MODFLOW….NOT: A Simple But Effective Solution to a Regulatory Question

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ABSTRACT

Coal Bed Methane development in the San Juan Basin of Colorado has raised concerns as to whether water produced from the gas-producing coal formation results in stream depletion necessitating regulation. Accordingly, the Colorado Oil and Gas Conservation Commission and the Colorado Division of Water Resources commissioned a study to evaluate stream depletions, specifying that the Glover-Balmer model (1954) be used. Given the geologic configuration of the basin and the fluid withdrawal characteristics, the question was also posed as to whether this methodology, given its simplicity, could be reasonably applied to assess the general magnitude of stream depletion within a regulatory framework.

Key elements of the hydrogeologic setting were incorporated into a simplified conceptual model that could be simulated using the Theis analytical model. Pressure changes simulated with the Theis model, given historic water production rates, were compared to pressure change observations to evaluate whether a simplified model could capture the general nature of system behavior. For regions where the comparison suggested that the method was reasonable, parameters derived using an automated parameter estimation procedure (PEST, Watermark, 2004) were utilized in the Glover-Balmer analysis to obtain a first-order approximation of surface water depletions at the coal formation surface outcrop. The outcrop was considered as the "stream" boundary, capturing the combined depletion to streams traversing the outcrop, springs, seeps and water-table storage within the outcrop.

This approach produced good results, both in terms of fit to observed data, and in comparison with results from far more complex numerical models. The reasons for this include:

- Using PEST to optimize parameter selection removed user bias from the process;
- The recharge boundary was configured to capture outcrop features relevant to the stream depletion analysis.

This work reminds us that simple techniques can provide useful results in complex systems, as long as key system factors are identified and represented.

INTRODUCTION

The San Juan Basin is a productive source of coalbed methane (CBM); in conjunction with the production of CBM is the production of water. A Colorado Oil and Gas Conservation Commission (COGCC) database of monthly CBM gas and water production for all wells in the basin from 1985 indicates that, through July 2005, more than 4.2 trillion cubic feet of gas and 400 million barrels (52,000 ac-ft) of water have been produced from CBM wells in the San Juan Basin in Colorado. The annual rate of gas production is continuing to rise and is projected to be above 450 billion cubic feet in 2005. Annual water production peaked in 1993 at nearly 34 million barrels (4,300 ac-ft) and has been relatively steady at close to 23 million barrels (3,000 ac-ft) since.

Because CBM water production could potentially result in stream depletions or reductions in spring flows that could impact water rights holders, a stream depletion analysis of present and projected impacts was commissioned. The study team was directed to apply the Glover-Balmer analytical method, although the team was given discretion to comment at the conclusion of the analysis on method utility and limitations. Additionally, the Division of Water Resources desired a delineation of the spatial area within which calculated stream impacts would exceed one tenth of one percent of the pumping rate following 100 years of pumping, a statutory criteria utilized in identifying areas subject to augmentation requirements when water is applied to beneficial use.

HYDROGEOLOGIC SETTING AND CONCEPTUAL MODEL

CBM in the San Juan Basin is produced primarily from the coals in the late Cretaceous Fruitland Formation. The Fruitland Formation and the adjacent Pictured Cliffs Sandstone, informally referred to as the Fruitland-Pictured Cliffs aquifer, are the source of the CBM produced water. The Fruitland-Pictured Cliffs aquifer is bounded to the north by a well-delineated outcrop of its component formations. The maximum elevation of the aquifer occurs approximately 10 miles east of Durango, where the formations crop out at an elevation of approximately 9,000 feet above msl. Along much of its outcrop reach in Colorado, Fruitland-Pictured Cliffs strata dip steeply southward towards the central portion of the San Juan Basin. Within a few miles, dips flatten and the Fruitland Formation dips to a minimum elevation of approximately 4,000 ft above msl in northern New Mexico.

As proposed by Kaiser et al. (1994), the Fruitland-Pictured Cliffs aquifer system consists of the more permeable Fruitland Formation coal seams and upper Pictured Cliffs sandstone tongues, confined between much less permeable shales and sandstones. Because of the sealing nature of the non-coal strata in the Fruitland Formation and the low permeability Kirtland Shale, the Fruitland-Pictured Cliffs aquifer transitions from an unconfined water table aquifer to a confined aquifer very rapidly in a basinward direction from its outcrop. Within the Fruitland Formation, porosity and permeability are greatest within the cleats of the coal seams. In addition to the coal seam permeability, fractures in the shales and sandstones that are adjacent to the coal seams are believed to provide local pathways for groundwater flow between the Pictured Cliffs Sandstone and the Fruitland Formation coal (Questa, 2000).

Permeabilities within the Fruitland-Pictured Cliffs aquifer are low. The distribution of permeability used in previous models (AHA, 2000; Questa, 2000) ranges from less than 1 millidarcy (md) in the central portion of the basin near the New Mexico border to greater than 100 md in some areas. A review of shut-in test results provided to COGCC between 2001 and 2005 reported permeabilities that ranged from 0.11 to 112 md, with most values falling below 10 md.

Several streams cross the outcrop of the Fruitland Formation, including the Animas River, the Florida River, the Los Pinos River and the Piedras River. Alluvial deposits associated with these streams, and enhanced permeability of the Fruitland along the outcrop, support the occurrence of recharge along the outcrop and a shallow flow system from recharge areas to the streams.

For this study, a conceptual hydrogeological model was adopted, similar to those of previous numerical modeling studies, which included the following features:

- Recharge flows from the outcrop areas to adjacent streams and to the basin aquifer;
- Flow in the basin aquifer is primarily through the Fruitland-Pictured Cliffs aquifer;
- Flow is severely restricted within the Fruitland-Pictured Cliffs aquifer as a result of the very low permeability of these strata, even within the coal seams;
- Flow within overlying or underlying formations is even further restricted, with virtually impermeable adjacent formations; and,
- Despite the very low permeabilities and local separations between coal seams comprising flow paths, in the aggregate, there is hydraulic communication within the Fruitland-Pictured Cliffs aquifer and between this aquifer and the streams where they traverse the outcrop areas.

METHOD FOR DEPLETION ANALYSIS

The Glover-Balmer (1954) depletion analysis is premised on several idealizations regarding aquifer conditions and geometry. There exist few natural environments that fully satisfy idealizations such as these; however, through careful configuration and application of the model, the error associated with divergence from the ideal case can be minimized. The idealizations inherent in the Glover analysis and comments regarding the application of the method to the San Juan Basin are provided below:

- *The aquifer is homogeneous, isotropic, and of semi-infinite extent*. Previous studies and the results of production well transient pressure tests have indicated that permeabilities for the Fruitland Formation coals vary, from areas with greater than 100 md in the Fairway and along the outcrop to less than 10 md in mid-basin areas. For this study, average parameters were required to approximate the aggregate behavior caused by spatially distributed parameters. This was accomplished through parameterization of a similarly idealized model of historic production, with the aid of an automated parameter estimation procedure (PEST).

- *The boundary at which depletions are calculated is a linear stream that fully penetrates the aquifer*, *where the streambed is in hydraulic connection with the aquifer*. The model geometry must be set up to best approximate this assumption, given the hydrogeologic setting. Because the primary streams cross the outcrop orthogonally, and are not well-connected to the aquifer except at the outcrop; and, because the outcrop is "stream-like" given both its storage capacity orders of magnitude greater that that of the confined aquifer and the enhanced permeability of the outcrop zone, the arc of the outcrop is taken as the constant-head boundary, or, "stream", for this analysis. No significant barriers between the CBM wells and the outcrop were identified that would negate an assumption of hydraulic connection from the wells to the streams at the outcrop.

- *Flow within the aquifer is horizontal*. Due to the sealing nature of adjacent formations, vertical flow to/from overlying or underlying formations is considered negligible and flow occurs primarily within the Fruitland-Pictured Cliffs aquifer; hence, this idealization is not considered problematic.

- *Flow is dominated by one phase*. This method only considers one-phase flow. Where water extraction and pressure changes dominate the flow regime, this assumption is acceptable. Where gas pressures dominate the flow regime, this method will not yield useful results.

Parameter Estimation

The Glover-Balmer method required identification of a single value for transmissivity and storage coefficient. Understanding that there is significant localized heterogeneity, effective average formation parameters were identified through parameter estimation techniques using an analytical model that employs the same simplifying assumptions as does the Glover analysis. The advantage of this method is not only that derived parameters reflect the history of well production rates throughout the basin and observed pressure changes at numerous monitoring wells, but also that the derived parameters are consistent with the modeling methodology to be employed. In other words, parameters obtained via history-matching using an idealized model will be applied in a similar idealized model. The resulting parameters are "effective averages" that take into account both the observed data and the model idealizations with respect to geometry, homogeneity and other simplifying assumptions.

Estimation of transmissivity and storage coefficient for the Fruitland Formation involved five primary areas of analysis. First, observation data were obtained and formatted for use in model calibration. Second, water production data from over 1,600 wells was obtained and formatted for use as model input. Third, a Theis analysis code was configured to calculate drawdown from historic pumping schedules. The analysis uses monthly production rates for each well to calculate pressure impacts over time at monitoring locations, and superimposes cumulative pressure impacts spatially and through time. Fourth, PEST was set up to optimize the fit between the Theis code calculated drawdown and the formatted observation data. Fifth, the model was calibrated to the observation data using PEST.

For the Theis analysis, model runs were made both with and without image wells. Image wells are required in situations where calculated draw-down impinges on boundary conditions. Since, a priori, the appropriate application for the San Juan Basin was unknown, both scenarios were run. For the image well analysis, each production well was matched with an image well located an equal distance from the Fruitland outcrop to the outside of the outcrop, injecting water at monthly rates equal to the production well pumping.

This analysis resulted in a transmissivity of 1.2 ft^2/day and a storativity of 3.1×10^{-4} for the northern portion of the San Juan Basin. If a range of net coal thickness of 20 to 100 feet is assumed, hydraulic conductivity falls in the range of 0.012 to 0.06 ft/day, which is equivalent to a permeability of 4.4 to 21 md. This range lies within that identified in the previous model investigations, but provides a parameter value that is specifically tailored to the simplified hydrogeologic assumptions inherent in the methodology identified for the depletion analysis. For the same range of coal thickness, specific storage falls in the range of 3.1×10^{-6} to 1.6×10^{-5} ft^{-1}. Previous numerical modeling studies (AHA, 2000; Questa, 2001; Cox et al., 2001) utilized 1×10^{-5} ft^{-1} for specific storage.

In the analysis described above, the Fruitland-Pictured Cliffs aquifer parameters derived for the northern area of the San Juan Basin provided a reasonable match to observed pressure responses at wells in the northern part of the basin; however, the same values did not provide a satisfactory match to the pressure response in another area, termed the “Ute” or “Fairway” region (S.S. Papadopulos & Assoc., 2006). Data indicate that gas saturation is higher and water saturation lower in this area. Use of a one-phase flow model may not be suitable for modeling pressure changes in this region.

Glover-Balmer Depletion Analysis

Using the optimized values of transmissivity and storativity obtained from the parameter estimation analysis, the Glover analysis was applied to CBM wells within the Colorado portion of the San Juan Basin to identify the area where stream depletions exceed one tenth of one percent of pumping within 100 years; and, to quantify current and future depletions at the streams/outcrop. The method was not applied to the highly productive Fairway region where the Fruitland-Pictured Cliffs aquifer may not be water saturated. To estimate depletion in this area, a different methodology would be required. The well pumping rate, pumping schedule and distance from each well to the constant-head boundary are required for the analysis. The water production history for the existing 1,686 San Juan Basin production wells was utilized for this purpose, along with projected production rates developed in concert with the contracting agencies. An average production period of 10 years was assumed in calculating stream depletion for the existing and projected future condition.

RESULTS

The area where stream depletions exceed one tenth of one percent of pumping within 100 years generally includes the area within about 10 miles of the outcrop. The analysis was not extended to the west, in the vicinity of the Fairway. However, it is recognized that most CBM wells have a production life significantly less than 100 years, a factor that will presumably be given some consideration in regulation, should the CBM-produced water be put to beneficial use.

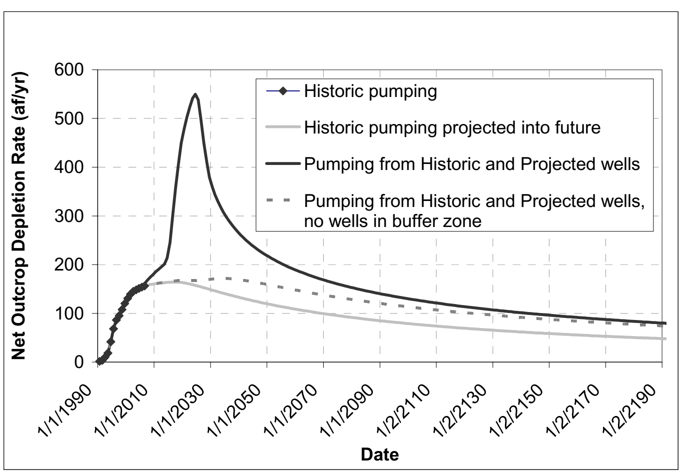

Figure 1. Calculated depletions to outcrop/stream boundary from CBM water production

To estimate the current magnitude of depletions, the Glover analysis was run using records of monthly water production rates to solve for basin-wide depletions at the Fruitland outcrop/stream location. The composite rate of depletion for all Colorado wells was calculated at 156 ac-ft/yr as of mid-2005. This quantity does not differ greatly from the depletions calculated in the previously developed numerical models—95 to100 ac-ft/yr for projected for 2005 for the Animas, Florida, and Los Pinos Rivers (Cox et al., 2001), particularly given that those models did not include the entire CBM production area.

Various projections of future impacts were made, considering a continuation of historic pumping until the end of production cycles, additional infill drilling, and additional infill drilling excluding drilling in a buffer zone within 1.5 miles of the outcrop (Figure 1). These projections provide a general indication of the degree of stream/outcrop depletions occurring or likely to occur, from CBM produced water. Some shift in timing may be associated with the conceptualization of stream depletion occurring at the stream/outcrop boundary, given that impacts to the water table region of the outcrop will be lagged prior to being manifested at the stream.

DISCUSSION

While the hydrogeologic setting of the San Juan Basin does not immediately suggest the suitability of an idealized model for hydrologic analysis, by identifying and capturing key system features in the analysis, a useable estimation of stream depletion has been developed. The key features that were incorporated included both "effective" boundaries and "effective" aquifer parameters. By recognizing that the outcrop functions as a "stream-like" boundary, and using the outcrop trace rather than orthogonally-located stream traces as the constant-head boundary for the solution; and, by identifying aquifer parameters through a calibration process involving an extensive production database and pressure observations within a similarly idealized model structure, the simple Glover solution was customized for application to a complex setting.

Given that a general correspondence of observed and simulated pressure values was achieved in calibration for the northern part of the basin, and, that model results were "in the ballpark" of those obtained with more detailed numerical models, this exercise demonstrates an acceptable application of a simple, idealized method, in a fairly complex hydrogeologic setting. However, the methods were not immediately successful for the Fairway region; in this case, additional analysis and likely an alternate method is needed. Regardless, this exercise reminds us that idealized analytical methods can be productive, particularly for a first-order indicator of general conditions.

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