3 April 2015

MEMORANDUM

To: Bob Jaques, Seaside Basin Watermaster Technical Program Manager

From: Gus Yates, Senior Hydrologist, Todd Groundwater

Re: Peer Review of Seaside Basin Groundwater Modeling Studies

Introduction

HydroMetrics Water Resources, Inc. (HMWRI) has completed several groundwater modeling studies of the Seaside Basin in recent years to support decision-making by the Seaside Basin Watermaster. These include the original model documentation report (HMWRI 2009), the 2014 model update report (HMWRI 2014a) and a safe yield analysis of the Laguna Seca subarea (HMWRI 2014b). The last of these raised fundamental questions about basin boundaries and yield, which prompted the Watermaster to request a technical peer review of the groundwater model, simulation results and conclusions drawn from those results. I have completed the peer review, and this memorandum summarizes my findings.

The review process was structured to include extraction of additional information from model simulations previously completed by HMWRI as well as additional testing of the model. These steps were beyond the typical scope of a peer review and added substantial value to the outcome. Instead of simply retroactively identifying weaknesses and speculating about their causes, I was able to investigate hypotheses and test potential model improvements. HMWRI staff facilitated these steps by running the model and its pre- and post-processing programs per my instructions. As a result of this hands-on approach, this memorandum presents more technical information—results not included in prior reports—than is commonly included in peer reviews.

Approach

The primary purpose of the groundwater model since its inception has been to address questions related to the yield of the basin and its subareas. The ability of the model to correctly represent existing and future water balances is central to its reliability for estimating yield. Water balances are linked to simulated water levels, and an error in one can be associated with an error in the other. The focus of the technical review consisted of applying this linkage to three potential model weaknesses to see whether they might result in incorrect yield estimates. One apparent weakness is the discrepancy between simulated and measured historical water levels evident for several wells in the Northern Coastal Subarea. A second potential weakness is that the estimate of Laguna Seca Subarea safe yield is much lower than estimates in previous studies. The third potential weakness is a discrepancy between simulated and measured water levels that is not very large but that is centered on the Laguna Seca-El Toro boundary. These possible weaknesses are described below, followed by the results of three model sensitivity tests designed to investigate causes and implications of the weaknesses.

The peer review also included obtaining additional clarification regarding details of the model input and output, in order to confirm that all aspects of the model are reasonable. These items were submitted as a list of questions to HMWRI, and the responses are potentially valuable for others involved in basin modeling and management. Accordingly, they are included in Appendix A.

The adjudication judgment includes the term “natural safe yield”, which is a legal concept that conflicts with physical processes that actually occur in the Seaside Basin. Consequently, the term is of little practical value for basin management. A discussion of the limitations of the natural safe yield concept is presented in Appendix B. The “operational safe yield” calculated by HMWRI accounts for all components of the water balance, including human effects on those components. It is based on empirical relationships between pumping and water levels and is a more realistic and useful metric for water management purposes.

Simulated Northern Coastal Water Levels and Water Balances

The model was calibrated to observed groundwater conditions during 1987-2013. The Paralta Well at the eastern edge of the Northern Coastal Subarea commenced operation in 1995 and immediately became one of the two largest producers in that subarea. Total groundwater production also increased at that time as a result of State Water Resources Control Board (SWRCB) Decision 95-10, which forced the largest retail water supplier in the region (California American Water Company, or Cal-Am) to shift much of its production from wells in the Carmel Valley to wells in the Seaside Basin. Measured water levels at many Northern Coastal wells began steadily declining in response to the increase in pumping. However, simulated water levels at many of those wells do not exhibit a long-term declining trend. **Figure 1** shows annual production from Northern Coastal Subarea wells during 1987-2013. The increase in total production of about 1,500 AFY at the onset of Paralta Well pumping in 1995 is clear. **Figure 2** shows hydrographs for four of the wells where the discrepancy between measured and simulated water-level trends can be seen. Other wells do not exhibit the discrepancy, such as the ones shown in **Figure 3**.

The discrepancies as of the end of 2013 were plotted on a map, and they formed a pattern consistent with failure of the model to gradually develop a pumping trough during 1995-2013 in either the Santa Margarita aquifer (model layer 5) or the Paso Robles aquifer (model layers 1-4). A pumping trough is a depression in the regional groundwater surface caused by a local concentration of pumping. In this discussion, the term refers to a persistent feature that gradually developed over a period of years. Seasonal water-level fluctuations occur in addition to the long-term trend. The model produces reasonable amounts of seasonal drawdown at major production wells, but not the long-term trend. Some management issues might related to seasonal drawdown, but long-term trends are what influence yield, overdraft and seawater intrusion

The discrepancy is illustrated by the map of differences between simulated and measured water levels (“residuals”) in the two aquifers, as shown in **Figure 4**. The discrepancies are indicated by the numbers next to some of the wells, which equal the simulated water level minus the measured water level. In the Santa Margarita aquifer (pink well symbols and labels), the discrepancy is largest near the midpoint of the eastern edge of the subarea and decreases to the west. It is still greater than zero near the coast. In the Paso Robles aquifer (blue well symbols and labels), the largest discrepancy is closer to the center of the subarea but diminishes more rapidly with distance to the north, west and south. It decreases to zero near the coast. Unfortunately, the number of points in each aquifer is not sufficient to completely define the pumping troughs. Also shown for comparison are circles representing the recent distribution of pumping in the Santa Margarita aquifer. The areas of the circles are proportional to the average annual production from that well during 2009-2013. If the aquifer is homogeneous, the pumping trough would be centered over the area with the highest concentration of pumping.

A possible explanation for the discrepancies between simulated and measured groundwater levels is that formation of a long-term pumping trough is prevented by too much simulated groundwater inflow. A pumping trough results when a localized area of relatively high groundwater pumping causes a local depletion of groundwater storage, which is indicated by the localized depression in water levels. However, pumping simultaneously pulls in water horizontally from surrounding areas. The rate of flow toward the area of concentrated pumping is proportional to the slope of the water-level surface toward the pumping depression. In technical terms, this a “head-dependent” response to pumping (“head” = water level). When the effects of pumping reach the boundaries of a subarea, they can increase the amount of inflow across the boundary. If aquifer transmissivity in the model is high, pumping will tend to increase inflow across the subarea boundaries rather than accumulate a depletion of storage within the subarea.

In the Santa Margarita aquifer in the Northern Coastal Subarea pumping can increase flow across five boundaries: the ocean, the Southern Coastal Subarea, the Northern Inland Subarea, the Salinas Valley basin to the north, and the overlying Paso Robles aquifer. Simulated annual net inflows across each boundary during 1987-2013 are shown in **Figure 5**. Each of those boundary flows will respond to a change in pumping. The sensitivity tests described below were designed to test the relative magnitudes of the boundary responses to determine whether one or more of them might be responsible for preventing the long-term development of a pumping trough.

Simulated Laguna Seca Water Balances

Yates and others (2002) estimated that average annual groundwater pumping in the Laguna Seca Subarea during 2000-2002 was approximately 1,000 AFY, and the safe yield was about 400 AFY. The original (2009) HMWRI groundwater model included the same estimate of average annual production during 2003-2007. Shortly thereafter, groundwater withdrawals began to decrease as a result of basin adjudication. The adjudication proceedings assumed a safe yield of 608 AFY for the Laguna Seca subarea, although no derivation of that estimate was presented (HMWRI 2014b). In the 2014 Laguna Seca yield analysis, HMWRI applied the equation for natural safe yield to obtain a yield estimate of 240 AFY. Future baseline pumping was projected to be 524 AFY, which in spite of being only half as much as historical pumping was still more than double the estimated natural safe yield.

Head-dependent flows in the Laguna Seca Subarea water balance are storage change, net inflow from the El Toro Subarea, net outflow to the Northern Inland Subarea and net outflow to the Southern Coastal Subarea. It is important to note that flow across these boundaries can be in either direction, can change over time or can be in different directions at different points along the boundary. “Net inflow” in this discussion equals inflow minus outflow summed for every model cell along the boundary and every model time interval in a year. In the case of the boundary between the Laguna Seca and El Toro Subareas, flow has been into Laguna Seca along the east-west boundary segment. The north-south boundary segment was historically a flow divide, which is the high point in the water-level profile midway between two pumping troughs. In this case, the pumping troughs are centered around the Laguna Seca golf courses and the Corral de Tierra wells. The position of the flow divide will change if pumping on either side increases or decreases. Consequently, the direction of flow at the fixed boundary line shown in the map and in the adjudication can change from net inflow to net outflow, or vice versa. **Figure 6** shows annual inflows and outflows for the Laguna Seca Subarea in the groundwater model during 1995-2013. Inflows from El Toro and outflows to El Toro are both fairly large in the groundwater model, and for clarity inflows and outflows are shown separately in the graph. Boundary flow is almost exclusively outflow at the Northern Inland and Southern Coastal Subarea boundaries. Recharge is also shown in the graph to put the magnitudes of the other inflows into context.

The Laguna Seca water balance in the groundwater model differs substantially from the most recent previous estimates. Yates and others (2002 and 2005) estimated that the subarea receives an average of 810 AFY of internal recharge (from rainfall, irrigation return flow and septic system percolation) and 180 AFY of net inflow from the El Toro Subarea, which together total 990 AFY. Their estimate of safe yield was 400 AFY, or 40 percent of total inflow. The HMWRI groundwater model includes 1,050 AFY of internal recharge and 760 AFY of net inflow from El Toro, for a total of 1,810 AFY of inflow—almost double the prior estimate. However, the natural safe yield was estimated to be 240 AFY, which is only about half of the prior estimate and only 13 percent of total inflows. In other words, the model incorporates a large amount of groundwater flow through the Laguna Seca Subarea, a relatively small fraction of which can be extracted within the subarea without causing long-term water-level declines.

The additional through-flow of groundwater is essentially northward, entering across the southern subarea boundary (from the area near the Bay Ridge and Robley wells) and exiting across the northern boundary (crossing the Laguna Seca Anticline and into the Northern Inland Subarea). Although HMWRI concluded that geologic evidence supports the the possibility of northward flow across the Laguna Seca Anticline, overestimating that flow could result in underestimating groundwater yield within the subarea. Furthermore, excess outflow to the Northern Inland Subarea could conceivably supply excess flow from the Northern Inland to the Northern Coastal Subarea. This means that the two possible weaknesses in the groundwater model could share a common cause. The inter-subarea flows were adjusted in the sensitivity simulations to explore this possibility.

Simulated Water Levels at Laguna Seca-El Toro Boundary

A third possible weakness in the groundwater model is smaller and more localized but could impact yield calculations because of its location. HMWRI found that even when Laguna Seca pumping was reduced to zero in the groundwater model, water levels in the eastern part of the subarea continued to decline as a result of pumping in the adjacent El Toro Subarea. On the one hand, this is physically plausible because the Laguna Seca-El Toro boundary is simply a flow divide, not a true barrier to groundwater flow. Pumping on one side of the boundary would be expected to affect water levels on the opposite side.

On the other hand, part of the simulated decline in water levels might be due to a localized calibration error. In the model update simulation of 1987-2013 (HMWRI, July 2014), the model over-simulated the amount of historical water-level decline at three wells near the Laguna Seca-El Toro boundary. Simulated and measured water-level hydrographs for those wells are shown in **Figure 7**. At the scale of the entire basin, this discrepancy is not particularly large, but it is centered on a controversial boundary segment. If whatever caused the discrepancy in the historical calibration simulation also applied to future simulations, it would tend to over-simulate water level declines, which would reduce the estimate of operational safe yield in the Laguna Seca Subarea.

Model Sensitivity Tests and Results

Three simulations of the 1987-2013 period were completed to explore the sensitivity of model results to changes in inputs that affect east-to-west flow between basin subareas. The objective of the tests was not to create fully-calibrated alternative models, but simply to test whether substantial changes in parameters that affect east-to-west flow could produce qualitatively different results. Specifically, results were examined to see whether alternative parameters resulted in a more pronounced pumping trough in the Northern Coastal Subarea or in a more gradual rate of water-level decline in the Laguna Seca Subarea. The three test simulations were:

- **Sensitivity Alternative 1a: Decreased hydraulic conductivity along Laguna Seca Anticline.** The Laguna Seca Anticline is an upward fold in geologic formations resulting from tectonic forces. It creates a buried “ridge” in the bedrock surface at the base of the basin. The anticline follows the boundary between the Laguna Seca and Northern Inland Subareas and continues east and north a couple of miles along the western edge of the El Toro Creek Valley. Previous studies of the basin reached different conclusions regarding the influence of the anticline on groundwater flow. Muir (1982) concluded that none of the geologic structures north of the Chupines Fault (the southern basin boundary) act as barriers to groundwater flow, but his focus was on faults in the coastal subareas. A later study focusing on the Laguna Seca subarea noted that the anticline pushes impermeable Monterey Formation up to an elevation above the water table and concluded that it represents “a major barrier to the north-south flow of ground water”

(Staal, Gardner and Dunne, Inc.,1988). HMWRI reviewed available geologic information and concluded that the barrier effect was restricted to the central part of the subarea boundary and that northerly flow from the Laguna Seca to the Northern Inland Subarea was possible farther to the east. The model was constructed to allow this flow. For the sensitivity test, a partial barrier was added to HMWRI's model by decreasing hydraulic conductivity (aquifer permeability) in all model layers to a relatively low value of 0.5 ft/day along a swath of model cells tracing the eastern end of the anticline. The location of the adjustment is shown in **Figure 8**.

- **Sensitivity Alternative 1b: Uniform, low hydraulic conductivity in Northern Inland subarea.** HMWRI used software (known as PEST) that "automatically" calibrates a groundwater model through a series of iterative model simulations and adjustments. This procedure resulted in quite variable hydraulic conductivity throughout the Northern Inland Subarea, which could have resulted in "preferred flow paths" along connected areas of high conductivity. Sensitivity Alternative 1b eliminated the possibility of high flow along preferred pathways by substituting a uniform zone of moderately low conductivity (5 ft/d) throughout the eastern two-thirds of the Northern Inland Subarea (all layers). The purpose was the same as for Alternative 1a, which was to diminish east-to-west flow across the Northern Inland Subarea.

- **Sensitivity Alternative 2: Steady-state water levels as initial water levels.** Simulated water levels climb steeply toward the southeastern corner of the El Toro Subarea. This region of high water levels could represent a large volume of stored groundwater. If that volume were incorrectly specified at the start of the simulation, it could slowly drain out during the course of the simulation and supply an excessive amount of east-to-west flow across the basin. Alternative 2 sought to eliminate this type of initial disequilibrium by constructing a stable set of initial water levels. This was completed by means of a steady-state simulation in which model inflows and outflows were held at constant values equal to their long-term averages, and the simulated groundwater surface was allowed to reach equilibrium with those inflows and outflows. The resulting water levels were used as the starting point of a transient simulation of the 1987-2013 period during which inflows and outflows fluctuated according to their historical seasonal and year-to-year variations.

Results of the three sensitivity simulations were plotted as hydrographs, water-level contour maps and water-balance pie charts, and then compared with output from the calibration simulation.

Northern Coastal Subarea Results

Hydrographs of selected wells are shown in **Figure 9** for the calibration simulation and the three sensitivity alternatives. The results for Alternatives 1a and 1b are vertically offset from the calibration hydrograph by a small amount, but the trends have the same slope. For this test involving only changes in parameters outside the Northern Coastal Subarea, a change in the hydrograph slope would indicate a change in estimated subarea yield. Because the slopes remained unchanged, the estimate of yield would not change. The hydrographs for Alternative 2 exhibit a different type of response. Initial water levels at the start of the Alternative 2 simulation were much higher than the initial water levels in the calibration simulation. Over a period of about 20 years, they converged with the calibration hydrograph as a result of compensating changes in groundwater flows across the subarea boundaries. At the end of the simulation period, no simulated pumping trough was evident.

Contours of simulated water levels in December 2008 throughout the basin are shown in **Figure 10** for the calibration simulation (20-foot contour interval) and in **Figures 11, 12 and 13** for Alternatives 1a, 1b and 2, respectively (10-foot contour interval).

Decreasing horizontal hydraulic conductivity along the Laguna Seca Anticline (Alternative 1a) produced a localized steepening of the regional east-to-west water-level gradient (Figure 11). Water levels were elevated on the south side of the anticline and lowered on the north side relative to the calibration simulation. However, the effect diminished with distance downgradient such that water levels in the Northern Coastal subarea were nearly the same as in the calibration simulation. Imposing a uniform and relatively low hydraulic conductivity of 5 ft/d throughout the eastern two-thirds of the Northern Inland subarea (Alternative 1b) produced a uniform gradient in that area, but the direction of flow was more northerly (Figure 12). Furthermore, a localized steepening of the regional gradient appeared along the western edge of the low-conductivity zone, such that downgradient water levels in the Northern Coastal Subarea were nearly the same as in the calibration simulation. As mentioned above, the different set of initial water levels implemented in Alternative 2 gradually converged toward the calibration water levels in the western portion of the Northern Coastal subarea, so that by December 2008 the two sets of contours were quite similar (Figures 10 and 13).

Water balances for each subarea were extracted from simulation results to identify how flows across subarea boundaries responded to the changes in parameters and water levels. Water balances are an accounting of all inflows, outflows and storage change for a defined region within the overall flow system. They include groundwater flows to and from adjoining areas. Comparisons of water balances between the sensitivity tests and the calibration simulation provide additional insight into model behavior and accuracy. For the Northern Coastal Subarea, the key question is why the calibrated model did not simulate the development of a pumping trough in layer 5 when pumping increased in 1995. The answer appears to be that the model responded to the increase in pumping with an increase in inflow across the subarea boundaries rather than responding with storage depletion within the subarea.

Figure 14 shows pie charts of average annual net inflows to model layer 5 in the Northern Coastal subarea during 1995-2013. Net inflows are shown separately from the east (Northern Inland, or NI), south (Southern Coastal, or SC), west (ocean), north (Fort Ord Main Garrison area) and above (Paso Robles Formation, or QTp). Sensitivity tests 1b and 1b forced a reduction in the amount of inflow from the Northern Inland Subarea, and the pie charts show how other components of the water balance responded.

The pie charts show that average annual storage depletion responded only slightly to the decrease in inflow from the east. In Alternative 1b, for example, Northern Inland inflow was 321

AFY less than in the calibration simulation, but the concurrent change in storage depletion was only 3 AFY.

Basically, the change in one boundary inflow caused changes in other boundary inflows rather than a change in storage. A pumping trough represents localized depletion of groundwater storage, so the model will not be able to simulate the pumping trough unless the model is able to accumulate some localized storage depletion. To develop a trough, the model would need to slow down the rate at which drawdown from internal pumping reaches the subarea boundaries.

Two potential causes of the lack of trough development were not explored with model sensitivity tests due to limitations of time and budget. The first is that a trough would be more likely to develop with lower values of hydraulic conductivity and/or storage coefficient[1] within the Northern Coastal Subarea, not just farther east. Lower values would be consistent with at least some available data. For example, the hydraulic conductivity near the Paralta Well in the Northern Coastal Subarea is over 200 ft/d in the HMWRI model, whereas aquifer tests by previous investigators produced an estimate of only 63 ft/d (Fugro West, Inc. 1997). A decrease in hydraulic conductivity or storage coefficient within the subarea might affect the estimate of yield because the relationships between pumping at production wells and water levels at monitoring wells within the subarea would change.

A second potential cause of the lack of trough development is the possible presence of fault barriers within the Northern Coastal Subarea. The Ord Terrace Fault trends northwest and has been mapped as passing through the Northern Coastal Subarea near the Seaside and Luzern wells (see Figure 4)(Clark and others, 1997). However, well logs and the observed lack of pumping responses between the Paralta and Ord Grove wells suggest that the fault—or one of two parallel fault planes—is located between those wells, which is slightly north of the mapped location (Joe Oliver, personal communication, April 4, 2015). Well logs also show a possible second fault plane between the Luzern and Playa wells (south of the mapped fault location). If the Northern Coastal Subarea is compartmentalized by faults, drawdown could be greater near major production wells than without the faults. In this case, however, the two largest production wells (Paralta and Ord Grove) are each in their own compartment, so an intervening fault would not tend to produce substantially different water-level results. Also, there are discrepancies in simulated versus measured water levels at the Playa and MSC wells southwest of both of the above possible faults. Those discrepancies would have to be explained by pumping and aquifer characteristics within that compartment, rather than by the distant effects of Paralta and Ord Grove pumping. Thus, internal faulting could theoretically contribute to the formation of localized pumping troughs, but it is not obvious how the possible fault locations described above would reconcile all of the water-level discrepancies observed in the Northern Coastal Subarea. The sensitivity tests of the model did not include the addition of faults, so this concept remains untested.

[1] The storage coefficient is the amount of water released by an aquifer per unit change in water level. It is a dimensionless volume ratio.

Laguna Seca Subarea Results

Hydrographs of sensitivity test results in the Laguna Seca Subarea are shown for four wells in **Figure 15**. The responses to the alternative simulations were similar at all Laguna Seca wells. Alternatives 1a and 1b both raised groundwater elevations in the Laguna Seca Subarea by restricting outflow into the Northern Inland Subarea, as expected. The alternative hydrographs gradually departed from the calibration hydrograph, but the effect was only a small percentage of the overall declining trend. In other words, the effect was not large enough to substantially alter the overall slope of the hydrograph and hence would not result in a substantially different yield estimate. Alternative 2 commenced with initial water levels tens of feet lower than in the calibration simulation. Given the absence of nearby head-dependent boundaries such as the ocean, water levels remained lower throughout the simulation. In spite of these very different initial conditions, the overall slope of the hydrograph was the same as for the other alternatives and the calibration simulation. Yield in these simulations is indicated primarily by long-term water-level trends. Thus, none of the alternative sensitivity tests appeared to justify a revision of the yield estimate.

Pie charts showing average annual Laguna Seca water balances during 1995-2013 are shown in **Figure 16**. In this subarea, flow at two of the boundaries (adjoining the Southern Coastal and Northern Inland Subareas) is predominantly outflow, so the net flows appear as negative numbers. Net flow across the El Toro boundary is predominantly inflow. Along that boundary, inflows and outflows are both fairly large, and a small net flow simply means the two are nearly equal. It does not mean that little water is moving across the boundary. Also, flow direction is not uniform along the boundary: inflow dominates along the southern segment, whereas outflow is common along the eastern segment.

Sensitivity tests 1a and 1b forced a decrease in outflow to the Northern Inland Subarea, and the pie charts show how other components of the Laguna Seca water balance responded. For example, the largest change in outflow to the Northern Inland Subarea was a decrease of 438 AFY under Alternative 1b. Storage depletion within Laguna Seca under that alternative was 129 AFY less than in the calibration simulation. That change equaled 30 percent of the decrease in outflow to the Northern Inland Subarea. Thus, storage was a larger part of the response than in the results for the Northern Coastal Subarea, but not big enough to greatly alter the slopes of simulated water-level hydrographs.

In the simulation of Alternative 2, net inflow from the El Toro Subarea was almost zero. This can be attributed to eliminating the high water levels in the southeastern corner of the El Toro Subarea, which apparently was the source of net inflow in the calibration and other alternative simulations. However, even the substantial change in inflow and initial water levels in Alternative 2 did not cause a tremendous change in the long-term rate of storage depletion (which decreased by 85 AFY, or 12 percent).

Like the other tests, Alternative 2 did not reveal an obvious error in the HMWRI estimate of Laguna Seca yield. However, the high rate of simulated south-to-north flow across the eastern end of the subarea and the low estimate of operational yield differ from a previous model of the area (Yates and others, 2002). An alternative model calibration incorporating lower values of hydraulic conductivity and/or storage coefficient might match observed historical water levels equally well but with less through-flow and a larger estimate of yield. This is possible because simulated drawdown would tend to be more localized around pumping wells and recharge within the subarea would not tend to flow out as rapidly. To illustrate the feasibility of an alternative calibration, a prior model (Yates and others, 2002) incorporated a hydraulic conductivity value within the Santa Margarita aquifer in the eastern half of the Laguna Seca Subarea that was only about one-fifth as large as the average value for that area in the HMWRI model (5 ft/d versus about 24 ft/d).

TECHNICAL CONCLUSIONS AND RECOMMENDATIONS

Northern Coastal Subarea Conclusions

- Decreasing the rate of east-to-west flow across the Northern Inland Subarea did not result in simulation of a pumping trough in the Northern Coastal Subarea. Hydrographs in the Northern Coastal Subarea were shifted up or down slightly but had the same slopes as in the calibration simulation.

- In the Northern Coastal Subarea, the storage response in model layer 5 to decreased inflow from the east was smaller than the change in flow across the other subarea boundaries (north, west, south and top).

- A plausible alternative hypothesis is that a combination of lower hydraulic conductivity and storage coefficient within the Northern Coastal Subarea might enable the model to simulate more of a trough. This would tend to make pumping drawdown more localized and could lead to a different estimate of subarea yield by changing the relationships between pumping at production wells and water levels at monitoring wells. This alternative hypothesis has not been tested.

- An incorrect assignment of pumping stresses to model layers could theoretically contribute to the lack of a simulated long-term pumping trough in layer 5. However, this mechanism seems unlikely because the model also under-simulated the pumping trough in layers 1-4.

- The hydrographs for sensitivity Alternative 2 gradually converged with the calibration hydrographs over the first 20 years of the simulation. This is the expected response in a flow region where boundary flows increase or decrease to counteract a change in pumping within the region. Because the alternative initial water levels were much higher or lower than measured historical water levels (that is, incorrect), this pattern does not indicate a need to revise the estimate of safe yield.

- Changes in simulated flow across the ocean boundary also accounted for a small fraction of the total response to decreased inflow from the Northern Inland Subarea (10-12 percent). This provides reassurance that large amounts of seawater intrusion are not the reason the model fails to create a long-term pumping trough.

Laguna Seca Subarea Conclusions

- The hydrographs for Alternatives 1a and 1b departed gradually from the calibration hydrographs at most wells, but only by a small amount. The alternative long-term declining trends were not sufficiently different from the calibration trends to justify a revised estimate of operational safe yield.

- Alternative 2 water levels in the southeastern corner of the El Toro Subarea were as much as 120 feet lower than in the calibration simulation. The absence of this large body of stored groundwater substantially decreased simulated groundwater inflow to the Laguna Seca Subarea, but it decreased outflow to the Northern Inland Subarea by a similar amount, so the net effect within Laguna Seca was relatively small.

- The relatively low estimate of Laguna Seca Subarea yield reported by HMWRI does not appear to be entirely the result of excessive amounts of groundwater "draining" out to the Northern Inland Subarea. If this had been the case, then Alternative 1a or 1b would have produced a much smaller declining trend in simulated hydrographs.

- The large difference between the Laguna Seca Subarea water balance in the groundwater model and previous estimates of the water balance illustrate the problem of "non-unique" model calibrations. This refers to a situation where two different models match measured water levels equally well. The current model and the previous model (Yates and others, 2002) both simulated measured water levels reasonably well, but with substantially different aquifer parameters and water balances. Available data are insufficient to determine whether one model is more realistic or better than the other.

General Conclusions

- The HMWRI model is a reasonable representation of the Seaside Basin groundwater flow system. No major errors in assumptions, data or results were identified during this peer review, and the simulated water levels generally matched observed water levels for the historical calibration simulation.

- The model is not entirely consistent with historical data and previous studies, and those differences should be kept in mind when evaluating simulation results. Aspects of model design and input that differ from previous studies include:

    - Hydraulic conductivity is higher in certain key areas, such as the eastern half of the Laguna Seca Subarea and the eastern part of the Northern Coastal Subarea (Santa Margarita aquifer in both cases).

    - The Laguna Seca Anticline is not a barrier to groundwater flow along most of its length.

- There is a large south-to-north flow of groundwater through the eastern part of the Laguna Seca Subarea.

Aspects of model output that differ from measured data or previous studies include:

- The model fails to simulate the historical development of long-term pumping troughs in the Paso Robles and Santa Margarita aquifers in the Northern Coastal Subarea, although simulated seasonal drawdown is reasonable at major production wells .

- The operational safe yield of the Laguna Seca Subarea is substantially smaller than prior estimates.

- These differences do not indicate that the model is incorrect, but rather that it is "non-unique". This means that alternative models with different aquifer parameters and water balances might simulate historical water levels equally well. This further implies that there is some uncertainty in model results.

Recommendations

- The geologic data used by HMWRI to reach conclusions regarding the effect of the Laguna Seca Anticline on groundwater flow should be documented more completely.

- The "operational safe yield" produced by the model (and described in HMWRI reports) should be used for basin management in addition to "natural safe yield", which is a technically flawed concept based on a partial water balance that ignores interactions among water balance components and the effects of human activities on recharge.

- The HMWRI model should be used for estimating the operational safe yield of the basin and subareas, and for simulating the effects of possible management measures. Additional simulations should be completed for management measures likely to be implemented. The additional simulations would test the sensitivity of the results to variations in model inputs that are poorly known yet have a strong influence on results. Input variables can be tested individually or in combinations that reflect different conceptualizations of the hydrogeologic system (for example, relatively high versus low hydraulic conductivity, strong versus weak effects of the Laguna Seca Anticline on groundwater flow, or low versus high initial water levels). If the sensitivity tests produce similar results for the prospective management measure, implementation can proceed with a high level of confidence. If the results are substantially different, model results should be considered relatively uncertain, and implementation should proceed accordingly.

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APPENDIX A. ADDITIONAL REVIEW COMMENTS

Discussions during meetings with HMWRI staff produced the following additional information about the groundwater model:

- The local variability in horizontal hydraulic conductivity in the model (visible in Figure 8) was produced by the automated calibration routine (PEST software). There are very few wells in the Northern Inland Subarea, and none with aquifer test data. Thus, actual hydraulic conductivity throughout this large subarea is largely unknown.

- Variations in the transmissivity of model layers also reflect variations in layer thickness. Geologic data supporting layer thicknesses was good in the Laguna Seca and coastal subareas but limited in the El Toro and Northern Inland Subareas.

- Automated calibration often results in high or low values of hydraulic conductivity around individual wells to improve the match between simulated and measured water levels. These are artifacts of the least-squares optimization algorithm in the calibration software and are not necessarily supported by hydrogeologic evidence. Examples of these "bullseyes" in the hydraulic conductivity distribution can be seen around the Toro 1 well (in layer 2) and Toro 3 well (in layer 3) in Figure 22 of the original modeling report (HMWRI, 2009).

- In the future baseline simulation (2013-2041), flow across the Laguna Seca-El Toro boundary reverses from westward to eastward within the first 10 years of the simulation. This results primarily from the baseline assumption that Cal-Am will discontinue pumping its Laguna Seca wells which causes Laguna Seca water levels to decline more slowly than El Toro water levels, eventually leading to the reversal of the gradient at this boundary.

- In the baseline scenario, the Standard Producer pumping in the Laguna Seca Subarea (where Cal-Am is the only Standard Producer) was eliminated by 2017. In the Natural Safe Yield scenario the Standard Producer pumping is eliminated immediately, and the Alternative Producers are cut back to meet the "natural safe yield" estimated to be 240 AFY.

- In Subtask 1.5 of the Laguna Seca analysis (HMWRI 2014b), the "wells south and east of the LSSA" are the ones listed in Table 3 of the memo, including the Toro wells.

- Declining water levels in the eastern part of the Laguna Seca Subarea and presence of the Northern Coastal Subarea pumping trough both raise the issue of the geographic scale over which overdraft is calculated. Over a broad region such as the entire basin, the water balance might be balanced while problems such as water-level declines or seawater intrusion might be occurring at some locations within that region. A pumping trough could develop in a basin with a balanced overall water budget. There inevitably ensues an argument among local stakeholders over who is "we" when it comes time to pay for a solution to the problem. Should all pumpers in the basin be cut back uniformly, when local wells in the trough itself have a much greater effect? There typically are tradeoffs between the amount of cutback and the area over which cutbacks are applied. One approach would be to vary the percent reduction by distance from the center of the trough (or the location of maximum decline).

- Laguna Seca Subarea groundwater pumping has decreased from the 1,000 AFY estimated by Yates and others (2002 and 2005) to a current amount of about 770 AFY. Cal-Am pumping accounts for 246 AFY of the current total and is expected to drop to zero as triennial pumping reductions continue to be imposed. This would leave approximately 524 AFY being pumped by "Alternative" Producers.

- The lower apparent yield of the Laguna Seca Subarea could also be partly due to the presence of a shallow groundwater system that intercepts rainfall and stream recharge before it reaches the underlying regional groundwater system. A shallow groundwater system could explain the presence of wetlands, riparian vegetation and base flow along Arroyo del Rey in areas where regional water levels are far below the ground surface. The shallow groundwater system was discussed in Yates and others (2002).

Appendix B. Natural Safe Yield

The term "natural safe yield" is a legal term that reflects a simplistic concept of groundwater basin water balances. The term appears in California Water Code sections relating to replenishment districts and municipal water districts (Sections 60350 et seq. and 71689.7). Unfortunately, the concept does not reflect reality in most California groundwater basins. In that respect, it is analogous to the artificial distinction in water rights law between "underflow" and "percolating groundwater". The flaws in the natural safe yield concept are as follows:

- Recharge is not "natural" in developed basins; it is influenced by human activities.
- The natural safe yield equation (see discussion on this below) includes only part of the water balance: pumping and storage change are excluded.
- The concept ignores the effects of pumping on flow across study area boundaries. This problem is exacerbated when natural safe yield is applied at the subarea level.
- By omitting storage change, the equation implicitly assumes that storage change is zero and that pumping will vary each year to maintain zero storage change. This is not how basins are operated. However, it is how a basin in steady state should operate over the long-term, i.e. not considering variations from year-to-year in the amounts of rainfall for recharge.

Each of these problems is elaborated below.

Recharge is Not Natural

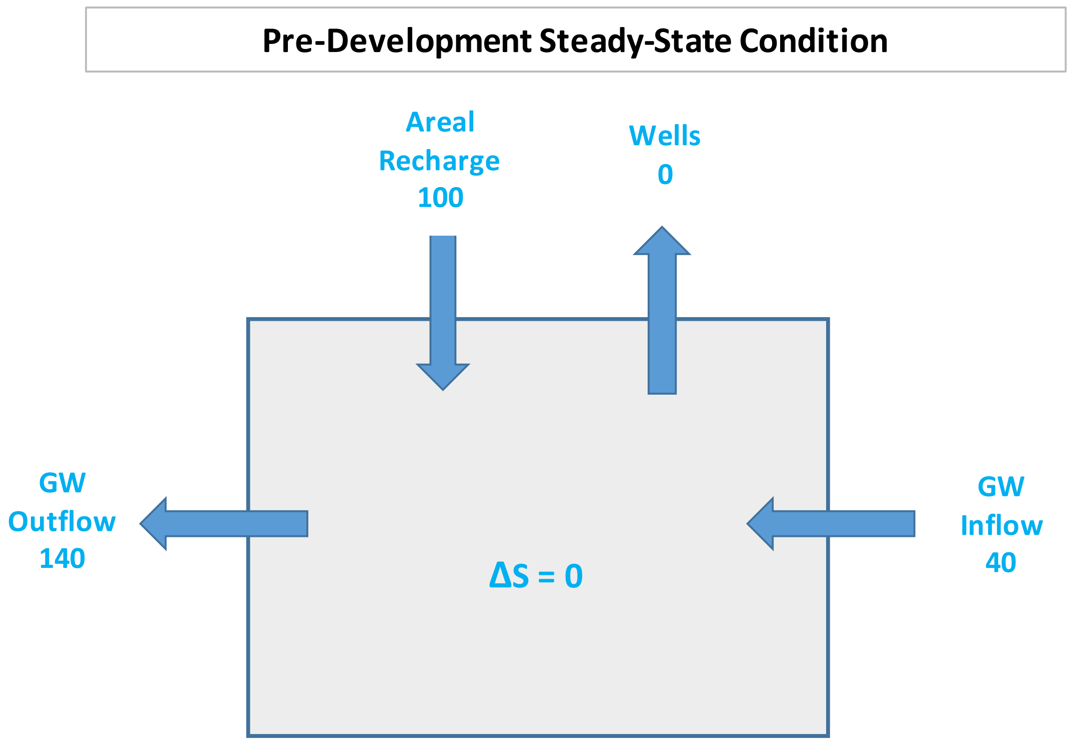
Groundwater recharge, inflow and outflow occurred under natural, predevelopment conditions, and those water balance items had long-term average values. However, recharge is altered by land and water use activities when lands overlying the basin are developed. For example, impervious surfaces alter rainfall runoff and infiltration patterns; replacement of natural vegetation with crops or irrigated urban landscaping changes root depths and soil moisture conditions during the wet season, which alter the amount of rainfall recharge; water and sewer pipes leak; stormwater and wastewater are collected and percolated into the basin through ponds and septic systems; groundwater pumping changes water levels, which alters the rates of stream percolation and groundwater inflow and outflow. Most of these changes increase the amount of recharge relative to pre-development conditions. That increase becomes part of the yield that can be pumped from the basin without inducing long-term water-level declines or other undesirable effects. Thus, the pre-development water balance is not relevant to post-development yield.

Pumping and Storage Change are Omitted

The natural safe yield equation is as follows:

Natural Safe Yield = Recharge + GW Inflow - GW Outflow

This is a partial water balance that omits pumping and storage change. Under pre-development conditions, pumping would have been zero and natural safe yield over a large number of years would also have been zero, because recharge plus groundwater inflow equal groundwater outflow under a condition of zero storage change. In fact, all undeveloped groundwater basins would have a natural safe yield of zero, which implies that there was no opportunity for groundwater development anywhere. The pre-development conditions are illustrated below in Figure 1, which shows a hypothetical water balance diagram.



Natural Safe Yield = Recharge + GW Inflow - GW Outflow

0 = 100 + 40 - 140

Figure 1. Basin Water Balance under Pre-Development Conditions

Following development, pumping changes the water balance, leading to an “unnatural” safe yield. This could also be a steady-state condition, where pumping is balanced by increased recharge, increased groundwater inflow and/or decreased groundwater outflow. This case is shown in **Figure 2**.

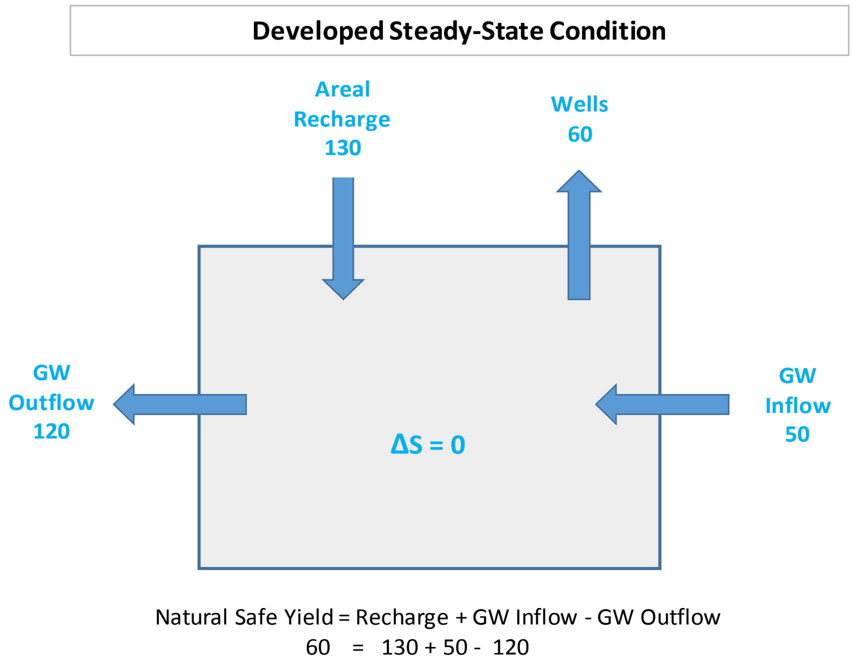


Figure 2. Water Balance for Developed Basin

Notice that the natural safe yield exactly equals the amount of pumping. This is the result of increased recharge under developed conditions combined with head-dependent boundary responses to pumping (see below). Changing the amount of pumping can change the estimate of natural safe yield if pumping is balanced by changes in boundary flows.

Head-Dependent Boundary Effects are Ignored

The natural safe yield concept ignores the existence of head-dependent boundaries, which are boundaries where the rate of flow is affected by the water-level gradient across the boundary. Pumping inside the basin changes the water levels, which changes the rates of inflow and outflow across the boundaries. Head-dependent boundaries can include horizontally adjacent aquifer regions, streams, rivers, the ocean, leakage from overlying aquifers, and evapotranspiration by phreatophytic vegetation.

Storage change is closely linked to head-dependent boundaries. In order for pumping to affect the head-dependent boundaries, water levels must decline, which represents a decrease in groundwater storage. In some cases, water levels stabilize once the change in boundary flow balances the increase in pumping. The system equilibrates at a lower set of water levels, and storage change returns to zero. In other cases—where boundary flows are not capable of balancing the increased pumping—storage depletion continues indefinitely and becomes part of the well yield. The natural safe yield equation implicitly enforces zero long-term change in storage, but it ignores the head-dependent boundaries and the change in storage associated with changing the boundary flows.

An increase in pumping simultaneously decreases storage and changes each of the head-dependent boundary flows. The distribution of the overall response among each of these depends on the location of pumping relative to the boundaries and hydrogeologic characteristics unique to the basin. This means that storage depletion cannot typically be eliminated without increasing net groundwater outflow, because raising water levels within the subarea will increase the rate of outflow. In the case of the Laguna Seca subarea, for example, pumping currently exceeds the HMWRI estimate of natural safe yield by 530 AFY (770 AFY pumping – 240 AFY natural safe yield = 530 AFY overdraft). However, decreasing pumping by 530 AFY would not eliminate storage depletion, because some of the decrease in pumping would be balanced by changes in flows across the subarea boundaries. That is, groundwater inflow would decrease and groundwater outflow would increase. This is one of the reasons why simulated water levels still declined in the central and eastern parts of the Laguna Seca subarea in the "Natural Safe Yield Scenario" (HMWRI 2014b, Figure 16).

Applying the concept of natural safe yield at the scale of subareas exacerbates the problem of head-dependent boundaries, because flows between subareas are head-dependent. For example, the Santa Margarita aquifer in the Northern Coastal Subarea is surrounded by five head-dependent boundaries. The water balance and amount of overdraft in each subarea is thus dependent upon pumping and overdraft in adjacent subareas. The Laguna Seca subarea would be "subsidizing" overdraft in the El Toro and Northern Coastal subareas if it were forced to eliminate its internal storage depletion. This is because groundwater flow from Laguna Seca to those other areas would increase.

Conversely, calculating a lumped water balance for the entire basin can fail to reveal areas of local overdraft and chronic water-level declines. This problem is compounded in the Seaside Basin because the adjudicated basin boundary does not include the entire groundwater flow system. Groundwater in the El Toro Subarea (officially outside the basin boundary) is actually hydraulically coupled to the Laguna Seca Subarea, so that external pumping affects internal water levels.

Calculated Annual Natural Safe Yield Assumes Zero Storage Change

When applied annually, the natural safe yield equation produces yields that are sometimes positive and sometimes negative, because groundwater storage is assumed to remain constant. It is difficult to grasp the physical or practical meaning of a negative safe yield value. Are groundwater users supposed to stop pumping, or even to pay the aquifer back? In practice, pumping from a basin typically remains relatively constant from year to year while recharge and storage changes fluctuate more widely. This simply demonstrates the value of groundwater basins as large storage reservoirs that moderate the effects of variable climate on water supply. The more common definitions of safe yield assume constant pumping and fluctuating storage, which is more consistent with actual operation of groundwater basins in California. When averaged over many years, both approaches should theoretically produce the same estimate of safe yield.