APPENDIX G

Steady-State MODFLOW and Transient-State OWHM (MERSTAN)
Model Evaluation and Application for City of Modesto Projects
(Todd Groundwater, September 2016)
September 29, 2016

TECHNICAL MEMORANDUM

To: Glenn Prasad, Associate Civil Engineer, City of Modesto
cc: Gerry Nakano, Vice President, West Yost Associates

From: Dan Craig, Senior Hydrogeologist, Lead Groundwater Modeler
       Phyllis Stanin, Principal Geologist / Vice President
       Liz Elliott, Senior Hydrogeologist, Modeler

Re: Steady-State MODFLOW and Transient-State OWHM (MERSTAN)
    Model Evaluation and Application for City of Modesto Projects

Todd Groundwater (Todd) evaluated and tested two United States Geological Survey (USGS) groundwater flow models of the Modesto region for application to ongoing projects for the City of Modesto (City). Both models simulate groundwater flow over the same area: from south of the Merced River to north of the Stanislaus River, and from west of the San Joaquin River to the Sierra Nevada foothills (Figure 1). The first model, released in 2007, is a steady-state model that simulates groundwater elevations during water year 2000 using the MODFLOW 2000 code (Phillips et al., 2007). The second model was completed in 2015 and consists of a transient-state model that simulates groundwater elevations from 1960 to 2004 using the MODFLOW One-Water Hydrologic Flow Model (OWHM) code (Phillips et al., 2015). The transient-state model is also referred to as the MERSTAN model. The USGS provided the model input and output files for both models (and executable OWHM computer code) to the City.

The City intends to apply the models to several projects including an ongoing evaluation of potential managed aquifer recharge (MAR) strategies. In order to allow for a more detailed evaluation of wellfield hydraulics associated with MAR strategies, Todd refined the regional steady-state model into a more highly-discretized local model, focused on the City’s water service area.

The model evaluation and refinement work included:

- review of two USGS Scientific Investigation Reports for the steady-state and transient models, along with the documentation report for the OWHM computer code (USGS, 2014)
• review of the model input and output files for the USGS steady-state and transient models
• performance of model test runs for the USGS steady-state and transient models and post-processing and evaluation of the results
• construction of a local “refined grid” version of the steady-state model for future use in evaluating MAR strategies
• development of modeling pre- and post-processing tools for future application of the regional and local models by the City.

Section 1 of this technical memorandum (TM) documents the construction and features of the regional steady-state model. Section 2 describes the local refined-grid steady-state version prepared for City use. Section 3 describes the transient-state MERSTAN model and features and use of the OWHM code. Section 4 describes approaches for future application of the models. Generalized instructions for modifying, operating, and post-processing the regional and refined-grid steady-state MODFLOW models and transient-state MERSTAN model for future City use also are included.

1: USGS REGIONAL STEADY-STATE MODFLOW MODEL

The regional steady-state model was originally constructed by the USGS using standard MODFLOW 2000 input file structure and executable code. The original MODFLOW model input files were imported into the Aquaveo Groundwater Modeling System (GMS) by others for the City in support of another project; the GMS files were provided to Todd for review and use for this model evaluation. Todd checked the imported files, ran a simulation, and post-processed results to ensure model performance. Additional details of the steady-state model are provided below.

Regional Steady-State Model Description and Input Parameters

Construction and application of the regional steady-state MODFLOW model was originally documented in the 2007 USGS Scientific Investigation Report (SIR) 2007-5009 (Phillips et al., 2007). The model simulates regional groundwater and surface-water flow over a 2,700 square kilometer (km²) area. Figure 1 shows the regional model area. The model comprises 16 layers (see inset on Figure 1), 153 rows, and 137 columns, with a uniform grid spacing of 400 meters. The westernmost 21 columns of the regional model (west of the San Joaquin River are entirely inactive. The model grid is rotated 37 degrees counterclockwise of true north, and is geo-referenced in the Albers 120 meters coordinate system. The model units are meters and days. All model input and output data use these units (e.g., aquifer hydraulic conductivities are in units of meters/day (m/day), pumping rates are in cubic meters per day (m³/day), and model layer elevations, thicknesses, and simulated groundwater elevations are in meters or meters above mean sea level).

The total thickness of the wedge-shaped model ranges from about 220 m near the Sierra foothills to 430 m along the western portion of the Central Valley near the San Joaquin River (Figure 1). The model layer thicknesses were built around the E-Clay (Layer 8) as described
in the 2007 SIR. Hydraulic conductivity was distributed using sediment texture by layer, except for the E-Clay, which was assumed to be homogeneous. A geostatistical approach was used to specify numerous TProGS-generated realizations of sediment facies. These texture distributions (sand, silty sand, silt, and clay) were then assigned calibrated values of horizontal and vertical hydraulic conductivity. Model Layers 1 through 7 are simulated as unconfined/convertible using hydraulic conductivities, while Model Layers 8 through 16 are simulated as fully-confined using transmissivities.

For the steady-state model, the USGS developed boundary conditions, recharge, and well pumping rates that are representative of water year 2000 hydrologic conditions. Model boundary conditions include specified heads along the lengths of the northern (northwestern), southern (southeastern), and western (southwestern) boundaries in all 16 model layers. The southwestern boundary corresponds to the San Joaquin River. The western segments of the Stanislaus, Tuolumne, and Merced Rivers are also represented using constant heads in Layer 1 only. The eastern (northeastern) boundary is specified as no-flow in all 16 layers.

There are 4,422 active pumping wells in the model, including municipal wells, other known private wells, and hypothetical agricultural wells spaced every 1,200 meters (Phillips, 2015). Many of the wells (including City wells) are represented in multiple model layers and are counted as multiple wells in the model. For example, there are 105 City wells in the model, but they are simulated as 314 model wells because most of the City wells pump from more than one model layer. Most (94 percent) of the simulated City wells pump from Model Layers 6 through 11.

Total recharge to the water table is simulated based on estimated agricultural water use and return flow rates, infiltration of precipitation, and leakage from surface water.

**Regional Steady-State Model Results**

The model calibration and overall results are described in the 2007 SIR. The model is generally well-calibrated in the City area. Groundwater flow in the different model layers is generally from east to west toward the San Joaquin River. Vertical gradients are generally downward from the unconfined upper aquifer system to the deeper water-bearing aquifer zones, where most of the municipal and agricultural pumping occurs.

Figures 2a and 2b show the simulated model steady-state groundwater elevations (heads) in Layers 1, 5, 10, and 15. Simulated heads indicate overall flow from the foothills on the east to the San Joaquin River on the west. Numerous cones of depression are present around some of the simulated pumping wells in the deeper model layers. There are localized downward vertical gradients between the shallow, intermediate, and deep aquifers (e.g., model Layers 1, 5, and 10). The vertical hydraulic head difference between Layers 5 and 10 ranges from a few feet beneath the City, to over 20 feet south and southwest of the City.

Some of the MODFLOW model cells in Layers 1 through 7 in the eastern portion of the domain are “dry”, inactivating these portions of each model layer. The largest extent of the
dry cells occurs in the eastern portion of Model Layer 1, where roughly half of the model cells are dry. This is illustrated on Figure 2a by the absence of groundwater elevation contours throughout the eastern portion of the model domain. The area of dry cells in each layer decreases with depth from Layer 1 through Layer 7, with only a small area of dry cells in Layer 7. These dry cell areas had to be accounted for in developing the refined grid local model. Regional model Layers 8 through 16 are fully-saturated.

Table 1 summarizes the water balance for the entire regional model, which represents water year 2000 (October 1999 through September 2000) conditions. Total boundary subsurface inflows and outflows are approximately 214,000 and 393,000 acre-feet per year (AFY), respectively. The total recharge simulated across the regional model is about 1,050,000 AFY, which exceeds total simulated pumping well discharge of about 870,000 AFY. The total simulated water year 2000 pumping from all City pumping wells is about 44,900 AFY, which is similar to the 1999 and 2000 calendar year City Pumping total of 45,140 and 42,100 AFY, respectively, as reported in the 2005 Integrated Regional Groundwater Management Plan (Bookman-Edmonston, 2005).

Table 1: USGS Regional Steady-State MODFLOW Model Water Budget Summary

<table>
<thead>
<tr>
<th></th>
<th>meters$^3$/day</th>
<th>feet$^3$/day</th>
<th>acre-feet/year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inflows</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Head Dependent Boundaries</td>
<td>722,386</td>
<td>25,510,816</td>
<td>213,761</td>
</tr>
<tr>
<td>Recharge</td>
<td>3,543,480</td>
<td>125,136,815</td>
<td>1,048,552</td>
</tr>
<tr>
<td><strong>Total Inflows</strong></td>
<td>4,265,866</td>
<td>150,647,636</td>
<td>1,262,314</td>
</tr>
<tr>
<td><strong>Outflows</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wells</td>
<td>2,939,191</td>
<td>103,796,533</td>
<td>869,737</td>
</tr>
<tr>
<td>Head Dependent Boundaries</td>
<td>1,326,675</td>
<td>46,851,099</td>
<td>392,577</td>
</tr>
<tr>
<td><strong>Total Outflows</strong></td>
<td>4,265,866</td>
<td>150,647,636</td>
<td>1,262,314</td>
</tr>
<tr>
<td>City Modesto Wells</td>
<td>151,594</td>
<td>5,353,477</td>
<td>44,858</td>
</tr>
</tbody>
</table>

Modifying and Running the Regional Steady-State Model

The regional steady-state model is fully-functional and can be modified, run, and post-processed using GMS or other MODFLOW 2000-compatible software. Modifications can be made using the GMS MODFLOW interface tools, or to the MODFLOW input files directly if the model is to be run in the DOS environment. For example, to change pumping well flow rates in the regional steady-state model, either the flow rates can be modified in the GMS MODFLOW>Optional Packages>Wells interface, or the MODFLOW .wel file can be directly modified using a text editor. In addition, potential injection wells can be added to the .wel file as needed. The steady-state well input data are included in an Excel workbook which includes model layer, row, column, well name, and flow rate information. Similarly the MODFLOW recharge .rch file can be edited directly or using the GMS interface to simulate surface recharge scenarios. GIS shapefiles, along with an Excel Workbook of simulated pumping well data used by the regional and local models, are included in Attachment 1.
copy of the GMS version of the USGS steady-state regional model (including all MODFLOW input and output files) is included as Attachment 2.

Model results including simulated groundwater elevation head contour maps can be easily constructed, and flow-budget results post-processed through GMS. Particle tracking simulations can be made using the MODPATH code. A MODPATH test run was performed using the GMS interface, and the flowpath model functions correctly.

While the regional model contains detailed aquifer characteristics including non-uniform layer geometries and hydraulic properties, it is coarsely-gridded and only provides a regional-scale simulation of the City service areas. More accurate simulation of the complex local groundwater flow patterns around the large number and relatively closely-spaced City supply wells within the Modesto Service Area requires a more finely-gridded local model. Such as model was constructed and tested as described below.

2: LOCAL Refined-Grid steady-state MODFLOW Model

In order to better simulate complex flow hydraulics and conduct accurate flowpath analysis around City wells, a refined local model was created from the regional steady-state USGS model. A description of the refinement methodology and features of the local model are provided below.

Local Refined-Grid Steady-State Model Approach

The local-scale steady-state model occupies a sub-area within the regional model domain as shown on Figure 1. Regional-to-local model conversion is sometimes referred to as “telescopic grid refinement.” Using this approach, all of the input data and simulation results are extracted from the regional model and re-interpolated to a local model grid. The regional model aquifer top and bottom elevations, hydraulic conductivities and transmissivities, and areal recharge values from the regional model grid are converted into discrete points, then interpolated into the refined model grid, such that the local model input parameters are essentially identical to those in the regional model. The groundwater elevations computed from the regional model are applied as initial conditions (starting heads) and specified head boundary conditions for the local-scale model. Application of regional model heads to local model specified head boundaries provides a flow simulation that is consistent with the regional model. The finely-spaced local model grid provides a more detailed representation of the local flow conditions, including drawdown and flow paths around City wells, while maintaining the aquifer characteristics and calibration quality of the regional model.

Local Refined-Grid Steady-State Model Description and Input Parameters

Figure 3 shows the local steady-state model area. The active local model area extends from the Stanislaus River on the north, to a southern boundary arc approximately 3 to 4 miles south of the Tuolumne River, and from the western boundary near the San Joaquin River to the regional model eastern boundary. This area was selected in order to incorporate City
production wells in the Modesto Service Area and wells in the Cities of Riverbank, Oakdale, and Waterford.

A new local model grid was constructed using a uniform 100 meter grid spacing. A 37-degree grid rotation was applied, identical to the regional model. There are 326 rows and 398 columns in the local model.

The top and bottom elevations and hydraulic conductivity values for each of the 16 model layers are identical to those in the regional model. Model Layers 8 through 16 were converted from “fully confined” to “unconfined/confined” in order to compare effective hydraulic conductivities in each layer.

For each of the 16 layers, active/inactive zones were defined based on the locations of dry cells in the regional model. The northern, southern, and western boundaries for each of the 16 model layers are identical, however the eastern boundary for each of Layers 1 through 7 are different than the eastern boundary for Layers 8 through 16 (Figure 3). Layer 1 has the smallest active model area, reflecting the dry cells in Layer 1 of the regional model. All boundary arcs in each of the 16 model layers were assigned specified heads, extracted from the calibrated regional model solution.

As discussed previously, there are 4,422 wells in the regional steady-state model. Roughly one third of these are in the local model. Rather than extracting the simulated wells from the regional model (and introducing location errors from the block-centered 400-meter regional model grid), individual municipal, agricultural, and other pumping wells were re-imported to the local model as discrete point objects at known coordinate locations. The original well location, depth, and pumping rate information used to construct the regional model was provided by the USGS. Well coordinates, well screen intervals and depths, and associated model layer assignments and pumping rates were imported and assigned to a GMS conceptual model coverage. The wells were then “mapped” to the local model grid. GMS allocates flow rates based on the model layer and well screen elevation intervals. The “map-to-MODFLOW” approach provides flexibility in editing well pumping rates for future model runs, as individual well points or the entire well attribute table can be opened and modified, then re-mapped to the MODFLOW model. The pumping rates used in the initial local model are average 2000 rates, as determined by USGS.

**Local Refined-Grid Steady-State Model Results**

The local model was checked, simulations were run, and the results post-processed. Figures 4a and 4b show the simulated steady-state local model heads in Layers 1, 5, 10, and 15. Consistent with the regional model, the simulated local model heads indicate overall flow from the foothills on the east toward the San Joaquin River on the west. Numerous cones of depression are simulated around the pumping wells in the various model layers. Vertical gradients are present between the shallow, intermediate, and deep aquifer zones. Comparison of the local model groundwater elevation contours in Layers 1, 5, 10, and 15 (Figures 4a and 4b) with the regional model (Figures 2a and 2b) illustrate that the local model flow solution is almost identical to the regional model.
A test MODPATH simulation was performed using the local model; the simulation ran successfully.

**Table 2** summarizes the water balance for the local steady-state model. Total boundary subsurface inflows and outflows are approximately 58,000 and 108,000 AFY, respectively. The total recharge simulated across the local model is about 297,000 AFY, which exceeds total simulated pumping well discharge of about 247,000 AFY. The total simulated pumping from all City pumping wells is about 43,000 AFY, approximately 2,000 AFY less than in the regional model because City wells in Grayson and Turlock are outside of the local steady-state model grid.

### Table 2: Local Refined-Grid Steady-State MODFLOW Model Water Budget Summary

<table>
<thead>
<tr>
<th>Inflows</th>
<th>meters$^3$/day</th>
<th>feet$^3$/day</th>
<th>acre-feet/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Dependent Boundaries</td>
<td>196,121</td>
<td>6,925,954</td>
<td>58,034</td>
</tr>
<tr>
<td>Recharge</td>
<td>1,003,991</td>
<td>35,455,608</td>
<td>297,091</td>
</tr>
<tr>
<td><strong>Total Inflows</strong></td>
<td><strong>1,200,112</strong></td>
<td><strong>42,381,560</strong></td>
<td><strong>355,126</strong></td>
</tr>
<tr>
<td>Outflows</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wells</td>
<td>834,312</td>
<td>29,463,466</td>
<td>246,882</td>
</tr>
<tr>
<td>Head Dependent Boundaries</td>
<td>365,460</td>
<td>12,906,098</td>
<td>108,143</td>
</tr>
<tr>
<td><strong>Total Outflows</strong></td>
<td><strong>1,199,773</strong></td>
<td><strong>42,369,566</strong></td>
<td><strong>355,025</strong></td>
</tr>
<tr>
<td>City of Modesto Wells</td>
<td>145,264</td>
<td>5,129,943</td>
<td>42,985</td>
</tr>
</tbody>
</table>

**Modifying and Running the Local Refined-Grid Steady-State Model**

A copy of the local steady-state model (including all GMS pre-processing and MODFLOW input and output files) is included as Attachment 3. The local steady-state model is fully-functional and can be modified, run, and post-processed using GMS. Input parameter modifications can be made using the GMS MODFLOW interface tools. The GMS “Conceptual Model” coverage for wells can be modified to add, delete, or move production well locations and change pumping rates. Injection wells or surface recharge alternatives can be simulated by modifying the appropriate input parameters. Forward or reverse MODPATH simulations can be made to predict flowpaths, fate of recharged or injected water, and travel times.

Other modifications to the local model can be made using the GMS tools. Specified-head model boundaries for each layer are included as map coverages, and can be modified and re-mapped to MODFLOW if desired. In addition, all of the regional model data generated using the GMS regional-to-local methodology were saved as 2-D scatter-point sets, and new local model areas, boundary conditions, or a revised grid can be defined and modified local models constructed using the saved data sets.
3: Transient-State USGS One-Water Hydrologic Flow Model

In 2015, the USGS completed construction of a transient groundwater model, with additional surface water simulation features, and using a new model code, the MODFLOW One-Water Hydrologic Flow Model (OWHM, USGS, 2014). This model is referred to as the MERSTAN model, named for the simulation area between the Merced and Stanislaus rivers. This section describes the OWHM code, MERSTAN model features, model simulation results, and recommendations for future use of the model.

One Water Hydrologic Flow Model

The OWHM is a new combined surface water-groundwater FORTRAN code that contains numerous new coupled surface water packages (subroutines) to simulate reservoirs, streams, soil water processes, and agricultural water demand and return flow, and land subsidence. The OWHM is similar to MODFLOW 2000 and 2005, in that it is a modular program that simulates groundwater and surface water using different subroutine modules or packages, and model input are formatted as separate package files. However, the main program is different than previous versions of MODFLOW. The model code uses a different input file structure and is not compatible with the MODFLOW 2000 or 2005 programs. A new version of the Farm Process Package is used in the model to simulate recharge on the landscape and estimate groundwater pumping for agricultural use. A new Streamflow Routing Package is used to route surface water in the Stanislaus, Tuolumne, Merced, and San Joaquin Rivers and irrigation canals. Reservoir Routing and new Riparian Evapotranspiration Packages are also included. The subsurface simulation also contains new subroutines for Unsaturated Flow, Horizontal Flow Barriers, and Subsidence. New parameterization features are used to simulate model layering and aquifer hydraulic properties.

Because OWHM uses a new computer program and input file structure, it is not compatible with current versions of MODFLOW pre- and post-processors such as GMS or Groundwater Vistas. However, simulated groundwater elevation output from the OWHM can be modified and imported to GMS and post-processed. Additional USGS utility programs can also be used to post-process the OWHM results, as described below.

Regional Transient-State MERSTAN Model Description and Input Parameters

Construction and application of the regional transient-state model was documented in the 2015 USGS SIR 2015-5045 (Phillips et al., 2015). The transient model covers the same area as the steady-state model (Figure 1). Like the steady-state model, the transient model comprises 16 MODFLOW layers, 153 rows, and 137 columns, with a uniform grid spacing of 400 meters, and is geo-referenced in the Albers 120 meters coordinate system. The transient-state model simulates groundwater and surface-water flow on a monthly basis from 1960-2004 using 540 monthly stress periods.

The model layer thicknesses are identical to the steady-state regional model. Like the steady-state model, hydraulic conductivity was distributed using sediment texture by layer.
Coarse and fine fraction “end member” hydraulic conductivities were adjusted during auto-calibration with PEST. The USGS states that final calibrated net hydraulic conductivities are similar to those in the steady-state model (Phillips, 2015).

Due to numerical instability, the USGS converted all subsurface model layers to fully confined, whereas the steady-state model used unconfined/convertible layer types for model layers 1 through 7. For the confined aquifer model, equivalent aquifer transmissivities were calculated from the layer thicknesses and calibrated hydraulic conductivities.

In the transient model, lateral boundary conditions are no-flow along the Sierra Nevada foothills and time-varying general-head elsewhere. The Farm Process Package 3 (FPP3) and Streamflow Routing Package 2 (SRP2) along with other model packages are used to calculate recharge from precipitation, irrigation return flow, and recharge from rivers and canals, along with a separate standard MODFLOW Recharge Package file for reservoir leakage. Leakage from the three reservoirs in the eastern portion of the model was specified as a constant value based on estimates. However, due to numerical instability, the estimated reservoir recharge rates had to be reduced by 75 percent in the final model in order to achieve model convergence. Numerical stability problems and implications for future use of the MERSTAN model are further discussed below on pages 12 and 13.

Measured pumpage in urban areas and irrigation districts was simulated at known pumping wells using a standard-format MODFLOW .wel file. Additional pumping from farm wells is simulated by the FPP3.

**Original MERSTAN Model and OWHM Program Files Provided by the USGS**

The USGS provided model input output and program files in the following folder structure:

- Contents
- Input
  - Data
  - FARM
    - Crops
    - ETfrac
    - ETo
    - Precip
- Output
- Source
- PEST.

The Input folder contains:

- all input files for the model
- the MF-OWHM executable
- a batch (.bat) file for running the model
• sub-folders Data and FARM contain data files specified in MF-OWHM input files
• the Farm Process is used to calculate areal recharge
• additional Recharge file is included for reservoir leakage
• Stream Flow Routing file is included
• Other semi-standard MODFLOW packages include a .bas file, with a separate .dis file, .wel and .ghb files (both appear standard), and a .pcg solver file
• data folder includes new format discretization zones and multiplier files for layer geometry and aquifer hydraulic properties.

The new parameterization file structure uses a “LPF2” file for aquifer layer properties, which also are defined in “MULT2” (array multiplier) and “ZONE”. The Input/DATA subfolder contains arrays of layer top and bottom (17 arrays), K zone arrays for Layers 1-7, Layer 8 (E-Clay), and Layers 9-16, S zone arrays for Layers 1-10, textures for Layers 1-16, IBOUND for Layers 1-16, and other Layer Property arrays. To run the MERSTAN model, double-click the batch (.bat) file in the Input folder.

The Output folder contains primary output files from the model, including:

• The listing file
• Head output file (in ascii .fhd format)
• Simulated & observed head file (.out)
• Cell-by-cell budget file (in ascii .bud format)
• Gage output files (simulated stage, flow, and other info. at gage locations in ascii .out format)
• SFR output by reach (cell)

The PEST Process was used for the transient MERSTAN Model, and PEST files are included in the Input Folder and in a separate PEST Folder.

The Source folder contains the source program files, etc., for the version of MF-OWHM used in this work. The src folder contains the FORTRAN source code. The bin folder contains the compiled binary executable. The example folder contains several test or example models created by the USGS. A .pdf of the MF-OWHM Report is included.

**Regional Transient-State Model Post-Processing**

Several software tools can be used to post-process the MERSTAN model results. Model output can be partially controlled using the Output Control (.oc) file, and print flags in some of the input package data files. Simulated heads and cell-to-cell flow budget can be written in either ascii or binary format, and subsequently post-processed using GMS and other utility programs.

To evaluate hydraulic head patterns over time, the MERSTAN heads were reformatted and read into GMS. A “mock” transient version of the GMS steady-state regional model was created by defining monthly stress periods from the transient model. The OWHM .nam file
(modesto_FMP3_60-04_PestParam_fast.nam) was modified to output binary heads as a .hed file (rather than the standard ascii .fhd file), which was then imported to GMS. The head results for any time step, model layer, or cross-section can then be plotted using the GMS contour tools. This mock transient GMS version of the regional model, for use in post-processing, is included as Attachment 4.

Water level trends over time were also plotted using the USGS utility program GW Chart (USGS, 2000). This program reads the formatted head file (.fhd) and can plot hydrographs for any model cell. Other USGS post-processing utilities, such as Modelviewer (USGS, 2002), Zonebudget (USGS, 1990), and ModelMuse (USGS, 2009), can be used to post-process simulated head and flow budget results. According to the USGS, ModelMuse has capabilities to import and modify the Farm Process Package. These USGS utilities and their documentation are included in Attachment 5.

Regional Transient-State Model Results

The MERSTAN model results were post-processed using GMS and the USGS utility software. Figures 5a/b and 6a/b show the simulated groundwater elevations in Model Layers 1, 5, 10, and 15 in January 1970 and December 2004, respectively. In the City area, overall simulated flow conditions for the two time periods are similar, with regional flow from east to west. Groundwater elevations decline in all model layers from 1970 to 2004. In particular, groundwater elevations decline significantly in the southeastern portion of the regional model between 1970 and 2004. In this area, relatively low water levels are also simulated in 1970 (in certain model layers, see Figure 5b), but by 2004, a larger cone of depression is simulated with lower water levels evident in all model layers, particularly the lower layers (Figures 6a and 6b).

Figure 7 is a hydrograph of simulated groundwater elevations for City Wells MOD001, MOD002, and MOD003. These wells were selected for post-processing to view water levels beneath the City center as an example; simulated groundwater elevations in any well or model grid cell can be graphed. The simulated water level hydrograph shows the effect of seasonal water-level pumping, with annual drawdown and recovery cycles in each water level data series. An overall decline in regional water levels occurs between the early 1970s and early 1990s, followed by a partial recovery in the late 1990s through 2004. Although not shown on the hydrograph, water level trends in the southern part of the model area continue a downtrend throughout the 1990s and 2000s.

Comparison of the transient-state MERSTAN model groundwater elevation contours in Layers 1, 5, 10, and 15 in 2004 (Figures 6a and 6b) with the regional steady-state MODFLOW model (water year 2000) (Figures 2a and 2b) reveal some minor differences in simulated elevations between the two models. Simulated steady-state groundwater elevations in Layers 10 and 15 are several meters lower than those simulated with the transient-state model. However, the overall flow patterns are similar for both models.
Modifying the MERSTAN Transient-State Model

The MERSTAN model can be modified to simulate different hydrologic conditions, well pumping patterns, or recharge rates. For the existing historical 1960-2004 simulation, some model modifications, such as changing municipal well pumping rates, can be performed relatively easily by modifying the MERSTAN .wel file. Changes to the non-Farm recharge file also can be made to simulate different recharge rate patterns. Other changes, such as to the FPP3, would require a greater effort in order to understand the large number of variables and input parameter values for agricultural processes and water use in the large study area. Post-processing the modified model can be accomplished as described above.

Updating the transient state model to simulate groundwater elevations since 2004 would require a significant level of effort. In order to update the model, new input values for pumping, land use and crop type, surface water delivery operations, and boundary conditions, and other variables would need to be incorporated and all source/sink input files would need to be modified.

The numerical instability issues encountered by the USGS could be problematic for future application of the MERSTAN. Modifications to certain input parameters could result in model non-convergence.

4: Future Application of Models for City Wellfield Analysis

Future model applications can be conducted with the tools described in this TM with or without additional modification, depending on project objectives. Both the steady-state and transient-state models can readily be used to evaluate City wellfield operations, feasibility and effectiveness of MAR projects, and potential water quality changes resulting from wellfield operations. Depending on the scenarios requiring evaluation for the ongoing LGA project, additional model modifications may be conducted.

Knowledgeable City staff can modify and run the local refined-grid steady state model with the purchase and installation of GMS software. The MERSTAN transient model can be run using the USGS executable including in the attachments (provided to the City separately on flash drive). Output from the MERSTAN model can be post-processed with the same GMS software package used for the local steady state model.

The regional and/or local refined-grid steady-state models can be easily modified with updated City pumping rates. Some changes in individual well pumping rates and City-wide pumping totals have occurred since 2000.

Groundwater flowpaths and well capture zones for different pumping and recharge scenarios can be simulated using MODPATH.

Depending on the specific future application of the MERSTAN model, local calibration results should be checked to better understand the reliability of the model to simulate predictive scenarios in certain areas. The transient-state MERSTAN can be updated beyond 2004. This
would require updating the source/sink input parameters and post-processing. The potential for numerical instability should be considered if significant modifications to the MERSTAN are attempted.
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