PROGRESS REPORT

Title Increasing Water Security through Horizontal Wells

Project Number 2013TX462B

Primary PI Dr. Hongbin Zhan

Other PIs Benjamin Blumenthal

Abstract

The use of non-vertical wells for groundwater production will allow greater production rates per well (and thus less wells) compared to traditional vertical wells. The number of vertical wells replaced by one horizontal well will be greatest in low permeability, thin aquifers. Therefore, locations with low aquifer quality will have greater access to groundwater upon the use of angle/horizontal wells. Furthermore, non-vertical wells may be advantageous for aquifer storage and recovery operations by minimizing buoyancy stratification.

While angle/horizontal well models have been developed, they typically ignore head (energy) loss within the wellbore which may be a limiting factor to angle/horizontal well use. Upon application of petroleum industry methodology, we have developed an easy to use model for common groundwater boundary conditions which incorporates intra-wellbore energy loss. Water resource managers will now be able to rigorously quantify the possible benefits of non-vertical wells and thus improve water availability in areas of low quality aquifers.

Problem and Research Objectives

The use of angle/horizontal wells for groundwater supply production increases production rate for a given drawdown (i.e. less drawdown for a given pumping rate) as there is greater contact with the aquifer (Joshi, 1988; Ozkan et al., 1989). The use of angle/horizontal well technology will thus facilitate greater groundwater production per well compared to similar vertical wells in the same aquifer. The utility of horizontal/angle wells compared to vertical wells will be greatest in thin aquifers and/or lower permeability aquifers. Two such projects have completed with this goal in mind (Jehn-Dellaport, 2004; Rash, 2001).

Furthermore, the use of horizontal wells for aquifer storage and recovery (ASR) would increase the productivity/injectivity of ASR wells (Pyne, 2005; Pyne and Howard, 2004; Zuurbier et al., 2013). In addition, recovery of injected water will likely increase when using angle/horizontal wells by allowing the wells to target thin, lower permeability aquifers which would minimize buoyancy stratification effects (Esmail and Kimbler, 1967; Kimbler, 1970; Kumar and Kimbler, 1970). The ability to extract more water from these thin, lower permeability formations would improve the utility ASR especially in brackish aquifers.

To date, several analytical models have been developed for groundwater flow to a horizontal well (Hantush and Papadopulos, 1962; Park and Zhan, 2002; Zhan et al., 2001; Zhan and Zlotnik, 2002). However, these models ignore head (energy) loss within the wellbore and assume uniform flux or uniform head along the length of the well. The investigation of head loss within the wellbore has only received limited study by the groundwater community (Chen et al., 2003). Numerical finite-difference models (MODFLOW-CFP) can be used to study head loss in the wellbore, but are difficult to implement due to stability and grid issues (Shoemaker et al., 2007).

Quantification of head loss within the angle/horizontal wellbore is important as it will affect the drawdown to production ratio and hence competitiveness when compared to vertical wells. With current models, a horizontal wellbore should increase in length towards infinity to achieve the least drawdown for a give production rate. However in reality, given an extremely high pumping rate, the length of the wellbore would become inconsequential as the head loss would be very high. In this latter case, a vertical well would be essentially the same as the angle/horizontal well given high enough pumping rates. In regards to ASR, head loss along the wellbore (and hence uniform flux assumptions) will impact recoverability of injected water and thus has been cited as a research need (Maliva and Missimer, 2010).

Materials/Methodology

As a result of the stability issues of MODFLOW-CFP and the requirement of user intervention to achieve accurate results, we chose to implement an automatable, analytical method. The petroleum industry has derived analytical angle/horizontal well solutions with incorporation of wellbore head loss (Dikken, 1990; Landman, 1994; Novy, 1995). However, these solutions used many unrealistic assumptions such as an fully penetrating well, 2-dimensional reduction of space, etc.

More recently, however, a solution methodology has been developed for a three-dimensional well in an anisotropic aquifer within a box shaped aquifer/reservoir (Ouyang and Aziz, 1998; Penmatcha and Aziz, 1999). Solutions to date have included a confined reservoir of infinite extent and a reservoir with all closed (no-flux) boundaries. In addition, the wellbore has a limited extent in the box to roughly the middle fifty percent and is bound along one principal axis (Babu and Odeh, 1988; Babu and Odeh, 1989).

Our work expands on that of the petroleum industry by allowing the wellbore to be at any location in the reservoir along any angle from point X_1,Y_1,Z_1 to X_2,Y_2,Z_2. In addition, we expand the boundary conditions to those found in groundwater systems, namely constant head (river/lake) and a leaky-aquifer. A conceptual diagram of our model may be seen in Figures 1 & 2.

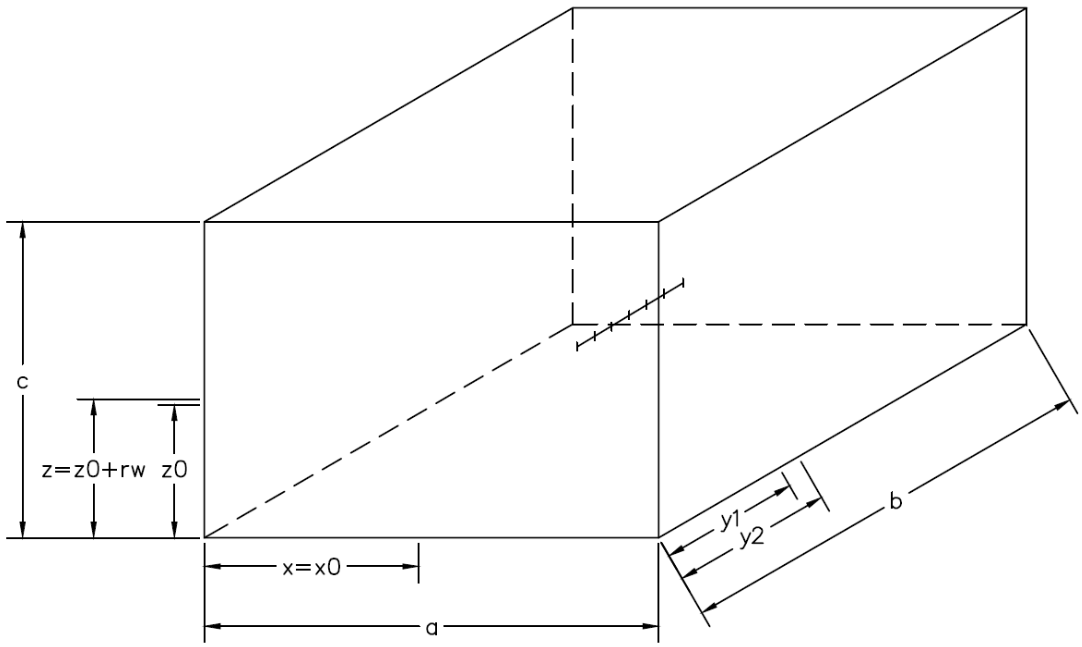

Figure 1. Conceptual diagram of the box-shaped reservoir/aquifer.

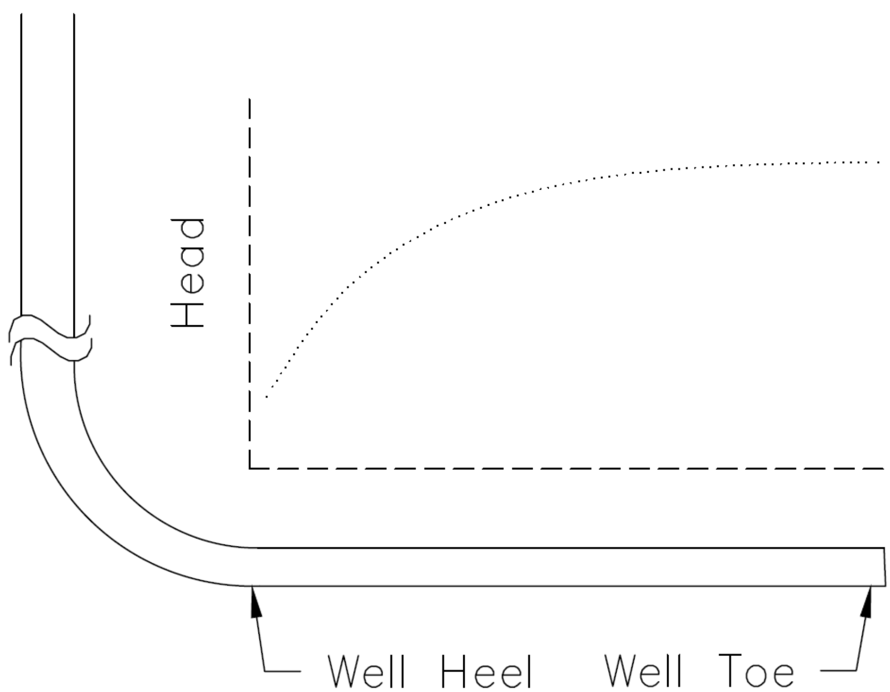

Figure 2. Conceptual diagram of the head (energy) along a horizontal wellbore.

Derivation of our model begins with the differential equation governing groundwater flow and a point sink represented by a delta function. We then compute the time Laplace transform and solve the boundary conditions using Fourier series. Upon solution of the boundary conditions, we take the inverse Laplace transform and now have the time derivative for a point sink. We then focus on the very slowly convergent Fourier series at time zero and find closed form solutions/approximations. Upon derivation of closed forms, we take the numerical time integral and numerical line integral from point X_1,Y_1,Z_1 to X_2,Y_2,Z_2 to represent the angle/horizontal/vertical wellbore. We now have a uniform flux line sink an aquifer with one of several boundary conditions. With the analytics of the problem complete, we now move to numerics.

A numerical implementation of the above equations is written in Matlab. To model the head (energy) loss in the wellbore, we use the principal of superposition and subdivide one long wellbore (angle, horizontal or vertical well) into many small uniform flux line sinks. Using superposition, we define the difference in head between one segment and the next using frictional and acceleration head loss equations.

As the aquifer is dynamically connected to the wellbore (both in reality and our model), this circular connection must be numerically solved as such. We first assume a uniform flux between each of the segments to establish a direction of flow via the energy loss equations. We then solve the matrix with the coupled aquifer. This updates the flux to some non-uniform distribution. We then re-solve the energy loss terms and continue the process until convergence is reached. With a solution obtained for a given number of segments, we then add segments and repeat the entire process; continually adding segments until the heel-most segment numerically converges.

This method is typically convergent around forty segments. Due to the automatic nature of the MATLAB code, one only needs to input a well and aquifer parameters, then wait for convergence. The minimal need for user intervention allows for ease of use and the computation of many different input parameters with relative ease.

Principal Findings

As we are still improving the model, we have yet to compute the benefits of a horizontal well for many input parameters and therefore cannot make specific statements on horizontal well production. From the model runs completed, however, we have noticed that the importance of head loss is relative to the permeability of the aquifer and the production rate. In addition, greater wellbore length in the aquifer has led to smaller drawdowns as expected. More interestingly, we have noticed that the production along the wellbore in greatest at the well ends (heel and toe). This increase appears to be of more importance than the wellbore head loss effects, but is yet to be rigorously confirmed. Preliminary output from the model for a steady state horizontal well may be seen in Figures 3 & 4.

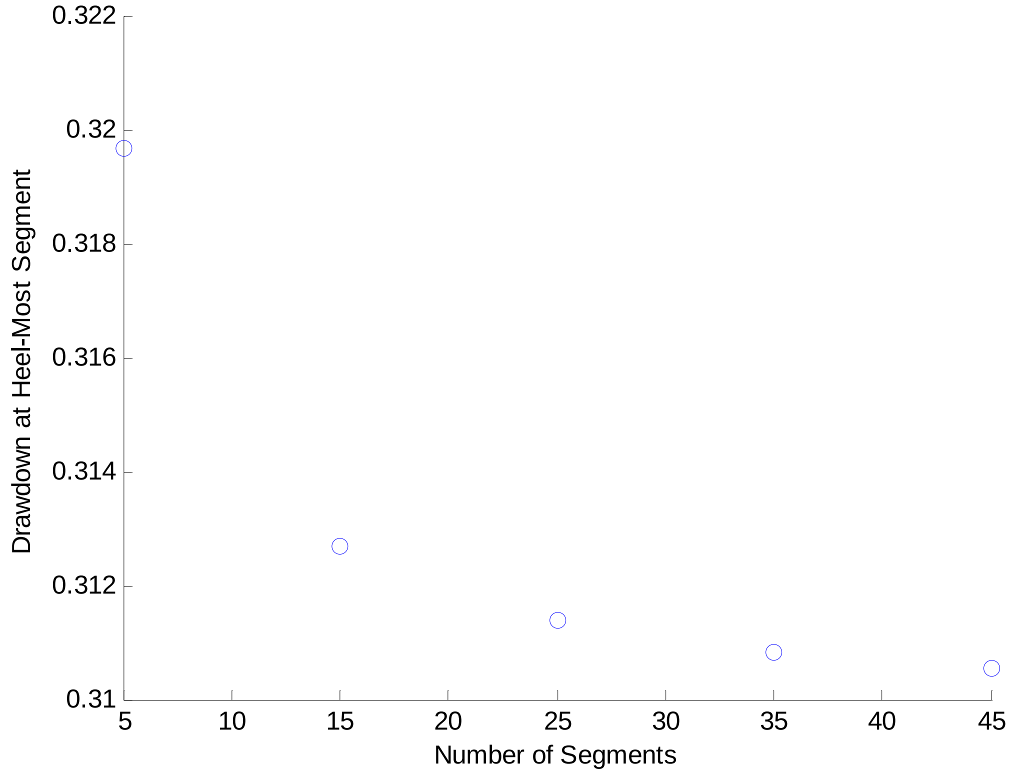

Figure 3. Increasing segments leads to convergence around 40 segments.

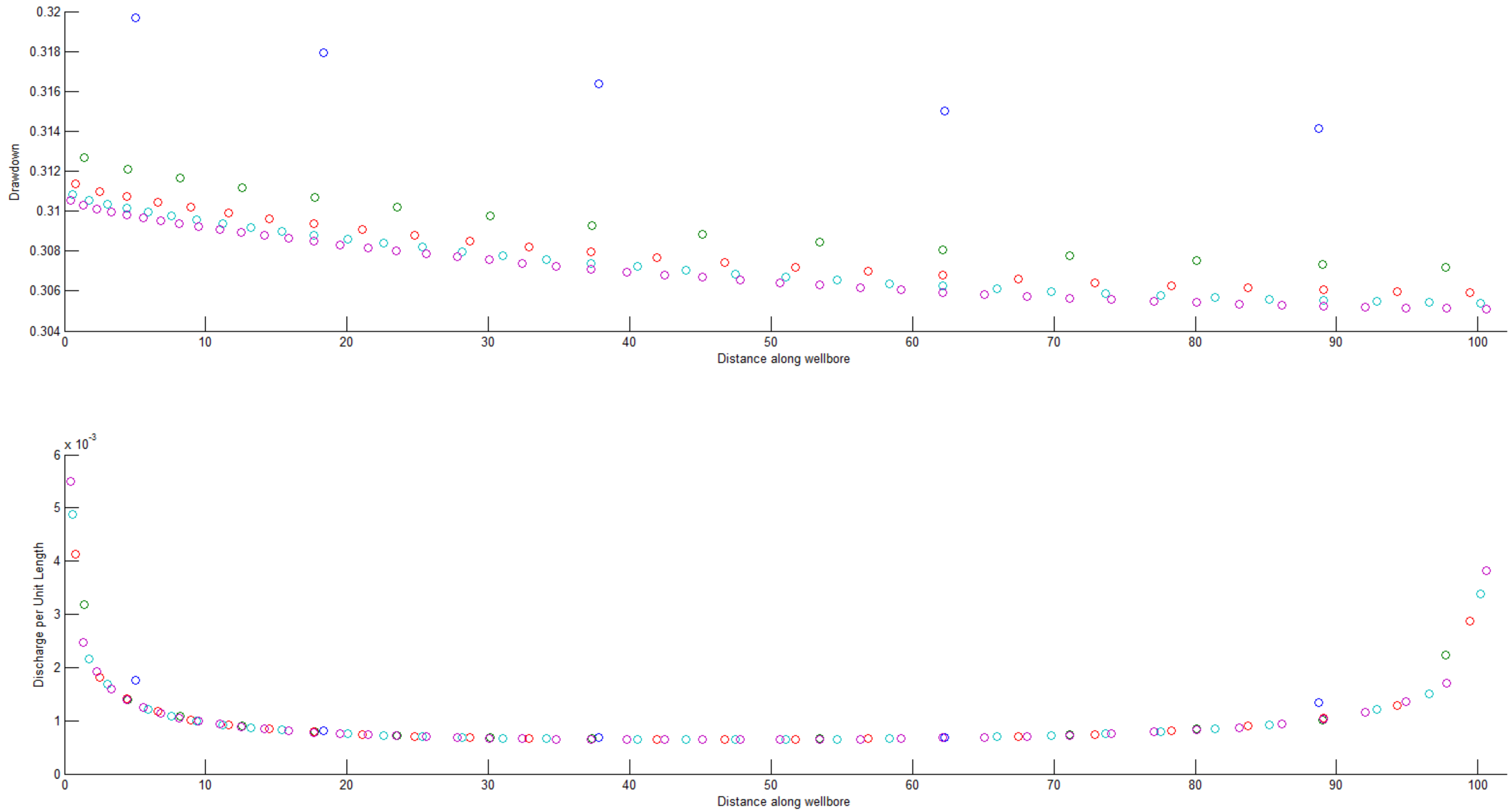

Figure 4. Top: Drawdown at each segment, notice the increase in drawdown towards the well heel – left side – due to energy loss (drawdown = initial head minus current head). Bottom: Discharge per unit length of the well, notice the peaks at well tips due to greater exposure to the aquifer.

Significance

Our research has led to development of an easy to use angle/horizontal/vertical well model for groundwater systems which incorporates intra-wellbore energy loss. Our model will allow water resource planners to rigorously assess the possible improvements of angle/horizontal well production against more commonly used vertical wells. Upon running the model with a variety of input parameters, general quantitative statements on angle/horizontal well production verses vertical well production will be made.

References Cited

Babu, D., and Odeh, A., Productivity of a horizontal well appendices A and B, *in* Proceedings SPE Annual Technical Conference and Exhibition1988, Society of Petroleum Engineers.

Babu, D., and Odeh, A. S., 1989, Productivity of a Horizontal Well: SPE Reservoir Engineering, v. 4, no. 04, p. 417-421.

Chen, C., Wan, J., and Zhan, H., 2003, Theoretical and experimental studies of coupled seepage-pipe flow to a horizontal well: Journal of Hydrology, v. 281, no. 1, p. 159-171.

Dikken, B., 1990, Pressure drop in horizontal wells and its effect on production performance: Journal of Petroleum Technology, v. 42, no. 11, p. 1426-1433.

Esmail, O. J., and Kimbler, O. K., 1967, Investigation of the technical feasibility of storing fresh water in saline aquifers: Water Resources Research, v. 3, no. 3, p. 683-695.

Hantush, M., and Papadopulos, I., 1962, Flow of ground water to collector wells: Journal of the Hydraulics Division of the American Society of Civil Engineers, v. 88, p. 221-244.

Jehn-Dellaport, T., 2004, Innovative Water Well Completion In The Denver Basin, Colorado: The Mountain Geologist, v. 41, no. 4, p. 211-217.

Joshi, S. D., 1988, Augmentation of Well Productivity With Slant and Horizontal Wells: Journal of Petroleum Technology, v. 40, no. 6, p. 729-739.

Kimbler, O. K., 1970, Fluid Model Studies of the Storage of Freshwater in Saline Aquifers: Water Resources Research, v. 6, no. 5, p. 1522-1527.

Kumar, A., and Kimbler, O. K., 1970, Effect of Dispersion, Gravitational Segregation, and Formation Stratification on the Recovery of Freshwater Stored in Saline Aquifers: Water Resources Research, v. 6, no. 6, p. 1689-1700.

Landman, M. J., 1994, Analytic modelling of selectively perforated horizontal wells: Journal of Petroleum Science and Engineering, v. 10, no. 3, p. 179-188.

Maliva, R. G., and Missimer, T. M., 2010, Aquifer storage and recovery and managed aquifer recharge using wells: Planning, hydrogeology, design, and operation, Sugar Land, Texas, Schlumberger, Methods in Water Resources Evaluation, v. 2, 578 p.:

Novy, R., 1995, Pressure drops in horizontal wells: when can they be ignored?: SPE Reservoir Engineering, v. 10, no. 1, p. 29-35.

Ouyang, L.-B., and Aziz, K., A simplified approach to couple wellbore flow and reservoir inflow for arbitrary well configurations, *in* Proceedings SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, 1998, Society of Petroleum Engineers.

Ozkan, E., Raghavan, R., and Joshi, S. D., 1989, Horizontal well pressure analysis: SPE Formation Evaluation, v. 4, no. 4, p. 567-575.

Park, E., and Zhan, H., 2002, Hydraulics of a finite-diameter horizontal well with wellbore storage and skin effect: Advances in Water Resources, v. 25, no. 4, p. 389-400.

Penmatcha, V., and Aziz, K., 1999, Comprehensive reservoir/wellbore model for horizontal wells: SPE Journal, v. 4, no. 3, p. 224-234.

Pyne, R. D. G., 2005, Aquifer storage recovery: a guide to groundwater recharge through wells, ASR systems Gainesville, FL, 608 p.:

Pyne, R. D. G., and Howard, J. B., 2004, Desalination/aquifer storage recovery (DASR): A cost-effective combination for Corpus Christi, Texas: Desalination, v. 165, p. 363-367.

Rash, V. D., 2001, Predicting Yield and Operating Behavior of a Horizontal Well, AWWA Annual Conference: Washington D.C.

Shoemaker, W. B., Kuniansky, E. L., Bauer, S., and Swain, E. D., 2007, Documentation of a Conduit Flow Process (CFP) for MODFLOW-2005: U.S. Geological Survey.
Zhan, H., Wang, L. V., and Park, E., 2001, On the horizontal-well pumping tests in anisotropic confined aquifers: Journal of Hydrology, v. 252, no. 1–4, p. 37-50.
Zhan, H., and Zlotnik, V. A., 2002, Groundwater flow to a horizontal or slanted well in an unconfined aquifer: Water Resources Research, v. 38, no. 7, p. 13-11-13-11.
Zuurbier, K., Stuyfzand, P., and Kooiman, J., 2013, The Freshmaker: enabling aquifer storage and recovery (ASR) of freshwater using horizontal directional drilled wells (HDDWs) in coastal areas, Eighth International Symposium on Managed Aquifer Recharge (ISMAR8): Beijing, China.

NOTABLE AWARDS AND ACHIEVEMENTS

Ben Blumenthal received a general fellowship from the Geology Department through Energy Cup in the amount of $5,000.