Properties of the Grande Ronde Aquifer in the vicinity of Moscow, Idaho from the Synthesis of Aquifer Test Results with Seismic Groundwater Response

by

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Senior Thesis
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May 16, 2014

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Abstract

The water supplies for the Palouse region come from the Miocene basalts of the Columbia River Basalt Group that form the Grande Ronde aquifer. Water levels in the Grande Ronde aquifer have been declining since the first wells were installed in the early 1900's. The Grande Ronde aquifer is compartmentalized into blocks horizontally as delineated by Owsley [2003. Characterization of Grande Ronde aquifers in the Palouse Basin using large scale aquifer test. MSc Thesis, College of Graduate Studies, University of Idaho, Moscow, ID] and Folnagy [2012Long-Term Grande Ronde Aquifer Stress Testing to Delineate Aquifer Compartmentalization and water Level Responses in the Palouse Groundwater Basin. MSc Thesis, Department of Geological Sciences, University of Idaho, Moscow, ID]. Lateral compartment 2 includes a City of Moscow municipal well, two University of Idaho production wells, and a Washington State DOE monitoring well. Recently, a value of aquifer specific storage was calculated for this compartment using groundwater fluctuations from large earthquakes. This paper uses this new value of specific storage along with the results of the previous aquifer tests to recalculate aquifer properties and provide an improved conceptual model for the Grande Ronde Aquifer in the vicinity of Moscow, Idaho. The effective thickness (net thickness of permeable zones) of the Grande Ronde Aquifer was found to be 105 m, about ¼ of the net thickness of the aquifer. The average hydraulic conductivity and porosity of these permeable zones were found to be 1.4 cm/s, and 30 % respectively, characteristic of highly fractured rock and/or well sorted interbed sediments. This result is high compared to the Columbia River Basalt in general, probably due to the relative abundance of permeable interbeds in Lateral Compartment 2.

INTRODUCTION

The Palouse Groundwater Basin (PGB) constitutes the source of groundwater for the greater Moscow-Pullman area, providing 95% of the municipal and university water supplies from the Miocene Columbia River Basalt Group. Most of the groundwater is obtained from the Grande Ronde formation. Due to the importance of the Grande Ronde as a water source it has been the subject of numerous studies that focus on quantifying the aquifer properties of the basin. The Grande Ronde aquifer is facing increasing demand and declining waters levels. The hydrogeology is not understood well enough for uniformly accurate characterization of the PGB; however, all indications to date suggest that the system will never reach equilibrium and will continue to drawdown. With limited recharge, as noted by previous research, municipalities have curtailed pumping

The lateral compartmentalization of the Grande Ronde aquifer is apparent from short-term (Owsley, 2003) and long-term (Moran, 2011; Folnagy, 2012)aquifer tests that show distinct spatial separation in drawdown plots. The Grande Ronde formation is divided into multiple, sub-horizontally oriented, producing zones that are separated vertically by low conductivity aquitards. Well responses between adjacent compartments lag as the pressure transients due to pumping pass through the low hydraulic conductivity aquitards that separate the producing zones in the various compartments. Figure 1 shows approximate dimensions of PGB lateral compartments. Figure 2 shows well locations in the vicinity of Moscow. City of Moscow municipal well M9, University of Idaho production wells UI3 and UI4, and the Washington State DOE test well are all in Lateral Compartment 2 (LC 2).

In this paper, aquifer properties of LC 2 will be evaluated using Storativity (S) and Transmissivity (T) estimates from a 372-day basin-wide aquifer test along with a specific storage (S_s) estimate that was ascertained using the water level responses in well M9 during the passage of seismic Rayleigh waves generated by several large distant earthquakes. These recalculated aquifer properties should provide an improved conceptual model for the Grande Ronde aquifer in the vicinity of Moscow, Idaho.

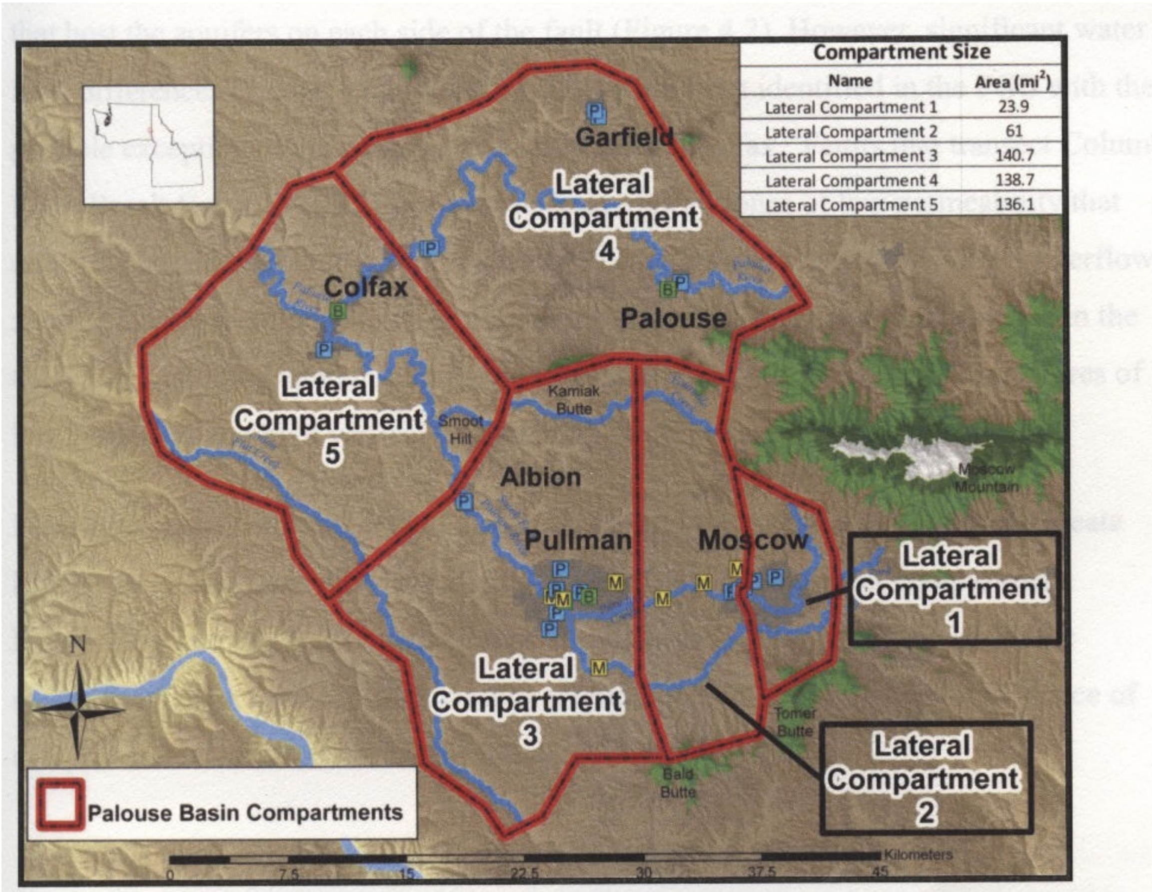

Figure 1. Lateral Compartments in the Palouse Basin Aquifer

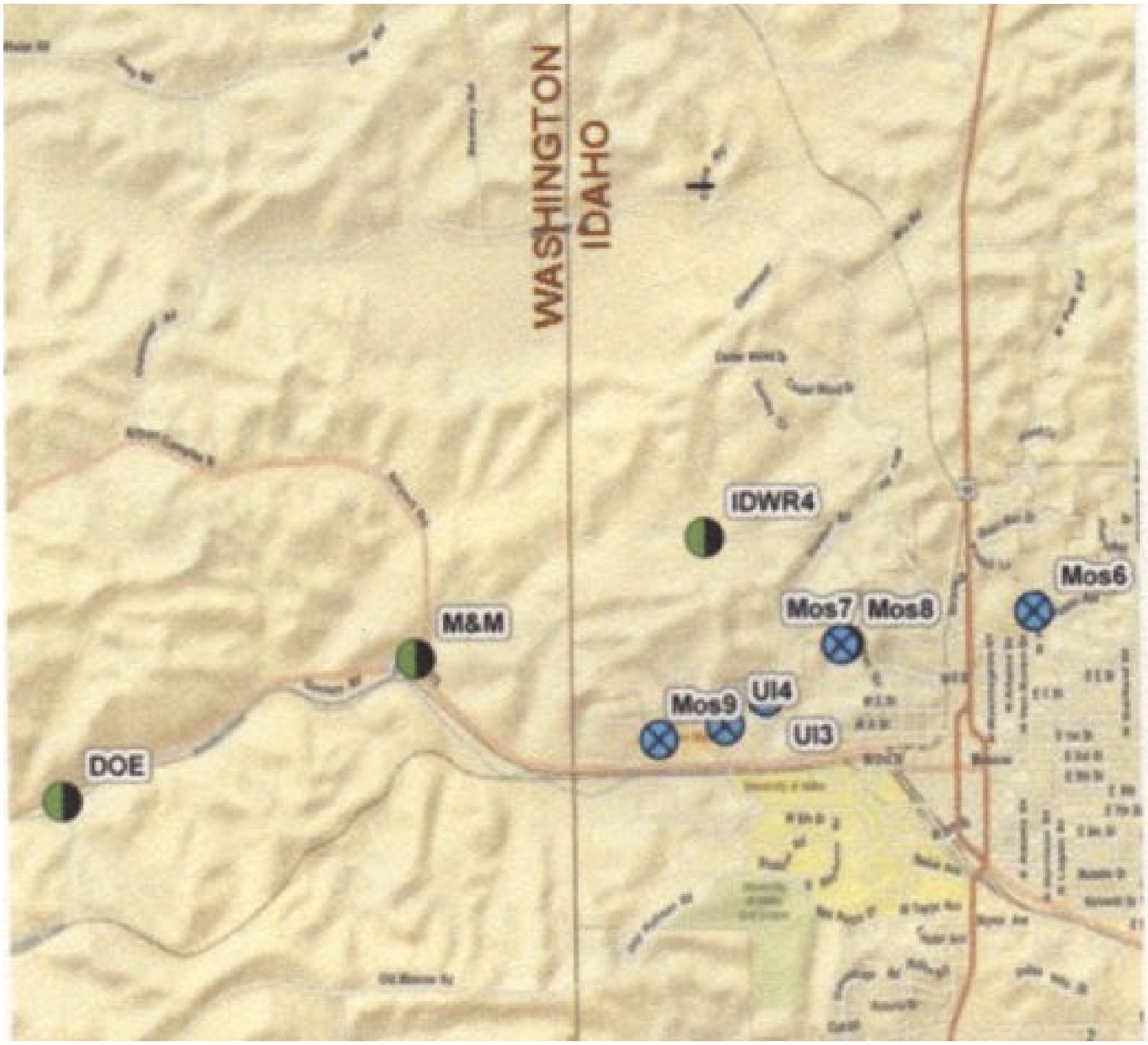

Figure 2. Wells in the vicinity of Moscow, Idaho.

METHOD

Aquifer Test

A 372-day basin-wide aquifer test of the Grande Ronde aquifer was conducted starting at 21:50 on 11/24/2009 (Moran, 2011). The primary objective was to investigate the comprehensive data set to glean new information on the behavior and hydraulic properties of the system. A secondary aim was to provide long-term (annual) estimates of the storativity and transmissivity for the Grande Ronde and to improve on previous estimates by compiling more detailed pumping and water level data over a longer time period. During the basin-wide test groundwater levels and municipal pumping schedules were recorded within the entire PGB from November 2009 through November 2010. This was completed for thirteen wells using non-vented Solinst pressure transducers (Leveloggers©). To record when the municipal wells were pumping. HOBO© U9 Motor On/Off Data Loggers (HOBO©), manufactured by Onset Computer Corporation, were installed on each of the well motors. These devices sense the presence or absence of the electromagnetic field generated by the turbine pump motor or the electrical wiring leading to a down-hole submersible pump, and record periods of pump activity accurate to a time increment of one second (HOBO© product manual, 2010). Additional pumping data were recorded by municipal well operators and compiled by the Palouse Basin Aquifer Committee (PBAC). Monthly pumping totals provided by each agency were used along with HOBO© data to calculate pumping rates for each well (Moran, 2011).

Estimates of storativity (S) and transmissivity (T) were made for the DOE well. For this well the effects of the intercompartmental leakage between compartments were simulated analytically with AQTESOLV® using three no-flow boundaries to define LC 2. The condition of groundwater communication with the rest of the PGB was approximated(i.e., AQTESOLV does not allow semi-permeable boundaries) by the absence of one no-flow boundary. This was needed because summertime pumping caused long-term system-wide drawdown and leakage through compartment boundaries. Data analysis shows that only three pumping wells (UI3, UI4, and M9) caused measurable drawdown in DOE directly. The nature of the hydraulic connection between M9 and the DOE was found to be not "horizontal". The producing zone (i.e., the aquifer) that connects the two wells is relatively thin compared to the basalt thickness. A shallow aquifer above this one also exists with data for the Central Premix (now Motley and Motley) and Champion Electric (Stoneway Electric Supply) wells showing significant time lags for hydraulic connection to the M9-DOE producing zone (indicative of vertical leakage from the overlying aquifer) (McVay, 2007). This is a leaky multiple-aquifer system consistent with the leaky Neuman-Witherspoon (1969) aquifer model.

The 372-day basin-wide aquifer test data were divided into 10-day windows (arithmetic time scale) to provide a method for curve matching using AQTESOLV®. Figures 3 A through 3 J show the 10-day windows and curve matching.

The curve matches show excellent approximations; however, the three sided compartment assumption is incorrect because LC 2 as simulated in AQTESOLV extends northward to infinity with no hydraulic connection with other compartments in the PGB. The 372-day average aquifer coefficients that yield the best matches were $T = 134{,}100\ m^2/day$ and $S = 1.6 \times 10^{-4}$ (Folnagy, 2012).

Specific Storage from Seismic Rayleigh Waves

The seismic Rayleigh wave response of municipal well M9 was recently evaluated by (Folnagy et al., 2013). This important supply well was shut down temporarily for pump repair for several months in 2012, giving an opportunity for the installation of a Solinst Levelogger® Gold data logger. The well is cased except for 27 m of screen adjacent to several interconnected highly permeable flow top units within the Grande Ronde aquifer. The top of the aquifer is at a depth of 198 m below land surface. The static level of the water rises to a height of 104 m above the top of this confined artesian aquifer. The borehole diameter above the screened intervals is 0.22 m. The barometric efficiency of the well is 0.97 (Folnagy et al., 2013).

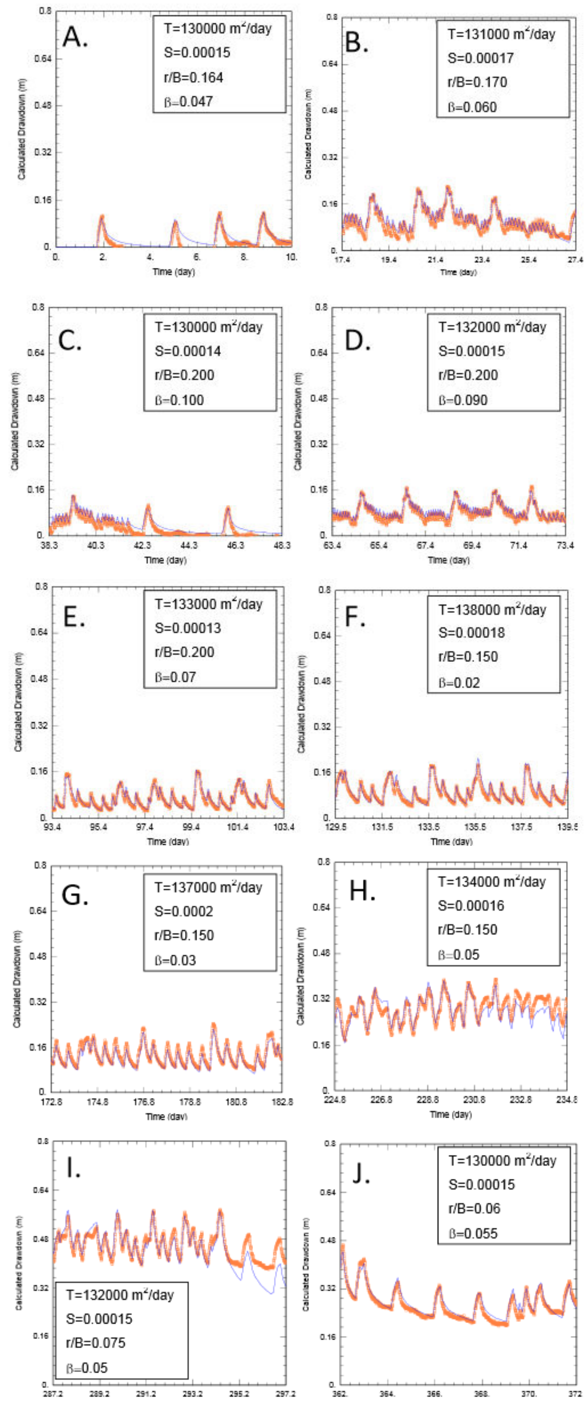

Figure 3

Figure 3. A-J. Neuman-Witherspoon (1969) AQTESOLV© predicted drawdown matches for the 10-day moving windows for the DOE well from the 372-day basin wide aquifer test (Folnagy, 2012)

Seismological theory (Shih, 2009; Stein and Wysession, 2003; Folnagy et al., 2013) predicts that S_s for a confined aquifer can be found by comparing, as the Rayleigh waves from large earthquakes roll by, earthquake seismograms to water level oscillations. To accomplish this, the so-called borehole amplification factor has to be known for the well. This factor depends on oscillation frequency, the borehole radius, initial height of the water column, screened aquifer thickness, T of the aquifer, and, to a minor extent, S_s (Bredehoeft, 1967). Because our quantity to be determined, S_s, is involved in the calculation of the borehole amplification factor, the method requires an iterative procedure for its solution. An initial guess of S_s is used to generate successively better approximations. However, as shown in Figure 4, S_s has only a minor effect on the borehole response, and convergence is quickly obtained.

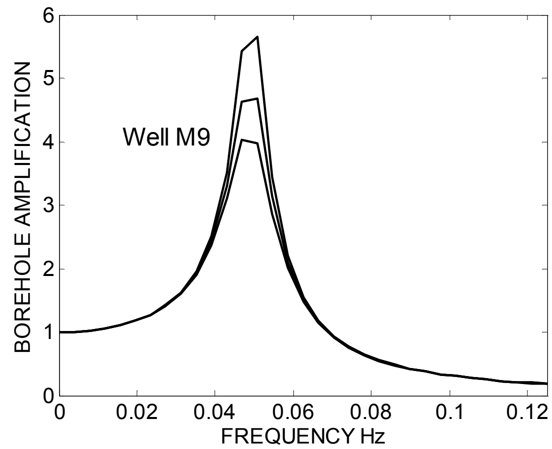

Figure 4. The borehole amplification factor for well M9 in Moscow, Idaho or aquifer storativity estimates of 10^{-3} (upper curve), 10^{-4} (middle curve) and 10^{-5} (lower curve).

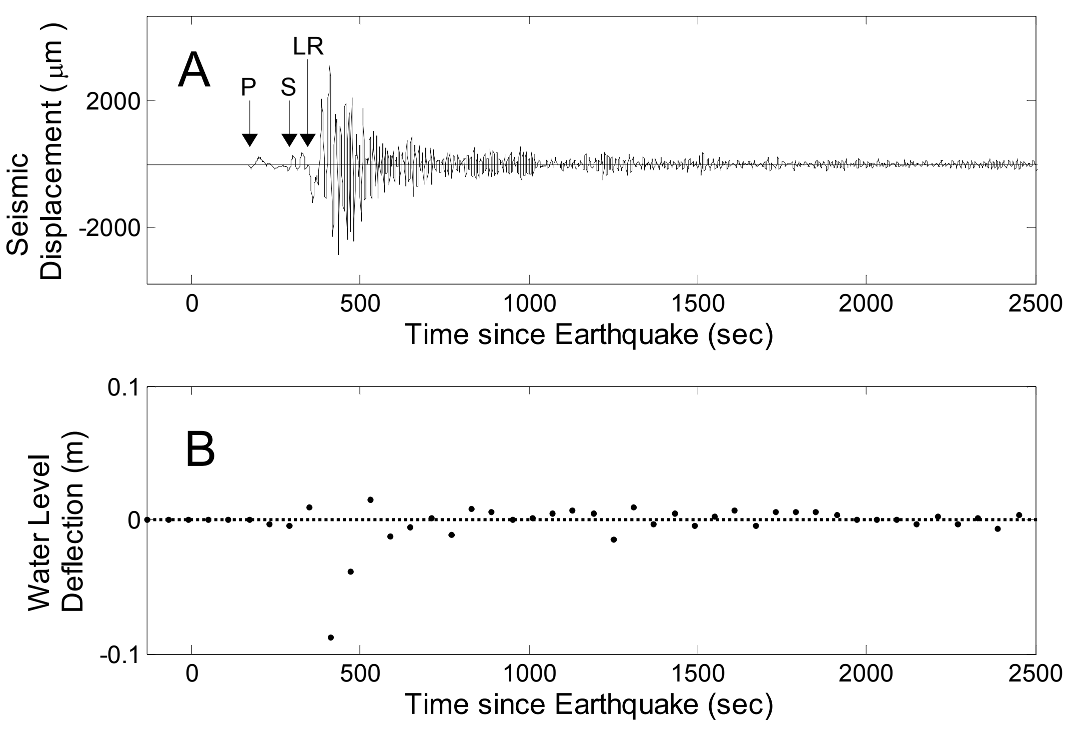

Figure 5. (A) The 2012 M7.5 Haida Gwaii Earthquake. Vertical ground displacement at municipal well M9 in Moascow, Idaho based on regional seismograph station BRAN.The Rayleigh wave arrives at the time indicated by LR and continues across the record. (B) Water level changes driven by the Rayleigh wave as sampled measured at one-minute intervals by a Solinst Levelogger® Gold data logger well recorder.

Rayleigh waves from three moderately large 2012 earthquakes (magnitude > 7.7) were studied.During the same time intervals as the Rayleigh wave arrivals, the data logger in well M9 was collecting measurements at one minute intervals (Figure 5, previous page). Twenty water level measurements immediately after the Rayleigh wave first arrival for each of the three separate earthquakes were used to find S_s .

Combining the data from the earthquakes, S_s was found to be $1.5 \times 10^{-6} \pm 0.2 \times 10^{-6}$ m^{-1}. However, this optimistic figure does not take into account sources of error that are difficult to quantify. The method assumes the aquifer is confined, uniformly porous, and free of heterogeneities. As with any aquifer test, uncertainties in these assumptions probably outweigh the calculated standard errors.

Method to Combine Aquifer Test and Seismic Results

By synthesizing the aquifer test and seismic results, estimates of the effective aquifer thickness, as well as hydraulic conductivity and porosity of these permeable zones can be made using conventional hydrogeologic formulas. By effective aquifer thickness, we mean the net thickness of the permeable aquifer zones within the larger Grande Ronde formation thickness. Effective aquifer thickness (b) can be calculated from:

$$b = S_s / S \qquad [1]$$

where:*S* is the storativity from the aquifer test and S_s is the specific storage from the seismic estimate. The hydraulic conductivity (K) of the permeable zones that form the effective aquifer thickness can be calculated using:

$$K = T / b \qquad [2]$$

Finally, the porosity (φ) of the permeable zones can be found using:

$$\varphi = BE\ S_s\ E_w\ \gamma^{-1} \qquad [3]$$

where: BE is the known barometric efficiency of the aquifer, γ is the specific weight of water, and E_w is the bulk modulus of water.

RESULTS

The parameters used in the calculation of aquifer properties are shown in Table 2. Using equation [1], the effective aquifer thickness was calculated for each 10-day window using the best fit S and T as described by Folnagy (2012). The average effective aquifer thickness in Lateral Compartment 2 of the Grande Ronde aquifer was found to be 105 meters, and ranged from 87 to 133 meters. This is considerably less than the estimate of 400 m commonly used in aquifer models of the basin. The effective aquifer thickness is the net thickness of all hydraulically connected permeable zones in the aquifer.

Using equation [2], the average hydraulic conductivity of these permeable zones is

1.4 ± 0.3 cm/s (1.4 x 10^{-2}± 0.3 x10^{-2} m/s). This value of K is typical of pervious highly fractured consolidated rock and/or extremely well-sorted sand/gravel(Bear, 1972). Using equation [3], the average porosity of the permeable zones in the aquifer is close to 30 %.

Table 1. Parameters used in the calculation of aquifer properties

Parameter	Value	Units	Symbol
Specific Storage	1.5 x 10^{-6}+/- 0.2 x 10^{-6}	m^{-1}	S_s
Storativity	Range from 1.3 x 10^{-4} to 2.0 x 10^{-4}	----	S
Transmissivity	Range from 130,000 to 138, 000	m^2/day	T
Barometric Efficiency	0.97	----	BE
Bulk Modulus of Water	2.20 x 10^9	Pa	E_w
Specific Weight of Water	9.80 x 10^3	Pa/m	γ

DISCUSSION

In the PGB,the Grande Ronde formation total thickness varies, but has been found to be over 400 meters at the western extend of the basin. The effective thickness calculated is 105 meters which shows that several low permeable zones (aquitards) separate interconnected producing zones (aquifers). Hydraulic communication between producing zones occurs through flow pinch outs, columnar hexagonal joints, vertical blocky joints, horizontal platy fractures and other heterogeneities such as rubbly lava flow fronts. Figure 6 shows interflow featuresof the Columbia River Basalt Group which can be referred to as rubble zones.Rubble zones containing fractures are abundant in the top and bottom portions of basalt flows and are not uncommon in the central portions (Sanford, 1997). Rubble zones along with

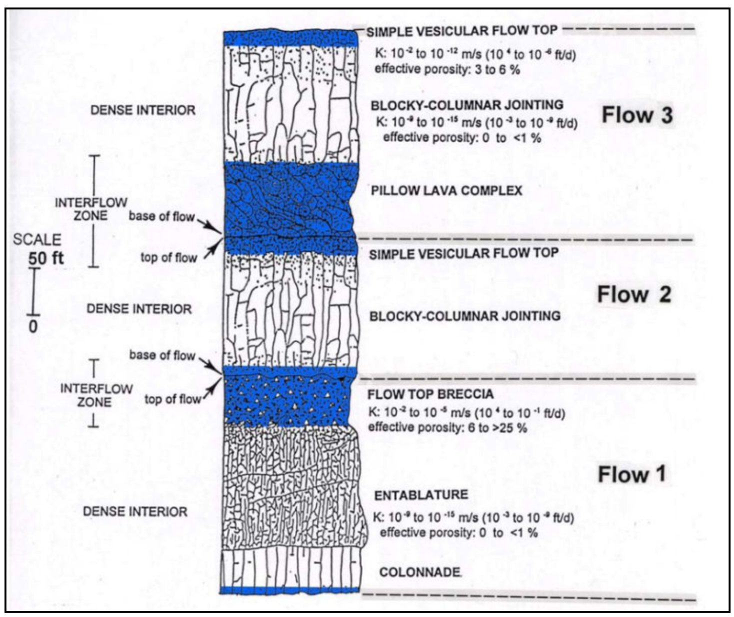

Figure 6. A measured Grande Ronde basalt section outcropping along the Snake River. The blue strata represent high permeability interflow rubble zones. After Porcello, 2009.

fluvial interbeds form most of the permeable zones in the Columbia River Basalt Group. In figure 6, these rubble zones represent a significant fraction of the measured section shown. However, Moran (2011) notes that, in general, rubble zones and interbedded sediments account for only 5% to 10% of the vertical sequence in the Columbia River Basalt Group. In contrast to these permeable zones, the remainder of a basalt section is massive basalt with porosity less than 1% in flow tops and less than 0.1% in flow interiors (Loo et al., 1984). The results of this study suggest that about ¼ of the Grande Ronde formation in Lateral Compartment 2 is composed of such rubble zones in addition to the sand-gravel interbed.

Figure 7 shows the geology and well construction for the wells in LC 2 (disregard wells Mos 8 and Mos 6). Estimating the thickness of interbeds (Latah Formation) and rubble zones (screened portion of the Grande Ronde) in the total Grande Ronde aquifer shows that our effective thickness of ¼ of the total thickness to be reasonable. Interbeds in the wells are about 24-32%of the total Grande Ronde thickness depending on the well. Interbeds in the Grande Ronde are not totally permeable because of fine grained clays mixed with alluvial sands. From figure 7, some interbeds are screened, showing they are areas of producing zones in the interbeds. Estimating the rubble zones in LC 2 is difficult, but using screened portions of the Grande Ronde, a useable estimate can be found. Using figure 7, UI3 has approximate 75 meters of screened Grande Ronde and about 25 meters of screened interbeds. Using the approximate Grande Ronde thickness of 400 meters our estimate is accurate. Looking at M9 well there is only about 5 meters of screened interbeds and about 50 meters of screened Grande Ronde. This is much closer to the usual 5-10% estimate that is usually used. A well construction report by Brown (1976) for the DOE well logged where water was seen in the drill core. About 28% of the well consisted of water, which is good evidence for our estimate.

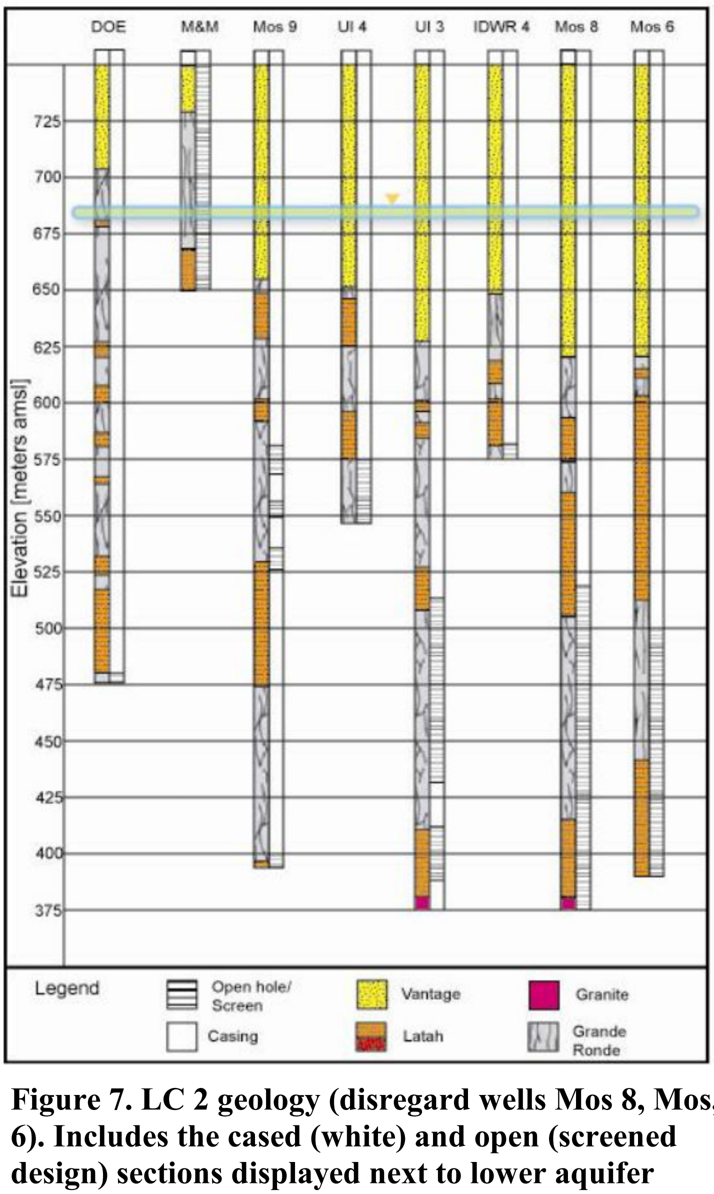

Figure 7. LC 2 geology (disregard wells Mos 8, Mos, 6). Includes the cased (white) and open (screened design) sections displayed next to lower aquifer geology with 2011 water level of ~684 meters amsl. From Folnagy, 2012.

Our estimate of ¼ net effective thickness seems to be consistent with the stratigraphy of LC 2. Looking at the geology of Lateral Compartment 3 (LC 3) (see figure 1) there is far less interbeds. Our estimate accounts for the permeable interbeds in LC 2, but with fewer interbeds our estimate could be inaccurate for LC 3 and the rest of the PGB.

While synthesizing the seismic results with 372-day aquifer test results, it is important to understand that the Rayleigh wave properties are controlled by global earth structure, not local aquifer parameters. Seismological theory predicts that all compartments of the aquifer are subject to the same dilational strain when the Rayleigh wave passes, regardless of the T and S of the individual compartments. However, the pressure head changes (and water level oscillations in a well) resulting from that dilatation are dependent upon the specific storage of the compartment in which the well is drilled. The groundwater in the Grande Ronde formation moves slowly through the dense basalt interiors and the compartment boundaries. The 372-day basin-wide aquifer test incorporate the effects of both T and S of the compartment boundaries while the method of using Rayleigh waves responds only to the specific storage of the local compartment. Therefore using seismic data produces a useable value of specific storage within compartments, but little information on the hydraulic connection between compartments.

Acknowledgments

We thank the Palouse Basin Aquifer Committee (PBAC) for providing partial funding, Steve Robischon of PBAC for collecting and providing the water level data, and the Pacific Northwest Seismic Network at the University of Washington for the seismic data. The IRIS DMS is funded by the people of the United States of America through the Instrumentation and Facilities Program of the National Science Foundation.

References

Bear, J., 1972. Dynamics of Fluids in Porous Materials. New York: Elsevier (reprinted by Dover Publications, 1988).

Bredehoeft, J.D., 1967. Response of well-aquifer systems to Earth tides. J. Geophys. Res. 72 (12), 3075-3087.

Brown, J.C., 1976, Well construction and stratigraphic information: Pullman test and observation well, College of Engineering Research, Washington State University, WA.

Folnagy, A.J., Osiensky, J.L., Kobayashi, D., Sprenke, K.F., 2013. Specific storage from sparse records of groundwater response to seismic waves. J. Hydrol. 503. 22-28.

Folnagy, A.J., 2012. Long-Term Grande Ronde Aquifer Stress Testing to Delineate Aquifer Compartmentalization and water Level Responses in the Palouse Groundwater Basin. MSc Thesis, Department of Geological Sciences, University of Idaho, Moscow, ID.

HOBO© U9 motor on/off data logger product manual. Onset Computer Corporation. Doc #9622-B, MAN-U9-004

Loo, W.W., Arnett, R.C., Leonhart, L.S., Luttrell, S.P., Wang, I., McSpadden, W.R., 1984. Effective porosities of basalt: A technical basis for values and probability distributions used in preliminary performance assessments. SD-BWI-TI-254, Basalt Waste Isolation Project, Rockwell Hanford Operations, Richland, Washington.

Moran, K., 2011. Interpretation of Long-Term Grande Ronde Aquifer Testing in the Palouse Basin of Idaho and Washington. MSc Thesis, Department of Geological Sciences, University of Idaho, Moscow, ID.

McVay, M., 2007. Grande Ronde aquifer characterization in the Palouse Basin. MSc Thesis, Department of Geological Sciences, University of Idaho, Moscow, ID.

Neuman, S.P., and P.A. Witherspoon. 1969. Application of current theories of flow in leaky aquifers. Water Resources Research, 5(4):817-829.

Owsley, D., 2003. Characterization of Grande Ronde aquifers in the Palouse Basin using large scale aquifer test. MSc Thesis, College of Graduate Studies, University of Idaho, Moscow, ID

Porcello, J.J., Toland, T.L., Lindsey, K. A., Burt, W., 2009. Influences of well construction on water level interpretation in aquifers of the Columbia River Basalt Group. Geological Society of America Abstract with programs, v. 41, no. 7, p.354.

Sanford, W.E., 1997. Correction for diffusion in C-14 dating of ground water. Groundwater, 35, 357-361.

Shih, D.C.-F., 2009. Storage in confined aquifer: spectral analysis of groundwater responses to seismic Rayleigh waves. J. Hydrol. 374 (1-2), 83–91.

Stein, S., Wysession, M., 2003. An Introduction to Seismology, Earthquakes, andEarth Structure, first ed. Wiley-Blackwell, New Jersey.