Modeling Semi-Permeable Boundaries in the Palouse Groundwater Basin

By: Andrew Spencer

Advisor: Jim Osiensky

Environmental Science Senior Thesis

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Abstract

Aquifers in the Palouse Groundwater Basin (PGB) supply water to several towns on the Palouse but sustainable use of the resource is in question because groundwater levels are declining. Accurate models of the basin would benefit management of water use. The advanced aquifer test software Aqtesolv is used to model groundwater levels in the basin. Results of an aquifer test from 2011-2012 show that the PGB is compartmentalized on at least an annual time frame. A centrally located compartment (herein called the Department of Ecology (DOE) compartment) in the PGB, exhibits hydraulic connectivity to neighboring compartments. However, the time frame of these connections is on a period of about one year. The theory of image wells is a way to simulate impermeable boundaries mathematically in the software.. Image wells are a feature in Aqtesolv, but since the DOE compartment experiences hydraulic connectivity to neighboring compartments, impermeable boundaries are not an accurate representation of the system. I hypothesize that the semi-permeable conditions of the system can be simulated by tweaking the use of image wells in Aqtesolv. A large number of image wells are needed to simulate impermeable boundaries in Aqtesolv so this research will run simulations using small numbers of image wells to create semi-permeable boundary conditions to match a portion of the observed drawdown data for the aquifer test. After the simulations, the matches to the observed data did not vary greatly among the different number of image wells used. Therefore, a non-unique solution exists when using image wells to simulate semi-permeable boundaries in the PGB.

Introduction

Groundwater levels in the aquifers of the Palouse Groundwater Basin (PGB) are declining (Folnagy, 2012, p. 169). Most of the water used in the region for irrigation, drinking, watering, etc., is provided from the aquifers beneath the towns of Palouse, Pullman, Moscow, Albion, Garfield, and Colfax. Over the last few decades extensive research has delineated many of the hydrogeologic properties of the basin. However, uncertainties still exist about the various aspects of recharge, discharge, flow, and compartmentalization.

The multiple, leaky aquifer system in the Grande Ronde basalts of the Palouse Groundwater Basin (PGB) appears to be compartmentalized (Folnagy, 2012, pg. 133). Geologic boundaries restrict flow horizontally between these compartments to some extent, with limited horizontal groundwater flow from one compartment to another because the boundaries have low but significant hydraulic conductivity (Folnagy, 2012, pg. 51). Drawdown data for the Washington DOE (Department of Ecology) observation well located between Moscow and Pullman are suitable to check the capability of an analytical model to accurately simulate the characteristics of the DOE compartment in the lower Grande Ronde aquifer. However, options in Aqtesolv™, an advanced aquifer test analysis software by HydroSOLVE (Reston, VA), need to be adjusted in order to represent horizontal, intercompartmental flow because only impermeable and constant head boundaries are available in the software (Duffield, 2007).

One aspect of aquifer test theory is the use of image wells and the principle of superposition to simulate impermeable boundaries. Impermeable boundaries prevent groundwater flow towards the pumping well. Aqtesolv simulates this condition by placing the optimal number of image wells at appropriate distances from the pumping well to form a mathematical, impermeable boundary. The image wells pump water at an identical rate to the pumping well which allows the image wells to form groundwater flow conditions (simulated hydraulic boundaries) that mimic the hydraulic qualities of geologic impermeable boundaries. The case of one boundary is easy to simulate with a single image well; however, for a closed compartment with four intersecting boundaries, many image wells are necessary, and those image wells must be balanced in two dimensions. Aqtesolv automatically uses as many image wells (up to 9999 wells) as are necessary to simulate impermeable boundaries for almost any conceivable combination of pumping wells. These impermeable boundaries, however, do not allow intercompartmental flow of groundwater to occur. In order to simulate intercompartmental groundwater flow with Aqtesolv, the number of image wells used by Aqtesolv must be manipulated by forcing the software to use a predetermined number of image wells (i.e., less than the optimal number determined by Aqtesolv).

The purpose of this project is to evaluate the nature of intercompartmental groundwater flow between adjacent compartments based on aquifer test drawdown data to help delineate the hydraulic properties of the basin aquifers. Integrating limited numbers of image wells into the model is believed to be one way that horizontal flow between compartments can be simulated. A specific objective in this thesis is to evaluate the appropriate number of image wells that will effectively force Aqtesolv to mathematically model compartmental boundaries as semi-permeable boundaries. As a result of this thesis research, more information will be made available for the stakeholders involved, and the information will help groundwater managers understand some of the ramifications of their pumping decisions.

Literature Review

This section includes a literature review of the relevant, previous hydrogeologic research conducted in the PGB related to the groundwater hydrology of the aquifer systems. Declining water levels have made the PGB an important area of study because groundwater is the sole source supply of potable water for the cities and towns of Moscow, Pullman, Palouse, Garfield, Colfax, and Albion. This issue has caused the proliferation of investigations of the hydrogeology of the basin, most of which could not be included in this review as they do not specifically pertain to the study.

In the early 1990's, the task of modeling the basin was oversimplified according to McVay (2007) who reviewed previous studies on the PGB. This shifted the focus of study from modeling, to determining the physical properties of the basin in order to better understand the hydrogeology. Investigations into recharge and age-dating such as (Douglas, 2004) as well as into the geologic factors that control the distribution of groundwater in the region such as (Bush, 2005) were mostly inconclusive, and led to a set of questions about the basin (McVay, 2007, p.4). These questions focused on the location of hypothetical geologic boundaries, the magnitude and temporal components of the hydraulic connectivity between the compartments formed by the boundaries, and the factors masking fluctuating groundwater levels such as barometric efficiency (McVay, 2007, p. 51).

There are differing responses among the Grande Ronde wells to pumping over a time span of days to weeks, but general annual water level declines all over the basin correlate approximately with the long-term records for the WSU test well in Pullman, Washington (Figure 1.1).

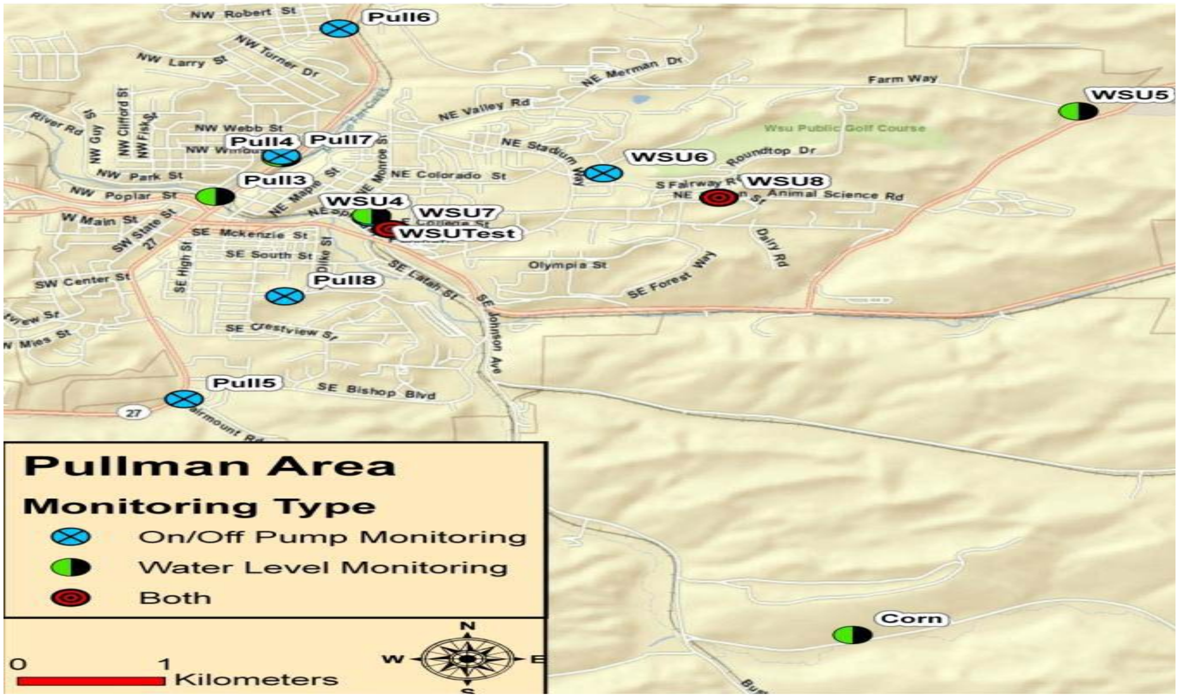

Figure 1.1: Location of the WSU test well (Folnagy, 2012, p.6).

However, these data often seemed misleading because different groundwater C-14 age dates spatially in the PGB originally were not interpreted as groundwater in different compartments (Folnagy, 2012, p. 51). One of the difficulties involved with determining the scope of hydraulic connectivity is that lengthy pump tests must be completed in order to make comparisons between short-term and long-term response times. Folnagy assisted Moran (2011) in the implementation of a 372-day aquifer test in order to help solve this dilemma. Results of the aquifer test confirm the compartmentalized nature of the aquifer system on daily, monthly and annual time scales. Folnagy (2012) describes how the PGB compartments are hydraulically linked. Figure 1.2 shows the compartments as delineated in Folnagy (2012). Lateral compartment 2 in figure 1.2 is the same as the DOE compartment referred to in this research.

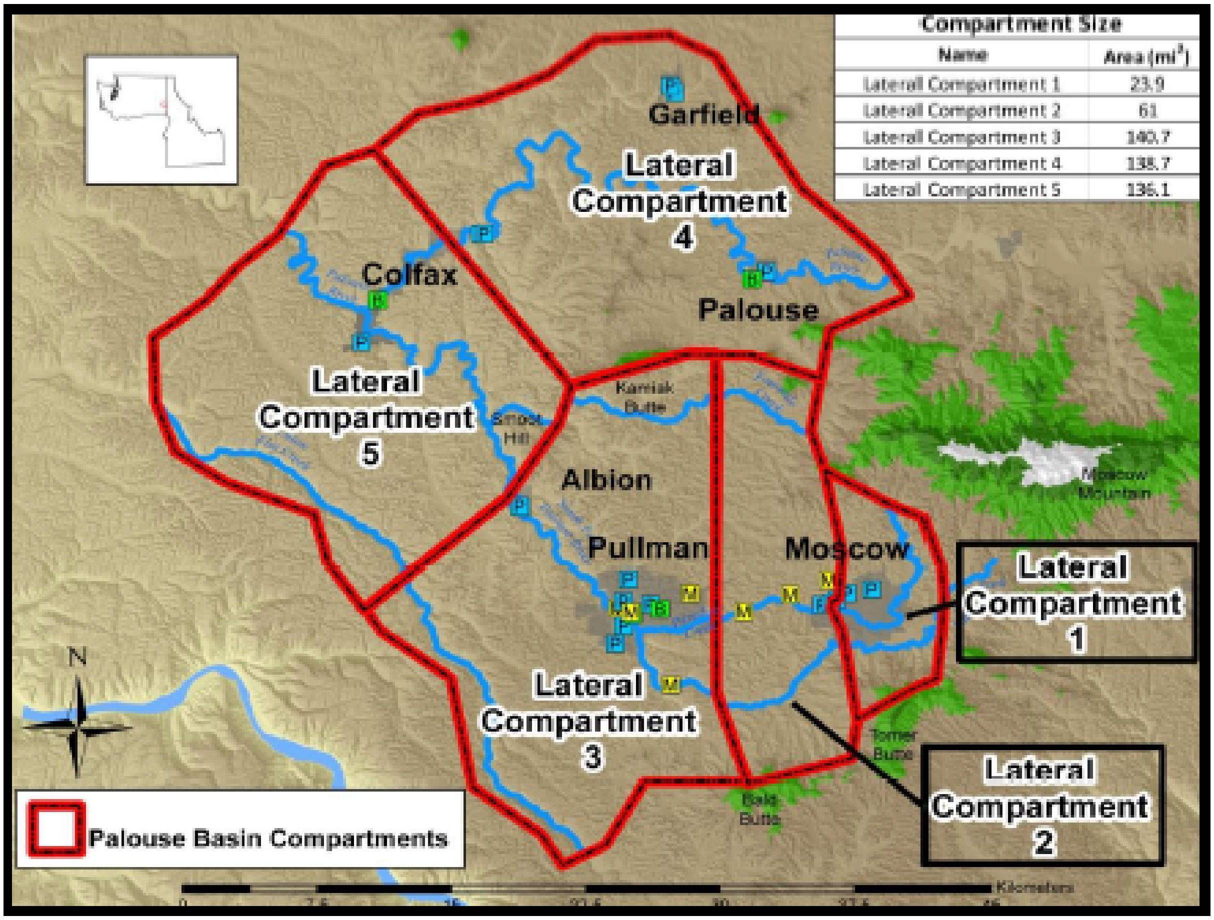

Figure 1.2 Aquifer compartments in the PGB (Folnagy, 2012, p.52).

Stress response times in the Grande Ronde wells located throughout the PGB were shown to be different over short-term observations, but generally similar over long-term observations which in most cases indicate connectivity over periods of years (Folnagy, 2012, p. 52).

The geologic barriers that can cause compartmentalization are numerous. As identified in Folnagy 2012, "fine grained interbeds, saprolite layers and buried soil horizons, folds, faults, dikes, and discontinuous fractures"(pg 53) could exist within the basin to restrict groundwater flow. Figures 1.3 and 1.4 show a few of these features.

Figure 1.3 Weathered basalt heterogeneities along the Snake River, southwest of Pullman.

Figure 1.4 Relatively fresh heterogeneities along the Snake River, southwest of Pullman.

Aquifer Tests

Aqtesolv is the main tool used by the researchers in the basin to simulate groundwater levels in terms of aquifer test drawdown. Aquifer test drawdown is the measured water level response of individual observation wells to controlled and measured pumping stresses. Drawdown mathematically is the numerical difference between a static non-pumping water level (h_o) in a well and the new water level (h) after pumping has started (i.e., h_o-h). Folnagy (2012) simulated the DOE compartment as bounded on three sides by impermeable boundaries (using the default number of image wells determined by Aqtesolv). The three sided compartment was open to infinity to the north to allow groundwater to flow into the compartment. This condition inaccurately represented the real conditions; however, the drawdown simulated by Aqtesolv for these conditions matched the observed data reasonably well. The limitations of Aqtesolv, combined with inadequate processing speed of the computer hardware, restricted the thoroughness of Folnagy's investigation.

Image Wells

One route of inquiry that was not adequately explored by Folnagy was the use of various numbers of image wells to represent the boundaries as semi-permeable rather than impermeable. Image wells are commonly used in aquifer test analyses to simulate impermeable boundaries. Impermeable barriers will have an effect on the drawdown of an aquifer caused by a pumping well. Image (imaginary) wells simulate impermeable barriers by drawing down aquifer levels in the same manner as a no flow geologic boundary. The image wells do not exist outside of the model; in the model they are placed at appropriate distances from the pumping well to mirror the location of the actual boundary. The hydraulic effects of the image wells create opposing groundwater gradients at the locations of the boundaries that preclude groundwater flow across the boundaries. These equally opposing forces simulate one or more impermeable boundaries.

For the models, mathematically the drawdown at each point in the aquifer is calculated by summing the drawdown caused by the pumping well and the drawdown caused by all of the image wells. Figures 1.5 and 1.6 are taken from the USGS Professional Paper on the Theory of Aquifer Tests and demonstrate how image wells simulate realistic conditions (Ferris et al., 1962, p. 144-149). Figure 1.5 demonstrates how the geologic boundary exists outside of the model. The resultant cone of depression in Figure 1.6 would be the end result of simulating this situation in Aqtesolv.

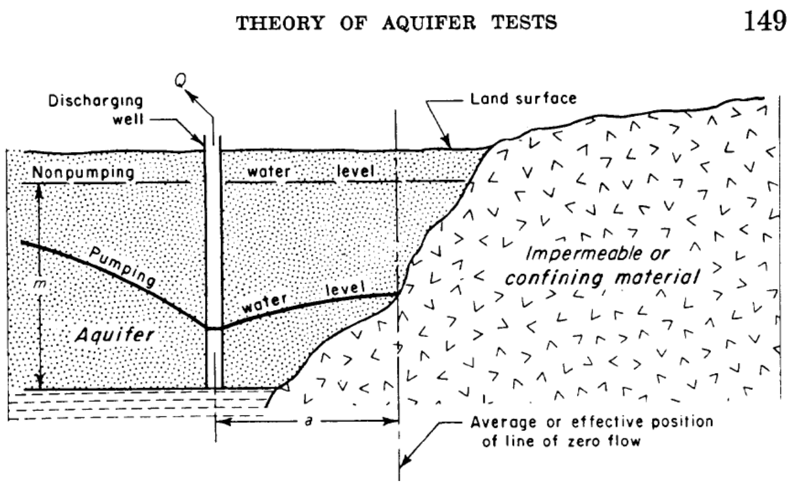

Figure 1.5 Hypothetical effects of an impermeable geologic boundary.

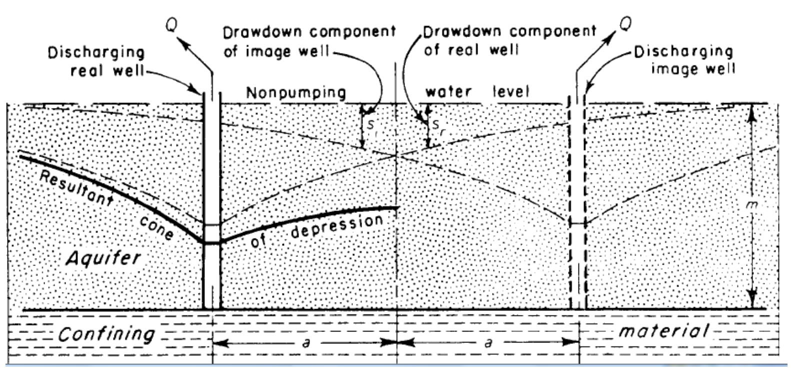

Figure 1.6 Hydraulic boundary caused by a pumping well and an image well.

If only one boundary exists, then only one image well is needed to simulate the drawdown effects of the pumping well in this situation. In situations with two or more boundaries, more image wells must be used in order to balance out the effects of the multiple boundaries. The number of image wells needed to simulate impermeable boundaries for the pumping conditions measured in the DOE compartment by Folnagy would require more than 840 image wells (Osiensky and Williams, 1997, p. 231). Fewer image wells mathematically would produce semi-permeable boundaries which we hypothesized to be similar to the semi-permeable boundaries of reality. The fewer the image wells used in the model, the more groundwater is allowed to flow across the boundaries (i.e., intercompartmental flow) that separate compartments. The differences between eight image wells and 48 image wells are shown in figures 1.7 and 1.8. More flow lines are entering the red compartment when eight image wells are used in figure 1.7 compared to figure 1.8 with 48 image wells.

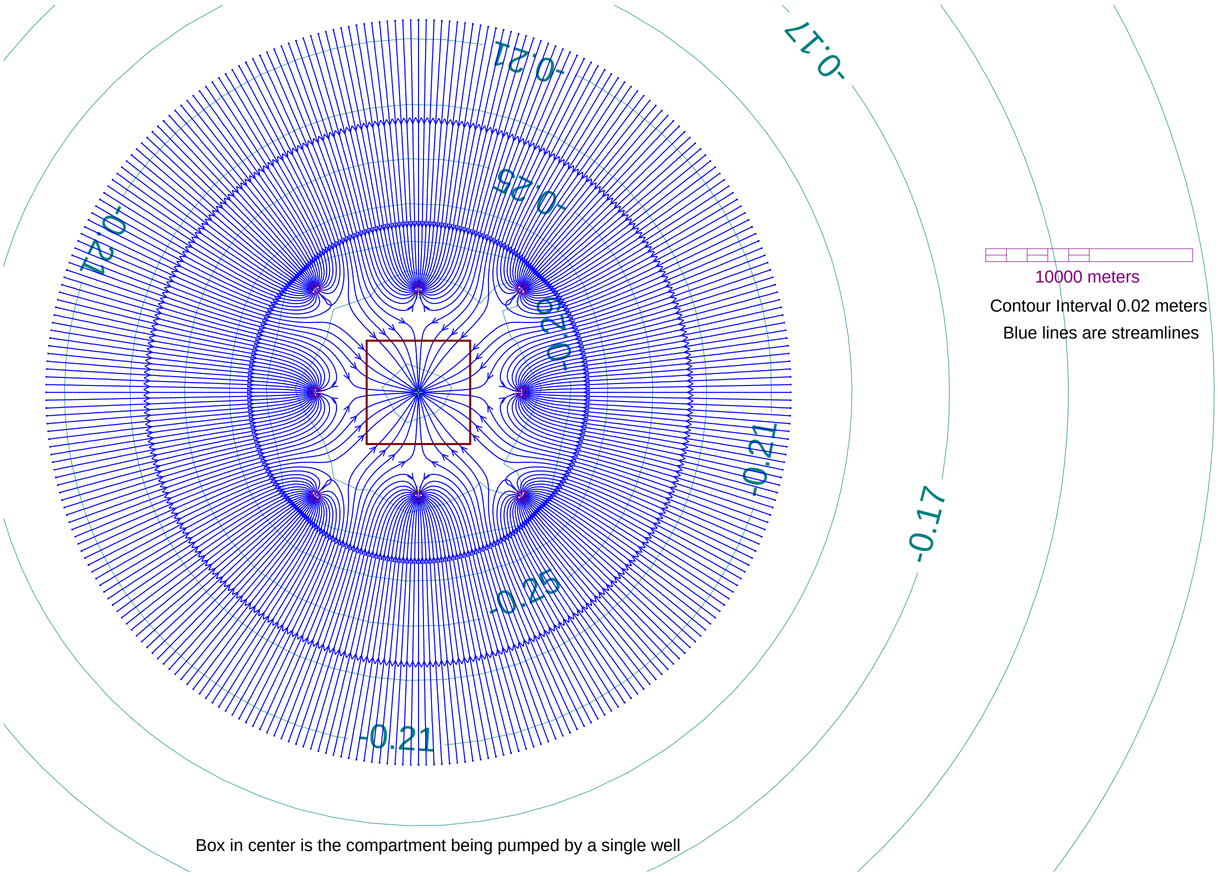

Figure 1.7: Drawdown contours and flowlines for eight image wells.

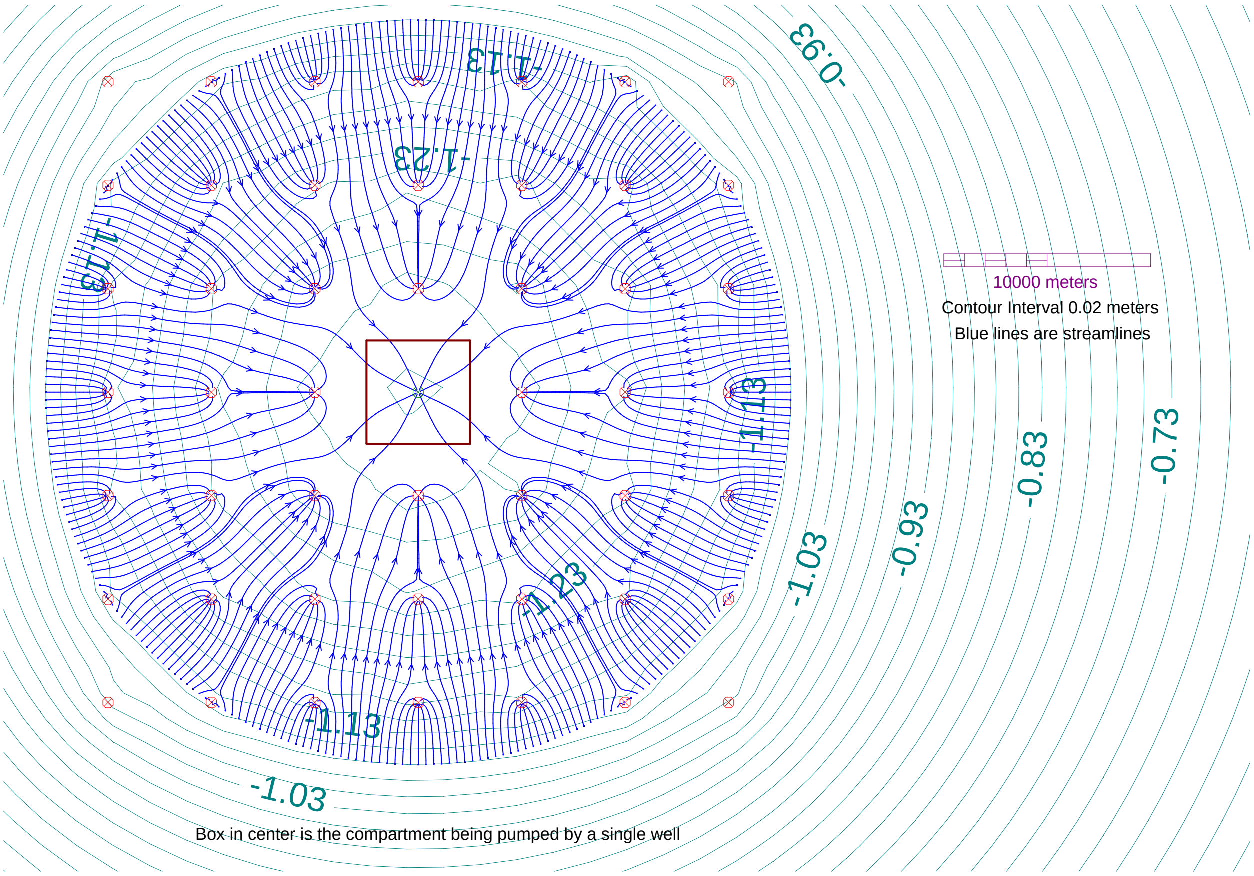

Figure 1.8: Drawdown contours and flowlines for 48 image wells.

Intercompartmental flow through four intersecting boundaries was evaluated in combination with the Neuman and Witherspoon (1969) leaky aquifer model (i.e., vertical leakage between two aquifers separated by an aquitard) to be consistent with our hydrogeologic conceptual model for the PGB. Image wells are automatically incorporated into Aqtesolv when boundaries are selected. The option to select the number of image wells used in the analysis was added by the software developer to reduce the CPU time needed to run preliminary simulations. To my knowledge, use of a limited number of image wells to simulate semi-permeable boundaries with Aqtesolv has not been published in the literature.

My analysis in Aqtesolv relies on the Neuman-Witherspoon (1969; 1972) method for modeling confined two-aquifer systems with leakage. The Neuman-Witherspoon method is defined as a "mathematical solution for determining the hydraulic properties of leaky confined aquifer systems (transmissivity and storage coefficient of the pumped aquifer; vertical hydraulic conductivity and storage coefficient of the aquitard; and transmissivity and storage coefficient of the unpumped aquifer). Analysis involves matching the solution to drawdown data collected during a pumping test. Observation wells may be screened in the pumped aquifer, unpumped aquifer or aquitard" (Folnagy, 2012, p.183). Hydrogeologically, the upper Grande Ronde basalts constitute the unpumped aquifer whereas the pumped aquifer is located in the lower Grande Ronde basalts; they are separated by an aquitard composed of basalt and sedimentary interbeds.

The results of this study should reveal whether it is plausible to limit the number of image wells used to model the semi-permeable boundary conditions that result in long-term, basin-wide, horizontal hydraulic connectivity in the PGB, and also improve the ability of Aqtesolv to represent the real processes. The following sections will detail the methodology and results of the tests.

Methods

The software Aqtesolv™ is used with the Neuman and Witherspoon (1969) model for leaky aquifers to simulate the aquifer test responses measured in the DOE well located within the DOE compartment. The parameters that Aqtesolv calculates with the Neuman-Witherspoon method are T (Transmissivity) and S (Storativity) for the pumped aquifer, β and r/B (leakage factors for the aquitard), and S2 and T2 (Storativity and Transmissivity for the unpumped aquifer). Image wells together with the principle of superposition are being used to investigate if it is feasible to simulate semi-permeable boundaries in the PGB using the aquifer test software Aqtesolv. Several different combinations of image wells are being tested in an effort to calibrate the analytical mathematical model to simulate semi-permeable boundaries instead of impermeable boundaries. Drawdown data collected at the DOE observation well for a 372-day aquifer test are being used for this research. Because of the immense amount of data available, combined with many image wells, computer processing speed is a major issue. In order to speed up the data processing, only the first 10 days of drawdown data are being used to evaluate the boundary testing methodology employed in this research. To evaluate how the degree of hydraulic continuity across boundaries changes with the number of image wells used, different combinations of image wells are tested: 0, 4, 8, 24, 48, and 80 image wells. These scenarios produce simulated drawdown curves that are then compared and matched (quality of fit) to the actual measured drawdown data collected for the DOE observation well. The results are produced from the automatic matching feature (i.e., automatic parameter estimation) in Aqtesolv, which finds the best statistical match to the observed data based on the method of aquifer test analysis selected, the aquifer and aquitard hydraulic parameters, and number of image wells used.

The parameters produced by the automatic matching become inputs for the model over the entire 372-day test simulation. Each image well combination is modeled, with the parameters produced from the automatic matching, for the entire 372-day test period. The automatic calibration feature in Aqtesolv also provides a diagnostic report of the quality of match which provides statistical information about the goodness of fit. During the matching, Aqtesolv performs iterations to reduce the value of the sum of the squared residuals (Duffield, 2007). If the match for each number of image wells converges, then the sum of squared residuals can be compared. It is recognized that the solution may be non-unique so that the parameters may still be manipulated to find an equally effective match, but with different parameter values. A visual comparison will be made between the matches if convergence is not acquired for all scenarios.

The two windows, 0-10 days and 362-372 days, will be compared between each image well combination. In addition, the matches provided by Folnagy (2012) will be compared with the results of this investigation to evaluate the two different methods for accounting for horizontal intercompartmental leakage in the basin.

Results

Each automatic estimation, using the different number of image wells (0, 4, 8, 24, 48, and 80), produced an RSS value. If the estimation converged then the resulting type curve match was the best statistical match that could be made using the Neuman-Witherspoon method. Table 1.1 lists the number of image wells with their corresponding RSS value as well as whether the simulation converged.

Table 1.1. RSS values for various combinations of image wells.

# of Image Wells	Converged?	RSS
0	Yes	0.389
4	No	0.307
8	Yes	0.306
24	Yes	0.306
48	Yes	0.306
80	Yes	0.306

Simulations run using 8, 24, 48, and 80 image wells provided equal statistical matches for the 0-10 day window. Only the 4 image well simulation did not converge, this result might have been influenced by the software not running through enough iterations of the model or the range of parameters that determined how much the simulation could vary the parameters was insufficient. The ranges input for the simulation were based on estimations of the parameters of the aquifers in the DOE compartment, so if those estimations were in error then the simulation might not have been able to perform as well. Even though the 4-image well simulation did not converge, visually, it produced a very similar quality of fit to the observed data when compared to the other image well simulations. Figures 1.9 to 1.14 show the 10-day windows for each image well simulation and the corresponding parameters produced from the simulations.

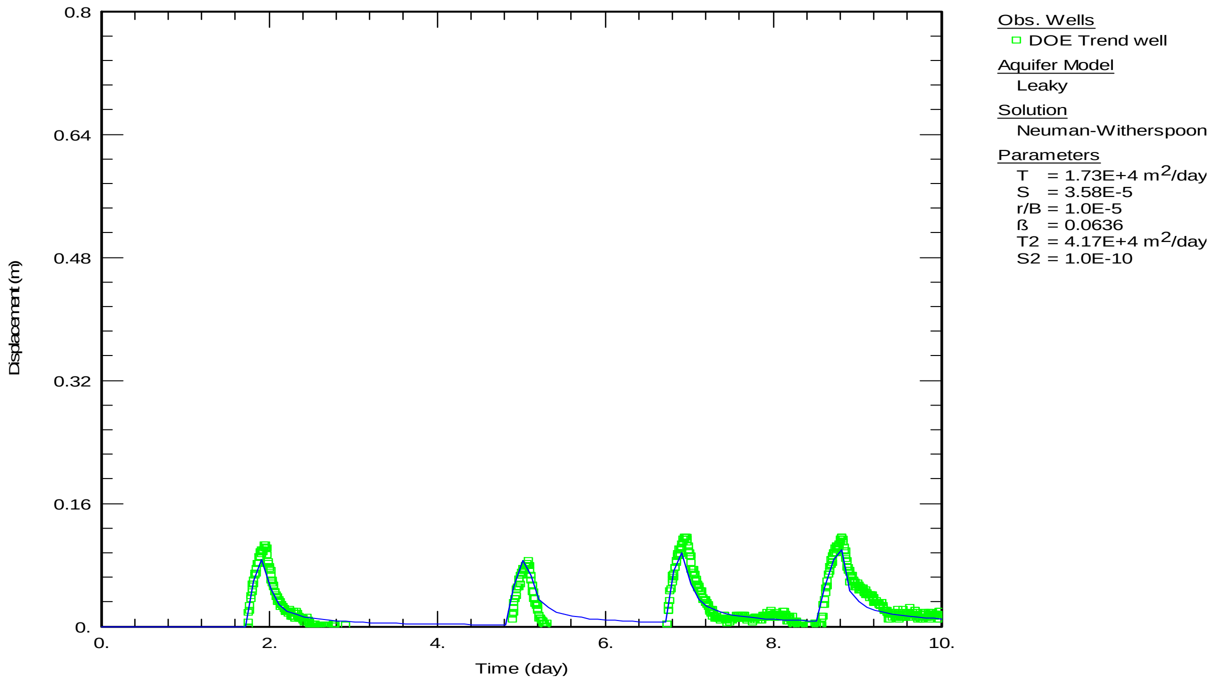

Figure 1.9: 0 to 10-day window with 0 Image Wells

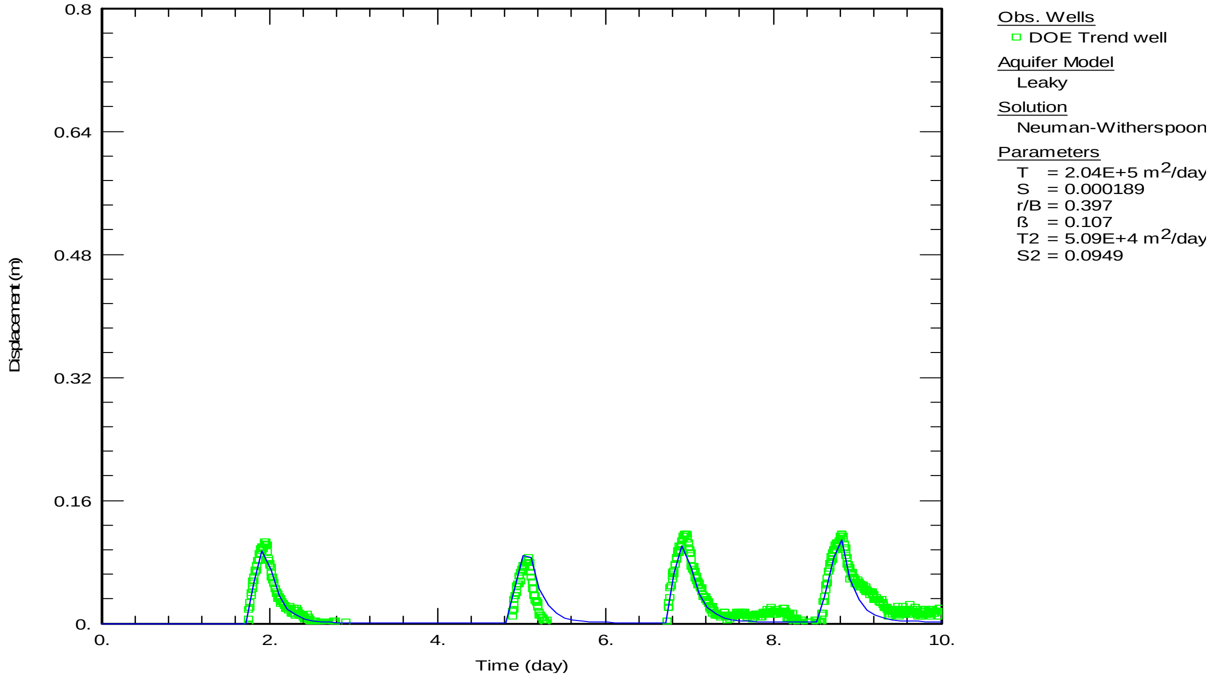

Figure 1.10: 0 to 10-day window with 4 Image Wells

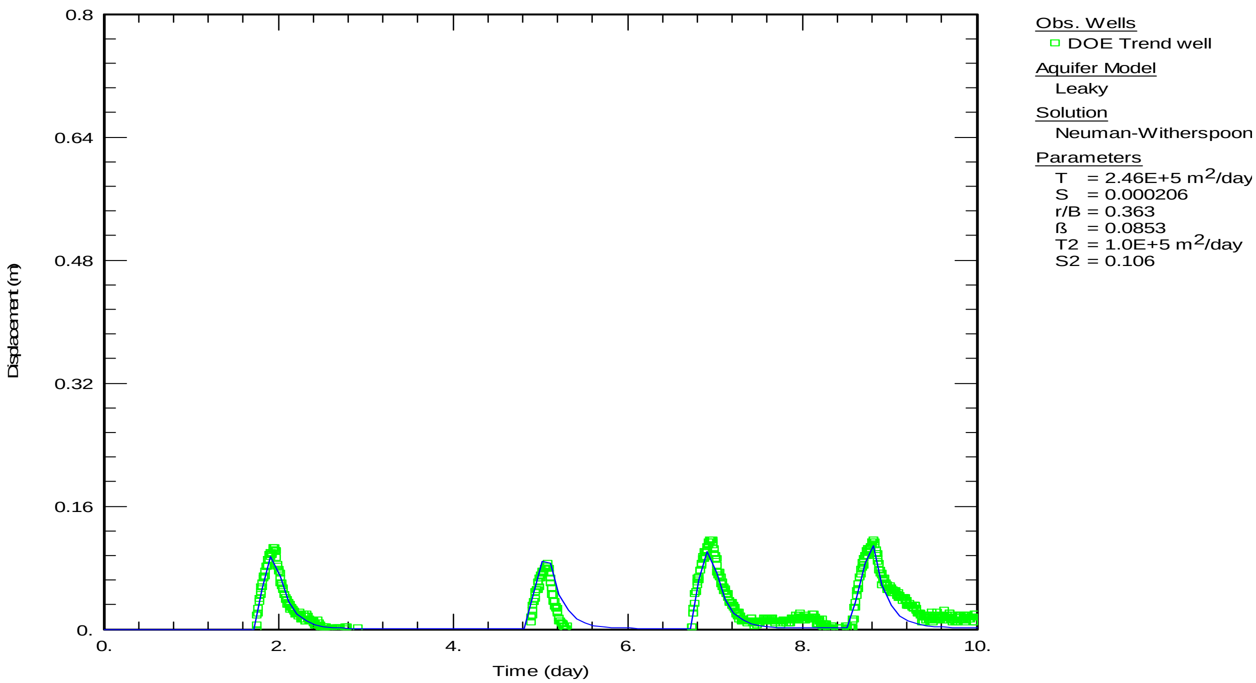

Figure 1.11: 0 to 10-day window with 8 Image Wells

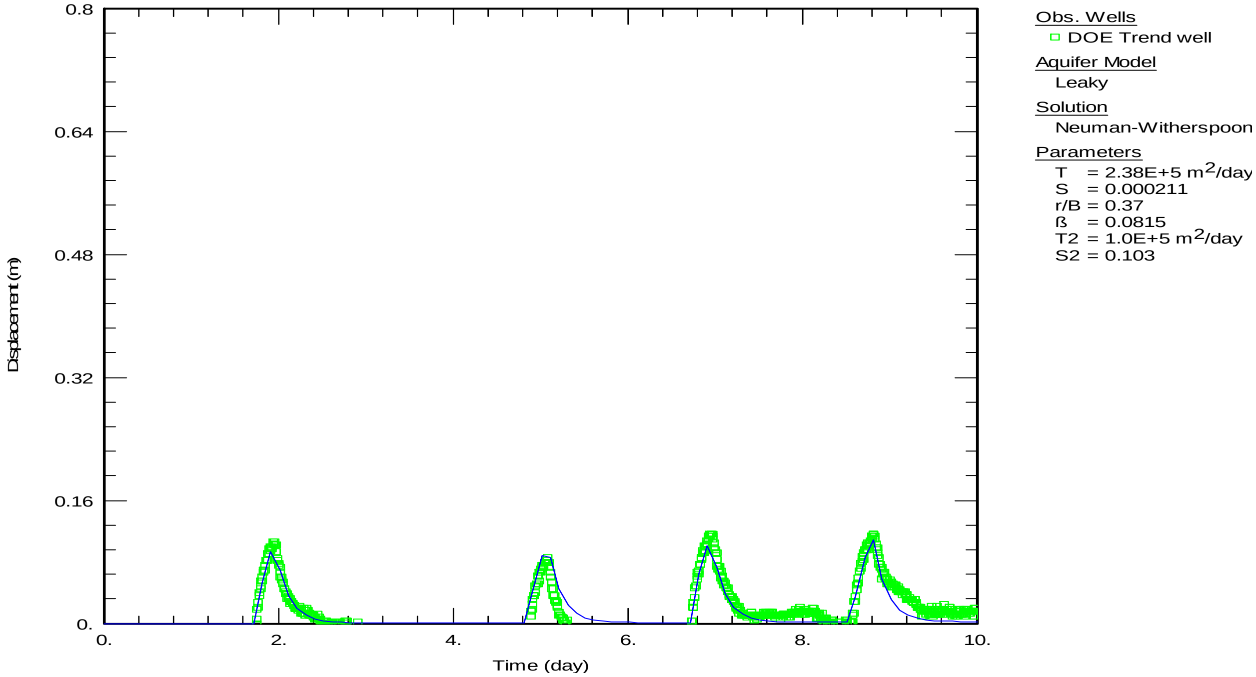

Figure 1.12: : 0 to 10-day window with 24 Image Wells

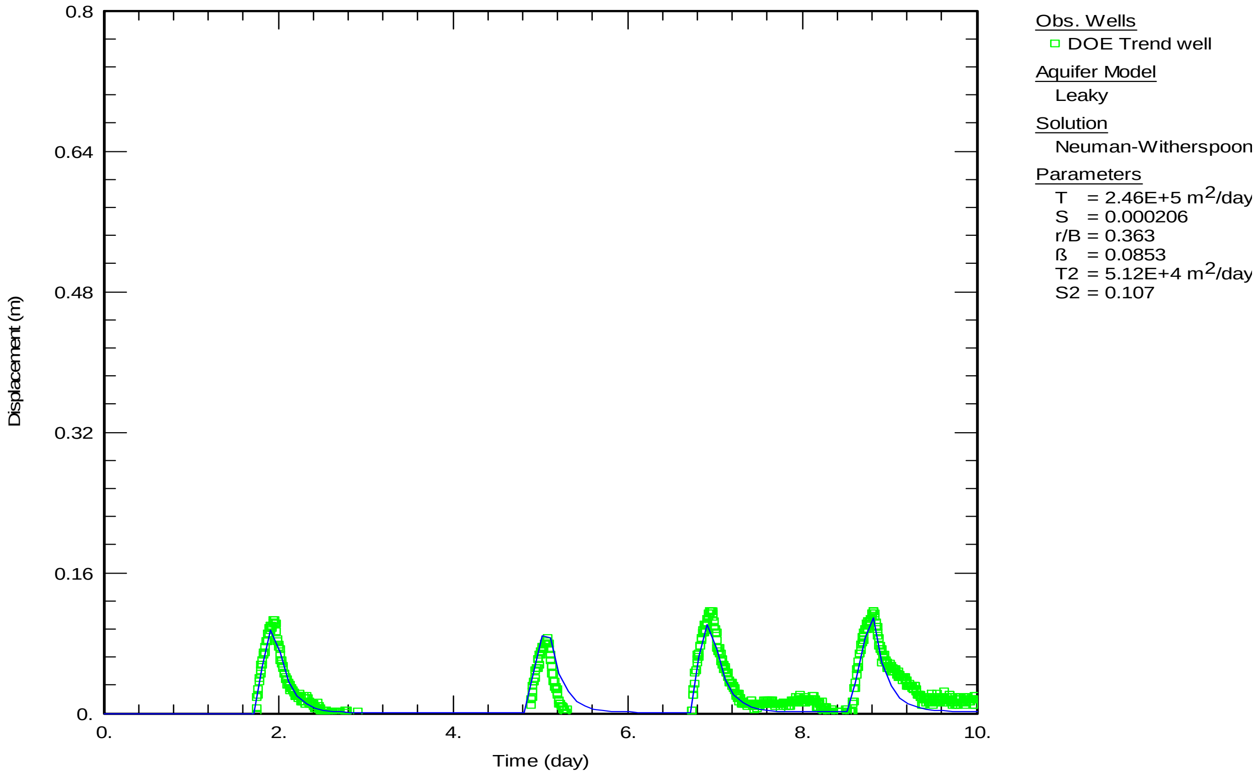

Figure 1.13: 0 to 10-day window with 48 Image Wells

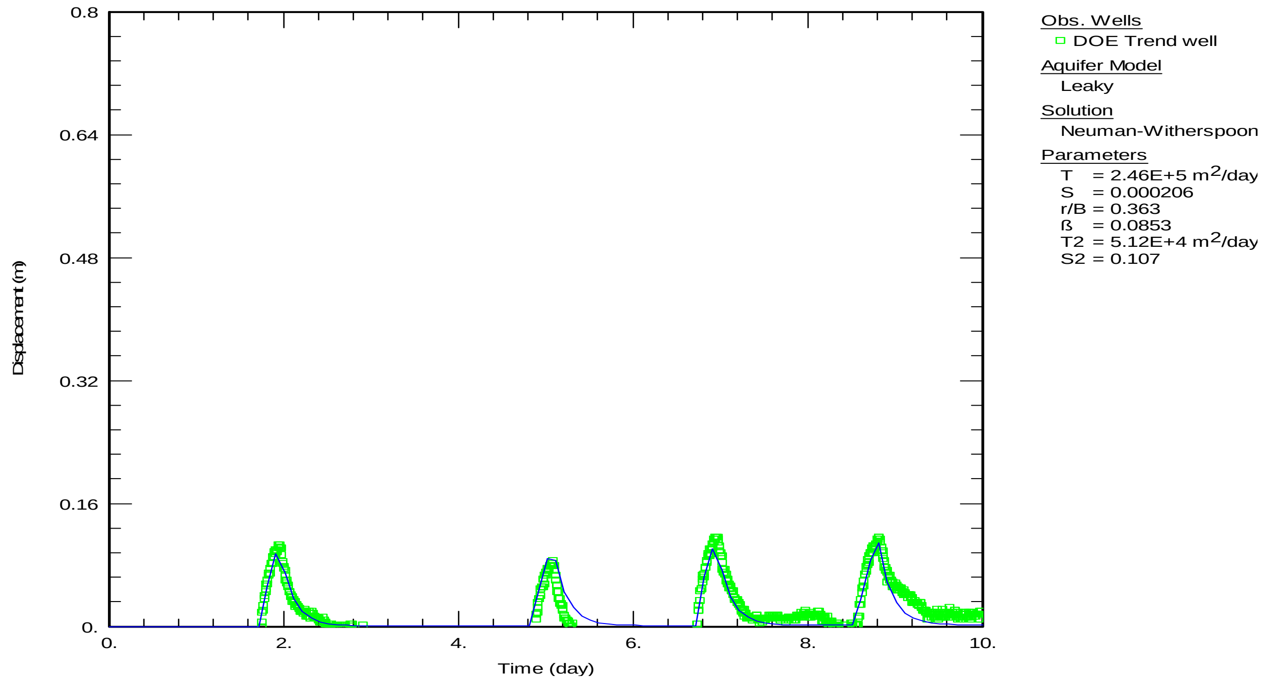

Figure 1.14: 0 to 10-day window with 80 Image Wells

Even though 8, 24, 48 and 80 image wells produced matches that are equivalent to each other statistically, the simulations produced estimated parameters that were different in each case except for equivalent parameters for 48 and 80 image wells. Although it appears adjusting the model with different numbers of image wells produces equally satisfying non-unique solutions, figures 1.9 to 1.14 show results from only the first ten days of the 372-day aquifer test. Figures 1.15 to 1.20 use the parameters produced from the automatic matching simulations for the first ten days of the aquifer test, and show the model predicted drawdown compared to the measured drawdown for each image well combination, for the 10-day window from 362 to 372 days.

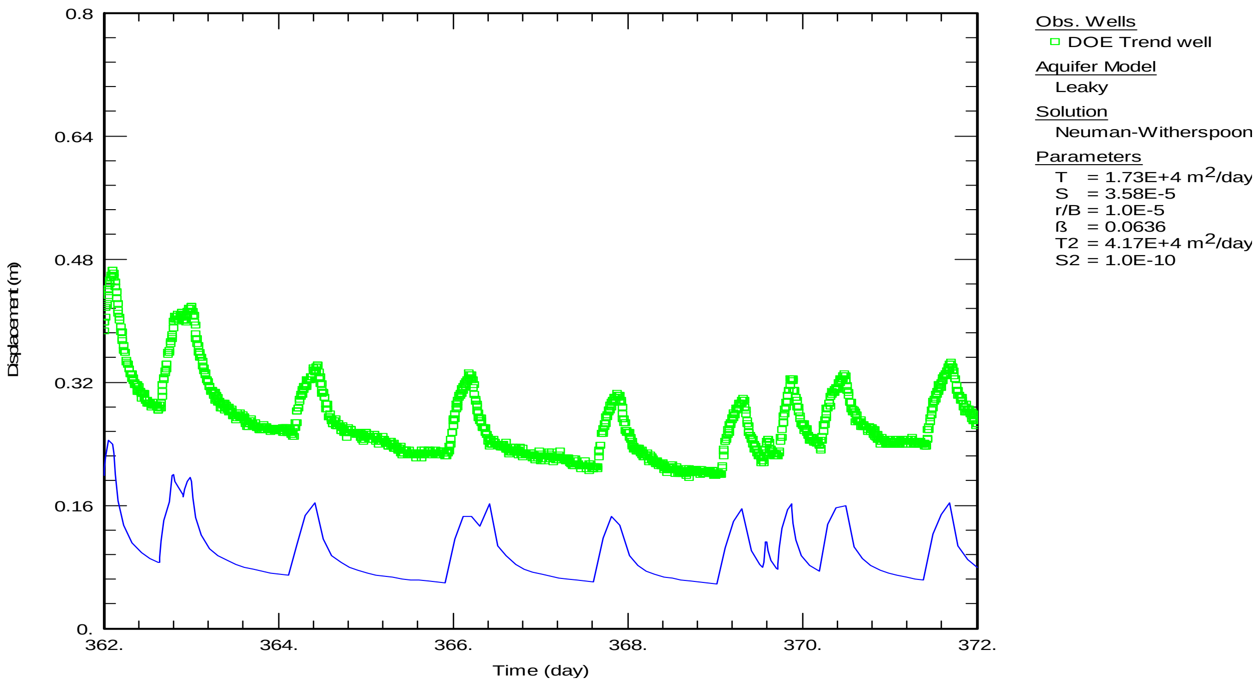

Figure 1.15: 362 to 372-day window with 0 Image Wells

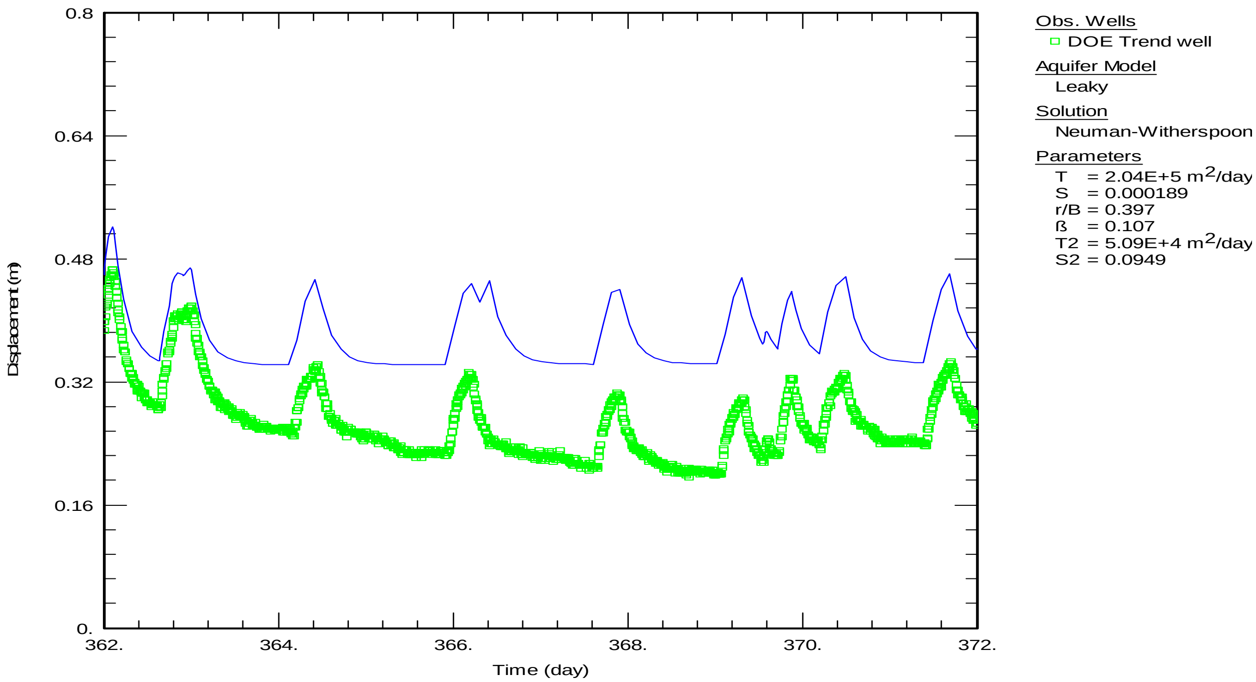

Figure 1.16: 362 to 372-day window with 4 Image Wells

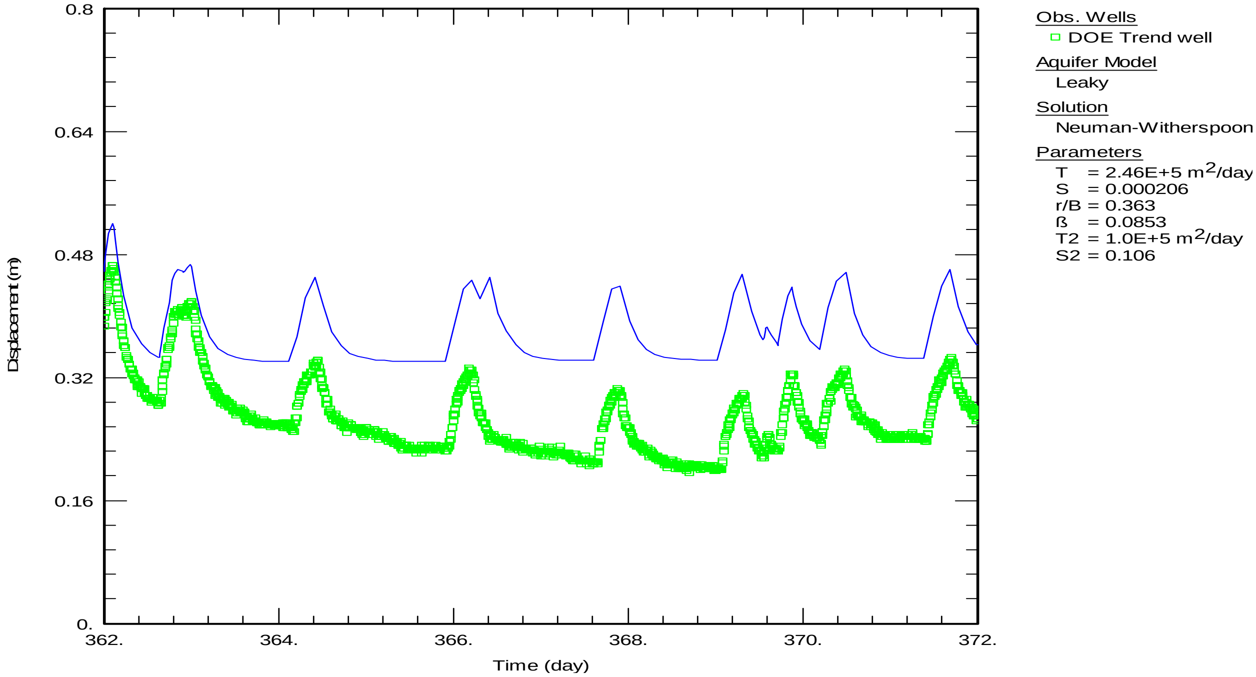

Figure 1.17: 362 to 372-day window with 8 Image Wells

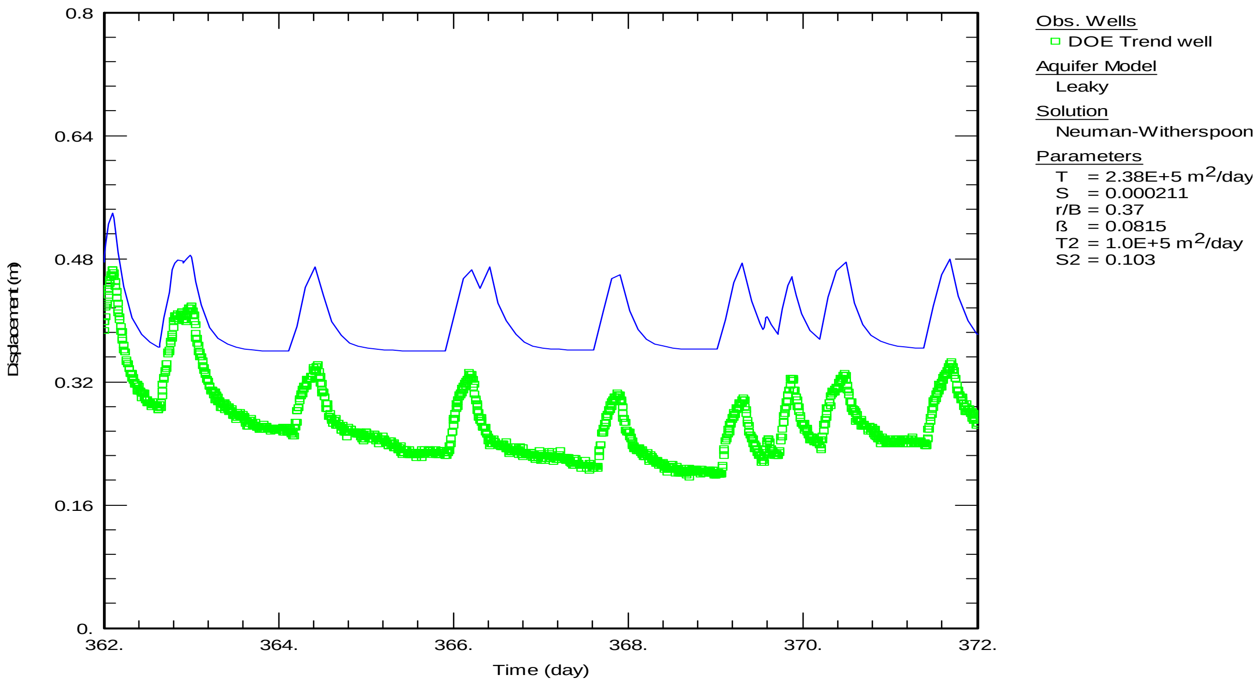

Figure 1.18: 362 to 372-day window with 24 Image Wells

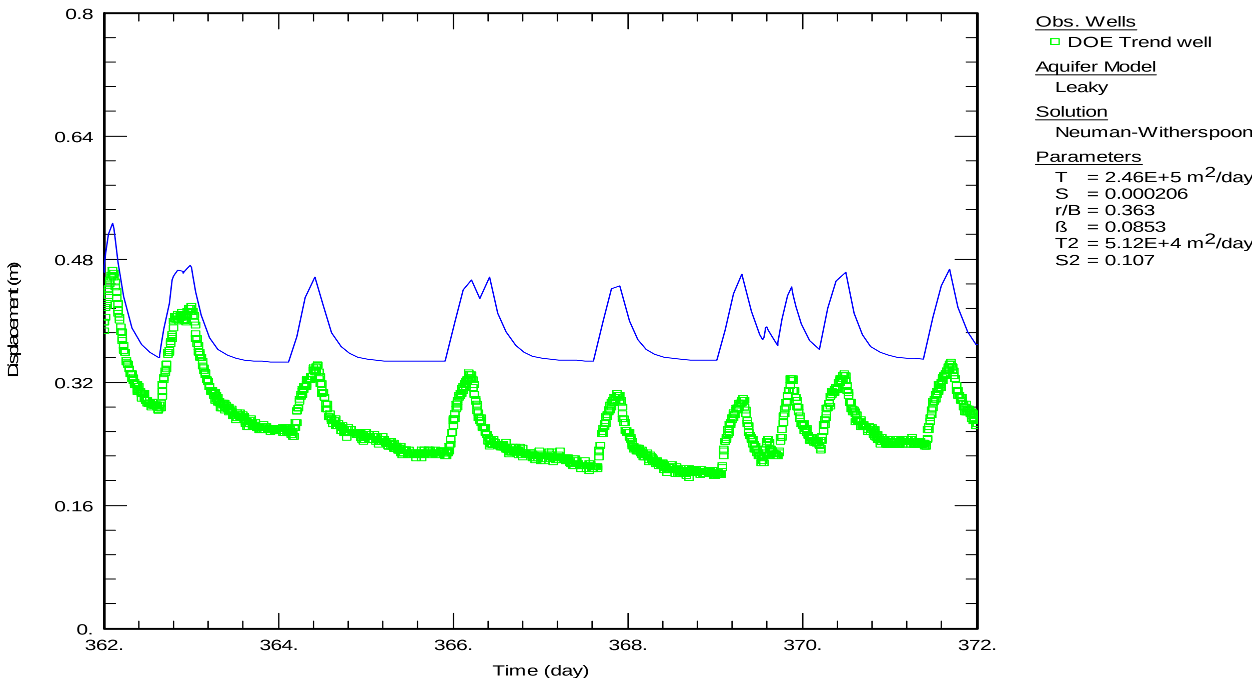

Figure 1.19: 362 to 372-day window with 48 Image Wells

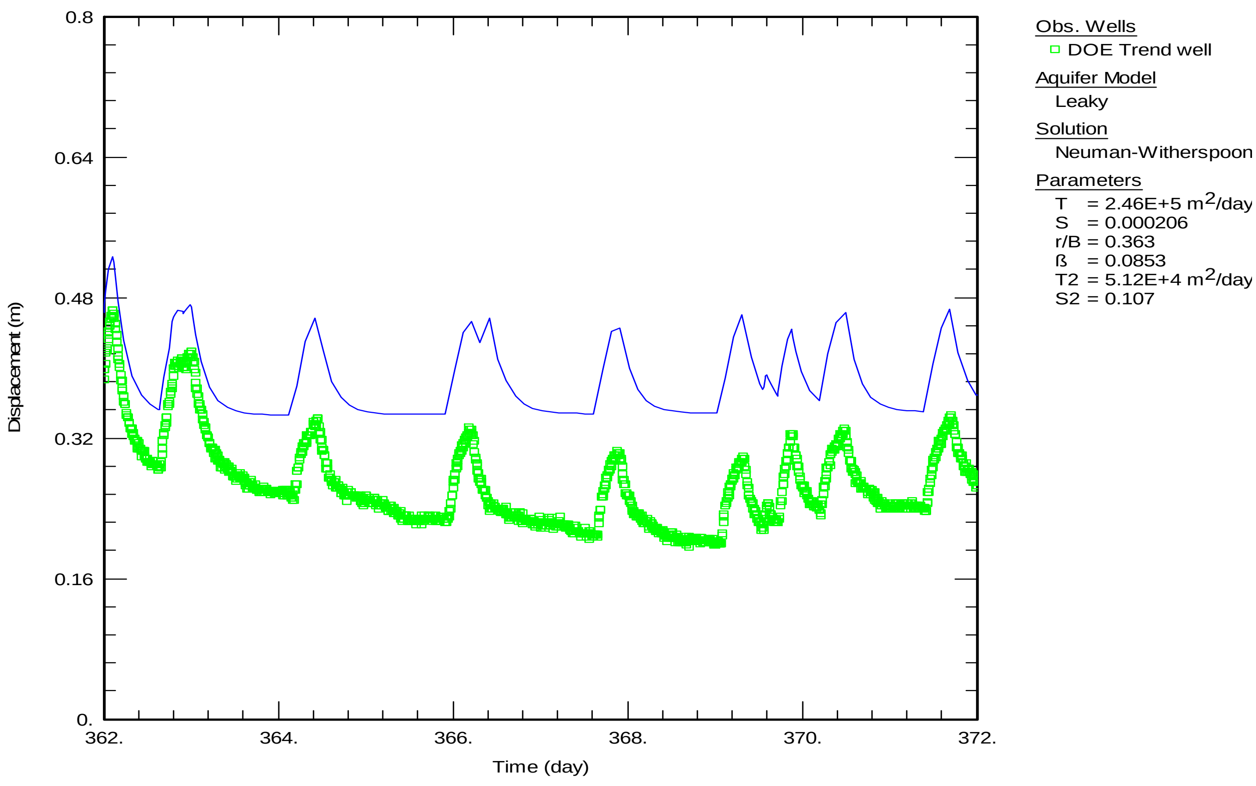

Figure 1.20: 362 to 372-day window with 80 Image Wells

Every simulation run for the 362 to 372 day window, except when zero image wells are used, overestimated the amount of drawdown in the aquifer. Zero image wells simulated an aquifer of infinite areal extent and underestimated the amount of drawdown in the aquifer. One potential reason for the discrepancy between the model results for 4, 8, 24, 48 and 80 image wells is that the observation well data were adjusted based on factors such as barometric pressure, earth tides, etc. and these adjustments could have overcorrected the data. Another possibility is that there was error in the collection of the data, either human or mechanical. For instance, sometimes the data logs showed periods when the pumping wells were activated but the supposed pumping did not show up in the data and the pumping did not occur according to managers of the pumping wells. The best work was done to account for these errors, but nonetheless some could have been missed. A third possibility, and one that most likely exists even if the other two possibilities do not, is that there are other conditions of the compartment that are not accounted for in the model which prevent the model from producing a better fit.

Visually, there is very little difference between Figures 1.9 through 1.12. The downward trend of the observed data in the 362 to 372 windows is not represented by the model. Trend corrections that were incorporated into the real data by Folnagy (2012) could explain why the trend is not accounted for by the image well simulations. A non-unique solution to modeling horizontal, intercompartmental flow for the DOE well in the PGB is apparent from the results.

In Folnagy (2012), the method used to create predicted drawdown curves did not adjust the number of image wells used to simulate semi-permeable boundaries. All three of Folnagy's boundaries were simulated as impermeable boundaries. Figure 1.21 and Figure 1.22 are from Folnagy's thesis and they show the first ten days and 362 to 372 windows for the DOE 372-day aquifer test, respectively.

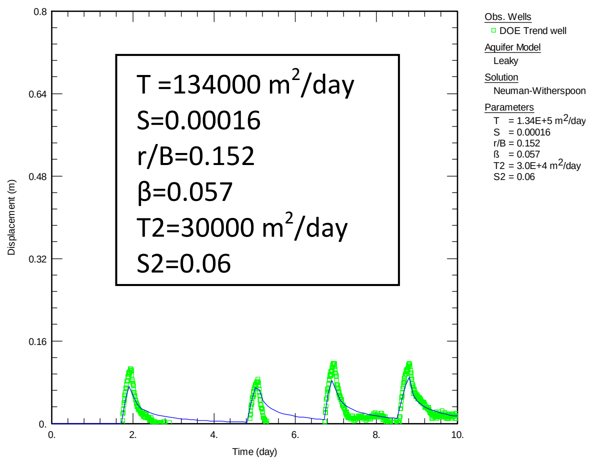

Figure 1.21

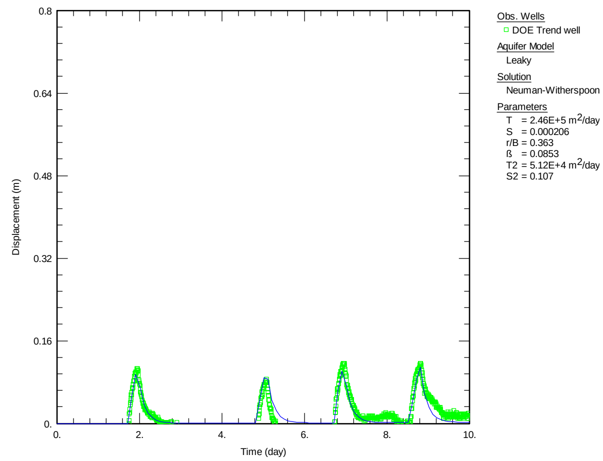

Figure 1.14

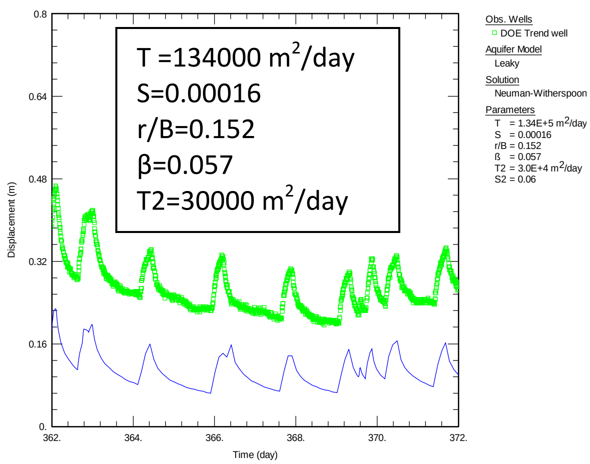

Figure 1.22

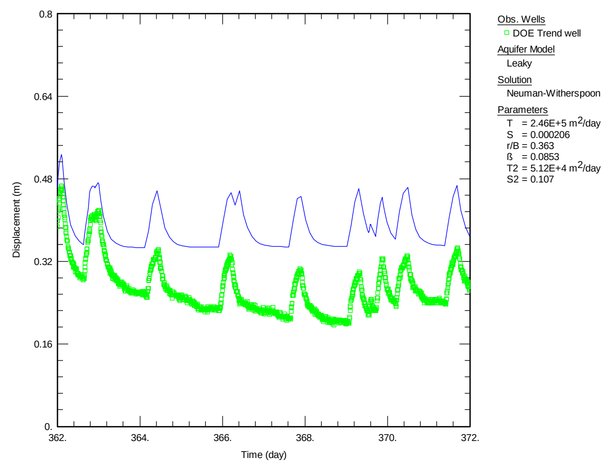

Figure 1.20

Visually, the matches by Folnagy (2012) are not as strong as the matches made from automatic simulations with 80 image wells. However, in the 362 to 372 day window from Folnagy (2012) the downward trend of the data is represented whereas in my simulations it is not. Based on this observation, the geologic boundaries of the DOE compartment may not completely enclose the compartment on all four sides. Further research is needed to recognize the source of the trend discrepancy.

Conclusions

The simulations in this research show that, like with all models, non-unique solutions are produced using the method of image wells to create semi-permeable boundaries.

Intercompartmental flow that is not simulated by Aqtesolv with four intersecting impermeable boundaries can be simulated by adjusting the number of image wells used by the software to mathematically model the boundaries. However, many possible combinations of horizontal flow (intercompartmental) and vertical leakage may result in equally good statistical matches as shown in figures 1.11 through 1.14. Using image wells to simulate semi-permeable boundaries in the DOE compartment appears to be an acceptable method for modeling the basin. Further tests must be done to determine if there is a statistically significant difference between the method used in Folnagy and the one used in this research.

Apart from statistics, the models developed in this research are consistent with a defensible conceptual hydrogeologic model for groundwater flow in the PGB whereas the previous model by Folnagy (2012) is not. However, the models in Folnagy (2012) did reproduce the trend in the observed data whereas the image well method in this research did not. Further questions were raised on whether the DOE compartment is geologically bounded on all sides or if there are hydraulic connections between sections of the impermeable boundaries.

Further studies should continue, especially related to quantification of the amount of groundwater that flows through each boundary with various combinations of image wells. These studies should provide more information on how to best match observed drawdown curves in the models.

References

Duffield, G.M. (2007) AQTESOLV for Windows Version 4.5 User's Guide, HydroSOLVE, Inc., Reston, VA.

Ferris, J.G., Knowles, D.B., Brown, R.H., and Stallman R.W. (1962) Theory of Aquifer Tests. *Geological Survey Water-Supply Paper 1536-E.* United States Geological Survey.

Folnagy, A.J.B. (2012). Long-Term Grande Ronde Aquifer Stress Testing to Delineate Aquifer Compartmentalization and Water Level Responses in the Palouse Groundwater Basin. Unpublished Master Thesis, University of Idaho, Moscow, ID.

McVay, M. (2007). Grande Ronde Aquifer Characterization in the Palouse Basin. Unpublished Master's Thesis, University of Idaho, Moscow, ID.

Moran, K. (2011). Interpretation of Long-Term Grande Ronde Aquifer Testing in the Palouse Basin of Idaho and Washington. (Master Thesis). University of Idaho, Moscow, ID.

Neuman, S.P., and Witherspoon, P.A. (1969) Theory of Flow in a Confined Two Aquifer System. *Water Resour. Res.*, 5(4):803-816, doi:10.1029/WR005i004p00803.

Neuman, S.P. and Witherspoon, P.A. (1972) Field determination of the hydraulic properties of leaky multiple aquifer systems. Water Resour. Res, 8(5):1284-1298.

Osiensky, J.L., and Williams, R.E. (1997). Potential Inaccuracies in MODFLOW Simulations Involving the SIP and SSOR Methods for Matrix Solution. Ground Water, 35(2):229-232.