WHITE PAPER

UNITED WATER CONSERVATION DISTRICT GROUNDWATER FLOW MODEL— SUMMARY OF OBJECTIVES, METHODS, AND INPUT FROM EXPERT-PANEL REVIEW

UNITED WATER CONSERVATION DISTRICT

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This White Paper is preliminary and is subject to modification based on future analysis and evaluation.

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1 INTRODUCTION

United Water Conservation District (United) is charged with managing groundwater resources in part to all of eight interconnected groundwater basins in Ventura County, California, and is a participant in development of Groundwater Sustainability Plans (GSPs) for seven of these basins under California's Sustainable Groundwater Management Act (SGMA). United is in the process of calibrating a numerical groundwater-flow model (the United model) constructed using U.S. Geological Survey's (USGS) Modular Three-Dimensional Ground Water Flow Model (MODFLOW) code to represent five of these interconnected basins. United intends to use its model as a planning tool to maximize the regional benefits of United's conjunctive use operations and projects operated by other local agencies. The United model may also be helpful for simulating various future pumping scenarios in support of groundwater management agencies' efforts to estimate basin-specific sustainable yields and evaluate overdraft mitigation measures at a suitable level of detail for planning and implementation.

2 OBJECTIVES

United, the Fox Canyon Groundwater Management Agency (FCGMA), and other stakeholders tasked with management of groundwater resources in the Santa Clara River Valley and Pleasant Valley groundwater basins of Ventura County (study area) have been working toward quantifying sustainable yields and mitigating impacts of groundwater overdraft for decades. Prior to promulgation of SGMA in 2014, United and FCGMA realized that a detailed groundwater model would be needed to effectively interpret historic groundwater-level trends and, more importantly, forecast impacts of potential future groundwater extraction, recharge, and management scenarios under consideration within the study area. As a result, United began developing a detailed groundwater flow model in 2012 to address aquifer-specific issues and to evaluate the feasibility of potential water-supply-development projects within the study area.

The United model is anticipated to be used by both United and FCGMA for planning and groundwater management activities, which will require predictive simulations of potential future pumping, recharge, and land- and water-use scenarios in Ventura County. United intends to use the model as a planning tool to maximize the regional benefits of its conjunctive use operations and projects operated by other local agencies. The FCGMA may use the model to evaluate the effectiveness of groundwater management strategies and regulatory policies on eliminating overdraft and saline-intrusion in the coastal areas of the Oxnard Plain. The initial and most pressing application of the model by the FCGMA may be to evaluate impacts of potential future water-use scenarios during development of sustainable-yield estimates for each basin, in support of groundwater sustainability planning. Eventually (in 2018) the extent of the active model grid will be expanded to include additional groundwater basins up the Santa Clara River Valley (Santa Paula, Fillmore, and Piru basins). At present, these basins are within the model domain, but are occupied by inactive grid cells.

3 METHODOLOGY

United's model development approach generally conformed with guidance provided by the U.S. Geological Survey (USGS; Reilly and Harbaugh, 2004) and the California Department of Water Resources (DWR) (2016). The United model is similar in scope to a two-layer MODFLOW model developed by the USGS in the 1990s (Hanson and others, 2003) for approximately the same domain (the USGS model). The active domain of the United model (at present) includes an area of approximately 150 square miles representing the following basins, as they are defined in DWR Bulletin 118 (DWR, 2003):

- Oxnard and Mound sub-basins of the Santa Clara River Valley basin
- Pleasant Valley basin
- western part of Las Posas Valley basin

The calibration period for the United model includes calendar years 1985 (when semi-annual reporting of groundwater pumping from wells became available throughout the modeled area) through 2012. A verification period of 2013 through 2015 was recently added to the United model. The calibration period for the USGS model includes calendar years 1891 through 1993. Much of the pumping included in the USGS model prior to 1985 was assumed based on crop production and population estimates.

The USGS model was an effective starting point for developing an understanding of aquifer boundary conditions and basin-scale hydraulic effects of pumping and recharge. However, the relatively coarse discretization of the USGS model (uniform 1/2-mile grid spacing, and the representation of six to seven distinct aquifers--several of which are separated by thick aquitards--with two model layers) limited the degree to which it could be calibrated and used to evaluate impacts of future pumping/recharge scenarios on specific aquifers.

The main structural differences between the United model and the USGS model are related to how aquifers are represented by model layers. The USGS model excluded the semi-perched (uppermost) aquifer, represented the five main confined aquifers in the region as two model layers, and modeled aquitards indirectly. In the United model, 13 hydrostratigraphic units (seven aquifers and six aquitards) are currently simulated as explicit layers.

Although calibration statistics for the USGS model indicated that simulated heads were commonly within 20 feet of measured heads in the upper aquifer system (UAS) near the coastline, model residuals exceeding 50 feet were common in the lower aquifer system (LAS) throughout the study area, and in both the UAS and LAS inland from the coast. A subsequent adaptation of the two-layer model by United, adding a third model layer to represent the shallow semi-perched aquifer system overlying the UAS and LAS in the study area, allowed simulation of groundwater conditions at the near-surface, but did not significantly improve calibration in the UAS and LAS, where most pumping occurs. Therefore, United went to considerable effort to review and update the hydrostratigraphic conceptual model for the study area, and then to construct the current 13-layer MODFLOW model, as described herein.

3.1 UNITED MODEL CONSTRUCTION

The updated hydrostratigraphic conceptual model for the basins was developed from review of geophysical and lithologic logs from hundreds of gas, petroleum, and water wells in the study area, followed by preparation of detailed hydrostratigraphic cross sections (locations of these cross sections are shown on Figure 1), resulting in significant adjustment to aquifer top and bottom elevations in key areas. In addition, the geometry of some faults and folds was adjusted in the conceptual model during construction of the cross sections. As noted above, the United model explicitly simulates all seven aquifers present in the study area, as well as the aquitards between the aquifers, as individual model layers. Inclusion of all six aquitards as model layers will allow simulation of land subsidence and solute transport (e.g., nitrate or chloride) across aquitards, if needed in the future.

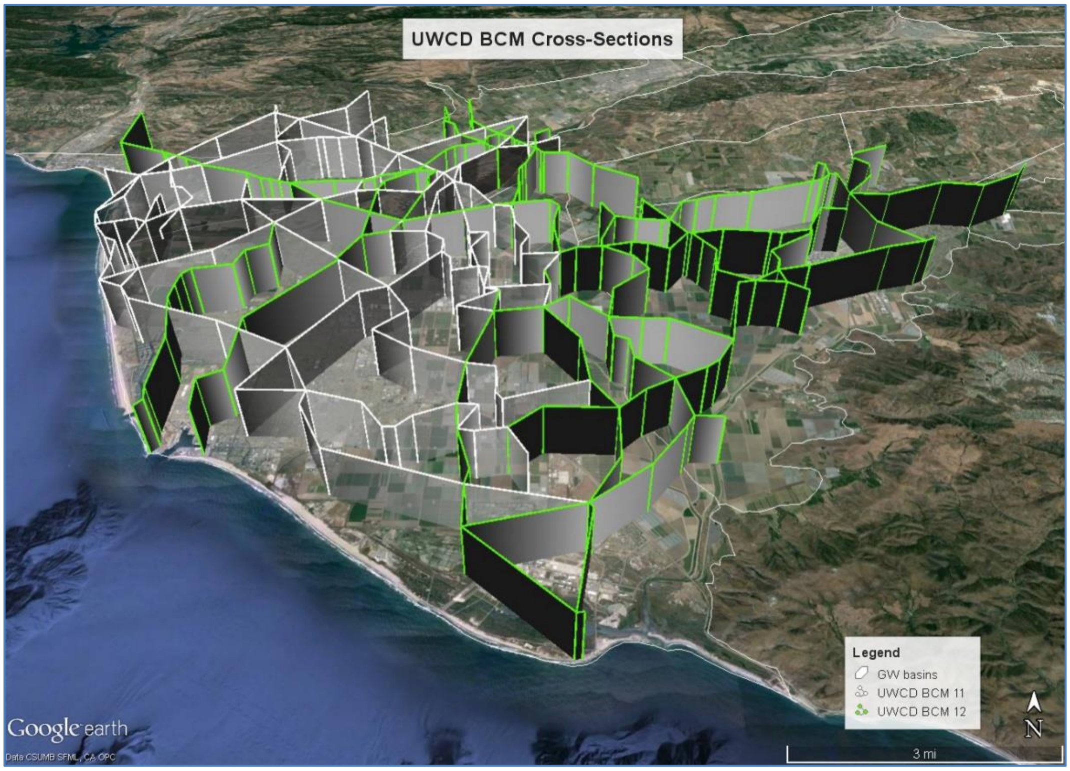

Figure 1. Locations of Hydrostratigraphic Cross Sections Prepared During Conceptual Model Development

The United model was constructed using the USGS's MODFLOW-NWT software, version 1.0.9 (Niswonger and others, 2011). The model domain and active grid are shown on Figure 2, and includes the Oxnard Plain (including the Forebay), Pleasant Valley, Mound, and West Las Posas basins, part of the Santa Paula basin, as well as the submarine (offshore) outcrop areas of the principal aquifers that underlie these basins. The calibration period of the United model was January 1985 through December 2012, with 336 monthly stress periods with variable recharge and pumping rates. The calibration period was selected based on the following considerations:

- The timeframe for model calibration was selected to span several cycles of dry and wet years so that the model can be demonstrated to simulate a wide range of climatic conditions. This calibration period included several dry periods, including the severe drought that culminated in 1990.
- The model calibration period also was a time of major changes in groundwater management in Ventura County, including the establishment of FCGMA and the efforts of the 1980s to reduce pumping in the UAS.
- Reporting of various data, including groundwater level measurements and pumping records, became more detailed and extensive starting in the early- to mid-1980s.

Monthly stresses (including extraction and recharge) were also added for the model verification period, from January 2013 through December 2015.

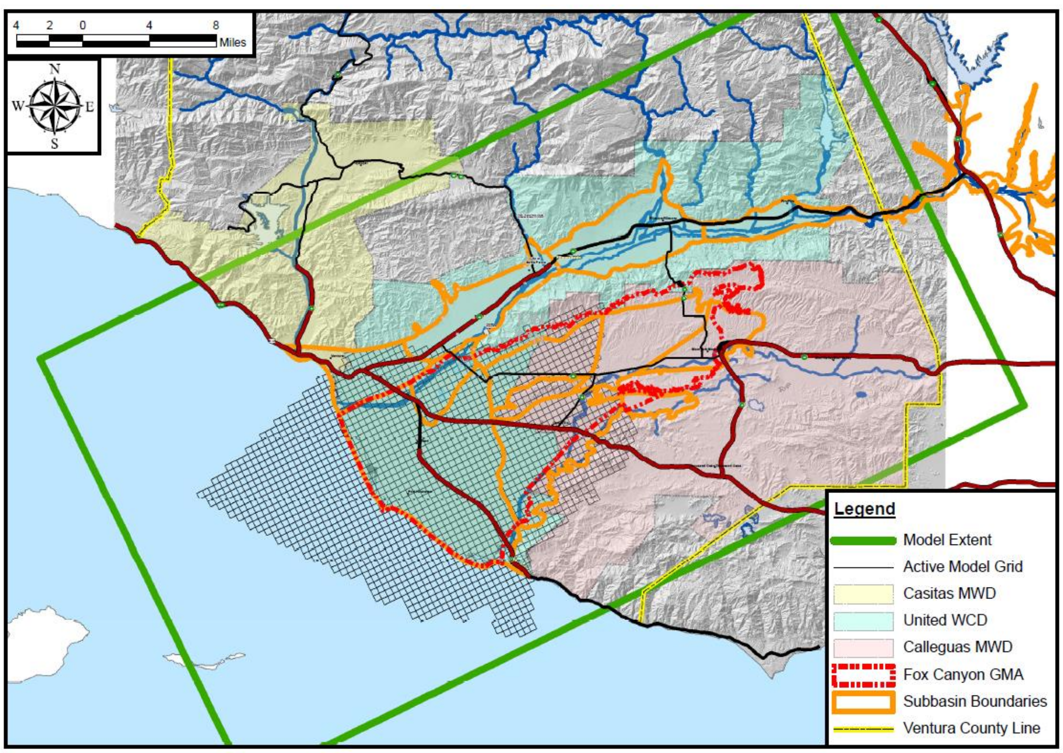

Figure 2. United Model Domain and Active Grid Area of Current Model

Packages currently in use by the United model include:

- Model configuration, solver, and output control: BAS, DIS, NWT, OC
- Hydraulic properties: UPW, ZONE, HFB
- Stresses: MNW2, WEL, DRN, RCH
- General-head boundaries: GHB

Boundary conditions vary across the active model domain, as follows:

- The eastern margin of the active model domain in West Las Posas basin adopts a no-flow boundary coincident with the East Las Posas basin boundary and the Central Las Posas fault.
- The eastern margin of the active model domain in Pleasant Valley basin consists of a no-flow boundary with the Santa Rosa basin, due to negligible cross-sectional area for groundwater flow from the Santa Rosa basin to the Pleasant Valley basin, and a specified flux boundary representing groundwater flow through alluvial deposits where Arroyo Las Posas enters the Pleasant Valley basin.
- The northeastern boundary of the active model domain currently terminates just inside Santa Paula basin, and is simulated as a general-head boundary.
- The northern margin of the active model domain coincides with the contact of Pleistocene and Holocene alluvial deposits with the San Pedro Formation near the northern edge of the Mound basin. Recharge into the San Pedro Formation (including the Hueneme and Fox Canyon aquifers) is simulated to occur within the San Pedro outcrop north of the model boundary.
- The southeastern margin of the active model domain coincides with the contact between Holocene alluvial fill deposits and poorly permeable bedrock of the Conejo Volcanics along the foothills of the Santa Monica Mountains. Mountain-front recharge to the Semi-perched aquifer is implemented in the model adjacent to this boundary.
- The southwestern margin of the active model domain extends offshore to the submarine outcrop areas of the Mugu aquifer and San Pedro Formation. This boundary is implemented as a general-head boundary to simulate the interaction of seawater with freshwater in aquifers that outcrop under the sea floor and submarine canyons.

3.2 UNITED MODEL CALIBRATION

A number of aquifer tests and slug tests were performed within the modeled area by United and the USGS. Review of the aquifer test results indicates that the hydraulic conductivities for the aquifers of the UAS typically range from 100 to 300 ft per day, and those in the LAS generally range from 10 to 50 ft per day. The inferred hydraulic conductivity values from the tabulated aquifer tests were used to set the range of initial aquifer parameters in the model. The groundwater flow model was calibrated by adjusting input parameters, including:

- hydraulic conductivity
- specific yield
- storage coefficient
- stream-channel conductance
- general-head boundary head and conductance
- horizontal flow barrier conductance
- recharge rates
- multi-node well conductance.

By comparing simulated groundwater levels with measured groundwater levels, and adjusting model input parameters to minimize differences between the two, a set of calibrated model parameters was determined to yield an improved fit based on manual and automated calibration simulations. The most sensitive parameter influencing calibration of simulated to measured hydraulic heads is hydraulic conductivity; this parameter is typically also subject to the greatest variability and uncertainty. Therefore, hydraulic conductivity commonly received the greatest degree of adjustment during model calibration. The vertical to horizontal anisotropy ratio is generally set to 0.1 (1:10) throughout the model. However, the vertical anisotropy ratio in the layers representing the aquifers of the UAS in the Forebay is 0.5 (1:2), to represent increased hydraulic communication between the UAS and the LAS in this area.

Results of calibration indicate that the model is well calibrated throughout most of the Forebay area, Oxnard Plain basin, and Pleasant Valley basin. The model is not as well calibrated yet in the Mound basin and the northeast area of the Pleasant Valley basin. The West Las Posas basin conceptual model is in development at this time; therefore, calibration has not yet been attempted in this basin. The areas of limited, incomplete or ongoing calibration (Mound and West Las Posas basins) are of minor relevance for modeling the effects of pumping on groundwater levels that affect the sustainability indicators of primary concern in the Oxnard Plain and Pleasant Valley basins.

Results of preliminary calibration efforts indicate that the United model shows significant improvement in overall calibration statistics for the Oxnard Plain and Pleasant Valley areas, and in improved simulation of groundwater-level responses to drought and wet-period cycles, compared to the USGS model. Simulation of all seven aquifers also allows use of more wells for calibration, increasing confidence that the model is capable of accurately simulating hydrogeologic conditions throughout the entire study area. This will allow model input and output at the level of detail anticipated to be needed for analysis of future pumping scenarios evaluated during sustainable yield evaluations for the study area.

4 EXPERT-PANEL REVIEW

In 2016, the model was peer-reviewed by an expert panel, including:

- Dr. Sorab Panday, of GSI Environmental, Inc., co-author of the two most recent versions of MODFLOW: MODFLOW-NWT and MODFLOW-USG;
- Jim Rumbaugh, of Environmental Simulations Inc., creator of the widely used MODFLOW pre- and post-processor, Groundwater Vistas; and,
- John Porcello, of GSI Water Solutions, Inc., a consultant with extensive experience in groundwater modeling in general, and specific experience with hydrogeologic conditions in Ventura County.

The expert panel was asked to focus on the following components of the model:

a. Model extent, grid size, discretization, and orientation.
b. Model layering compared to conceptual stratigraphic model.
c. Time discretization.
d. Numerical convergence criteria and closure.
e. Aquifer parameters, including horizontal hydraulic conductivity and vertical anisotropy, storage coefficient/specific yield.
f. Boundary conditions, including no-flow, constant-flux, constant-head, and general-head boundaries within model, as well as initial head configuration and horizontal-flow barriers representing geologic faults.
g. Implementation of transient aquifer stresses, including pumping, recharge from various sources, drains, surface-water/groundwater interaction (including groundwater interaction with seawater).
h. Water budget results over time, including groundwater underflow between basins, between aquifers, and discharge and recharge to/from surface-water bodies (e.g., rivers and ocean).
i. Calibration data and representativeness of calibration period.
j. Calibration results, methods of evaluation, bias (geographically and by layer).
k. Consistency of calibrated input parameters and water-budget results with conceptual models.
l. Sensitivity analysis and results (sensitivity analysiswas not complete by the time of the Expert Panel model review, and will be reviewed at a later date).
m. Overall suitability of the model for the intended purposes, and potential limitations on its use.

The expert panel provided "the following key observations regarding the model's significant and most substantive simulation capabilities" in a preliminary review memorandum in July 2016, following completion of their initial review of the United model:

- "The model's layering and choice of boundary conditions is appropriate for simulation of the very complex geologic and hydrostratigraphic conditions that exist in the Oxnard and

Pleasant Valley groundwater basins – specifically the discrete multiple layered aquifers and aquitards; the moderate to strong compartmentalization of certain aquifers by faults; the significant well-to-well variability in the depths and aquifers which are furnishing groundwater to production wells in each groundwater basin; the strong influence of UWCD's managed aquifer recharge programs (spreading basins) on groundwater elevations and flow directions; and the complex three-dimensional nature of the ocean interface and its interaction with each shallow and deep aquifer zone along the coast and offshore.

- The model provides an accounting of groundwater budgets and flow conditions for current land use and water use conditions. This includes the conditions that have been observed during the current drought, which began during the end of the calibration period and has continued through the period being used for model verification (2013 through 2015).
- The model is well-calibrated to changes in groundwater levels over time, including through multiple series of drought years (1985 through 1991; 1999 through 2003; 2012 to present) and above-normal rainfall years (1992-1993, 1997-1998, 2004-2005) which together comprise a hydrologic cycle composed of highly variable rainfall and streamflow conditions. Additionally, the calibration time period accounts for the gradual historical increase in dry-weather baseflows that occurred in Arroyo Las Posas from the late 1980s through the 1990s, which has substantially increased the annual volume of groundwater recharge to the Pleasant Valley basin.
- UWCD has invested considerable time and resources in updating and refining the hydrostratigraphic model, creating a new model with discrete representation of each aquifer and aquitard, and estimating the detailed recharge processes of a nearly three-decade time period. This effort has had a direct beneficial effect on the ability of the model to simulate the historical fluctuations in groundwater levels that have occurred in the past. Model-simulated hydrographs of groundwater level changes and scatter plots of the groundwater-level-change residuals (the differences between modeled and measured changes) indicate that the model is simulating the month-by-month and year-by-year aquifer system responses to fluctuating natural hydrologic conditions (rainfall and streamflows), groundwater pumping, and managed aquifer recharge quite well, though in a few areas it was noted that groundwater level recovery during high-rainfall years is under-predicted."

The Expert Panel concluded that "the model is nearly ready for use in planning studies," and provided 10 specific recommendations for refining the model—most of these recommendations were incorporated during 2016. The Expert Panel's final specific recommendation was to issue a modeling report before, or simultaneously with, releasing the model to the public and announcing the model development effort to be "complete." Model documentation is currently in preparation, in response to this recommendation, with an anticipated release in summer or fall of 2017.

5 REFERENCES

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