Evaluation of a pumping test of the Snake River Plain aquifer using axial-flow numerical modeling

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Abstract The Snake River Plain aquifer in southeast Idaho is hosted in a thick sequence of layered basalts and interbedded sediments. The degree to which the layering impedes vertical flow has not been well understood, yet is a feature that may exert a substantial control on the movement of contaminants. An axial-flow numerical model, RADFLOW, was calibrated to pumping test data collected by a straddle-packer system deployed at 23 depth intervals in four observation wells to evaluate conceptual models and estimate properties of the Snake River Plain aquifer at the Idaho National Engineering and Environmental Laboratory. A delayed water-table response observed in intervals beneath a sediment interbed was best reproduced with a three-layer simulation. The results demonstrate the hydraulic significance of this interbed as a semi-confining layer. Vertical hydraulic conductivity of the sediment interbed was estimated to be about three orders of magnitude less than vertical hydraulic conductivity of the lower basalt and upper basalt units. The numerical model was capable of representing aquifer conceptual models that could not be represented with any single analytical technique. The model proved to be a useful tool for evaluating alternative conceptual models and estimating aquifer properties in this application.

Résumé La plaine de la rivière Snake, au sud-est de l'Idaho, est située dans une épaisse séquence de basaltes stratifiés et de sédiments intercalés. Le degré auquel la stratification s'oppose à l'écoulement vertical n'a pas été bien évalué, mais c'est un phénomène qui doit exercer un contrôle réel sur le déplacement des contaminants. Un modèle numérique d'écoulement axial, RADFLOW, a été calibré sur des données d'essais de pompage fournies par un dispositif de packers en série en 23 intervalles en profondeur dans quatre piézomètres, dans le but de tester des modèles conceptuels et d'estimer les propriétés de l'aquifère de la plaine de la rivière Snake au Laboratoire National d'Ingénierie et d'Environnement de l'Idaho. Une réponse retardée de la nappe observée dans les intervalles sous un sédiment intercalé a été reproduite le mieux par une simulation à trois couches. Les résultats montrent l'importance hydraulique de ce niveau intercalé fonctionnant comme un niveau semi-captif. L'évaluation de la conductivité hydraulique des sédiments intercalés a fourni des valeurs inférieures de presque trois ordres de grandeur à la conductivité hydraulique verticale des unités de basalte inférieure et supérieure. Le modèle numérique a été capable de représenter les modèles conceptuels d'aquifères qui ne peuvent être représentés par aucune technique analytique unique. Le modèle s'est révélé être un outil efficace pour évaluer des modèles conceptuels alternatifs et pour estimer les propriétés d'un aquifère dans cette application.

Resumen El acuífero del Snake River Plain, al Sudeste de Idaho (Estados Unidos de América), se desarrolla en una secuencia potente de basaltos estratificados, con intercalación de sedimentos. No se ha podido determinar con precisión el grado a partir del cual la estratificación impide el flujo vertical, pero es una característica que puede ejercer un control substancial en el movimiento de contaminantes. Se ha calibrado un modelo numérico de flujo axial, RADFLOW, con los datos recogidos en un ensayo de bombeo mediante un sistema de obturadores extensible, utilizado en 4 pozos de observación y a 23 profundidades diferentes. El objetivo consistía en evaluar diversos modelos conceptuales y determinar las propiedades del acuífero en el Laboratorio Nacional de Ingeniería y Medio Ambiente de Idaho. La mejor forma de simular el retraso observado en la respuesta del nivel freático en algunos intervalos situados bajo una intercalación de sedimentos ha sido obtenida con un modelo tricapa. Los resultados demuestran que esta intercalación actúa hidráulicamente como una capa semiconfinante. Se ha estimado que la conductividad hidráulica vertical de la intercalación es unos tres órdenes de magnitud menor que la correspondiente a las unidades basálticas inferior

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y superior. El modelo numérico ha sido capaz de simular esquemas conceptuales del acuífero que no podían ser representados por medio de técnica analítica alguna. En esta aplicación, se ha constatado que el modelo es útil para evaluar modelos conceptuales alternativos y para estimar las propiedades del acuífero.

Keywords Axial flow models · Basalt aquifer · Conceptual models · Hydraulic testing · Snake River Plain

Introduction

Pumping test analyses typically require formulating a conceptual model of the aquifer being tested. That model may include attributes such as whether the aquifer is confined or unconfined, the degree of layering, the approximate physical properties of the layers (e.g., whether an aquitard may be "leaky"), the aquifer thickness, and what portion of the aquifer is open to pumping and observation wells. Typically, an analytical technique is selected that approximates the conditions of the conceptual model. Analyses of the pumping test data either substantiate the conceptual model, or result in modification of the concept.

The layered basalts and interbedded sediments hosting the Snake River Plain aquifer in southeast Idaho do not present clear evidence for development of a conceptual model. The aquifer is generally considered unconfined; however, the layered nature of the materials creates potential for localized confining effects. Deeper portions of the aquifer may respond as confined, at least for short duration pumping events. The sequence of basalt and sediment layers is likely hundreds of meters thick, although the effective bottom of the aquifer is uncertain because of a gradually decreasing permeability with depth (Mann 1986). Groundwater flow is thought to occur primarily along the nearly horizontal basalt flow contacts (Garabedian 1992), implying anisotropy in the vertical plane. Sediment interbeds and dense basalt flow interiors may be effective confining layers on a local scale. Although the geologic stratification is well defined in places, the hydrogeologic stratification cannot be directly determined and is not well understood. A high degree of uncertainty occurs in selection of a conceptual model and the appropriate analytical technique for pumping test analysis.

Axial-flow numerical modeling was employed in the analysis of pumping test data of the Snake River Plain aquifer at the Idaho National Engineering and Environmental Laboratory (INEEL) to evaluate alternative conceptual models and to avoid having to conform to the prescribed assumptions of analytical techniques. For example, analytical techniques commonly applied for the evaluation of an aquifer bounded by a leaky aquitard require assumptions that either there is no drawdown in adjacent aquifers and no storativity in aquitards (Hantush and Jacob 1955), or that the aquitards have a sufficiently small hydraulic conductivity and are sufficiently thick such that drawdown effects do not propagate through the aquitards (Hantush 1960). Representation within a numerical model allows users to apply their full understanding of the subsurface to tailor a more appropriate conceptual model. The wide variety of combinations of physical conditions that can be evaluated with numerical simulations provides an improved capability of representing actual conditions of the aquifer. Numerical modeling permits full use of subjective information such as lithology reported in drillers' logs in combination with the data derived from pumping tests.

An axial-flow numerical model was selected to evaluate response of the aquifer to pumping from a production well at the Idaho Nuclear Technology and Engineering Center (INTEC) at the INEEL in southeast Idaho. The location is shown in Fig. 1. The selected finite-difference, axial-flow model, RADFLOW, is capable of representing confined and unconfined conditions in a layered system with the assumption of near infinite lateral extent and lateral homogeneity and isotropy (Johnson et al. 2001). The RADFLOW model was calibrated to time-drawdown data collected at multiple depths in four observation wells using a straddle-packer system. The packers were inflated at selected intervals in the observation wells to determine drawdown in the isolated intervals using a pressure transducer. The trial and error calibration tested three conceptual models of varying degrees of complexity and provided corresponding estimates of aquifer properties. Detailed descriptions of the conceptual models and calibrations are provided in Frederick and Johnson (1996).

Several authors have used numerical models to evaluate pumping test data. Rushton and Booth (1976), Lakshminarayana and Rajagopalan (1977, 1978), Rathod and Rushton (1984, 1991), Bennett, et al. (1990), Butler and McElwee (1990), Rutledge (1991), Reilly and Harbaugh (1993), Pandit and Aoun (1994), and Lebbe and Van Meir (2000) among others, have applied, developed, or promoted the use of numerical models for pumping test analysis. Lebbe and De Breuck (1995) used an inverse numerical model to evaluate error resulting from application of analytical techniques to conditions which partially violate assumptions of those techniques. Van der Kamp (2001) stated that use of numerical models for aquifer test analysis is likely to become more common as methods become more sophisticated. Finite-difference and finite-element codes have been developed for pumping test analysis in one, two, and three dimensions. The popular MODFLOW code has been adapted to include a solution in cylindrical coordinates specifically to evaluate drawdown around a well (Reilly and Harbaugh 1993).

The purpose of this paper is to describe a unique application of pumping test analysis applying a numerical model. Although numerical models have been previously applied to pumping test analyses, the potential for developing an improved understanding of the conceptual model has apparently not been sufficiently emphasized

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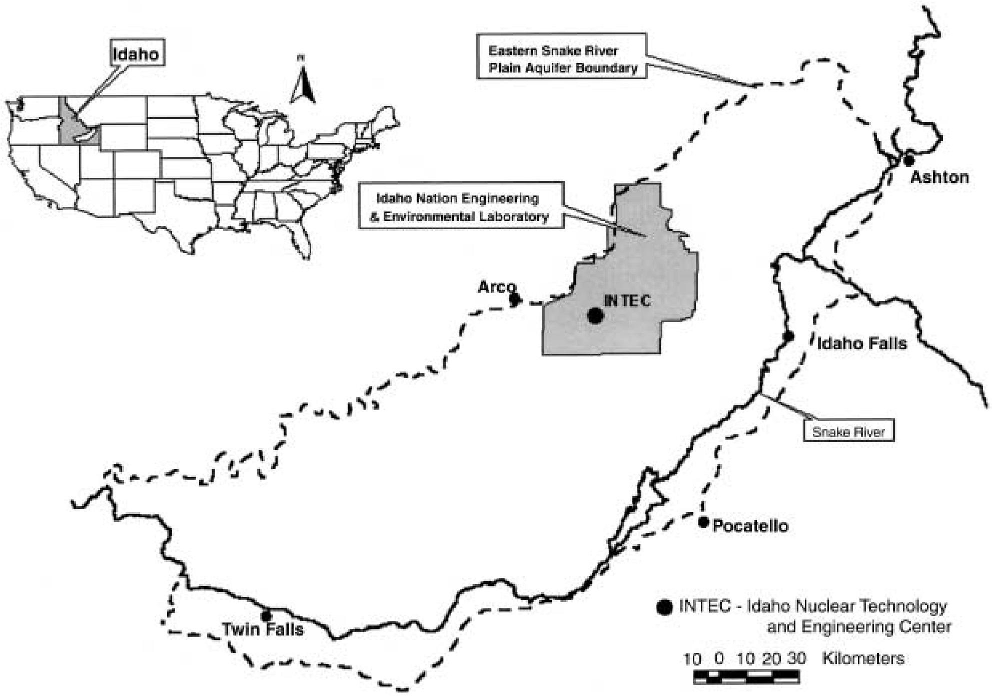


Fig. 1 Map showing the eastern Snake River plain aquifer

because application of numerical modeling has not been widely applied in practice. Because numerical models provide the opportunity to calibrate a number of parameters, there is a potential to develop highly non-unique property estimates. The staged calibration procedure that is presented illustrates incrementally building the understanding of the conceptual model to minimize the tendency to build overly-complex models that are highly non-unique in the inverse solution.

Site Description

The eastern Snake River Plain aquifer occupies about 28,000 km^2 of southeastern Idaho (Fig. 1) and is hosted in layered basalt and interbedded sediments. Basalt thickness may be in excess of 900 m in places. Locally, effective aquifer thickness is difficult to define because of a high degree of areal variability and a gradually decreasing permeability with depth (Mann 1986). Regional-scale modeling studies simulated the aquifer as four layers with a collective thickness ranging from 150 to over 900 m (Garabedian 1992). Individual basalt flows average about 6 m in thickness and it is believed that the highly fractured contacts between basalt flows provide the primary conduits for groundwater flow. This highly layered structure creates a high yielding aquifer that has a transmissivity that, in places, is estimated to be nearly 10^6 m^2/day (Garabedian 1992). The layering also creates anisotropy of unknown magnitude in the vertical plane. The aquifer is generally considered unconfined, but the layered nature of the deposits may cause the aquifer to respond as a confined system for short duration pumping events, depending on the stratigraphy in a specific location. A more detailed description of the aquifer hydrogeology can be found in Garabedian (1992) and Johnson et al. (1999).

Groundwater contamination from past practices at the INEEL has provided the incentive for extensive aquifer characterization efforts in parts of the Snake River Plain aquifer that are potentially affected. One of the investigations conducted by the State of Idaho INEEL Oversight Program and the Idaho Water Resources Research Institute at the University of Idaho focused on the area surrounding the INTEC, previously named the Idaho Chemical Processing Plant. A straddle-packer was successively deployed in four observation wells to monitor response of specific zones of the Snake River Plain aquifer to pumping from the INTEC production wells. Observation wells, identified as USGS-44, USGS-45, USGS-46, and USGS-59, were located 790–1,280 m from the production wells (CPP-01 and CPP-02) as shown in Fig. 2. Time-drawdown data from a total of 23 intervals in the four observation wells were used to evaluate a conceptual model of the aquifer and estimate aquifer properties.

In the area surrounding the INTEC, detailed core and geophysical evaluations have provided estimates of the spatial continuity of the major basalt flow groups and sediment interbeds (Anderson 1991). A hydrogeologic cross section through the area encompassing the pumping and observation wells described in this analysis is provided in Fig. 3. The basalt flow groups E through G and the I group are comprised of multiple individual basalt flows that are between 3–8 m thick (Anderson 1991). In contrast, basalt flows in flow group I tend to be thicker, in some cases exceeding 27 m. The E through G flow groups are separated from flow group I by a sediment layer deposited during volcanic quiescence. The effect of the sediment layer on vertical movement of groundwater is unknown. Similarly, the layered nature of multiple basalt flows is expected to provide some degree of impedance to vertical flow, but the magnitude is unknown.

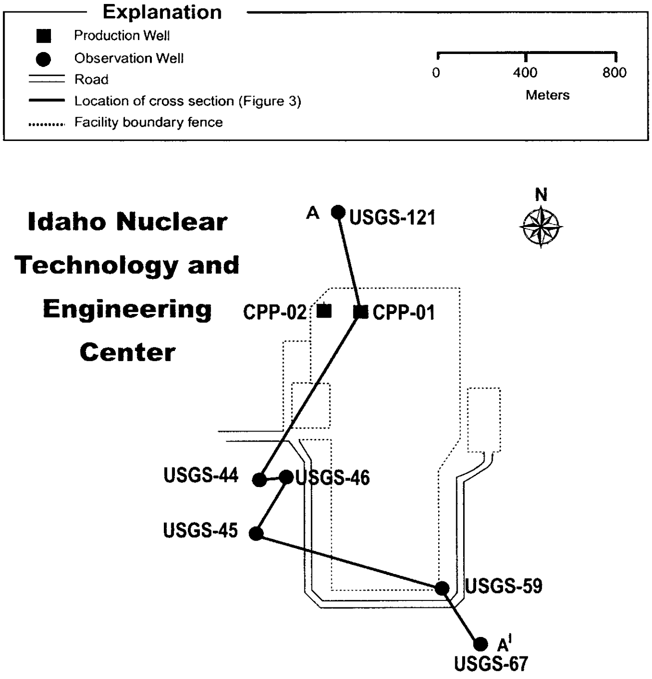


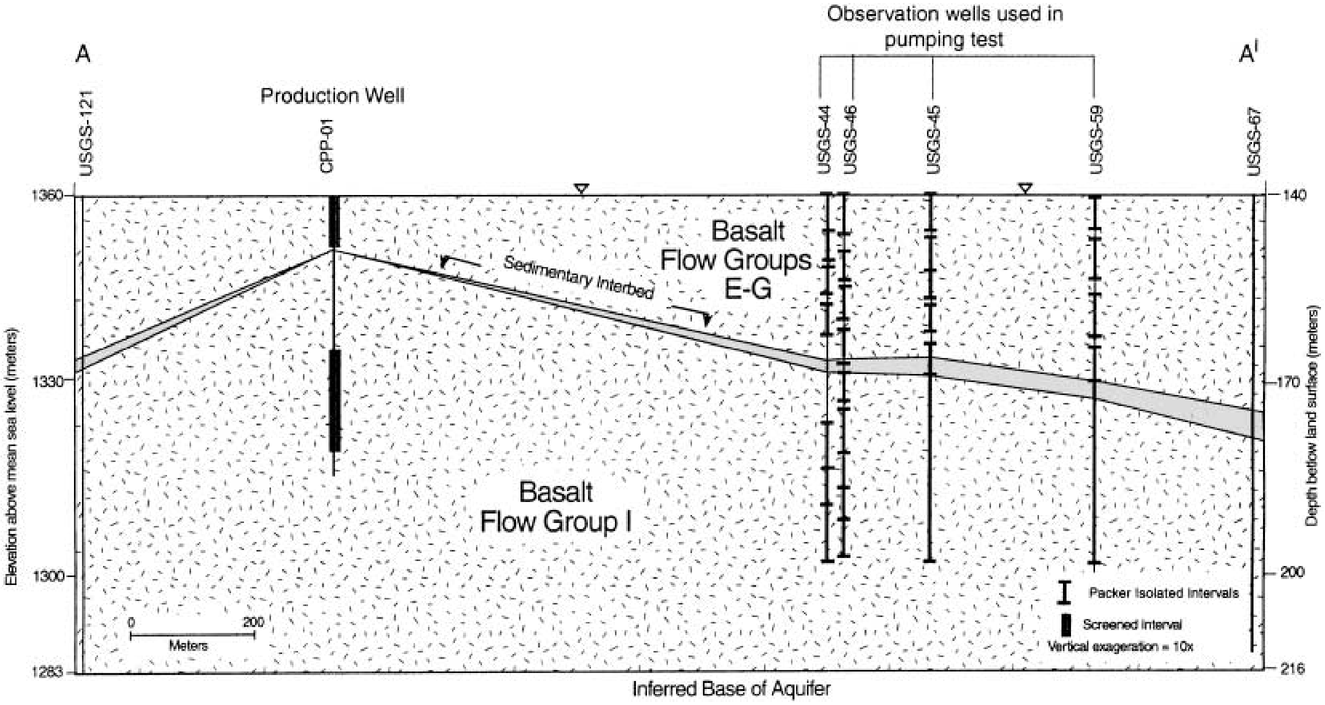
Fig. 2 Location of selected production and observation wells at INTEC

Fig. 3 Generalized geologic cross section of the aquifer at the INTEC. Observation wells have open hole construction below the water table, and CPP-01 is cased in intervals not shown as screened

Pumping Test Procedure

The four observation wells used in this investigation are cased near, or slightly below, the water table and are constructed as open holes for about 60 m, from the water table to the bottom of the well (Fig. 3). A straddle-packer was used to isolate intervals of the aquifer that were 4.6 to 6.1 m long. The two rubber packers were inflated at positions along the length of the open portion of the selected observation wells where video and caliper logs indicated a smooth borehole wall would provide an adequate packer seat. Pressure transducers were used to monitor hydraulic head above, within, and below straddled intervals that were 4.6–6.1 m long. Pressure readings were taken at frequencies as high as one per second, with a resolution of less than 2 mm, which is comparable to some of the smaller values of drawdown included in the analyses. With the exception of the deepest interval in each well (Fig. 3), only measurements from the middle transducer, between the inflatable packers were used for the pumping test analysis. This provided greater assurance that observed drawdowns were associated with a specific depth in the aquifer. More information on the straddle-packer system can be found in Frederick and Johnson (1996).

In order to evaluate drawdown in a total of 23 depth intervals in four observation wells, it was necessary to repeat the pumping test multiple times with the straddle-packer located at different intervals or wells in each repetition. The regular pumping cycle of the two INTEC production wells provided the opportunity for repetitive testing. The two wells are similarly constructed, pumped at a rate of 0.187 m^3/s in a continuous cycle of approximately 4 h on followed by 6 h off. The INTEC facility water requirements dictate periods of well operation that



cannot be significantly altered for the pumping test requirements. The two wells (CPP-01 and CPP-02) are not used simultaneously, but are used on monthly rotation. Because both production wells are of nearly identical construction and of similar distance and orientation to the observation wells (maximum radius difference of 7%), the analyses did not discriminate between the production wells. Production wells are screened in two intervals and terminate about 46 m below the water table (Fig. 3).

Numerical Model Description

RADFLOW, a finite-difference, axial-flow model (Johnson et al. 2001), was calibrated against pumping test data to evaluate alternative conceptual models and estimate aquifer hydraulic properties. Axial-flow assumes radial symmetry of flow and properties. Because radially symmetric variations in properties are not normally encountered, the model has been simplified to assume laterally homogeneous conditions.

An accompanying spreadsheet interface simplifies model construction and evaluation of results. Several simulation constants, such as grid and time discretization, are automatically computed based on entered aquifer characteristics and pumping test duration. The model will simulate up to 24 layers (an earlier version was used in the test described in this paper that accommodated more layers) with user-defined properties of thickness, vertical and horizontal hydraulic conductivity, specific storage, and specific yield. The user indicates which layers are being pumped and defines the total discharge rate. RADFLOW distributes the pumping rate to individual layers in proportion to the product of horizontal hydraulic conductivity and thickness of the layer. The model will treat confined and unconfined systems and provides for a moving upper boundary reflecting changes in water table elevation. No-flow conditions are established by RADFLOW along the upper, outer, and lower boundaries of the cylindrical domain as shown in Fig. 4. The outer boundary is established at a distance sufficiently far to have negligible effects on the drawdown in the observation wells. The lower boundary is located by the user at a depth believed to represent the lower limits of the flow system. The upper boundary is either established by an aquitard or the water table. The inside boundary corresponds to the radius of the pumping well and is represented by fixed flux (along open intervals) and no-flow conditions (because of symmetry) at depths identified as not being open between the well and aquifer. The user indicates locations of observation wells and RADFLOW produces and compares simulated time-drawdown data to observed values for the prescribed distances and depths. A more complete discussion of RADFLOW is provided in Johnson et al. (2001).

Analysis Procedure and Results

General Description

Time-drawdown data from each of the tested intervals of the four observation wells were collectively evaluated by application of the RADFLOW model. Pumping test data from each interval were compared to simulated drawdowns for conceptual models composed of one, two, and three layers. Time-drawdown data from wells USGS-44, -45, and -59 were less complete than those from well USGS-46, and, consequently, were assigned less weight in the calibration. Three conceptual models were evaluated because of the uncertainty regarding the hydrogeologic stratification associated with basalt flow groups. Model layers were established to approximate a sedimentary interbed, and thin (i.e., flow groups E–G) versus thick (i.e., flow group I) basalt flows. In each case, the aquifer properties of a layer were represented as homogeneous within the layer.

The total aquifer thickness was represented as a series of 41 model layers (Fig. 4). Most of the aquifer was simulated with model layers of 1.525 m thickness, however, model layers near the bottom of the aquifer (below the depth of observation wells) had thicknesses as large as 6.1 m. Each hydrogeologic layer was comprised of multiple model layers. Properties of all model layers within each hydrogeologic layer were assigned homogeneous values. The number of model layers was established to provide a reasonable representation of each of the conceptual models and allow simulation of drawdown at depths approximately corresponding to the many depths of observations. The model grid spacing in the radial dimension increased progressively away from the pumping well by a factor not exceeding approximately 1.5.

A common response was observed in each of the four observation wells. The time-drawdown plot of Fig. 5 shows less drawdown in shallow intervals (those immediately below the water table) than in deeper intervals. The characteristic “S” shape commonly attributed to delayed response of unconfined aquifers (Neuman 1974) was generally apparent in the deeper intervals. Although observed drawdowns were very small, less than 1 cm in some instances, they greatly exceeded the accuracy of the transducers (0.15 cm under static conditions) and the consistency of the observations from multiple intervals and multiple pumping cycles supports their credibility.

Simulated drawdown was generated by RADFLOW at radial distances from the pumping well corresponding to the distances of the observation wells, and at depths corresponding to the average depths of the intervals for the shallow (flow groups E–G) and deep (flow group I) zones identified from Fig. 3. Estimates of vertical and horizontal hydraulic conductivity, specific storage, and specific yield were adjusted by trial and error procedure to achieve a near best match to observed drawdown in multiple intervals for each conceptual model.

In each of the simulations the aquifer was assumed to extend from the phreatic surface to 76 m below the water table. A no-flow boundary represents the bottom of the

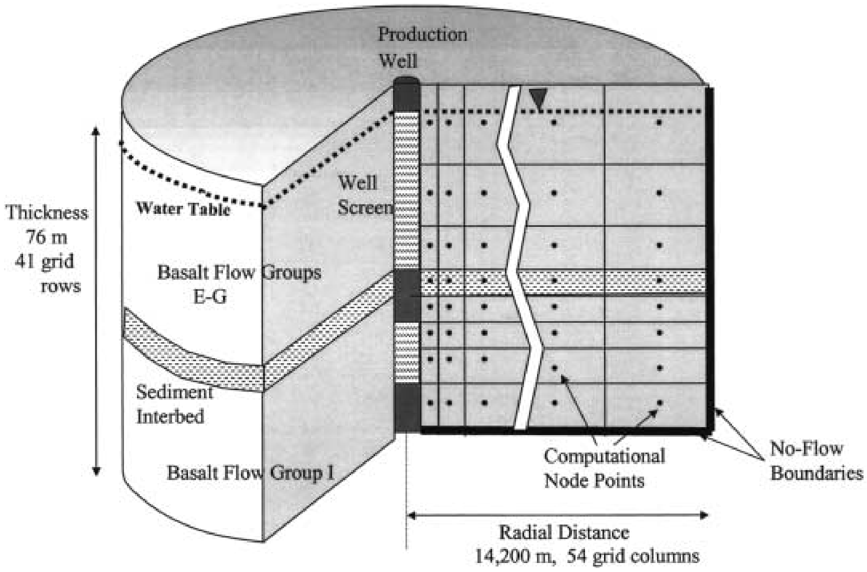


Fig. 4 Conceptual and numerical representation of the pumping test at the INTEC facility

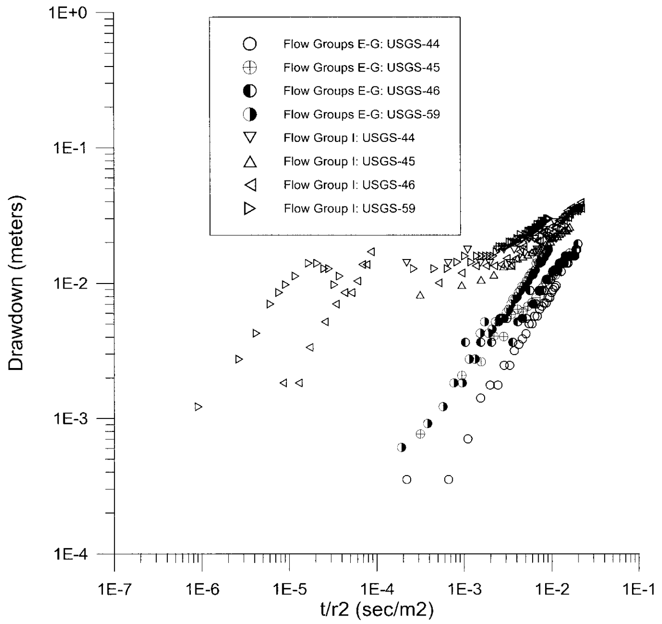


Fig. 5 Observed time-drawdown data in the principal stratigraphic units

aquifer about 30 m below the bottom of the production wells and 15 m below the bottom of the observation wells. The actual thickness of basalts is much greater; however, the permeability appears to decrease with depth (Mann 1986) and layering potentially decreases the vertical hydraulic conductivity (relative to horizontal) reducing the likelihood that deeper portions of the formation play a significant role in localized flow to the production wells. A no-flow outer boundary was established 14.2 km from the pumping wells: sufficiently distant that the boundary had negligible effects on drawdown in the observation wells. Negligible effects of the outer boundary were determined by evaluating sensitivity of drawdown to changes in boundary distance. The hydrogeologic layering defined in the model is represented throughout the model domain (the cylindrical section of the aquifer within the outer boundary). The hydraulic integrity of the layers, however, has a diminishing impact on drawdown at the observation wells as one progresses radially outward beyond the observation wells. This suggests that the developed conceptual models, and calibrated aquifer properties, are most representative of the region between the production and observation wells and probably should not be inferred to exist throughout the entire model domain represented by a cylinder with a 12-km radius.

Conceptual model development began with the most simplified model and progressed to more complex conceptual models. This procedure gradually expanded the understanding of the system and demonstrated the improvements in calibration that are achieved by the more complex representations. The one-, two-, and three-layer conceptual models are illustrated in Fig. 6.

Single-Layer Model

A single-layer, homogeneous, anisotropic (vertical hydraulic conductivity less than horizontal), and unconfined aquifer was the first representation of the system that was evaluated. The anisotropy in an unconfined system results in a delayed response in the deeper portions of the aquifer, such as discussed by Neuman (1974). The selected best match between simulated and measured drawdown resulted from a horizontal hydraulic conductivity of 1.2 cm/s, a vertical hydraulic conductivity of 0.005 cm/s, and a specific storage and specific yield of 4×10^{-7} m^{-1} and 0.01, respectively. Although the horizontal hydraulic conductivity may appear unusually large, it is comparable in magnitude (compensating for aquifer thickness) to results observed by Ackerman (1991) and other investigators. As shown in Fig. 7a, the simulation failed to adequately match early-time draw-

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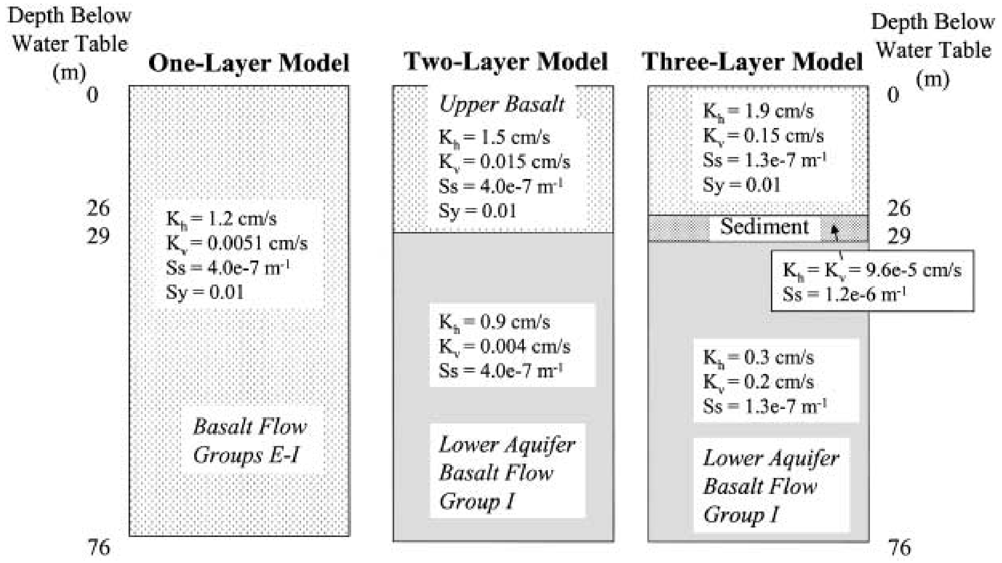

Fig. 6 Conceptual models and property estimates

down in shallow intervals and late-time drawdown in the deeper intervals. As a result, it was determined that a single layer did not adequately represent the system, so a two-layer conceptual model was developed.

Two-Layer Model

A two-layer model (Fig. 6), identical in total thickness and radial extent to the single-layer model, was evaluated to determine if a two-layer model provided a substantial improvement in simulating drawdown resulting from the pumping test. The layers were defined based on what appeared to be the most geologically distinct groups of basalt flows (Anderson 1991). The upper layer, consisting of thin basalt flows corresponding to flow groups E–G, is generally separated from the thicker basalt flows of the underlying I flow group by a sedimentary interbed. The hydrologic separation of these groups is evident from the distinct responses to pumping in the observation wells (Fig. 5).

Layer properties were initially estimated by matching time-drawdown data to Neuman type curves for unconfined aquifers (Neuman 1974). Average vertical and lateral hydraulic conductivities for the upper three intervals in well USGS-46 were used to represent the upper unit. Average values from the lower four intervals were used to represent the lower aquifer unit. Well discharge was simulated as withdrawn from both the upper and lower aquifers, in proportion to the hydraulic conductivity at depths corresponding to the screened interval (Fig. 4). Trial and error model calibration failed to significantly improve the match between measured and simulated values. Final estimates of layer properties are provided in Fig. 6. Specific yield and specific storage estimates were the same as those used in the single-layer model. As shown in Fig. 7B, these estimates failed to adequately represent the degree of separation apparent in the time-drawdown data between upper and lower zones, indicating a more complex model may be needed.

Three-Layer Model

The layers of the three-layer model conceptually correspond to the sedimentary interbed at the top of flow group I and the overlying and underlying aquifer units. A stratigraphic conceptual model of the three-layer system was formed from the generalized cross section of Fig. 3 and from information in drillers' logs and is presented in Fig. 6. The hydrogeologic significance of the sediment interbed was also apparent from the distinct response exhibited by transducers above or below this layer (Fig. 7). This concept was represented in the numerical model as three internally homogeneous layers. As with the two-layer model, well discharge was proportioned between upper and lower layers according to length of the screened interval and hydraulic conductivity of the respective layers. Vertical and horizontal hydraulic conductivity and specific storage were calibrated in each layer to visually achieve the best possible match to observed time-drawdown data. Specific yield of the single and two-layer models was found acceptable for the three-layer model as well. Values are presented in Fig. 6.

Comparisons of the simulated and observed response for observation wells USGS-46 and -59 are shown in Fig. 8. Early time data from well USGS-46 in the upper aquifer exhibited the poorest match between simulated and measured values. Drawdown at early time in the upper intervals of this well was greater than predicted by the numerical model. It is believed that this departure is associated with leakage around the packers or complexities of the real system that are not represented in a three-layer model, which portrays each layer as having uniform hydraulic properties and thickness.

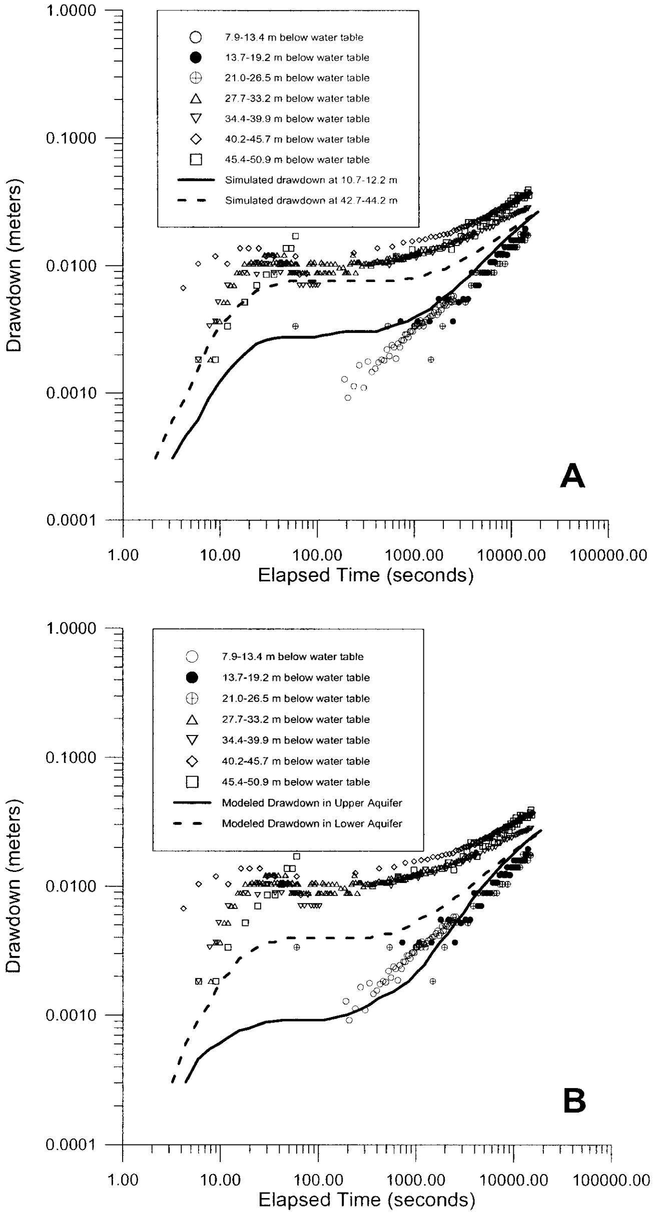

Fig. 7A, B Simulated drawdown versus observed drawdown in USGS-46. **A** One-layer model; **B** two-layer model

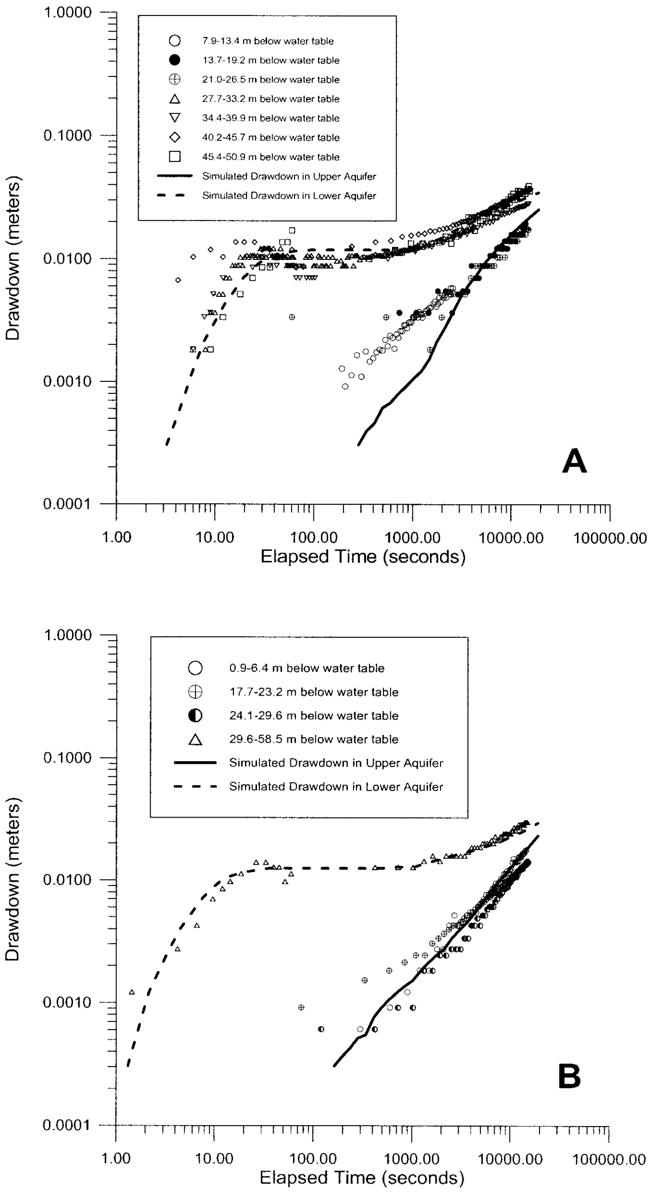

Fig. 8A, B Simulated drawdown with the three-layer model versus measured drawdown in the observation wells. **A** USGS-46; **B** USGS-59

The effects of uncertainty in aquifer thickness were evaluated through sensitivity analysis of the three-layer model. Changes in aquifer thickness, ranging from 50 (approximate completion depth of the production wells) to 120 m, impacted the magnitude of drawdown in the lower layer, but did not substantially affect the shape of the time-drawdown curves. Misrepresentation of aquifer thickness may result in errors of parameter estimates, mostly hydraulic conductivity, but do not alter the basic conceptual model.

Conclusions

The one- and two-layer models produced similar estimates of specific yield and specific storage (Fig. 6). Horizontal and vertical hydraulic conductivity of the single-layer model were within the range evaluated for individual layers of the two-layer system. The two-layer model produced the best match to measured data when the upper layer was simulated with hydraulic conductivity values greater than those of the lower layer.

The three-layer model was visually judged to produce the best fit to observed data (Fig. 8). It is believed that this results from an improved representation of the real system and from a greater number of parameters being adjusted during the trial-and-error calibration process. Layers were established to represent idealized geologic units: one above the sedimentary interbed at the top of flow group I, the sedimentary interbed itself, and one below the interbed. These units were explicitly represented in the numerical model. The specific yield and specific storage of the one- and two-layer models were determined to be acceptable for all layers of the three-layer model through trial and error calibration. Horizontal and vertical hydraulic conductivity estimates were greatest for the upper layer and orders of magnitude smaller for the unit representing the sediment interbed, indicating the potential confining nature of this unit. It is expected that the estimated values of hydraulic conductivity represent an average value for the modeled hydrogeologic units, and that most of the flow is concentrated in basalt flow contacts that will have larger values of hydraulic conductivity than the estimated values. The hydraulic conductivity estimates are not unreasonable relative to results from other tests of the Snake River Plain aquifer. Uncertainty of aquifer thickness does affect estimates of aquifer properties, but does not alter the basic conceptual model.

This analysis was based on the combined data of pumping tests from 23 depth intervals from four observation wells. Evaluation of quantitative estimates of horizontal and vertical hydraulic conductivity, specific storage, and specific yield were definitely valuable; however, the greatest benefit of the analysis has probably been the advancement of the conceptual model. Previous geologic investigations have documented the geologic stratification of the system; however, the understanding of the hydrologic significance of the geologic units has not been well understood. The estimated four orders of magnitude difference in hydraulic conductivity of the sediment layer relative to the upper and lower units implies that this interbed may partially impede vertical flow in the system. Although this conclusion cannot necessarily be applied throughout the aquifer, it does indicate that similar sedimentary interbeds may warrant special consideration, particularly when modeling contaminant transport.

The use of a numerical model in this analysis provided several advantages over analytical techniques. The numerical model is better able to represent the layered conceptual model of the system, thereby taking better advantage of the geologic knowledge already developed for the system. The numerical model allows the user to easily formulate different conceptual models and use pumping test response to improve insights into the conceptual nature of the system. Although the trial and error process educates the user on the sensitivity of the models to different aquifer properties, the application of inverse models or parameter estimation routines can provide additional and quantitative insights into parameter correlation and non-uniqueness. The RADFLOW model has been used with the PEST (Doherty 1998) parameter estimation software in a similar application described in Johnson et al. (2001). Finally, the use of numerical models does not constrain the hydrologist to the many conceptual assumptions of analytical techniques. The final model developed for the Snake River Plain aquifer included three layers, anisotropic in the vertical plane, partially penetrating pumping and observation wells, and unconfined (delayed yield) conditions, and the simulation model resembled generalized geologic interpretations of the area.

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