APPLICATION OF THREE-DIMENSIONAL GEOLOGIC MODELS IN DEVELOPING GROUNDWATER-FLOW MODELS

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INTRODUCTION

Three-dimensional (3D) geologic models have been used to define the geologic framework of complex regional aquifer systems. These models define the stratigraphy and structure of lithologic units using data points defined by surface contacts, drill-hole data, and (or) geophysical data. Where data are missing, data points are derived from known data points on the basis of geologic principles. In recent years, 3D geologic models have been used to define the model domain and hydraulic properties of regional 3D groundwater-flow models. This paper illustrates how 3D geologic models were used to describe the geologic framework and provide the basis for groundwater-flow simulations of the Central Valley aquifer system in California and the Death Valley regional groundwater flow system (DVRFS) in Nevada and California. The groundwater availability of the Central Valley of California is being assessed as part of the U.S. Geological Survey (USGS) groundwater availability program (Faunt 2009). The Death Valley regional groundwater flow system (DVRFS), which contains the Nevada Test Site and Yucca Mountain, is being studied in cooperation with the Department of Energy (Belcher 2004). The geologic conditions and groundwater use in the Central Valley and the Death Valley regions are quite different, providing an opportunity to compare the 3D geologic modeling approach in two different geohydrologic regimes.

CENTRAL VALLEY

California's Central Valley has been one of the most productive agricultural regions in the world since the 1950s. Most crops are irrigated with surface-water diversions and (or) groundwater pumping. About one-fifth of the Nation's groundwater pumping is from the Central Valley aquifer system. The Central Valley contains many communities, industries, and ecosystems that depend directly or indirectly on groundwater; consequently, the competition for available groundwater resources is intensifying. The objectives of the Central Valley groundwater availability study were to develop an understanding of the groundwater system and to develop modeling tools to quantify the region's water resources, and the human activities and climate variability affecting them so that possible future water-use conflicts could be reduced or avoided. In order to understand the status of the groundwater system, the geologic framework, hydraulic properties, and storage properties of the aquifer system were assessed.

The Central Valley is a large sediment-filled trough between the Coast Ranges and the Sierra Nevada. The valley is filled with sediments of deep marine, shallow-marine, deltaic, and continental origin. Most of the sediments comprising the heavily pumped aquifer system are of continental origin and are derived from the major rivers and their tributaries that drain the adjoining mountains. The hydrologic system in Central Valley is complex, in part, because of the heterogeneous nature of the valley fill. In this study, a texture model was developed to define the hydraulic properties of the valley-fill deposits. Sediment texture was defined as the percentage of coarse-grained sediment within a specified subsurface depth interval (Laudon and Belitz 1991). Although grain shape and sorting are often included as texture characteristics, they were not included as part of the texture classification used in this study. The texture model was developed by compiling and analyzing approximately 8,500 drillers' logs, describing lithologies up to 950 meters (m) below land surface. The lithologic descriptions on the logs were simplified into a binary classification of coarse- and fine-grained sediment. The percentage of coarse-grained sediment was computed for each 15-meter depth interval. Geostatistical techniques (3D kriging) were used to analyze spatial correlations of the percentages of coarse-grained textures using a 1.6 km spatial grid at 15-m depth intervals from land surface down to 700 m below land surface (Figure 1). The texture model reflects estimated regional, spatial, and vertical heterogeneity in the aquifer system. The heterogeneous texture model correlates to sediment source areas, independently mapped geomorphic provinces, and factors affecting the development of alluvial fans--demonstrating the utility of using readily obtained drillers' logs as a source of lithologic information.

The texture model was used to assess the vertical and lateral hydraulic conductivity distribution and the storage property distribution for the 3D numerical groundwater flow model developed for the region. The texture model was upscaled form 15-m depth intervals to a 10-layer groundwater flow model. A method for estimating hydraulic conductivity based on the correlation of percentage of coarse-grained deposits to hydraulic conductivity was developed. The horizontal and vertical hydraulic conductivity estimates for each textural end member are based on the power mean of the hydraulic conductivity of the coarse- and fine-grained end members and the percentage of these end members in each model cell. In the case of the Central Valley properties, the power mean results in a geometric mean in the horizontal direction and averages approaching a harmonic mean in the vertical direction. Initially, only one value of hydraulic conductivity for each of the end members was used. Geomorphic provinces and stratigraphic units were used to subdivide the domain because the details in the hydraulic observations could not all be represented with just two end members.

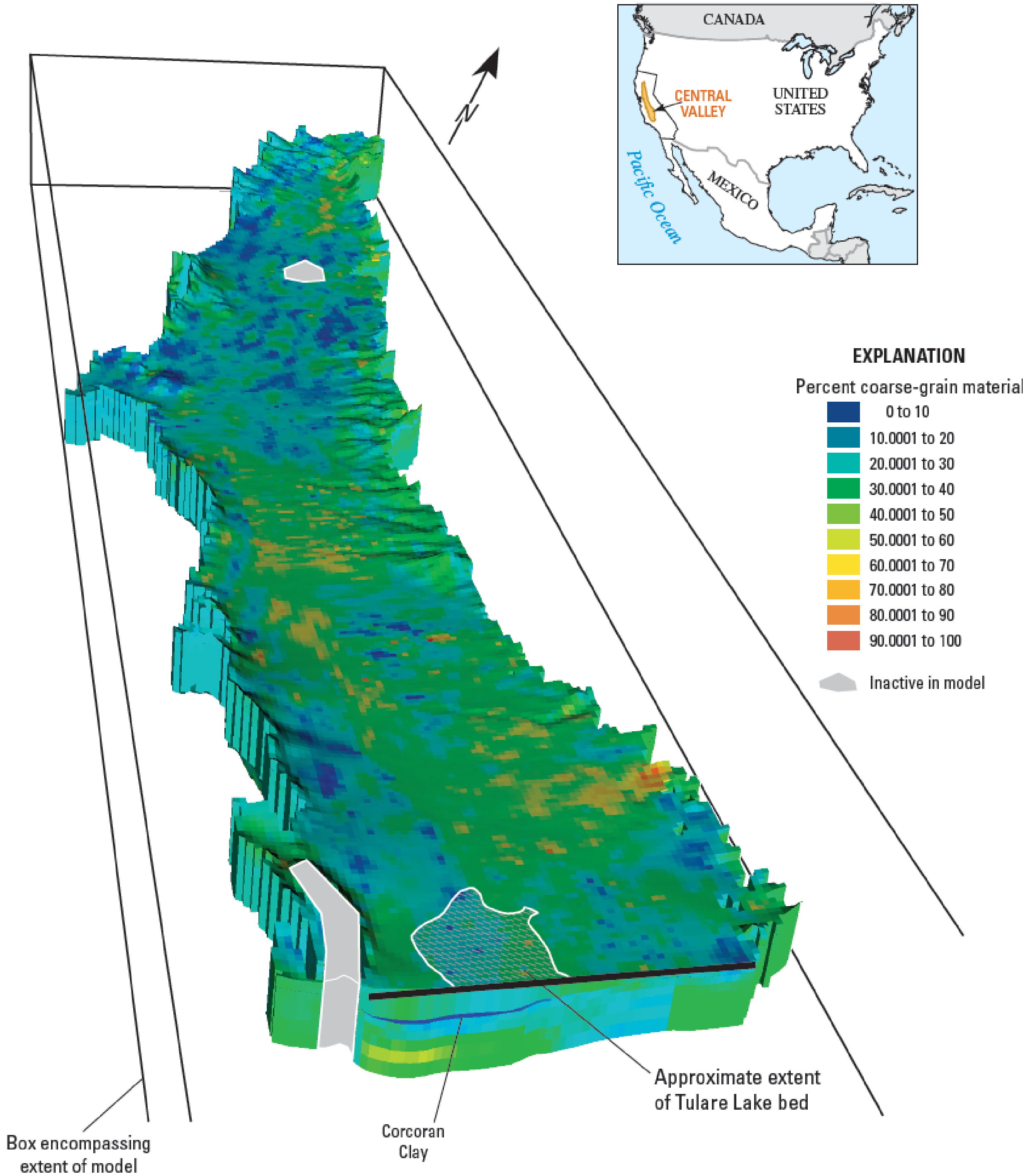

Figure 1. Block diagram of the northern three-fourths of the Central Valley texture model with cutaway in south.

DEATH VALLEY

The DVRFS occupies a scarcely populated desert region in Nevada and California where groundwater is used minimally but is the primary water source. Regional groundwater flow predominantly is through a thick Paleozoic carbonate rock sequence affected by complex geologic structures from regional faulting and fracturing that can enhance or impede flow. Spring flow and evapotranspiration are the dominant groundwater discharge processes. Relative to the Central Valley, small amounts of groundwater are withdrawn for agricultural, commercial, and domestic uses. Interest in the DVRFS is driven by the need to: (1) understand the groundwater flow paths and travel times associated with potential movement of radioactive material from the Nevada Test Site (NTS); (2) characterize the groundwater system in the vicinity of the proposed high-level radioactive waste repository at Yucca Mountain; and (3) address a variety of potential effects of groundwater usage on users down-gradient from the NTS and Yucca Mountain, including the agricultural communities in the Amargosa Desert, Death Valley National Park, and Native American interests (Belcher, 2004).

The DVRFS consists of Precambrian and Paleozoic crystalline and sedimentary rocks, Mesozoic sedimentary rocks, Mesozoic to Cenozoic intrusive rocks, Cenozoic volcanic tuffs and lavas, and late Cenozoic sedimentary deposits. Geologic data from geologic maps, cross sections, and borehole lithologic logs were used to subdivide these rocks or deposits into 27 separate hydrogeologic units (HGUs). A 3D geologic model, referred to here as a hydrogeologic framework model (HFM), was developed to represent the geometry of the HGUs (Figure 2). Approximately 70 regional geologic cross sections, reflecting a consistent interpretation of regional structural style, and approximately 7,000 lithologic contacts between HGUs from borehole information provided the subsurface control for the HFM. Gridded surfaces from other 3D geologic models constructed for the Nevada Test Site (NTS) and Yucca Mountain also were used. The HFM defines regional-scale hydrogeology and structures for thicknesses ranging from 4,000 m to 8,000m. The model has 1,500-m horizontal resolution and variable vertical thickness for the HGUs. Faults thought to be hydrologically significant were used for offsetting HGUs in the HFM.

The HGUs were used to develop the vertical and lateral hydraulic conductivity distribution and the storage-property distribution for the DVRFS 3D numerical groundwater-flow model. Available geohydrologic information indicated that the HGUs needed to be subdivided into zones to better represent the variation in hydraulic properties in individual HGUs resulting from facies changes, different structural provinces, and other types of alterations. A total of about 100 HGUs and related zones were identified in the HFM. The hydraulic conductivity and storage properties of the 27 HGUs and related zones were estimated on the basis of pumping tests, values reported in the literature, and previous models in the area. Initially, the hydraulic properties were lumped into four classes: valley fill aquifer, volcanic rocks, carbonate aquifer, and confining units. The groundwater-flow model has the same 1,500-m horizontal resolution as the HFM; however, the vertical resolution of the two models is different. The groundwater-flow model separated the DVRFS into 16 layers of variable thickness that are parallel to the water table and thicken with depth. The hydraulic properties stored in the HFM were upscaled to the groundwater-flow model by utilizing the HUF Package of MODFLOW (Andermann et al. 2000). As calibration proceeded, the hydraulic conductivity and storage properties assigned to the different classes were modified on the basis of the HGUs and zones in the HFM until simulated hydraulic head and discharge measurements approached measured values.

SUMMARY AND APPLICATION OF 3D GEOLOGIC MODELS IN FLOW MODELS

The application of 3D geologic models for developing and constraining groundwater-flow models was presented for two different geologic settings: (1) Central Valley–an alluvial aquifer system and (2) Death Valley–a carbonate-rock aquifer system. In the alluvial aquifer system, the geologic model was defined utilizing texture information, and in the carbonate rock aquifer system the model was defined using mapped HGUs. Both groundwater-flow models started with a simple set of parameters, representing only the dominant subsurface characteristics represented by the geologic models. In both geologic settings, the use of a small number of parameters at the beginning of the groundwater-flow model calibration allowed for a clear evaluation of gross features of the subsurface. Subsequently, composite scaled sensitivities, and flow and head observation residuals, were used to determine whether the geologic models could be subdivided to produce additional parameters that could be estimated with the available data. In the future, uncertainty in the results of the groundwater-flow model simulations could be reduced by improving on the quality, interpretation, and representation of the 3D geologic model and the spatial variability of material properties within the model.

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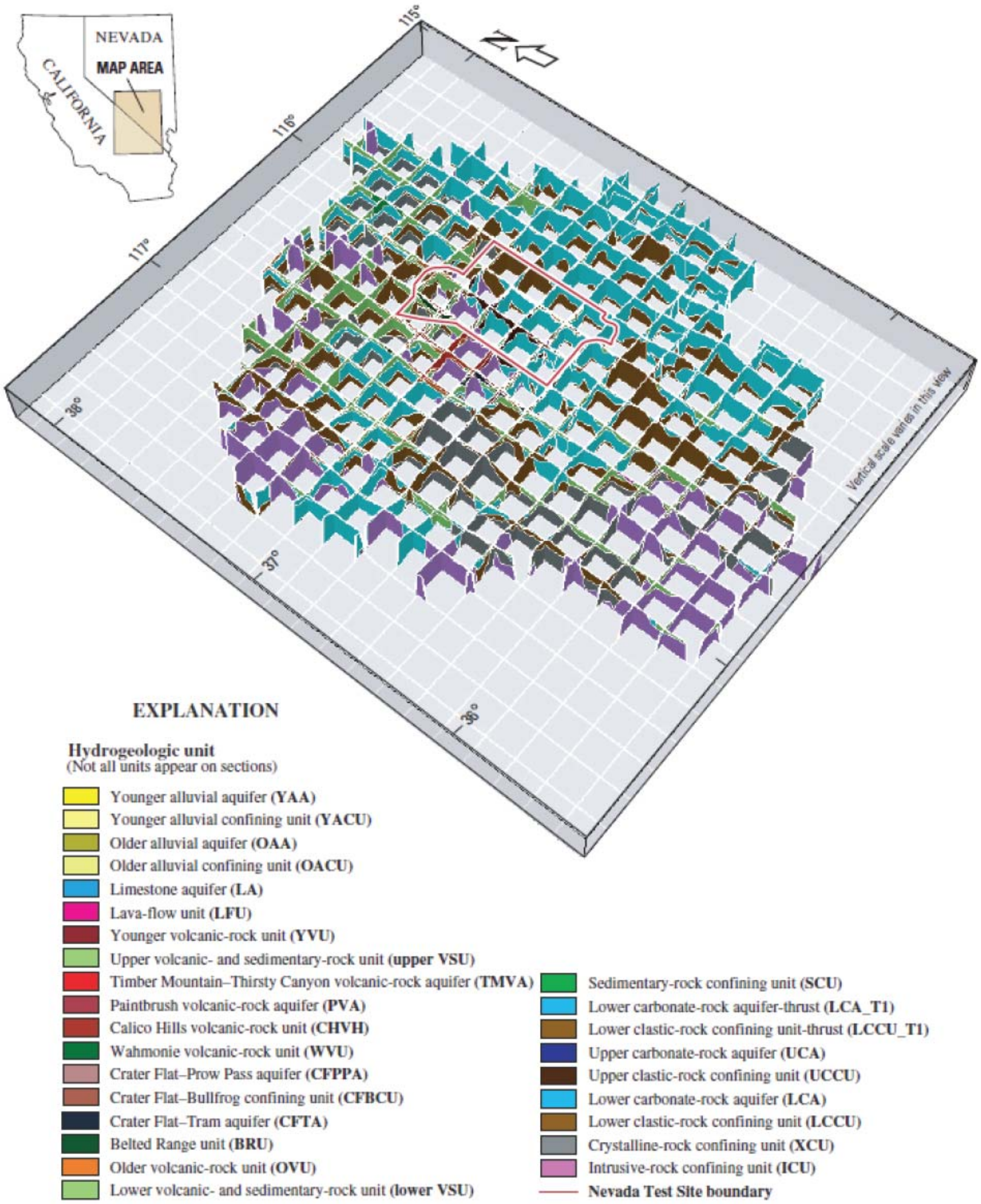

Figure 2. Oblique view of the three-dimensional hydrogeologic framework model for the Death Valley regional flow system. A fence diagram shows the distribution of the hydrogeologic units.