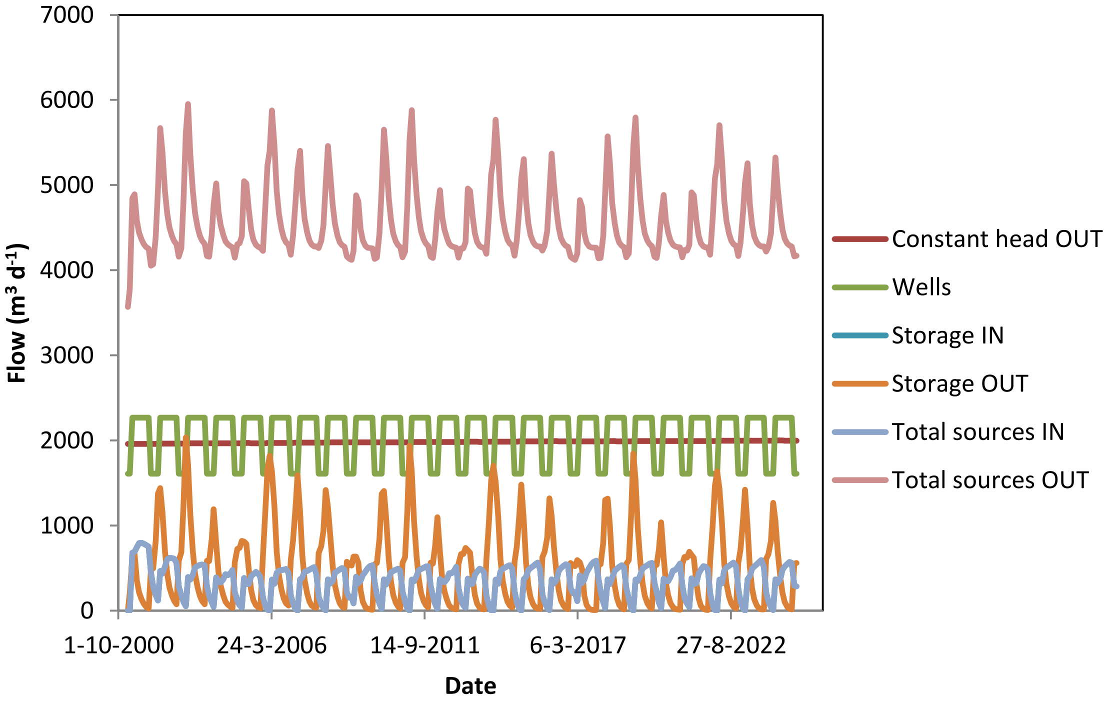


W-E cross-section. Nr.3

Appendix X: Transient model results



Transient model result for Wanapum Aquifer. Total sources IN is the total flow from sources (wells, boundary, rivers, drains, storage) into the Wanapum Aquifer. Total sources out is the total flow out of the Wanapum into these sources. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).



Transient model result for Grande Ronde Aquifer. Total sources IN is the total flow from sources (wells, boundary, rivers, drains, storage) into the Grande Ronde Aquifer. Total sources out is the total flow out of the Grande Ronde into these sources. The model run was performed on data of 2001-2008. This input has been repeated twice (2009-2016 and 2017-2024).