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Comment on “*An unconfined groundwater model of the Death Valley Regional Flow System and a comparison to its confined predecessor*” by R.W.H. Carroll, G.M. Pohll and R.L. Hershey [*Journal of Hydrology* 373/3–4, pp. 316–328]

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Discussion

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SUMMARY

Carroll et al. (2009) state that the United States Geological Survey (USGS) Death Valley Regional Flow System (DVRFS) model, which is based on MODFLOW, is "conceptually inaccurate in that it models an unconfined aquifer as a confined system and does not simulate unconfined drawdown in transient pumping simulations." Carroll et al. (2009) claim that "more realistic estimates of water availability" can be produced by a SURFACT-based model of the DVRFS that simulates unconfined groundwater flow and limits its withdrawals from wells to avoid excessive drawdown. Differences in results from the original MODFLOW-based model and the SURFACT-based model stem primarily from application by Carroll et al. (2009) of head limits that can also be applied using the existing MODLOW model and not from any substantial difference in the accuracy with which the unconfined aquifer is represented in the two models. In a hypothetical 50-year predictive simulation presented by Carroll et al. (2009), large differences between the models are shown when simulating pumping from the lower clastic confining unit, where the transmissivity is nearly two orders of magnitude less than in an alluvial aquifer. Yet even for this extreme example, drawdowns and pumping rates from the MODFLOW and SURFACT models are similar when the head-limit capabilities of the MODFLOW MNW Package are applied. These similarities persist despite possible discrepancies between assigned hydraulic properties. The resulting comparison between the MODFLOW and SURFACT models of the DVRFS suggests that approximating the unconfined system in the DVRFS as a constant-saturated-thickness system (called a "confined system" by Carroll et al., 2009) performs very well.

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1. Introduction

The DVRFS model critiqued by Carroll et al. (2009) is a groundwater flow model of the Death Valley regional groundwater flow system, which includes the proposed high-level nuclear waste disposal site at Yucca Mountain, the Nevada Test Site (NTS), Death Valley National Park, and other sites of national importance. Funded predominantly by the US Department of Energy, the US Geological Survey developed this model using the simulation code MODFLOW. The model is documented in detail in Faunt et al. (2004). Following the nomenclature used by Carroll et al. (2009), this comment calls the model the "MODFLOW model."

The MODFLOW model does not use MODFLOW's unconfined model layer capability. Instead the DVRFS unconfined aquifer, in which the actual saturated thickness varies over time, is approximated using a model layer in which the simulated saturated thickness used to calculate transmissivity remains constant over time. Within the constant-saturated-thickness layer, storage changes over a given period of time are calculated as specific yield times simulated head change. This approximation greatly enhances computational speed and stability, especially during calibration when some attempted sets of parameter values produce computed heads that differ substantially from measured heads.

Carroll et al. (2009) claim that the constant-saturated-thickness approximation (which they call the "confined system" approach), together with a lack of automatic reduction of withdrawals from wells based on head limits, makes the MODFLOW model "conceptually inaccurate." They present an alternative model based on SURFACT (Hydrogeologic Inc. (HGL), 2007), referred to here at the "SURFACT model," which they claim improves upon the MODFLOW model. They claim the improvement is derived primarily by simulating unconfined groundwater flow using variable-saturated-thickness layers and automatically reducing withdrawals from wells based on head limits to avoid simulated drawdown below the bottom of the well. This comment discusses (1) the rationale for using the constant-saturated-thickness approximation to represent the DVRFS, (2) the similarity between the MODFLOW and SURFACT models' simulated responses to pumping when the MODFLOW model's Multi-Node Well (MNW) Package is used to

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limit withdrawals from wells based on head limits, and (3) other issues concerning the SURFACT model.

2. Constant-saturated-thickness approximation of the unconfined system

One of the primary objectives of the DVRFS project was the construction and calibration of a transient model that simulates the groundwater conditions from pre-development through 1998 (Belcher et al., 2004; Faunt et al., 2004). The focus of the resulting MODFLOW model was to assess regional flow patterns and their variations at Yucca Mountain and the Nevada Test Site. During the calibration period (pre-development through 1998), water use is minor on a regional scale and, except for local increases in drawdown late in the simulation period, drawdowns are small relative to the saturated thickness of permeable units within the groundwater system. The model simulates more than 15 m of drawdown in the Amargosa Desert and Pahrump and Penoyer Valleys during the last few years of the simulation period. Additionally, two isolated mining wells just west of the NTS have more than 15 m of drawdown. These areas total less than 360 km^2, less than one percent of the modeled area. Because of the relatively minor water use and local nature of the drawdown observed in the field, a constant-saturated-thickness approximation with an unconfined storage coefficient was chosen for the MODFLOW model to achieve fast and stable model runs that facilitated investigation of important aspects of the groundwater system dynamics.

Unconfined systems can be difficult to model because of extra computational burden and possible nonlinear instability. But if drawdowns are relatively small compared to initial saturated thickness of the unconfined unit(s), speed and stability can be gained with minimal loss of accuracy by holding the saturated thickness constant. Approximating an unconfined aquifer as having constant saturated thickness is a well-known modeling technique (Neuman, 1974; Bear, 1979; Marsily, 1986; Hill, 1998; Hill et al., 2000; Reilly, 2001; Rushton, 2003; Reilly and Harbaugh, 2004) that does not, in itself, constitute a conceptual error. The approximation is useful for linearizing the groundwater flow equations to enable superposition of solutions (Reilly et al., 1987; Reilly and Harbaugh, 2004) and has been used in aquifer-test analysis (Masterson and Barlow, 1996) and numerical groundwater models (Souza and Voss, 1987; Danskin, 1998; Hanson et al., 2003, 2004; Wylie, 2004; Franssen and Stauffer, 2005; Gingerich and Voss, 2005; Oki, 2005; Barlow and Ostiguy, 2007).

For simulation of steady-state flow, one can iterate, setting the top of the model to the estimated top of the unconfined system (the water-table elevation), solving for new heads, resetting the model top to the new simulated water table, etc., until the model top coincides with the water table. If the iterations are fully converged, the resulting constant-saturated-thickness simulation is numerically equivalent to an unconfined simulation. An iterative approach was used to generate the steady-state solution in the MODFLOW model, and convergence was sufficient to ensure that the elevation of the model top represented a good approximation to the water-table elevation, particularly in the areas of interest (Faunt et al., 2004).

For simulation of transient flow, one can set the model top to the initial water-table elevation and proceed to simulate drawdowns with the constant-saturated-thickness model. The simulated drawdowns are accurate as long as they remain a modest fraction of the initial saturated thickness, because the transmissivity (thickness multiplied by hydraulic conductivity) of the constant-saturated-thickness system will remain close to that of the unconfined system. The relevant saturated thickness is that of the uppermost hydrologic unit, which can span multiple model cells vertically. Our experience suggests that satisfactory accuracy can be expected for drawdowns of less than 10% of initial saturated thickness, and that even larger relative drawdowns can yield acceptable results. In the MODFLOW model, the relevant saturated thickness (which is on the order of a kilometer, except in localized areas) is generally much greater than the drawdowns, which are typically less than 15 m except in the limited areas noted above. Therefore, the constant-saturated-thickness approximation used in the MODFLOW model was appropriate for its intended purpose of characterizing regional-scale groundwater flow during the calibration period.

3. Head limits and a hypothetical 50-year predicted drawdown

The MODFLOW model was originally intended to simulate conditions that extended from pre-development through 1998 (Belcher et al., 2004, pp. 8–9). Besides this intended use, Belcher et al. (2004, p. 9) identified a number of potential longer term applications of the MODFLOW model. One of these applications was to assess the potential effects of continued and/or increased offsite water use on NTS water supplies. Carroll et al. (2009) apply SURFACT's "fracture well" (FWL) technique to both the original simulation time-frame and prediction conditions. This technique "adjusts water withdrawal ... from a potentially over-pumped well such that heads do not drop below a well's screened interval" to simulate the DVRFS. This comment refers to this technique as applying head limits to pumping wells.

For the calibration period, Carroll et al. (2009) report that the SURFACT model's simulated heads in the vicinity of some wells are closer to observed values than those computed by the MODFLOW model. In the MODFLOW model described by Faunt et al. (2004), some drawdowns below the bottom of the well screen were tolerated because they occurred far (tens of miles away) from areas of primary interest, which were Yucca Mountain and the Nevada Test Site. These drawdown features do not affect the general hydrodynamics of the aquifer.

Of significance is whether applying the head limit during model calibration is likely to improve the accuracy of the model and its predictive ability. A difficulty with using head limits is that simulated pumpage may be altered inappropriately. The pumpage defined in the MODFLOW model is based on the best records or estimates available, and disregarding them for the sake of improving the fit between modeled and observed heads does not necessarily improve conceptual or predictive accuracy. Using head limits in this way may simply result in a model that achieves a better fit by incorrectly altering the imposed pumpage. A more comprehensive approach to evaluating wells for which simulated drawdowns are unrealistic is likely to be more successful. Such an approach would include reviewing the model representation of hydrogeologic properties, relevant boundary conditions, and borehole configurations (well radii, skin factors, and screen lengths), in addition to the pumpage rate.

Carroll et al. (2009) incorrectly compare the capabilities of SURFACT's FWL technique with those of the MODFLOW WEL package, instead of the MNW package, which was used in the MODFLOW model described by Faunt et al. (2004). Like SURFACT's FWL technique, MODFLOW's MNW package can limit withdrawal so that simulated water levels in the pumping well remain above pump intakes (Halford and Hanson, 2002). Limiting withdrawal as proposed by Carroll et al. (2009) can be useful for examining higher pumping rates in the model and for future predictions. For comparison, the hypothetical simulation of Carroll et al. (2009) was reproduced using the MODFLOW model with the MNW package, with water levels in the pumping well constrained as in the SURFACT model. The well attempts to pump 5000 m^3/d for 50 years past the original simulation period, and recovery is simulated for another 50 years. Fig. 1 shows that the results computed by the constant-saturated-thickness MODFLOW model with head-limited withdrawals are very similar to those computed by the unconfined SURFACT model (Carroll et al., 2009, Fig. 12).

The slight differences shown in Fig. 1 may result from differences in simulated hydraulic properties introduced during conversion between the MODFLOW Hydrogeologic-Unit Flow (HUF) package and the SURFACT Block-Centered Flow (BCF) package and (or) the different algorithms used by SURFACT's FWL and MODFLOW's MNW packages to adjust flow as head in the well reached the bottom of the well. A complete analysis of these differences is beyond the scope of this comment, but the conversion from HUF to BCF is discussed in the next section of this comment.

Even for the pumpage site selected by Carroll et al. (2009), for which an extremely large pumpage of 5000 m^3/d is imposed in the low-permeability clastic confining unit on the edge of the valley, the constant-saturated-thickness approximation works well. The proposed pumping rate is typical of an irrigation supply well that would be completed in alluvial fill in which the transmissivity is about two orders of magnitude higher. The ability of the MODFLOW model to reproduce the results from the SURFACT model in this extreme scenario further supports the utility of the constant-saturated-thickness approximation.

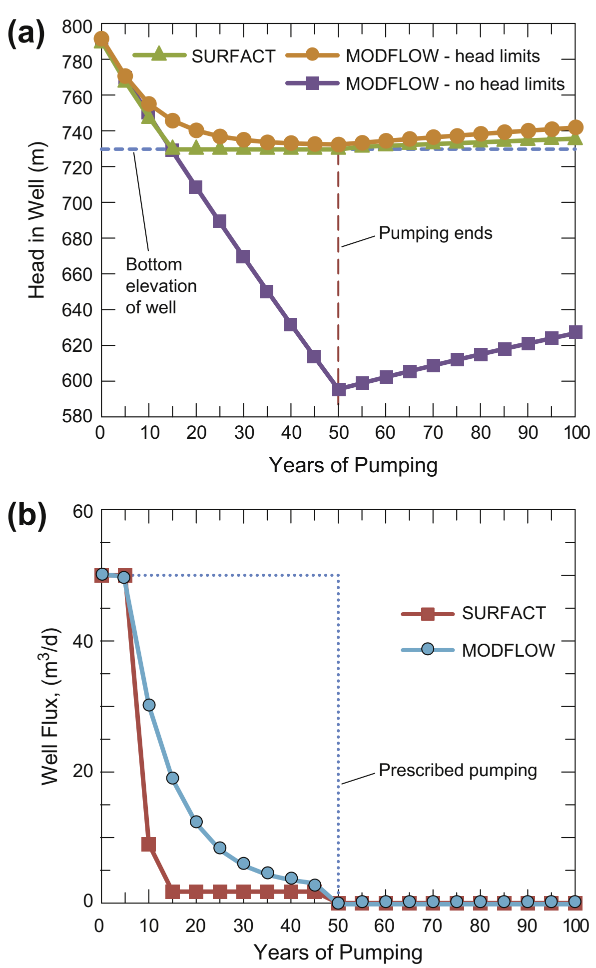

Fig. 1. (a) Head drawdown in a hypothetical well south of the Nevada Test Site simulated using the MODFLOW and SURFACT models given 50 years pumping at 5000 m^3/day (1480 acre ft/yr) followed by 50 years of recovery. For the MODFLOW model of Faunt et al. (2004), the head drawdown is shown with and without head limits activated in the model. (b) Prescribed pumping rate compared with pumpage simulated by the SURFACT and MODFLOW models using head limits at the pumping well.

4. Other issues concerning the SURFACT model

Carroll et al. (2009) claim that the averaging scheme used to compute interblock conductance values in SURFACT (which, like MODFLOW, uses a block-centered grid) is better than the scheme used in MODFLOW's HUF package (p. 320). They investigate some theoretical ramifications of the different averaging schemes using a suite of analytical solutions and idealized numerical simulations (pp. 323–324 and Fig. 9). They fail to demonstrate convincingly, however, that the SURFACT scheme produces a more accurate model of the DVRFS. Carroll et al. (2009) Fig. 10, which compares DVRFS model results along a two-dimensional transect, shows that the SURFACT and MODFLOW models compute similar heads over most of the transect. In the western portion of the Greenwater and Black Ranges, where the results differ by tens of meters, the difference may be due to loss of highly permeable LFU material (Carroll et al., 2009, Fig. 4b) from the saturated thickness due to drawdown, which is not accounted for in the MODFLOW model. In the Spring Mountains, where the results differ by hundreds of meters, heads computed by the SURFACT model significantly overshoot the top of the model. Here, the DVRFS model represents heads more accurately than the SURFACT model; heads computed by the DVFRS model are within 50 m of observed heads in this area. Carroll et al. (2009) suggest that raising the top surface of the model to land surface elevation would improve the heads computed by SURFACT (p. 326), but they do not attempt such an adjustment.

A potentially problematic aspect of the interblock conductance calculations not accounted for by Carroll et al. (2009) is related to the use of "effective" cell vertical hydraulic conductivities in the SURFACT model. According to Carroll et al. (2009, p. 322), "[t]ranslation of MODFLOW's geological model packages HUF2 and KDEP ... into SURFACT's modified BCF4 package was accomplished by extracting effective cell properties from the [MODFLOW model]," including vertical hydraulic conductivities. Even if SURFACT and MODFLOW used the same averaging scheme to compute interblock conductances, however, the resulting vertical conductances could still differ in the SURFACT and MODFLOW models. This is because, in MODFLOW's HUF package, vertical conductance is computed from the vertical hydraulic conductivities in two half-cells: the bottom half of one cell and the top half of the cell below it (Anderman and Hill, 2000). The top and bottom halves of a given cell can contain different hydrogeologic units and, therefore, can have different vertical hydraulic properties. The scheme used in the SURFACT model, in which each cell apparently is assigned a single value of vertical hydraulic conductivity, affords fewer degrees of freedom than does the scheme in HUF. Therefore, computing effective cell vertical conductivities independently (for example, by computing a vertically averaged value for each cell independently of the other cells in the same vertical stack) generally does not yield the same vertical conductances as in the original HUF-based model. To obtain the same vertical conductances, one must compute the effective cell vertical conductivities in a specific, sequential way. Carroll et al. (2009) do not explain how they computed their effective cell vertical conductivities, so it is not known whether they used the appropriate sequential procedure. Thus, in addition to the difference in hydraulic properties resulting from the use of a different averaging scheme, Carroll et al. (2009) may have introduced error into the vertical conductances by basing them on effective cell vertical conductivities. It is possible that such error contributes to the differences in simulated heads in the Spring Mountains (Carroll et al., 2009, Figs. 10a and e), where recharge is relatively large and differences in vertical conductance values are likely to be important.

Because Carroll et al. (2009) did not evaluate individually the effects of the various differences between the MODFLOW and SURFACT models, except for limits on withdrawals based on head limits, it is difficult to know which, if any, of the changes represent real improvements to the model, and which are responsible for specific differences in model results. Still, their results (Table 2 and Fig. 11) suggest that, with the exception of drawdowns at certain wells, the SURFACT and MODFLOW models performed similarly in terms of overall model fit. In fact, Carroll et al. (2009) state that their unconfined model ''helps validate'' calibrated model parameter estimates obtained using the MODFLOW model, although is not known how the SURFACT model would have performed had it been recalibrated.

5. Conclusion

The evidence presented by Carroll et al. (2009) does not support the conclusion that their SURFACT model of the DVRFS ''represents an evolution of the USGS [MODFLOW] model toward greater conceptual accuracy'' and is ''capable of producing more realistic estimates of water availability.'' Furthermore, Carroll et al. (2009) fail to support their claim that the USGS's DVRFS model, which is based on MODFLOW, is ''conceptually flawed'' because it approximates the unconfined as having constant saturated thickness. The additional analysis described in this comment supports the validity and utility of the approximation. Overall, the SURFACT and MODFLOW models perform similarly in terms of model fit to observations.

For the calibration period, other than the high mountain ranges, the biggest differences between the SURFACT and MODFLOW models occur at relatively few wells where heads are drawn down significantly below well screens in the published MODFLOW model but are prevented from doing so in the SURFACT model. The differences are local, affecting heads only in close proximity to the wells. At these wells, heads computed by the SURFACT model are in closer agreement with head observations because the simulated head is governed by the imposed head limit. However, the simulated pumpage rate differs from best known values. Thus, instead of the SURFACT model being more accurate than the MODFLOW model, it may be that reduced errors in computed heads are being traded for increased error in pumpage at these wells.

In a hypothetical scenario introduced by Carroll et al. (2009) that involves heavy pumping of a well beyond the calibration period, head-based limits on pumping can be imposed through the MODFLOW model's MNW package (which was used in the DVRFS model) to yield results very similar to those obtained using the SURFACT model. For calibration simulation and when simulating the hypothetical scenarios, differences in performance between the SURFACT and MODFLOW models exist primarily because of differences in withdrawals from certain wells, and not because saturated thickness remained constant in the MODFLOW model.

The analysis presented in this comments shows that the MODFLOW model is conceptually sound and an appropriate tool for evaluating regional groundwater availability in the DVRFS under pumping conditions from the calibration period and a wide range of potential pumpage scenarios. In addition, while use of the constant-saturated thickness approximation is useful and accurate in many circumstances, the MODFLOW model can be used without this approximation in situations that require simulation of changes in saturated thickness.

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