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Dear Ms. Peek

This letter constitutes my review of USGS SIR 2011–5029 as you requested on Thursday, April 26, 2012

Sincerely,

Eileen Poeter

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REVIEW OF GROUNDWATER MODEL PRESENTED IN USGS SIR 2011–5029

PURPOSE

The purpose of this letter is to review the model presented in USGS SIR 2011–5029 (Christenson et al., 2011) with respect to its applicability for determining acceptable volumes of groundwater withdrawal from the Eastern Arbuckle-Simpson aquifer. The USGS SIR 2011–5029 report (Christenson et al., 2011) will be referred to as the report. The model presented by Christenson et al. (2011) will be referred to as the model or the MODFLOW model in this letter.

Christenson, Scott, Osborn, N.I., Neel, C.R., Faith, J.R., Blome, C.D., Puckette, James, and Pantea, M.P., 2011, Hydrogeology and simulation of groundwater flow in the Arbuckle-Simpson aquifer, south-central Oklahoma: U.S. Geological Survey Scientific Investigations Report 2011–5029, 104 p.

INTRODUCTION

The report provides information on long-term average stream flow depletion and 75 percent exceedance (25th percentile) of stream flow in response to groundwater withdrawals distributed as an equal proportionate share. The 75 percent exceedance of stream flow is deemed to be important because "aquatic habitat and the aesthetic beauty of the springs and streams of the eastern Arbuckle-Simpson aquifer are sensitive to low flows".

As expected, the percent depletions of long-term average stream flow can be approximated by subtracting the annual volume of groundwater withdrawn in a model simulation from the annual volume of stream flow and dividing by the stream flow before subtracting the withdrawn volume. Variation from the percentage at specific locations occurs due to the location of the pumping relative to the locations of calculated stream flow.

Less intuitive is the determination of the 75 percent exceedance of stream flow because this depends not only on the budget proportions but also on the buffering of stream flow from aquifer recharge and withdrawals by the diffusivity of the aquifer. A lower diffusivity (lower transmissivity and/or higher storage coefficient) produces a higher 75 percent exceedance value thus allows for larger groundwater withdrawals with less impact than a higher diffusivity.

The model was reviewed with respect to its applicability for determining the impact of groundwater withdrawal on long-term average stream flow depletion and 75 percent exceedance of stream flow. Comments on the model are grouped under the headings: Model Construction; Steady-State Calibration; and Transient Calibration. The comments identify items that may have enough impact on stream depletions to make a difference when making socio-political decisions related to acceptable withdrawals. The scope of this project did not provide for undertaking the work that would determine the magnitude of impact of the identified items, thus the conclusion section of this report provides recommendations for work to be done before using the model to determine acceptable levels of groundwater withdrawal.

MODEL CONSTRUCTION ISSUES

Simplification: In general, simplifications of the groundwater system made to construct the MODFLOW model were reasonable. These include use of relatively homogeneous hydraulic conductivity (with large anisotropy) and recharge rates, as well as use of confined layers. However, the treatment of storage properties was overly simplified given its strong influence on the prediction of interest which is intended for use in making major decisions regarding water rights.

Storage Coefficient: Although much effort was applied to representing the distribution of hydraulic conductivity and recharge in the model, no effort was made to represent the spatial distribution of storage properties. One value of specific storage was applied to the entire model domain and the sensitivity of model results to the value of specific storage was not assessed.

Page 2 of the report explains that a range of storage coefficients were calculated "Storage coefficients calculated by regional methods ranged from 0.00211 to 0.07475." Page 46 notes that the only aquifer test conducted for the study was not conducted for a long enough period of time to obtain a value for storage coefficient with confidence: "Although the test was not of sufficient duration to confidently determine a storage coefficient, the best fit between the analytical solution and the recovery data was achieved with a storage coefficient of 0.011."

Reference is made to a storage coefficient value of 0.008 reported in Oklahoma Geological Survey Circular 91 which was prepared by Fairchild, R.W., Hanson, R.L., and Davis, R.E., in 1990, and titled Hydrology of the Arbuckle Mountains area, south-central Oklahoma. The storage coefficient from that report was selected for the model. Review of that report is beyond the scope of this work. As noted in the Christenson et al. (2011) report, the regional methods used by both Christenson et al. (2011) and Fairchild et al. (1990) are based on limited data. Consequently, it is likely the resulting value of storage coefficient is not representative of the system and the spatial variation has not been assessed.

When approximating an unconfined system with a confined aquifer type in MODFLOW, the product of thickness and specific storage in the uppermost layer should equal specific yield. However, the assumed storage coefficient of 0.008 is converted to a specific storage of $8x10^{-6}m^{-1}$ and applied to every cell in every layer of the model. The top layer of the model is 20 meters thick. This means that when the water level drops one meter in the top layer of the model (i.e. a one meter decline in the water table), only a 0.0002m depth of water is released. Or in English units, a 1 foot decline in the water table yields 2 one-thousandths of an inch of water.

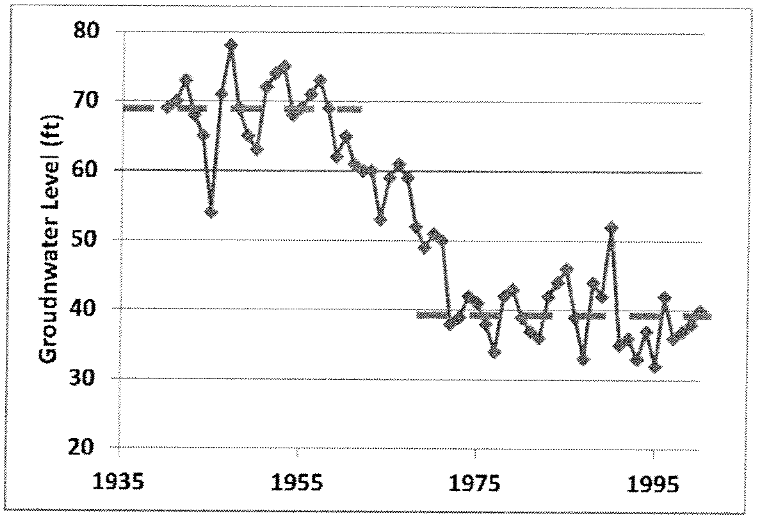
The sensitivity of the 75 percent exceedance of stream flow to different values and distributions of storage coefficient needs to be evaluated. A lower diffusivity in the model will moderate the simulated variations in stream flow, thus would indicate that more groundwater could be withdrawn and produce the same acceptable low flow. It is likely that, like hydraulic conductivity, storage coefficient is different for the different lithologic groups. The storage coefficient of the uppermost layer needs to represent specific yield. Further modeling would need to be undertaken to evaluate the magnitude of these impacts on the 75 percent exceedance of stream flow.

Stream conductance: There is an unusual discussion explaining stream conductance in the report. The report states that conductance of drains is set to a high value of 1000m/day. Conductance does not have units of length per time, rather it has units of length squared per time. A value of 1000 is input for conductance in the model files so 1000 meters^2/day was used for the modeling. The report does not explain how the value of 1000 was determined. When the MODFLOW drain package was developed, it was assumed the stream bed material had lower hydraulic conductivity than the model cell such that essentially the entire head loss between the stream and the aquifer takes place across the stream bed. Conductance is generally defined as length of the stream segment in a cell, times width of the stream, times the vertical hydraulic conductivity of the stream bed, divided by the thickness of the stream bed. All of the drain segments in the model were assigned the same conductance regardless of their width in the field or their length in a given model cell. The width of streams in the modeled area is on the order of 15m and the length traversing a cell is on the order of the cell size (200m) so assuming a thickness of 1 meter for the stream bed sediment then their Kv is 0.3m/day or about 1 foot/day and three feet thick. It is not clear whether this was the intent of the model team.

Steady-state time steps: Another unusual input item is the use of 4 time steps for the steady state solution. This causes MODFLOW to calculate the same steady state solution four times when the model is executed.

STEADY STATE CALIBRATION ISSUES

Unsubstantiated steady-state data for steady-state calibration: The steady state model was calibrated to synoptic data from August 1995. The report implies that use of synoptic data justifies a steady state calibration. However, having synoptic data does not mean that the system is in a steady state (i.e. in equilibrium where inflow equals outflow and storage is not changing). If the system is in a state of change when synoptic data are collected, the data may include changing heads in some areas (e.g. mounds of dissipating hydraulic head that a steady state calibration would estimate to have higher recharge and/or lower hydraulic conductivity than occurs in the field). The report implies that the system is in steady state because water levels in some wells changed only a fraction of a percent of the saturated thickness during the period of synoptic data collection. If the difference in head between wells was substantially more than a fraction of a percent of the saturated thickness, then this fact would indicate that there was not a significant error in the synoptic head distribution due to the data being collected over a number of days rather than instantaneously. However, such an observation does not indicate that the system is at steady state. Rather it may be far from steady state but changing slowly because of a low diffusivity. A steady-state condition could be supported by showing that hydrographs have an average horizontal section with variations up and down above and below the horizontal average as illustrated in the following image. However such a hydrograph analysis was not presented. For the illustration provided, if other wells and stream hydrographs throughout the model domain exhibited a similar pattern, then an average annual steady state model could be calibrated to average annual conditions from 1940 to 1955, followed by a transient calibration that reaches a new average steady period after 1973.

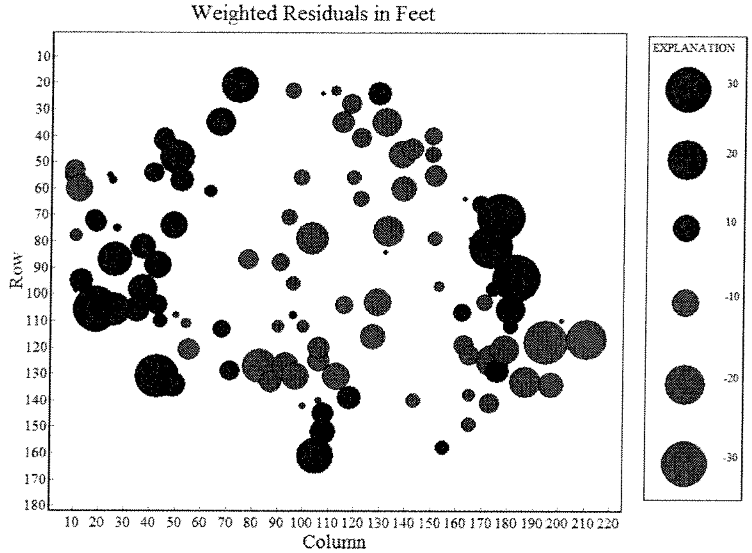


Multi-level nature of observation data ignored: The report states that the water levels used to calibrate the model came from holes with long open intervals. The modelers recognized that the simulated equivalent to the observation should be weighted by the hydraulic conductivity of the contributing layers. However rather than using multi-layer observations as provided for by the MODFLOW observation package, the observations for wells with long screens were assigned to the layer containing the bottom of the well. It is not clear how much effect this has on the calibration or the results.

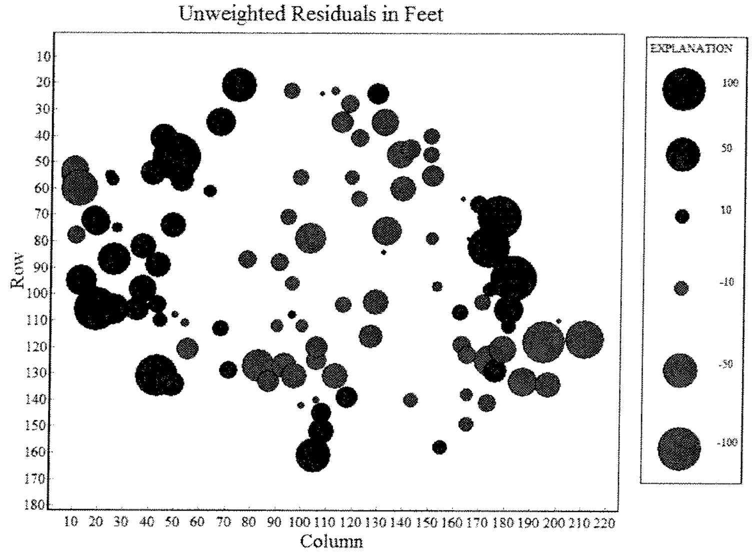
Lack of presentation of parameter estimation process and prediction sensitivities: The report states that the MODFLOW-2005 parameter estimation package was used to calibrate the model. However the report and associated files do not present the parameter estimation process. The report mentions that some parameters were insensitive to the observations used for calibration, but the sensitivities were not presented nor included in the model files. In spite of this insensitivity the report states that the parameter values were fixed to intermediate estimated values for additional calibration work. The reader is left wondering why the original parameter values were not used as the insensitivity would lead to irrelevant changes in parameter values. The values may not be important if the predictions are not sensitive to those parameters but prediction sensitivity is not presented in the report.

Spatial bias of residuals: Weighted residuals resulting from a model calibration should have a mean near zero, a normal distribution, and be randomly distributed in space and time. When residuals are viewed on a map, the large and small absolute values and the negative and positive vales should not exhibit a pattern. This is not the case for the Arbuckle-Simpson model where negative residuals dominate the center of basin as illustrated in figure 33 of the report and emphasized in the figure below by showing negative residuals as red and positive as blue. Residuals are calculated as the observed value minus the simulated value. So a negative residual indicates the simulated head is higher than the observed head. Thus, generally the heads are too high in the central portion of the model domain and too low on the perimeter. This bias should be corrected. Further modeling would be required to determine how this affects the predicted flows or the report conclusions. To facilitate direct comparison between the observed and simulated heads, the unweighted residuals are also shown with a different bubble size as indicated in the legends. The weights are the same on all head observations except the few that are non-synoptic in the post-Simpson unit and those heads have half the weight of the rest of the heads. So the primary difference between the plots is the decrease in residual due to the weights being less than one.

Weighted Residuals in Feet



Unweighted Residuals in Feet



TRANSIENT CALIBRATION ISSUES

Initial conditions for transient simulation: The transient calibration period extends from October 2003 through September 2008. A transient model run must begin with initial heads that represent conditions at the start of the transient period. The steady state calibration was for August 1995 so it was not reasonable to use heads from that simulation, thus an additional steady state run was conducted to be representative of the potentiometric surface on October 1, 2003.

The report states that the starting point for the transient model was obtained by adjusting the recharge rate of the steady state model by trial-and-error to minimize the difference between observed and computed flow at the Blue River near Connerville, Oklahoma, and the Pennington Creek near Reagan, Oklahoma, stream gages. However the resulting recharge rates are not provided and the files for this run were not on the web site. The report does not explain whether all recharges were adjusted by the same factor or if the factor was varied spatially. The report does not explain whether the factor was more or less than one. The report does not explain how different the flows were before adjustment of recharge and how much improvement was achieved.

It is likely that the system was in a transient state at the start of the period so rather than using heads from an adjusted steady state run, initial heads should have been established by running the 1995 model in a transient mode to October 2003 and saving those heads for starting the transient simulations.

Separate steady state and transient calibrations: Standard practice is to roughly calibrate a model to steady state conditions and then conduct a coupled steady-through-transient calibration, matching all available data in one calibration run.

Only two transient calibration targets were used: The only transient calibration targets were base flow to the Blue River near Connerville and Pennington Creek near Reagan. Standard practice is to use all available data.

Match to transient heads not reported: Graphs showing the observed and simulated transient heads are shown in figure 38 but the heads were not used for the transient calibration and the quality of fit is not provided.

Transient calibration did not optimize the value of storage coefficient: Transient calibration typically involves estimating storage parameters such that model simulations match time-varying field observations, but storage coefficient was not considered in the transient calibration of the report. The transient calibration consisted of setting specific storage to $8x10^{-6}$ m^{-1} for all cells and adjusting recharge factors on RORA-recharge values by trial-and-error in order to match stream flow.

Initially recharge was set on the Arbuckle-Timbered Hills unit north and south of the Sulphur fault based on analysis of stream flow from the 5 year period for the Blue River and Pennington Creek respectively, with reduced factors for recharge on the Simpson and post-Simpson units equal to the same factors as used in the steady state calibration. The estimated parameter values from the transient calibration were factors on recharge computer by the RORA program. An overall reduction of recharge was estimated with recharge north of the Sulphur fault being about 0.93 and south of the fault being 0.81 of the value estimated by RORA. Further model work would need to be done to determine whether a different set of recharge values coupled with changes in other model parameters and/or changes in the surface water analysis would produce an acceptable model fit and yield a different conclusion regarding low flows resulting from specific equal proportionate shares. Given the importance of storage coefficient to determining low flows, storage coefficient needs to be considered in a transient calibration that 1) includes transient head observations as well as stream flows and 2) uses automated parameter estimation techniques to assure an optimal solution.

PREDICTIVE SIMULATIONS

The simulations of groundwater withdrawals were undertaken using the same 5-year sequence of recharge events as the period October 2003 through September 2008. The 5 year period was repeated with the same 5-year recharge and using the initial head distribution from the end of one 5-water-year period as the starting condition for the next simulation until the total groundwater discharge to streams and springs for the entire 5-year simulation period changed less than 1 percent. Although not specifically stated the report suggests that an acceptable value be selected for the 75 percent exceedance of stream flow for Blue River near Connerville, Oklahoma, and Pennington Creek near Reagan, Oklahoma, and the MODFLOW model be used to determine the equal proportionate share that would produce that value.

CONCLUSIONS AND RECOMMENDATIONS

Given the importance of determining a safe and fair equal proportionate share, the model evaluation should be rigorous. The issues and deficiencies outlined in this report illustrate that the model is not ready for use in making policy decisions. The following steps are recommended before the model is used as the basis for determining safe yield from the Eastern Arbuckle-Simpson aquifer.

1) Use the model to determine the influence of a higher storage coefficient on the 75 percent exceedance of stream flow for Blue River near Connerville, Oklahoma, and Pennington Creek near Reagan, Oklahoma. A model run with a homogeneous storage coefficient of 0.08 would provide insight on the potential impact of a more rigorous estimate of storage coefficient on the 75 percent exceedance of stream flow at those locations.
2) If item 1 indicates a notable difference in the 75 percent exceedance of stream flow then conduct a more rigorous analysis of the storage coefficient including: a) evaluation of its spatial distribution in the regional analyses; and b) aquifer tests of sufficient duration to evaluate storage coefficient at a number of locations in the study area.
3) Evaluate the value used for stream conductance including: a) discussion of the physical conditions represented by the value; b) confirmation that those conditions are representative of the field area; evaluate whether the results are sensitive to the value used for conductance.
4) Use only one time step for steady state simulation.
5) Analyze hydrographs to select a steady period for the steady state portion of the calibration and use average annual values for targets.
6) Use the multi-level observation feature of MODFLOW for calibration targets in wells with long screens.
7) Present the details of the parameter estimation process including: a) providing parameter estimation package files; b) explaining the logic used throughout the process; c) presenting parameter sensitivities; d) justifying use of estimated values of insensitive parameters at an arbitrary point in the calibration process.

8) Evaluate the cause for spatial bias of the residuals and make appropriate adjustments to the conceptual model.
9) Conduct a calibration that includes both steady and transient simulations. The steady situation could be a calibration to average annual conditions followed by a warm-up period with no observations followed by the 2004-2008 transient calibration period.
10) Include all available heads and flows as observation targets in the transient portion of the calibration.
11) Include storage coefficient as a parameter in the transient calibration.
12) More transient head data may be necessary to obtain a reliable transient calibration and such data collection should begin as soon as possible.
13) Evaluate prediction sensitivities.