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Evaluation of the Use of Fracture-Flow Solutions to Analyze Aquifer Test Data Collected from Wells in the Eastern Kentucky Coal Field

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Abstract

The Eastern Kentucky Coal Field, which is part of the Appalachian Coal Field, is characterized by argillaceous sedimentary rocks that yield low quantities of groundwater. Most large yields are related to a complex array of secondary permeability features that include shallow and tectonic fracture sets and transmissive coal units. Porous interbedded sandstones provide storage and are transmissive as well.

A study was undertaken to evaluate the use of published, double-porosity fracture solutions and single-vertical and -horizontal fracture solutions to analyze drawdown data collected from five aquifer tests located at three sites in the Eastern Kentucky Coal Field. Linear-feature analysis was used to select the location of each tested well, and the wells were completed as open holes that contained fractures. The aquifer tests were conducted on the entire open interval of each well, and ranged in duration from 5.3 to 12.7 hours. Drawdown and recovery measurements were collected from producing and observation wells. For comparative purposes, this study applied confined, leaky, and unconfined conventional well-flow solutions to the collected aquifer test data.

Because a characteristic double-porosity curve was not observed in any of the collected drawdown data, the double-porosity solution was found to be inappropriate for any of the five analyzed aquifer tests. Single-fracture solutions were found to be appropriate to all five of the analyzed aquifer tests. Because of insufficient observation-well data, and because aquifer tests were conducted over multiple water-producing fracture zones, the single-fracture solutions could not be used in this study to infer the geometry of the encountered fracture zones. For three of the five analyzed aquifer tests, the collected observation-well drawdown data fit a leaky-aquifer solution, which assumes no storage in the aquitard; this suggests that the observation wells were connected to the pumping well via a network of fractures. The unconfined-aquifer assumption proved inappropriate for all of the analyzed aquifer tests. Overall, the transmissivity, hydraulic conductivity, and storativity values determined from the single-fracture solutions and confined and leaky conventional well-flow solutions were very consistent for individual sites, suggesting that each of the applied solutions produced reasonable estimates of these parameters for the analyzed wells. For all sites tested, the mean transmissivity, hydraulic conductivity, and storativity were 1.4×10^{-1} ft^2/min, 3.9×10^{-2} ft/min, and 3.9×10^{-4}, respectively.

Introduction

Conventional well-flow equations used to analyze aquifer test data are thought to be inadequate to describe groundwater flow through fractured rocks. Applying these well-flow equations to aquifers that have flow through both the rock matrix and fractures can produce misleading results, causing the aquifer properties to be either overestimated or underestimated (Gringarten, 1982). According to Kruseman and De Ridder (1994), conventional well-flow equations can only be used in very low-permeability rocks where the fractures are numerous enough and evenly distributed throughout the aquifer. In this case flow will occur through the fractures and will be similar to that in an unconsolidated homogeneous aquifer.

Well-flow equations have been developed to take into account ground-water flow in fractures. With these equations, the drawdown data collected from a aquifer test can be analyzed to characterize the properties of the fractured aquifer A review of the published literature indicates that well-flow equations based on two conceptual models, double-porosity and single-fracture, are applicable to ground-water flow in the fractured sandstone aquifers of the Eastern Kentucky Coal Field. Yet, according to published literature, neither the double-porosity nor single-fracture solutions have been applied to aquifer-test data collected from wells in the region.

The goal of this study was to assess the viability of using double-porosity and single-fracture solutions to analyze the aquifer test data collected from five wells at three sites in the Eastern Kentucky Coal Field. This assessment was conducted by completing the following tasks: (1) the double-porosity and single-fracture solutions were applied to the drawdown data collected from the pumped and observation wells at the three sites, (2) conventional well-flow solutions were applied to the drawdown and recharge data collected from the pumped and observation wells, and (3) the aquifer values determined from the fracture solutions were compared to the values determined from the conventional-well flow solutions (Andrews, in review). The preliminary findings of this study are presented in this paper.

Regional Geology and Hydrogeology

The Eastern Kentucky Coal Field is part of the Appalachian Coal Field, which extends from Pennsylvania to Alabama. The coal field is a large, intricately dissected upland characterized by narrow, crooked valleys and narrow, irregular, steep-sided ridges. Most of the smaller creeks have narrow valley floors, whereas larger streams have floodplains of moderate width. Local relief increases from 300 ft in the north near the Ohio River to about 2,500 ft in the south along Pine Mountain, near the Tennessee-Kentucky border (Price and others, 1962).

More than 90 percent of the bedrock underlying the coal field belongs to the Late to Middle Pennsylvanian Breathitt Group. These rocks consist of shale, siltstone, argillaceous and lithic sandstone, coal, and some thin limestones. The distribution of these rock types varies both laterally and vertically because of the complex depositional setting of the coal field (Chesnut, 1992).

Superimposed on the strata of the coal field is a network of shallow and tectonic fractures set that control shallow ground-water flow (Ferguson, 1967; Wyrick and Borchers, 1981; and Kipp and Dinger, 1991). Kipp and Dinger (1991) observed shallow fractures in a valley bottom that had both vertical and horizontal (bedding plane) orientations.

Constant-head pressure-injection tests have determined that coals and fractures are the most permeable units in the coal field. The mean hydraulic conductivity of coals and fractures were 2.2×10^{-4} ft/min and 1.6×10^{-3} ft/min, respectively. Sandstones have a mean hydraulic conductivity of 2.7×10^{-5} ft/min (Andrews and others, in review).

Site Descriptions

This study analyzed aquifer tests that were conducted on five wells at three sites near the villages of Hitchins, Isom, and Jackson within the Eastern Kentucky Coal Field. One of the analyzed wells was at the Hitchins site (well H-1), another at the Isom site (well I-1), and three were at the Jackson site (wells J-1, J-2, and J-3). The depth of the wells ranged from 62 to 142 ft. All wells were drilled in a valley bottom, located using linear-feature analysis, completed as open holes, and contained fractures (Dinger and others, 2002). Lithologies and fractures in each well were identified from an analysis of drill cuttings and down-hole camera surveys.

All aquifer tests were conducted on the entire open interval of each well and ranged in duration from 5.3 to 12.7 hours. The pumping rates ranged from 3.7 to 64 gal/min. Drawdown and recovery measurements were collected from producing and observation wells. The distance between observation wells and producing wells ranged from 81 to 370 feet. Two observation wells were used at the Jackson site, but only one observation well each was used at the Hitchins and Isom sites.

Methods of Aquifer Test Analysis

The drawdown aquifer test data collected from the five wells were analyzed using seven fracture solutions. Three of the solutions assume a double-porosity system (Warren and Root, 1963; Kazemi and others, 1969; and Bourdet and Gringarten, 1980). Three of the solutions assume a single-vertical fracture system (Gringarten and Witherspoon, 1972; Gringarten and Ramey, 1974; and Ramey and Gringarten, 1976). One solution assumes a single-horizontal fracture system (Gringarten and Witherspoon, 1972).

For comparative purposes, four conventional, nonfracture well-flow solutions were applied to the collected drawdown and recovery data. Three of the solutions assume a confined and unconfined aquifer (Theis drawdown, Theis recovery, and Hurr-Worthington) (Kruseman and De Ridder, 1994), and one solution assumes a leaky aquifer with no storage in the aquitard (Hantush and Jacob, 1955).

Summary and Conclusions

The double-porosity solution was not appropriate for any of the five analyzed aquifer tests. Even though multiple water-producing fractures and sandstones were encountered in wells J-1 and J-2 at the Jackson site, no double-porosity curve was observed in the drawdown data collected from these tests. If double-porosity solutions were applied to the collected drawdown data, assuming the data represented early pumping times, the calculated values (transmissivity, storativity, and hydraulic conductivity) would be the same as those calculated from conventional, nonfracture well-flow solutions (Kruseman and De Ridder, 1994). The double-porosity solutions were not appropriate for wells H-1, I-1, and J-3 because each well intersected discrete water-producing fracture zones. Coal seams were observed in wells H-1 and I-1 during the drilling process, but significant groundwater was not encountered until the fracture zones located beneath the coal seams were intersected. Similarly, a weathered sandstone encountered in well J-3 did not produce significant groundwater.

Even though the single-fracture solutions were appropriate for all five analyzed aquifer tests, these solutions could not be used to infer the geometry of the encountered fracture zones. Wells J-1 and J-2 intersected multiple water-producing zones and possible water production from coal seams. Because the aquifer tests for these wells were conducted over the multiple water-producing zones, no attempt was made to use these solutions to infer the geometry of the encountered fracture zones. Wells H-1, I-1, and J-3 intersected discrete water-producing fracture zones. Because there was no observation well data for the analysis of well H-1 and observation well data from one well for the analysis of well I-1, the single-fracture solutions could not be used to infer the geometry of the encountered fractures. Gringarten and Witherspoon (1972) recommended that drawdown data collected from two or more observation wells be used in order to use the single-fracture solutions to infer the geometry of a fractured aquifer. Even though the analysis of well J-3 was completed using observation data collected from two wells, there was no definitive match of the drawdown data to the single-fracture type curves.

In this study, the single-fractures solutions were only used to estimate the transmissivity, hydraulic conductivity, and storativity of the discrete water producing fractures encountered in wells H-1, I-1, and J-3. Because wells J-1 and J-2 contained multiple water-producing zones and possible water production from coal seams, the single-fracture solutions were only used to estimate transmissivity and storativity of the entire well and to speculate on the hydraulic conductivity of the water-producing intervals.

In order to better assess whether the single-fracture solutions are appropriate to infer the geometry of the encountered fractures, additional aquifer tests of longer length, using more observation wells, should be conducted on the tested wells. Longer tests with more observation wells would yield more drawdown data to compare to the single-fracture type curves. Additional observation wells would also be helpful in mapping the extent of the encountered fractures. For the best results, the water-producing intervals encountered in each well should be isolated with a packer, and the additional aquifer tests should be conducted on the isolated zones.

This study found that the unconfined aquifer solution was inappropriate for four of the five analyzed aquifer tests. Analysis of wells I-1, J-1, J-2, and J-3 resulted in specific yield values that did not fall within the typical range for unconfined aquifers, as cited by Freeze and Cherry (1979). Because no observational well data were available for the analysis of well H-1, we could not determine the appropriateness of the unconfined aquifer solution for this well.

Of the applied conventional well-flow solutions, the Hantush and Jacob (1955) solution, which assumes a leaky aquifer, fit best with all observation-well data collected from the aquifer test of wells J-1 and J-2 and observation data collected from one well during the aquifer test of well J-3. The National Research Council (1996) suggested the leaky-aquifer model for an aquifer consisting of a single-horizontal fracture bounded by a rock mass that is either permeable or contains a network of smaller fractures. For pumping well J-3, which intersected a single water-producing fracture zone, the fit of this leaky solution suggests that the one observation well is connected to the pumping well via a network of fractures. This conclusion is consistent with the fracture geometry described by Ferguson (1967), Wyrick and Borchers (1981), and Kipp and Dinger (1991), who have documented a close network of fractures in valley bottoms of the Appalachian Coal Field. For pumping wells J-1 and J-2, which intersected multiple water-producing zones (fractures and sandstones), the fit of this leaky solution suggests that the observation wells are connected to the pumping wells via a network of fractures. Because multiple water-producing zones were encountered in pumping wells J-1 and J-2, however, additional aquifer tests must be conducted on each water-producing zone in order to verify the applicability of the leaky-aquifer model to describe the fracture geometry between these pumping and observation wells.

Analysis of the aquifer tests of wells H-1, I-1, and J-3 using the confined and leaky conventional well-flow solutions yielded transmissivity, hydraulic conductivity, and storativity values that were similar to those determined from the single-fracture solutions. The hydraulic conductivity values determined from these analyses were consistent with hydraulic conductivity values estimated for fractured rocks of eastern Kentucky, and support the initial assumption that water from these wells was produced from discrete fracture zones. For wells J-1 and J-2, the estimates of transmissivity and storativity determined from the single-fracture solutions were found to be similar to the transmissivity and storativity values determined from the confined and leaky conventional well-flow solutions. Because of the overall consistency in hydraulic conductivity, transmissivity, and storativity values at individual sites, we conclude that the single-fracture solutions and conventional well-flow solutions produced reasonable estimates of these parameters for the analyzed wells. For all sites tested, the mean transmissivity, hydraulic conductivity, and storativity were 1.4×10^{-1} ft^2/min, 3.9×10^{-2} ft/min, and 3.9×10^{-4}, respectively.

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Biographical Sketches

Robert E. Andrews received a B.A. degree in geology from the College of Wooster, Wooster, Ohio in 1990 and is currently completing an M.S. degree in geology with specialization in hydrogeology at the University of Kentucky. Robert has been an employee of the Kentucky Geological Survey since 1992. Currently, he works in the Water Resource Section of the Survey as the principal investigator on a project using remote-sensing and drilling techniques to locate high-yield water wells in the Eastern Kentucky Coal Field.

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