Understanding Complex Models using Visualization: San Bernardino Valley Ground-water Basin, Southern California

Zhen Li and Wesley R. Danskin
U.S. Geological Survey, zhenli@usgs.gov, wdanskin@usgs.gov, San Diego, California, USA

ABSTRACT

Continuing advances in simulation software, such as MODFLOW, have made it possible to represent many different physical processes. Unfortunately, this increase in both the number and complexity of simulated processes can create challenges for scientists constructing the model, decision makers using the results, and the lay public supporting the work. Three examples of visualization are developed to better understand key hydrodynamic interactions in the San Bernardino Valley ground-water basin. Of primary interest are the relations between pumpage and stream losses, and between stream recharge and potential liquefaction. The visualizations combine historical data and model results in animated maps and graphs for the simulation period 1945–2030. The resulting video clips contribute to improved understanding and insights about ground-water flow in the basin and are viewed frequently by project scientists, by water managers at board meetings, and by the lay public on a project website. The full text of this paper, including color figures and animations, is available at http://ca.water.usgs.gov/sanbern/vis/index.html.

INTRODUCTION

Ground water is inherently difficult to understand. In contrast to surface water that is viewed commonly by both researchers and the lay public, aquifers and the ground water flowing through them are largely hidden from view. Key ground-water processes such as evapotranspiration, recharge, stream infiltration, and even pumpage are largely unseen. The interaction between these processes, and the changes in interaction over time, are even more difficult to understand.

This inherent difficulty in understanding ground-water flow means that understanding ground-water models is equally difficult for anyone developing them or trying to interpret their results. During the past two decades, ground-water flow models have evolved to include complex geology, many recharge and discharge processes, and hundreds of stress periods. This evolution has resulted in large model input files and detailed model results that are difficult to understand or critique using traditional techniques. Historically, scientists used maps, hydrographs, and statistics to help develop, calibrate, and critique their models. These continue to be helpful, but cannot represent the complexity of many simulated systems. Fortunately, the increasing computer resources that make complex simulations possible also enable enhanced visualization of model input and output. Use of the Internet allows this visualization to be provided simultaneously to a diffuse audience in a highly efficient manner.

In this paper, three examples from the San Bernardino Valley ground-water basin are used to demonstrate how visualization can help communicate information from a ground-water flow model to different audiences. For additional visualizations, readers are referred to the project website at http://ca.water.usgs.gov/sanbern/vis/index.html.

EXAMPLES OF VISUALIZATION

The ground-water basin of San Bernardino, California, has many of the challenging characteristics described above: a complex ground-water flow system; a simulation model of the system with multiple physical processes and many stress periods; and an abundance of decision makers who are interested in, and rely on, results of the model (Danskin and others, 2006). The MODFLOW model developed for this alluvial basin includes two layers representing the unconfined and confined flow systems, respectively. Of primary interest in the San Bernardino area are the relations between pumpage and stream losses, and between stream recharge and potential liquefaction. To better understand these relations, it is most effective to visualize spatial and temporal variations for one physical process at a time, then to combine these single-process visualizations for the key relations. The following visualizations demonstrate three individual physical processes including ground-water pumpage, streamflow gains and losses, and depth to ground water. The animations were generated with visualization software (Tecplot, http://www.tecplot.com)[1] using the San Bernardino Valley ground-water flow model, and are posted on the Internet as video clips.

Visualization 1: Ground-water pumpage. In this synchronized animation, ground-water pumpage data is presented in four dimensions (fig. 1). On the map, the size of the dots is proportional to the average annual extraction rate for each pumping well. Even though the total annual pumpage stays relatively constant, as indicated in the graph, the areal distribution of pumpage is skewed toward the center, downstream part of the basin. Of particular interest is the predominance of pumpage near the downstream reach of the Santa Ana River.

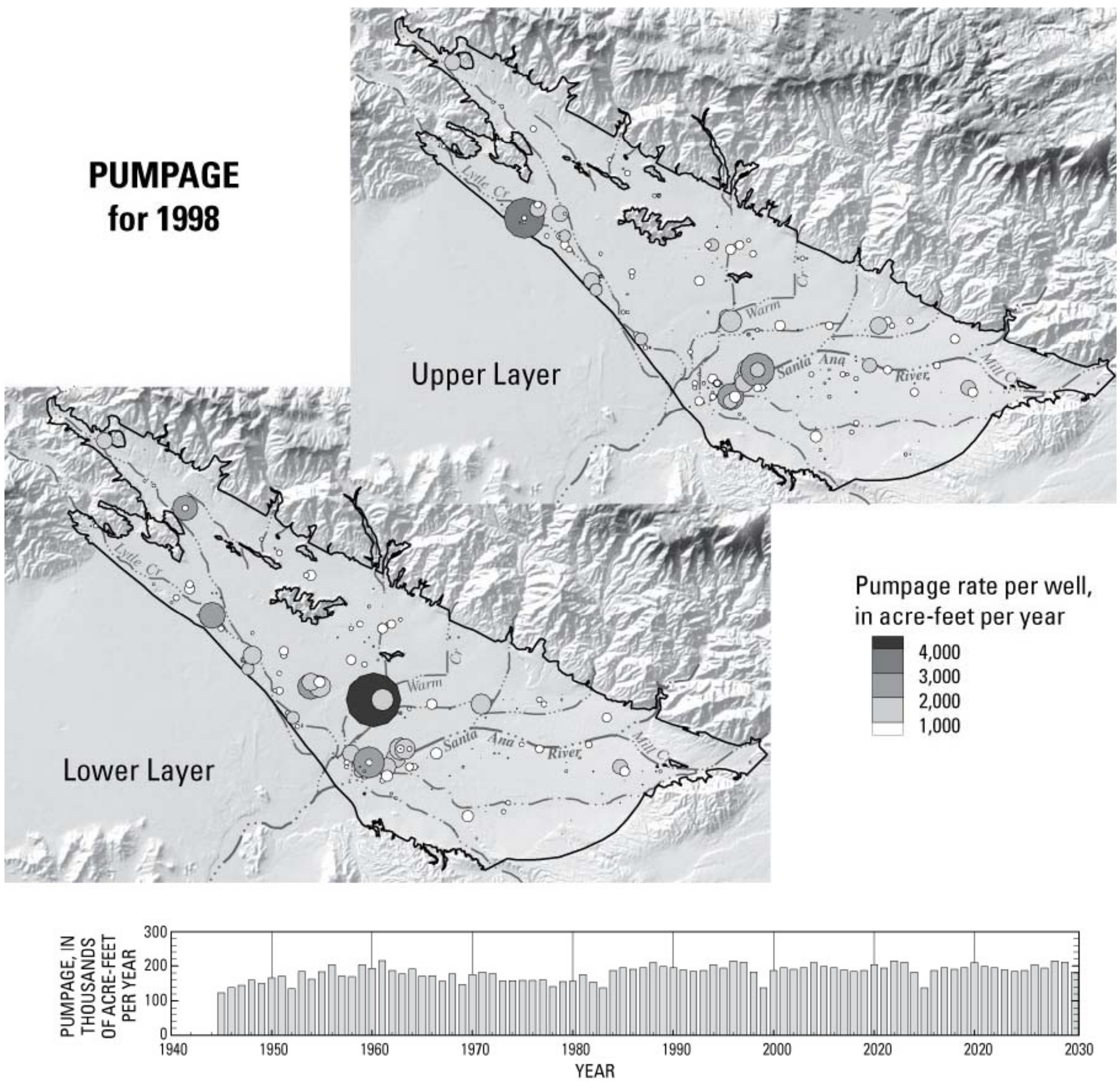

Figure 1. Annual ground-water pumpage for individual wells for each model layer (map) and for the entire San Bernardino Valley ground-water basin, California (graph). Colored animation of this figure is available at http://ca.water.usgs.gov/sanbern/vis/animations/Pumpage.html.

Rather than using traditional one- or two-dimensional methods to view historical pumpage data, animation allows the viewer to see how pumpage is distributed within and between the upper and lower model layers, and how pumpage varies from year to year at individual wells and across the basin.

Visualization 2: Streamflow gains and losses. This animation shows gaged stream inflows and outflows as well as simulated gains and losses for the entire stream network in the ground-water flow model. Blue (light gray, fig. 2) indicates stream loss to the ground-water system; red (black, fig. 2) indicates stream gain for each model cell. The graphs summarize annual values of gaged flow and simulated gain and loss. The linked animation of the map and graphs illustrates important spatial and temporal characteristics of the stream-aquifer system.

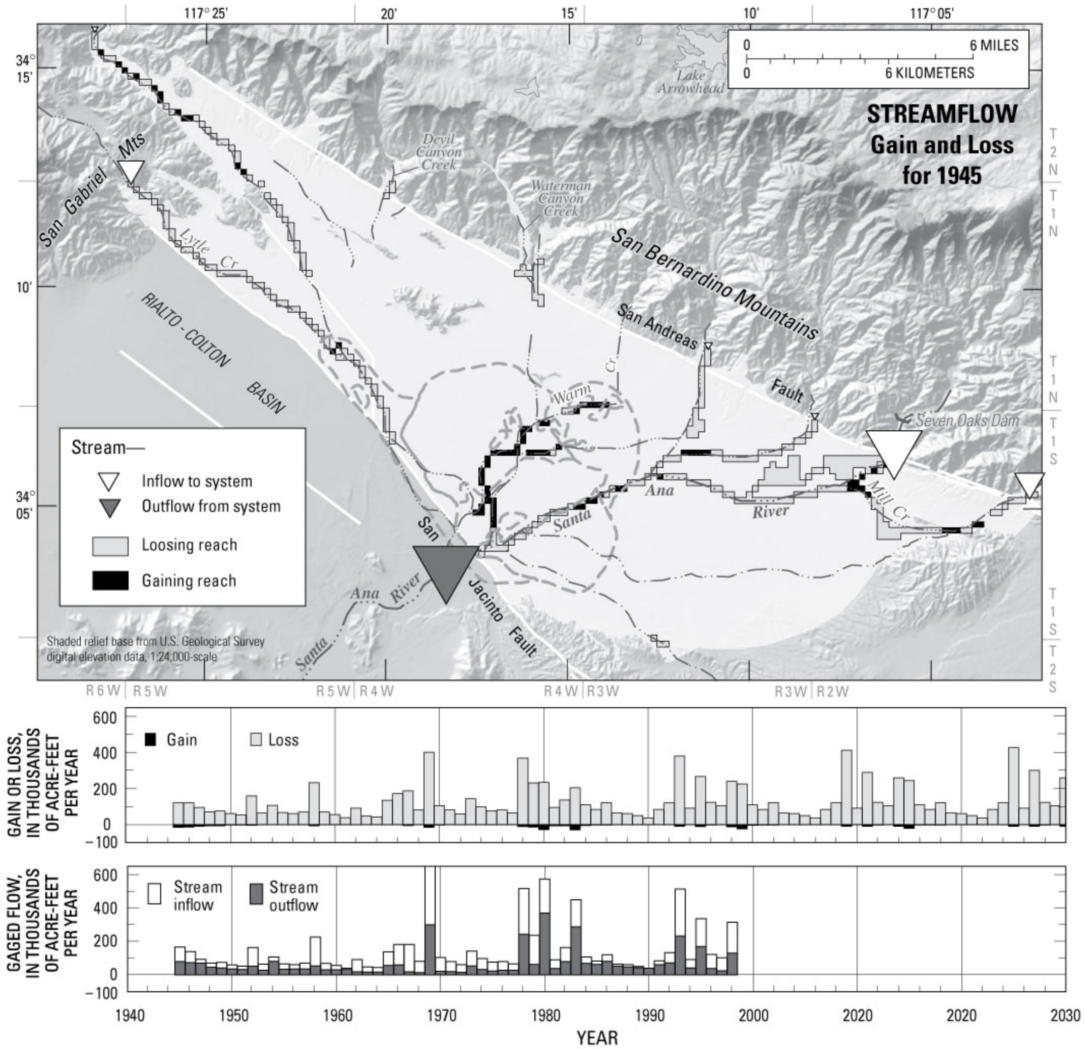

Figure 2. Simulated streamflow gains and losses (map) and gaged stream inflow and outflow (graph) for the San Bernardino Valley ground-water basin, California. Colored animation of this figure is available at http://ca.water.usgs.gov/sanbern/vis/animations/StrInExfil.html and http://ca.water.usgs.gov/sanbern/vis/animations/StrInOut_B.html.

Gaged inflows of the Santa Ana River, Mill Creek, and Lytle Creek are significantly greater than inflows from other creeks. Gaged outflow occurs near the San Jacinto Fault where streams converge and exit the basin. During years with above-average runoff, streamflow loss occurs along the entire length of both major streams, the Santa Ana River and Lytle Creek. During years with average or below-average runoff, streamflow loss occurs only near the mountains. Streamflow gains occur primarily downstream near the center of the basin, in particular along Warm Creek. As indicated in the lower graphs, streamflow gains occur during earlier years (1945–50), and during a sequence of years with above-average runoff (1978–85 and 1993–98).

An advantage to this detailed, animated viewing of model results is an opportunity for the scientist to better calibrate the model to observed spatial and temporal responses of the stream-aquifer system. For example, the gains of Warm Creek, but not the Santa Ana River were well documented prior to the modeling, but much of the documentation was from personal observations, not measured data. This animation illustrates that the simulated stream-aquifer system responds similar to the qualitative observations, thereby giving more credence to the model calibration.

Decision makers can see from this visualization that during wet years the basin rejects some of the additional runoff, and that this rejected recharge may flow downstream to other potential users, as indicated by the large outflow in the same year. Based on these model results, and ideally confirmed by streamflow measurements, decision makers might be prompted to investigate additional use of off-channel artificial-recharge basins to capture more of the local runoff.

Through the use of these animated visualizations, the lay public, without knowledge of the intricacies of ground-water flow and stream-aquifer interaction, can appreciate the complexity of the system that the scientists are trying to understand and the decision makers are trying to manage. The knowledge gained from the visualization may increase their awareness of the importance not only of modeling, but also of continued data collection.

Visualization 3: Depth to ground water. This animation illustrates the depth to ground water, a vitally important water-management criterion used to prevent liquefaction and land subsidence (fig. 3). Because the basin is bounded by two major faults, the San Andreas on the north and the San Jacinto on the south, liquefaction during a major earthquake is a constant concern (Ziony, 1985).

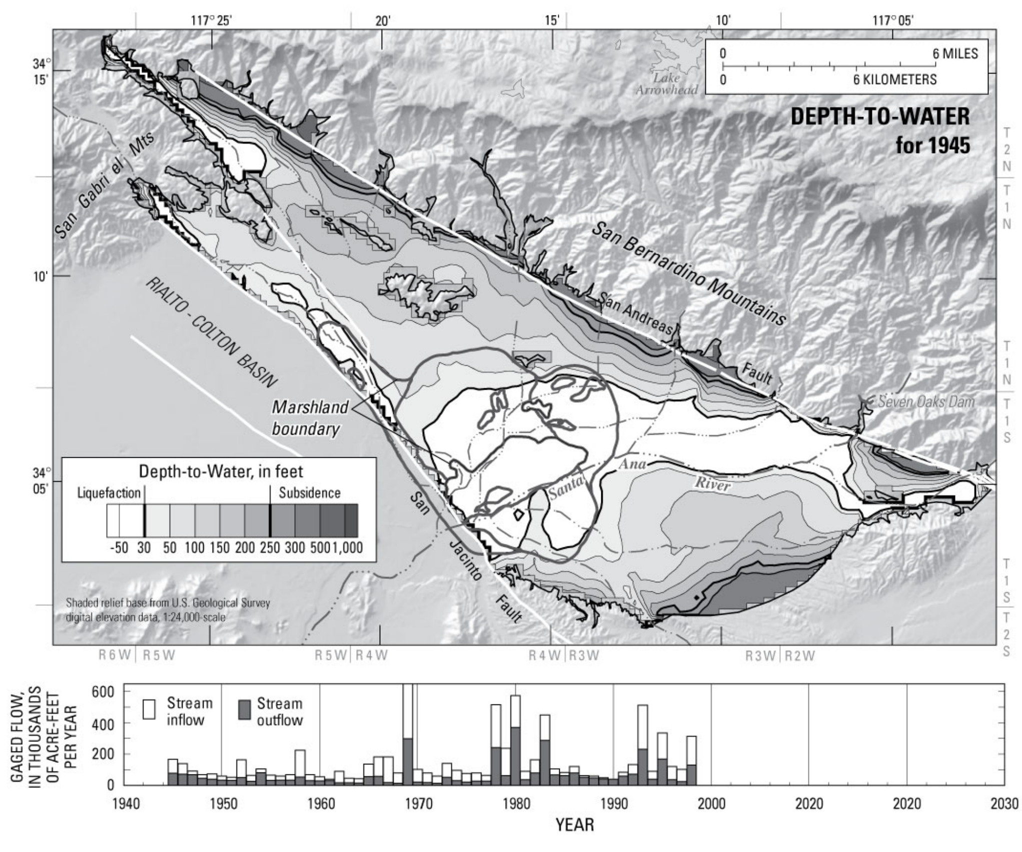

Figure 3. Simulated depth to water (map) and gaged stream inflow and outflow (graph). Colored animation of this figure is available at http://ca.water.usgs.gov/sanbern/vis/animations/DTWm.html.

An area of particular concern is the former (circa 1900) marshland, underlain and surrounded by an area of fine-grained deposits (outlined with green line; dark line in figure 3). To prevent liquefaction, the depth to ground water needs to be at least 30 feet below land surface (Matti and Carson, 1991). To prevent land subsidence, depth to ground water should not exceed the historical maximum in the area of the fine-grained deposits, which was about 250 feet.

In this animation, former marshland and fine-grained areas are the focal point. When the areas turn white, liquefaction is possible; when the areas turn yellow or red, subsidence is likely. In earlier years, the shallow depth to water (white zone) contracts dramatically as a result of continuous pumping and low stream inflow. The area expands in the 1980s and the late 1990s in response to a sequence of wet years with much greater stream inflow. The animation allows a quick comparison with historical conditions: land subsidence occurred in the 1960s, and high ground-water levels were present in the 1980s. Perhaps more importantly, the animation shows the likely reoccurrence of these conditions if historical runoff (1983–98) is repeated during years 1999-2030.

DISCUSSION

The three animations can be viewed individually as shown above, or linked to run simultaneously as done on the project website (http://ca.water.usgs.gov/sanbern/vis/, click video in "Stream infiltration and exfiltration with synchronized pumpage"). Comparing the animations using either technique facilitates understanding the relations among pumpage, streamflow gains and losses, and liquefaction potential. Animations 1 and 2 show that the areal distribution of pumpage allows streamflow gains to occur in Warm Creek but not the Santa Ana River. Animations 2 and 3 show that liquefaction potential comes and goes over time, is contemporaneous with a sequence of above-average runoff years, and is not controlled by nearby pumpage. Recharge from runoff appears to have a much greater influence on depth to ground water than pumpage does. Perhaps most important, the animations give a sense of the large areal magnitude and relatively quick reoccurrence of the liquefaction potential.

These basic concepts gained from the animations seem to be equally apparent to the authors who created the model, to the decision makers who are using the model results, and to the general public who is seeking to understand local water resources. For each audience, the animations are able to communicate the basics of the complex hydrogeology of the San Bernardino Valley quickly and efficiently. As new questions emerge, the animations can serve as accessible means to improve specific and general understanding of the ground-water flow system.

REFERENCES

Danskin, W.R, McPherson, K.R., Woolfenden, L.R., 2006. Hydrology, description of computer models, and evaluation of selected water-management alternatives in the San Bernardino area, California, U.S. Geological Survey Open-File Report 2005-1278, 178 p. and 2 pl.

Matti, J.C., and Carson, S.E., 1991, Liquefaction susceptibility in the San Bernardino Valley and vicinity, southern California—a regional evaluation: U.S. Geological Survey Bulletin 1898, 53 p.

Ziony, J.I., ed., 1985, Evaluating earthquake hazards in the Los Angeles region—an earth-science perspective: U.S. Geological Survey Professional Paper 1360, 505 p.

[1] Mention of trade names or manufacturers does not imply endorsement by the U.S. Government.