Modeling the Influence of Conjunctive Water Use on Flow Regimes in the South Platte River Basin Using the South Platte Decision Support System Groundwater Flow Model

Project Completion Report

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Executive Summary

For this project (2015-2016), simulation results from the SPDSS groundwater flow model and from a local “daughter” model were compared with field data in the LaSalle/Gilcrest area. Construction of a new refined model for the area also was commenced. The project was divided into three phase:

- Phase 1: Compared measured and simulated water table data for the LaSalle/Gilcrest area using the basic-scale SPDSS groundwater flow model, for the years 1950-2006
- Phase 2: Using a small model extracted from the SPDSS groundwater flow model, compare measured and simulated water table data for the LaSalle/Gilcrest area
- Phase 3: Using available borehole data and land surface topography, create new hydraulic conductivity maps and being construction of a refined MODFLOW model for the LaSalle/Gilcrest area

Completion of Phase 1 revealed that in many areas in the LaSalle/Gilcrest area, the simulated water table elevation by the model is much lower than the observed elevation. This is a serious limitation, as the presence of shallow water tables is a major current concern for the residents of the area, and therefore a model to be used as a scenario simulator must be accurate in simulating shallow water tables. Results from Phase 2 did not show any improvements in consistently simulating shallow water tables accurately. Although Phase 3 did not result in a completed MODFLOW model, creating a refined layered map of hydraulic conductivity using lithology from 346 boreholes in the area will lead to a refined model that will be tested against water table data. The development of such a model will lead to an accurate assessment of groundwater flow dynamics within the local region.

1. Background

The surface watershed of the South Platte River Basin (SPRB) lies on alluvial deposits that form an unconfined aquifer system connected with the surface water, with a thickness that reaches 200 ft in the lower SPRB. The aquifer, which sustains the base flow in the river, is recharged by infiltrations from precipitation and irrigation canals, as well as seepage from surface water bodies and streams. The SPRB constitutes a major source of water for eastern Colorado and has allowed agricultural growth to approach 1 million acres of irrigated cropland. Conjunctive use of surface and groundwater resources in the SPRB is regulated accordingly with the 1969 Groundwater Administration Act (Senate Bill 81), which requires all non-exempt groundwater rights to come into priority. Prior to 2003, about 9,000 groundwater irrigation wells were active in the SPRB (Nettles, 2011) with augmentation requirements of 5-10% of their water consumptive use in order to protect surface water rights. Following legislative changes that occurred in 2003-2004, water resources have been administered following strict priority rules since 2006, with all non-exempt wells required to have a decreed augmentation plan that replaces 100% of their stream depletion. As a consequence of the increased cost for acquiring augmentation water, in the last six years, about 4,000 wells have been totally or partially curtailed from pumping (Nettles, 2011), potentially resulting in reduced aquifer drainage and rising water table levels in several areas of the SPRB.

In 2012, CSU started a research project funded by the Colorado Water Conservation Board (CWCB) to study the critical linkages between groundwater pumping for irrigation and the coupled groundwater/surface water regimes in the SPRB. This study has relied on the use of the alluvial groundwater flow model developed as a fundamental component of the South Platte Decision Support System (SPDSS). The SPDSS was developed starting in 2001 by the Colorado Department of Natural Resources (DNR), the CWCB and the Division of Water Resources (DWR) in order to support State officials and water users in the optimal planning and management of water resources (Colorado Water Conservation Board, 2001). The SPDSS groundwater flow model was developed by CDM-Smith (2008, 2011) using the USGS finite-difference groundwater flow code MODFLOW (Harbaugh, 2005). The model simulates, on a monthly step, flow regimes over the entire area of the SPRB in Colorado (~2,500 mi^2) during the 1950-2006 time period and constitutes a crucial tool to support and improve the planning and management of water resources in the SPRB.

Over the last 4 years, the overarching goal of the project has been to provide the CWCB with an independent evaluation of the SPDSS groundwater flow model, highlighting model capabilities, strengths, and weaknesses. In the first 4 years, CSU focused on the following tasks:

1. Analysis of model grid and time discretization to provide general considerations and directions regarding the spatial and temporal scales for which the SPDSS model seems most adequate as water management simulation tool;
2. Analysis of representativeness of hydrological stress data used in the model with respect to the SPRB hydrogeology;
3. Test the numerical robustness and stability of the model with respect to hypothetical, yet realistic, changes in hydrologic stress conditions;
4. Sensitivity study on increased stream augmentation by aquifer recharge, changes in aquifer pumping, and effects on groundwater and surface water flow regimes of drought conditions; and
5. Verify adequacy of analytical models (e.g. Glover) to assess the impact of well pumping on streamflow.

For phase 5 (2015-2016), the SPDSS model was used to compare simulated results with local data in the LaSalle/Gilcrest area. The spatial extent of the SPDSS model and the spatial extent of the LaSalle/Gilcrest area are shown in Figure 1. In Phase 2, a “daughter” model was extracted from the SPDSS basin-scale model, with simulation results compared with water table data within the LaSalle/Gilcrest area. In Phase 3, hydrogeologic data were collected and analyzed for the area. Figure 2 shows the map of groundwater depth for Spring 2012 from a reported published by the Colorado Geological Survey, constructed using measurements from a network of monitoring wells in the area. Many areas have a groundwater depth of less than 5 feet from the ground surface, demonstrating the severity of the groundwater problem in the area

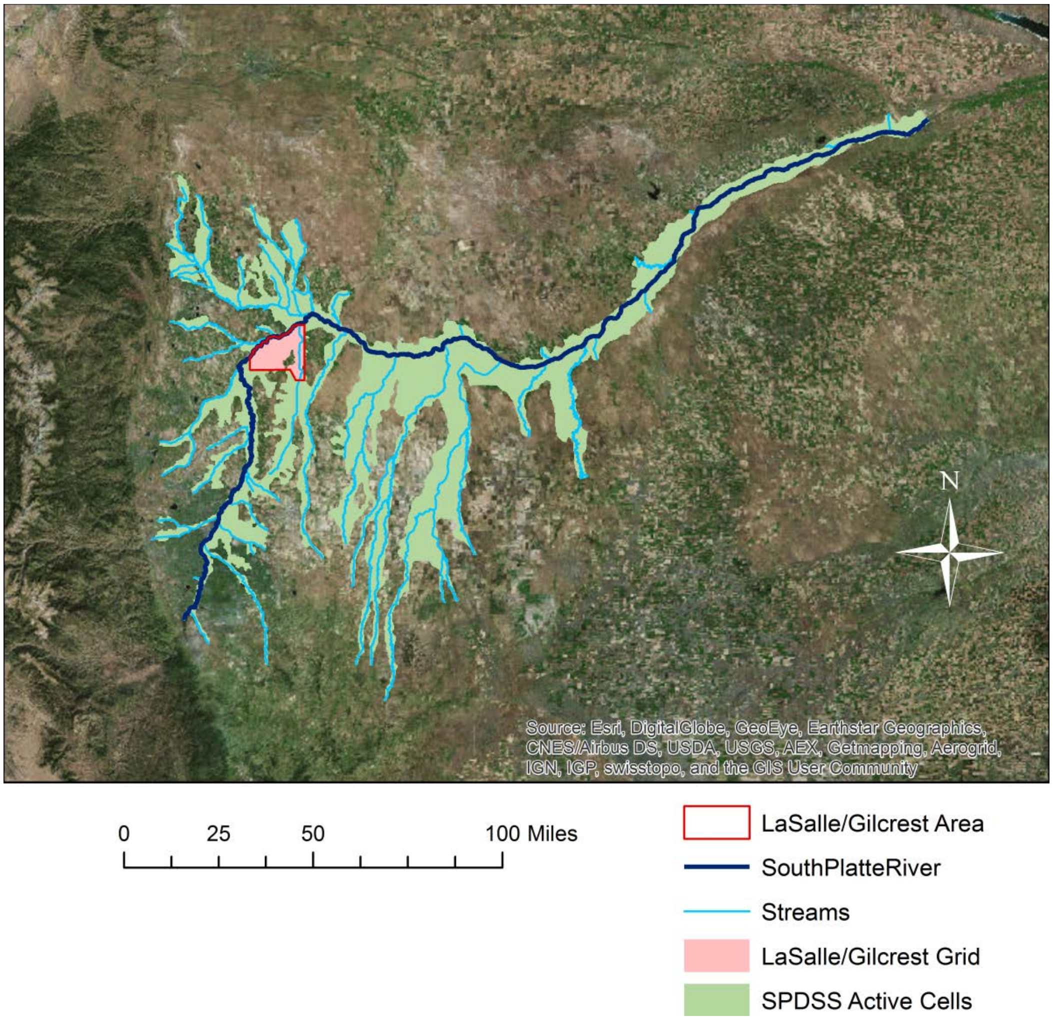


Figure 1. The spatial extent of the SPDSS modeling grid.

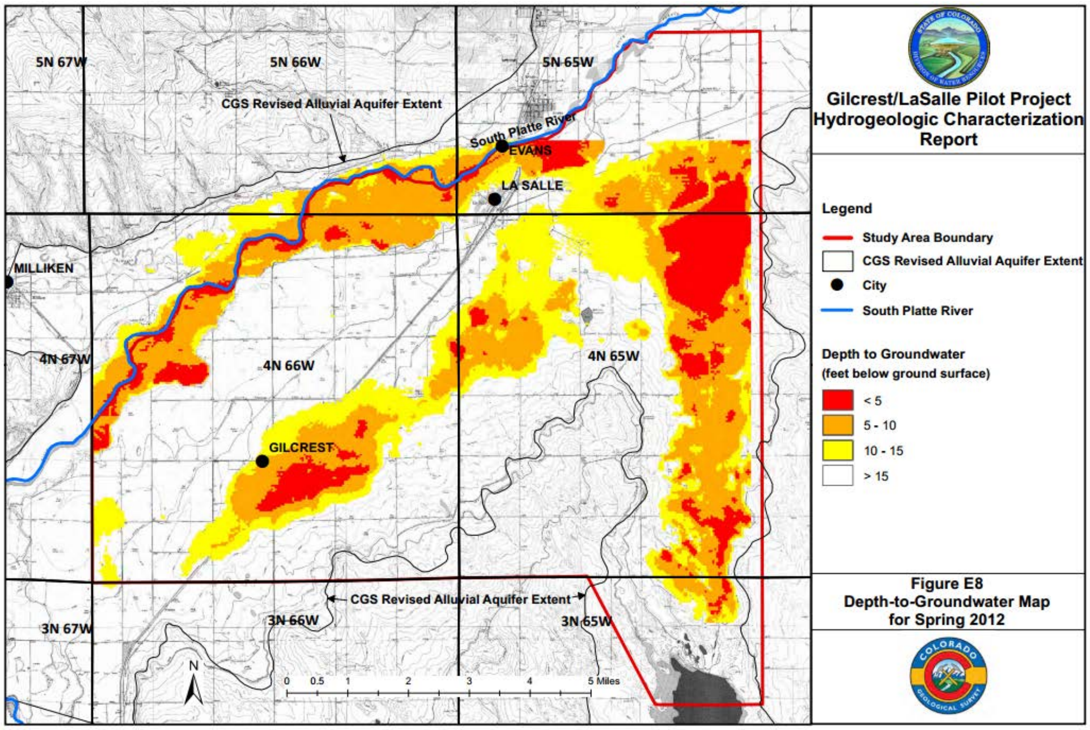


Figure 2. Depth to Groundwater (feet below ground surface), constructed through network of monitoring wells in the LaSalle/Gilcrest area. Map provided by Colorado Geologic Survey (Gilcrest/LaSalle Pilot Project Hydrogeologic Characterization Report).

<u>Phase 1</u>: Compare Water Table Elevation in LaSalle/Gilcrest Area (SPDSS Model)

In phase I, groundwater hydraulic head values from the SPDSS 1950-2006 simulation are compared with groundwater elevation data from monitoring wells in the LaSalle/Gilcrest area. There are a total of 45 monitoring wells in the area maintained by CCWCD, CSU, and the DWR, with their locations shown in Figure 3. Measurements from the wells cover the time period from 1940 to 2012. Most of the wells have measurements twice a year, and a few wells were measured on a daily basis between 2005-2012. There are approximately 2,500 water table measurements available for the 1950-2006 simulation period.

Figure 4 (pages 6-8) shows comparison of simulated and observed time series of water table depth for 16 monitoring wells. Results for the other 29 wells also were compared, but are not shown here. As seen in the 16 plots, the simulated and observed values are very close at several of the monitoring wells. However, at many locations the model over-predicts the depth to water table (i.e. under-predicts water table elevation), sometimes by tens of feet. This is also seen in a 1:1 plot of the observed and simulated values (Figure 5), and a histogram of the residuals between the observed and simulated values (Figure 6). In many areas the model is not simulating shallow water table elevation correctly.

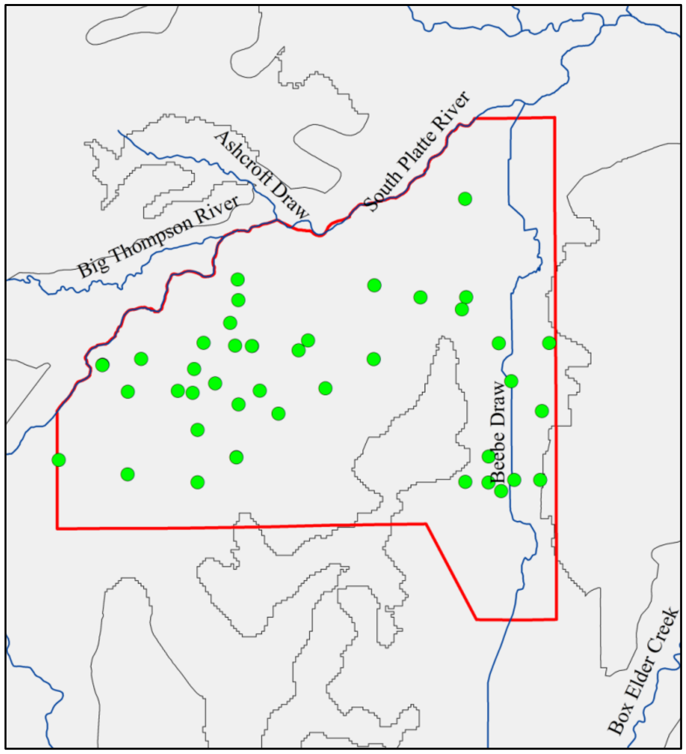
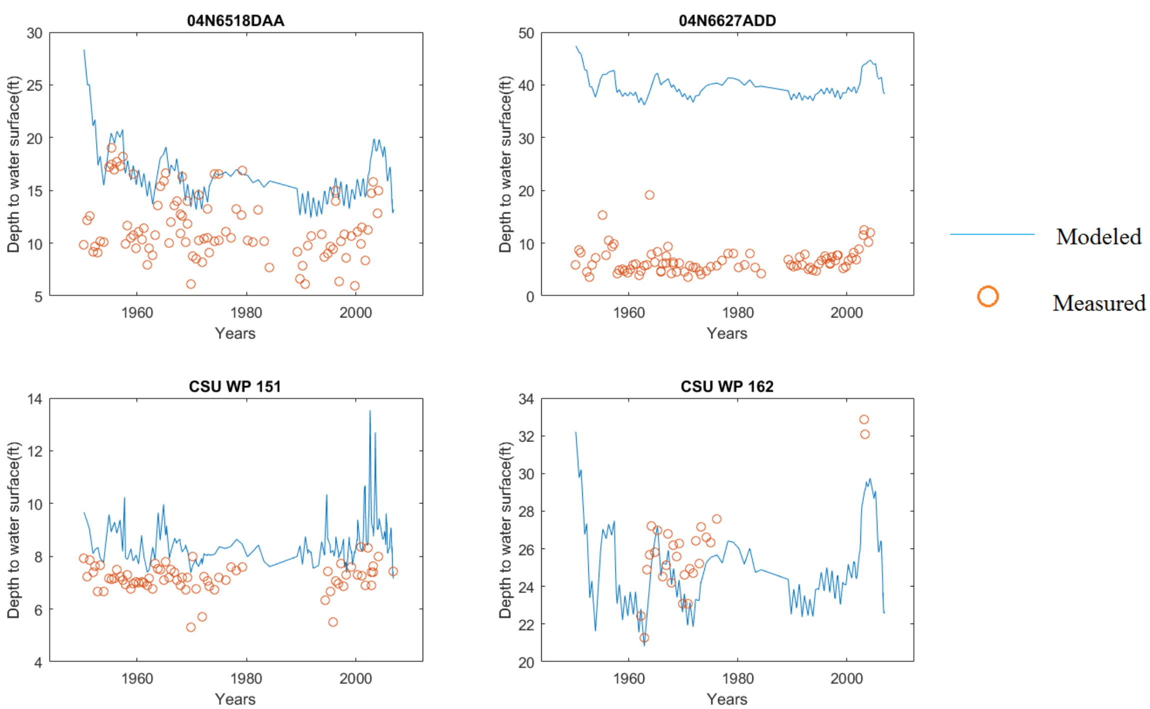
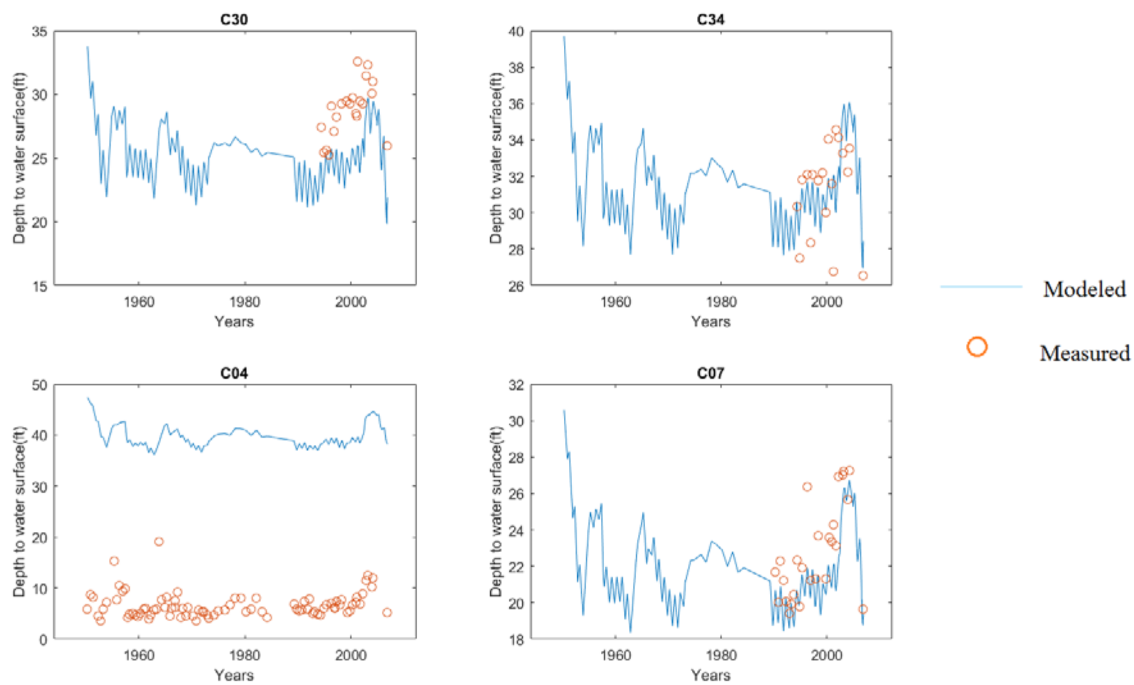


Figure 3. Monitoring wells in the LaSalle/Gilcrest study area. Data from these wells are compared with results from the SPDSS model




C01
C02
C32
F16
Depth to water surface(ft)
Years
Modeled
Measured


C30
C34
C04
C07
Depth to water surface(ft)
Years
Modeled
Measured

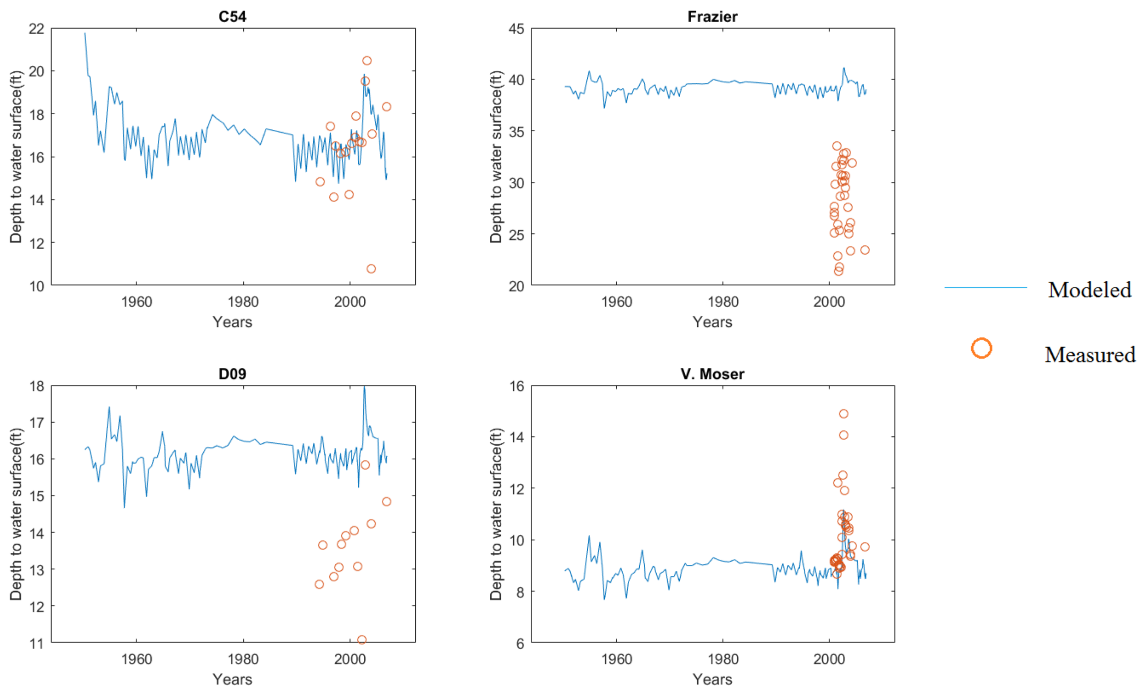


Figure 4. Time series of simulated (SPDSS) and observed depth to water table (ft) at monitoring well locations in the LaSalle/Gilcrest area.

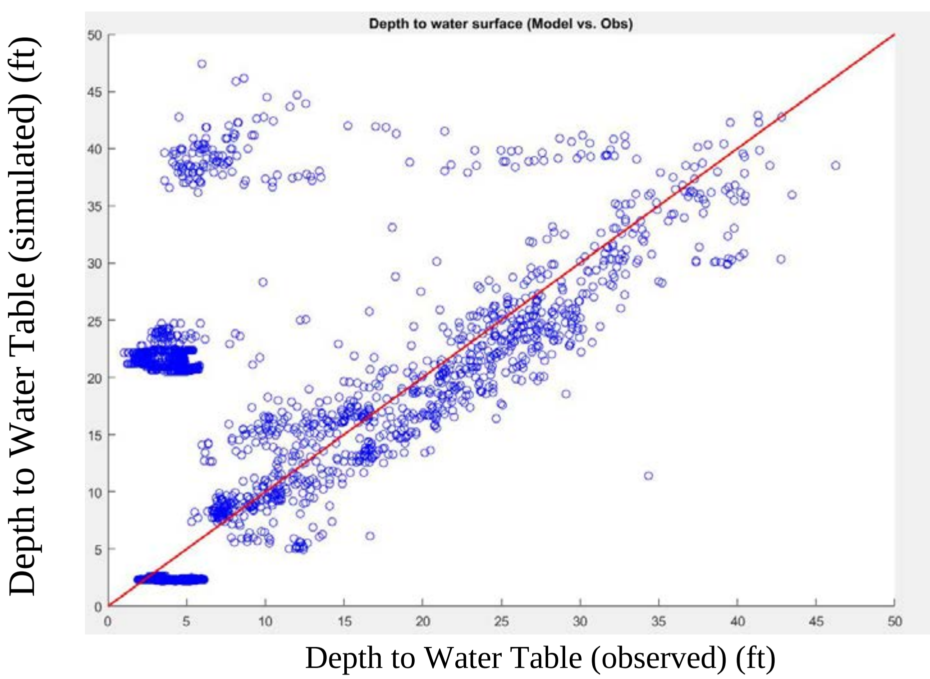


Figure 5. 1:1 plot for all modeled and observed depth to water table, in the LaSalle/Gilcrest area.

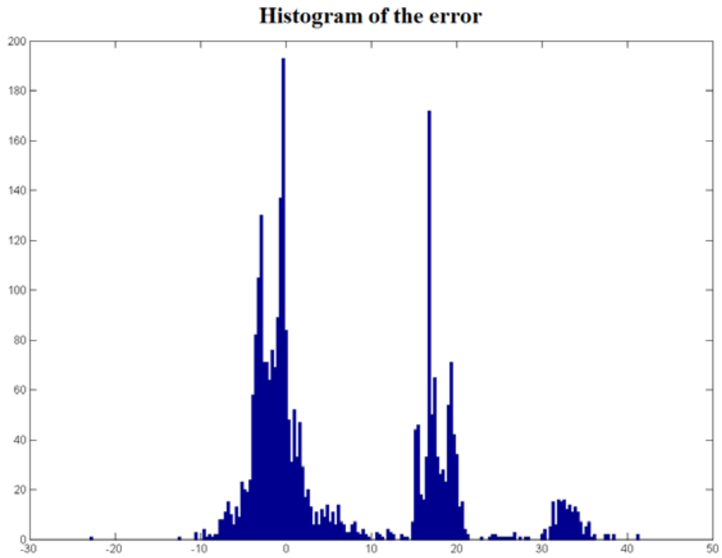


Figure 6. Histogram of residuals between observed and simulated values of depth to water table.

Phase 2: Compare Water Table Elevation in LaSalle/Gilcrest Area (Extracted Model)

In Phase 2, a model for the LaSalle/Gilcrest area is extracted from the basin-scale SPDSS model. MATLAB is mainly used to extract all the input files of from the basin-scale model and create new input files for the daughter model. The daughter model has one layer, 60 columns, and 60 rows, as shown in Figure 7.

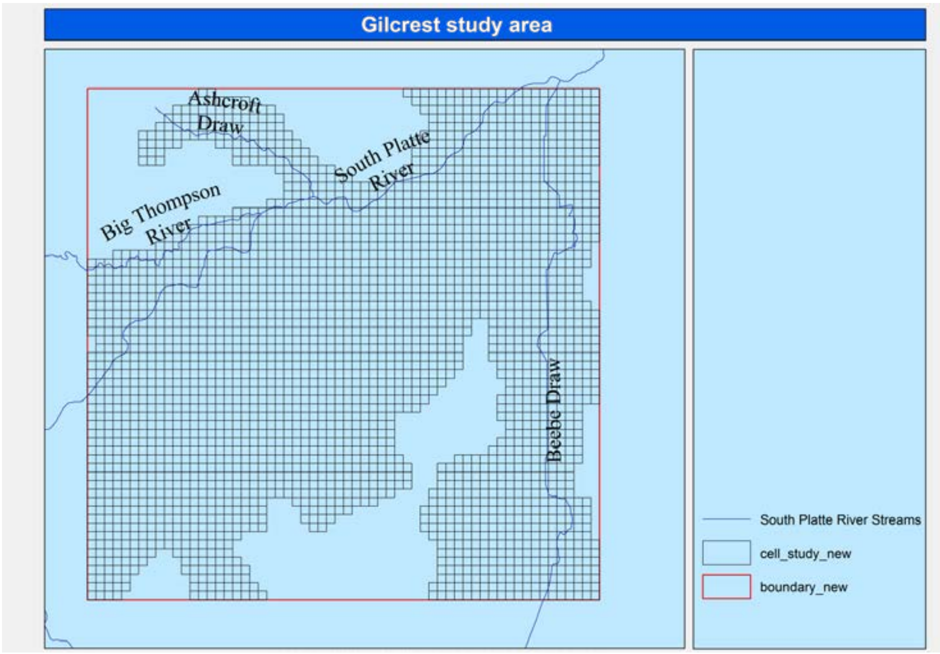


Figure 7. Finite difference grid for the LaSalle/Gilcrest study area, extracted from the grid of the basin-scale SPDSS model

There are seven input files that were created for the daughter model:

1. Basic file (.bas) - The basic file stores the information of active and inactive cells and initial head in all cells. There are about 870 of 3600 (24%) of cells that are inactive in the extracted small model. The initial head represents the water table level distribution in the alluvial aquifer in 1950, and is shown in Figure 8.

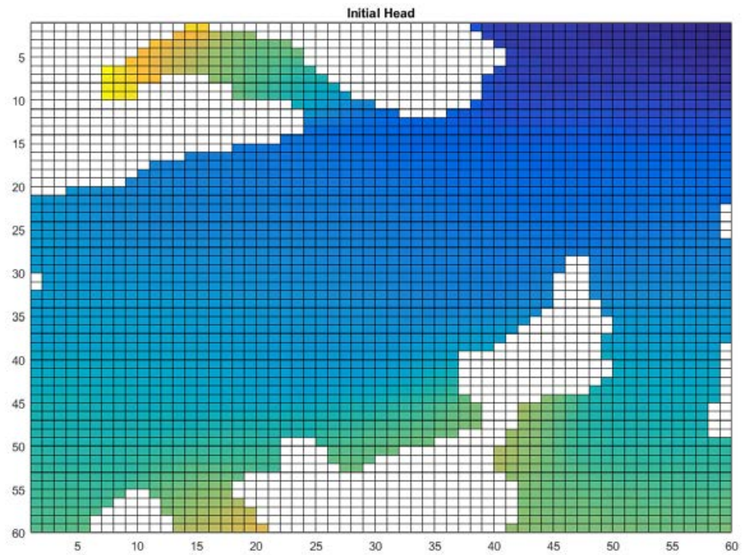


Figure 8. The initial head map (for 1950).

2. Discretization file (.dis) - The discretization file includes the grid information: number of layers, rows, and columns, width and height of each cell, top and bottom elevation, and stress period and time step. The model top elevation is plotted in Figure 9. The elevation ranges from 4620 to 4940 meters.

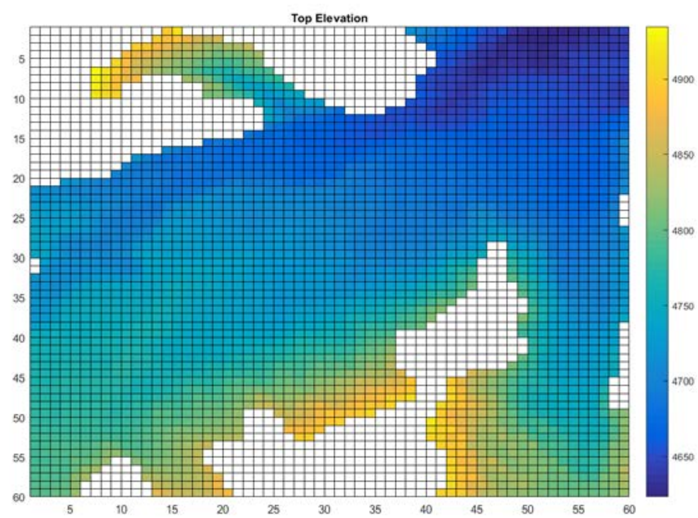


Figure 9. The top elevation plot of the LaSalle/Gilcrest study area in the model

3. Layer property flow file (.lpf) - This file contains the layer property information: hydraulic conductivity, specific storage, and specific yield. The horizontal hydraulic conductivity map is showed in Figure 10. Values range from 300 to 600 ft/day with higher values in the west and lower in the east. The vertical hydraulic conductivity is specified as three times as the horizontal hydraulic conductivity. Specific storage and specific yield are assigned as constants: 1×10^{-6} and 0.2, respectively

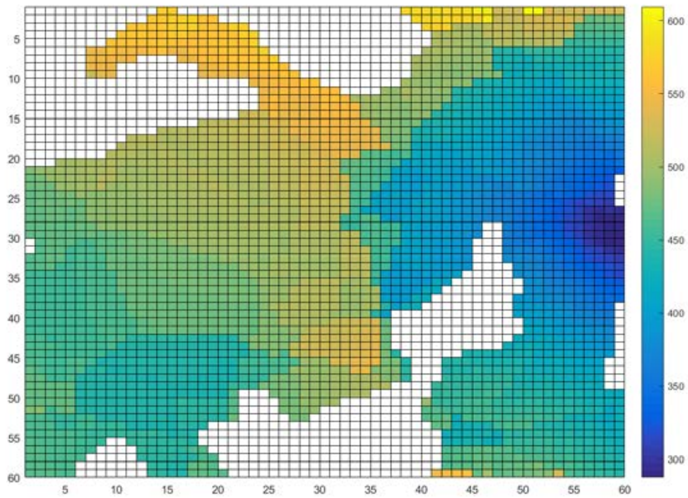


Figure 10. The hydraulic conductivity map in the study area.

4. Recharge file (.rch) - This file contains the recharge to the aquifer throughout each of the 684 simulation stress periods. The recharge in this model accounts for deep percolation from irrigation, seepage from canals and surface reservoirs. The four figures below show the recharge rates in February, April, June, and August of 2006.

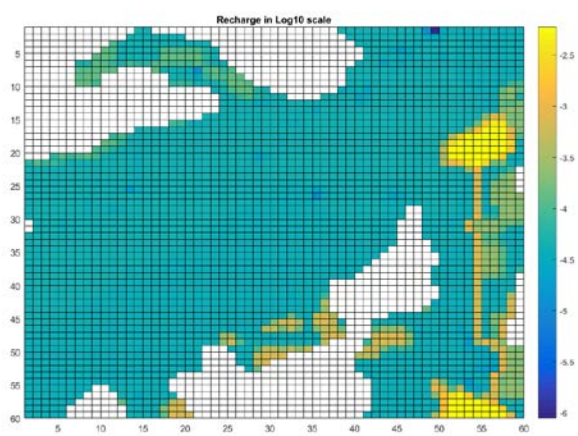


Figure 11. Recharge map in February of 2006

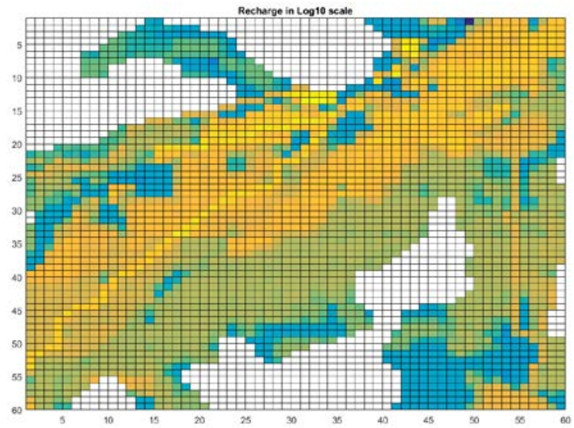


Figure 12. Recharge map in April of 2006

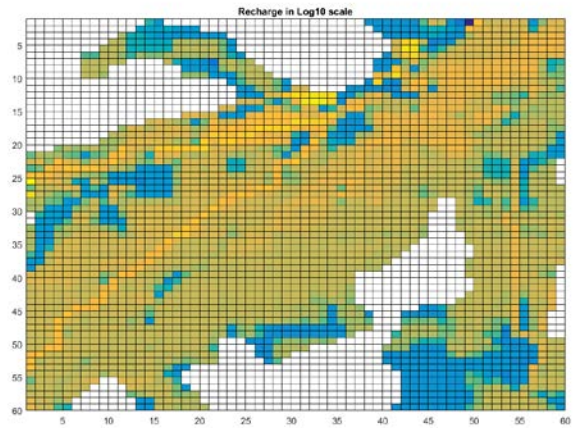


Figure 13. Recharge map in June of 2006

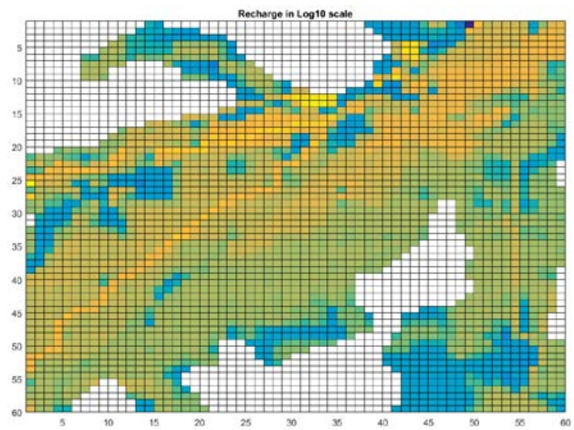


Figure 14. Recharge map in August of 2006

5. Well file (.wel) - The Well package includes well pumping locations and rates. It also includes well injection rates. In this case, several wells represent pumping, most of them represent inflow or outflow from the underlying Denver basin aquifer. Figure 15 shows the well locations in the year 2000. There are about 2500 cells has either pumping or injection.

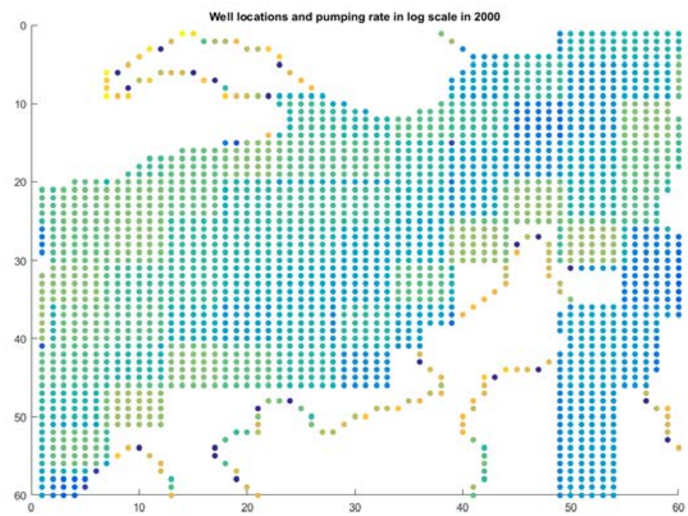


Figure 15. Well locations map and pumping or injection rate in log scale in 2000

6. Streamflow routing file (.sfr) - There are four main streams within the study area: South Platte River, Big Thompson River, Ashcroft Draw, and Beebe Draw. In this file, stream reaches are numbered. Properties of the stream like flowrate, riverbed conductance and river width are specified. Figure 16 shows the stream conductance (ft^2/day) in each cell.

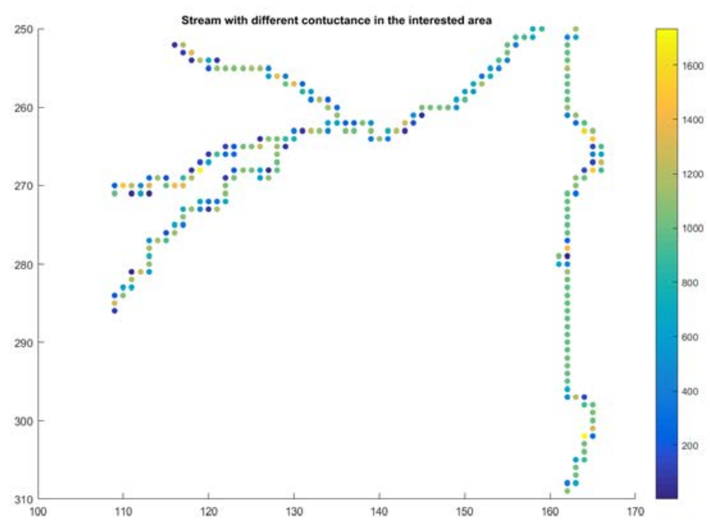
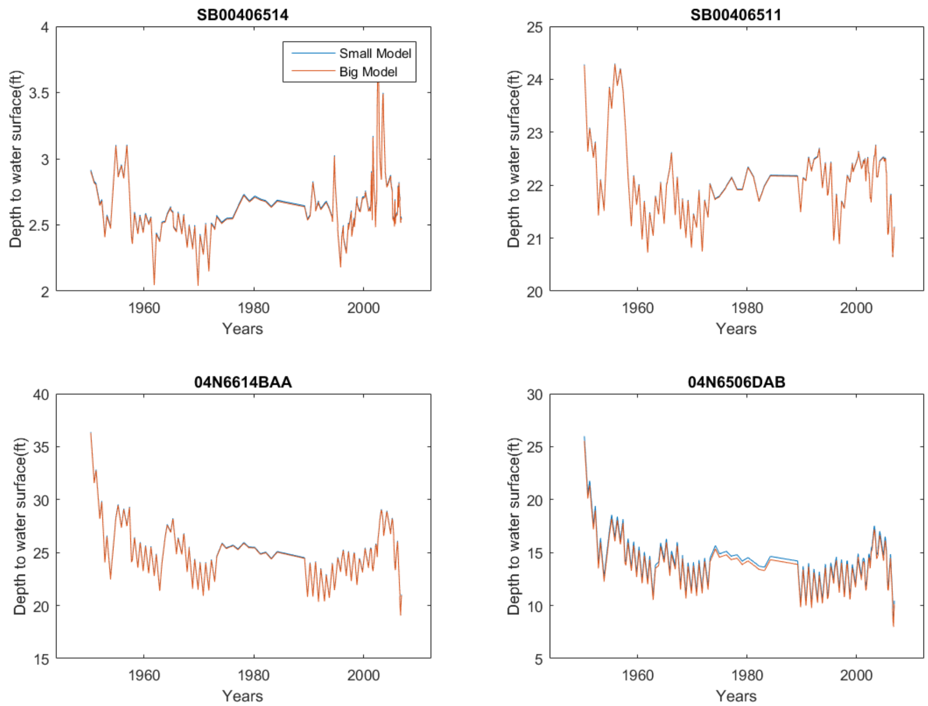


Figure 16. Streambed conductance map in study area

7. Constant head boundary file (.chd) - In the basin-scale model, head-dependent boundary conditions are specified at the end of the downstream of South Platte River. However, in the extracted small model, all the boundary cells are supposed to be assigned boundary conditions. In this case, the constant head boundary package is used. In this file, time-variant specified head are assigned before and after each stress period for each boundary cell. All the head values used in this file are extracted from groundwater hydraulic head simulation results from the SPDSS model.

After extracting all the input files from the big model, the daughter model was run for 1950-2006 and simulated values were compared to SPDSS values at the locations of the 45 monitoring wells. Results are shown in Figure 17 for 12 of the well locations. As can be seen from the results, the basin-scale model and daughter model perform almost exactly the same in the LaSalle/Gilcrest area, except for CSU WP 167. Therefore, the daughter model also over-predicts depth to water table at the locations of the monitoring wells, similar to the results shown in Figures 5 and 6.



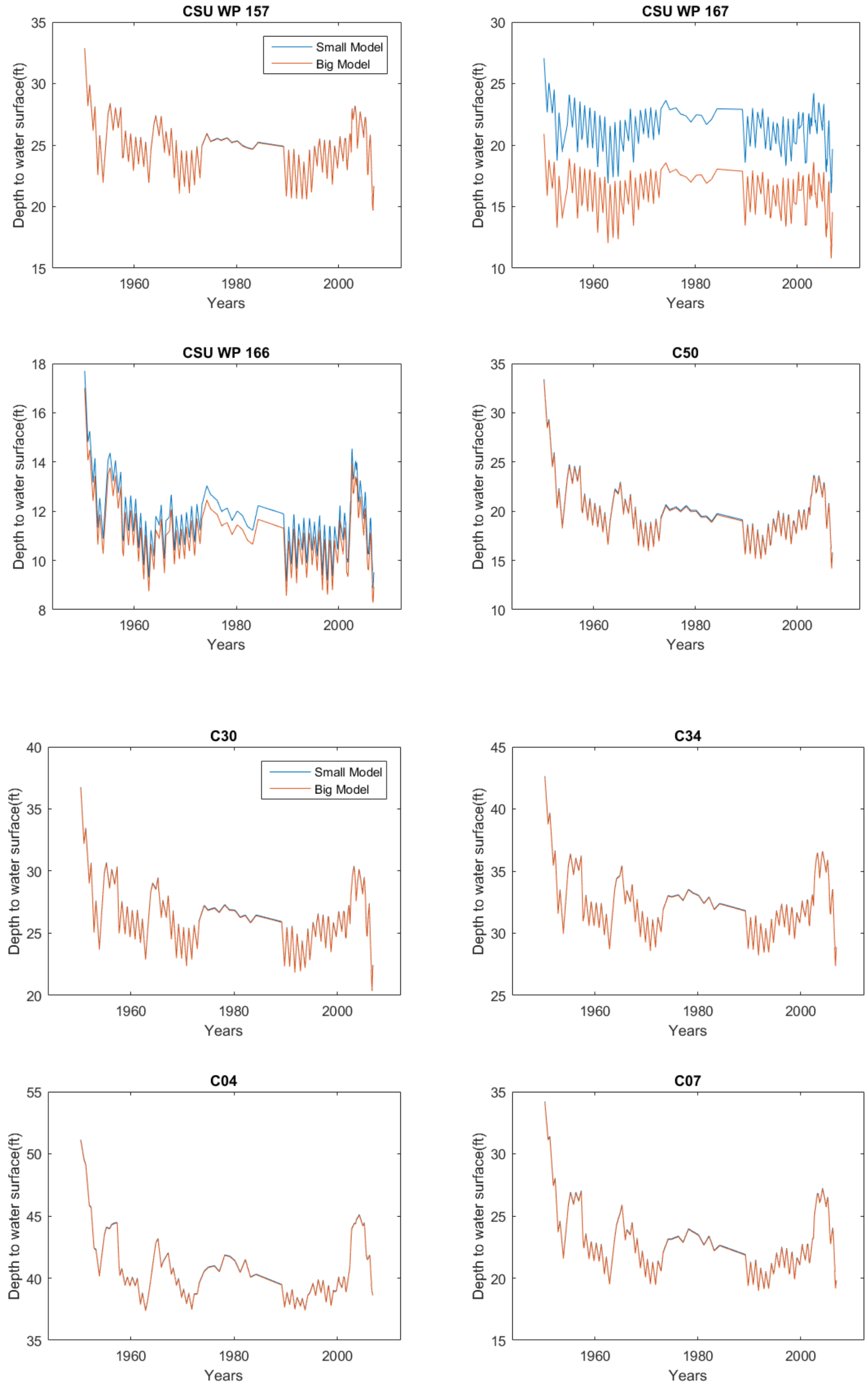


Figure 17. Head value comparison of SPDSS model and daughter model at locations of monitoring wells in the LaSalle/Gilcrest area.

<u>Phase 3</u>: Commence Construction of Refined Groundwater Model for LaSalle/Gilcrest Area

In Phase 3, a refined model grid is constructed and new layering of hydraulic conductivity is simulated for an eventual MODFLOW model of the LaSalle/Gilcrest area. Since data collection and model construction are ongoing, only a few model inputs will be shown here.

1. Model finite difference grid – The cells of the new grid are half the size as the cells in the SPDSS, resulting in 120 columns and 120 rows. Depending on the desired resolution of the geologic layering, the model could have as many as 21 layers. The top of the model coincides with the ground surface elevation, which is obtained from 30-m resolution Digital Elevation Model from the USGS (see Figure 18). The bottom of the model coincides with the bedrock elevation, which is obtained from data points from the Colorado Geological Survey. Locations of data points are shown in Figure 19.

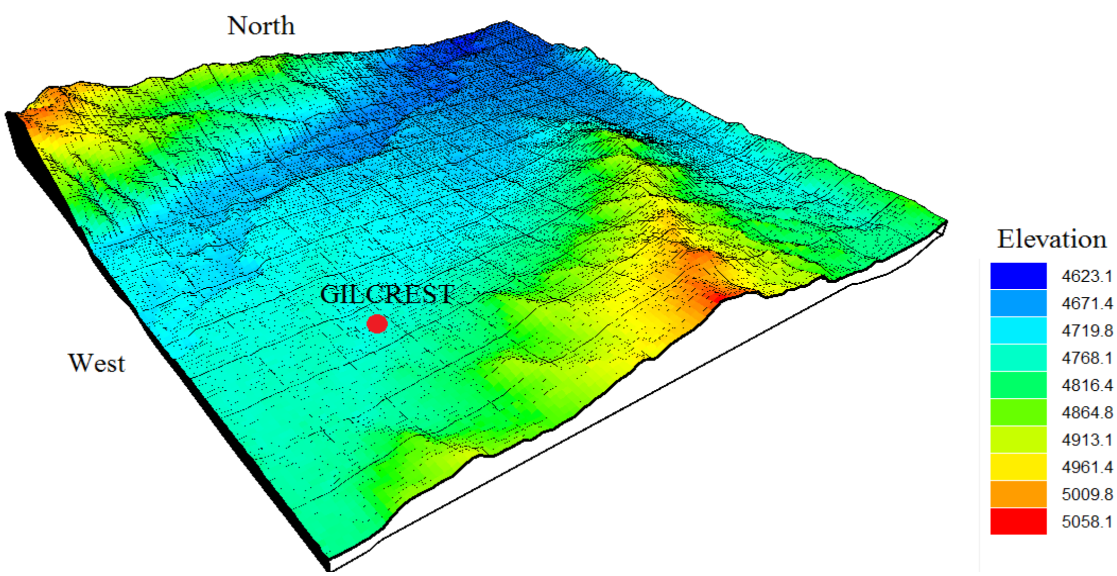


Figure 18. Ground surface elevation (ft), as obtained from a 30-m resolution DEM.

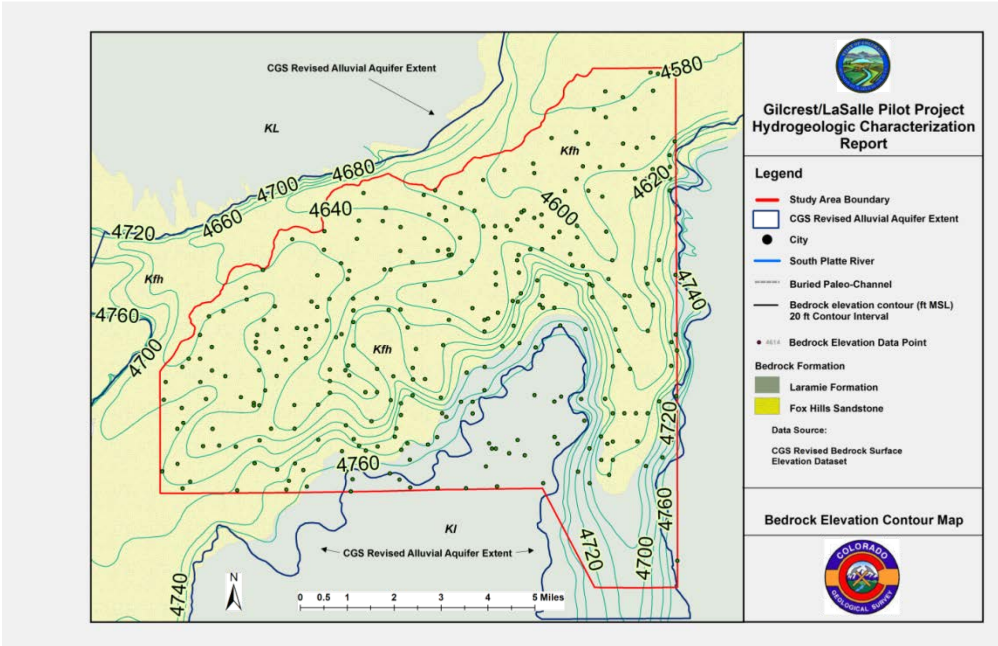


Figure 19. Points of measured bedrock elevation and resulting contour plot.

2. Hydraulic conductivity map – The refined model seeks to provide a 3D hydraulic conductivity map that can be used to provide refined groundwater flow dynamics. Data from 346 boreholes in the area (see Figure 20), as obtained from the Colorado Geologic Survey, are used to construct a 3D material map and then translate to hydraulic conductivity. The procedure to construct the map is:
    a. *Separate borehole data* - The layers of the borehole data are separated by their locations, and materials from each borehole are matched to create individual vertical layers.
    b. *Assign hydraulic conductivity (K) to soil type* - There are eight different soil types including combination of two different soils from the borehole data. The average value of the range of *K* of each soil type is assigned. Table 1 shows the *K* value for each material type.
    c. *Interpolate data* – Grid cells between borehole locations are assigned a K value using Natural Neighbor interpolation (see Figure 21). The *K* either gradually increase or decrease but no interpolated value higher than the highest value or lower than lowest value.

The resulting *K* maps of the layers located at 15 ft, 45 ft, and 60 ft below the ground surface are shown in Figures 22, 23, and 24, respectively. Figure 25 shows a comparison between the average *K* of the alluvial layers and the contoured *K* plot of the Colorado Geologic Survey, showing similarities in high *K* in areas adjacent to the South Platte River.

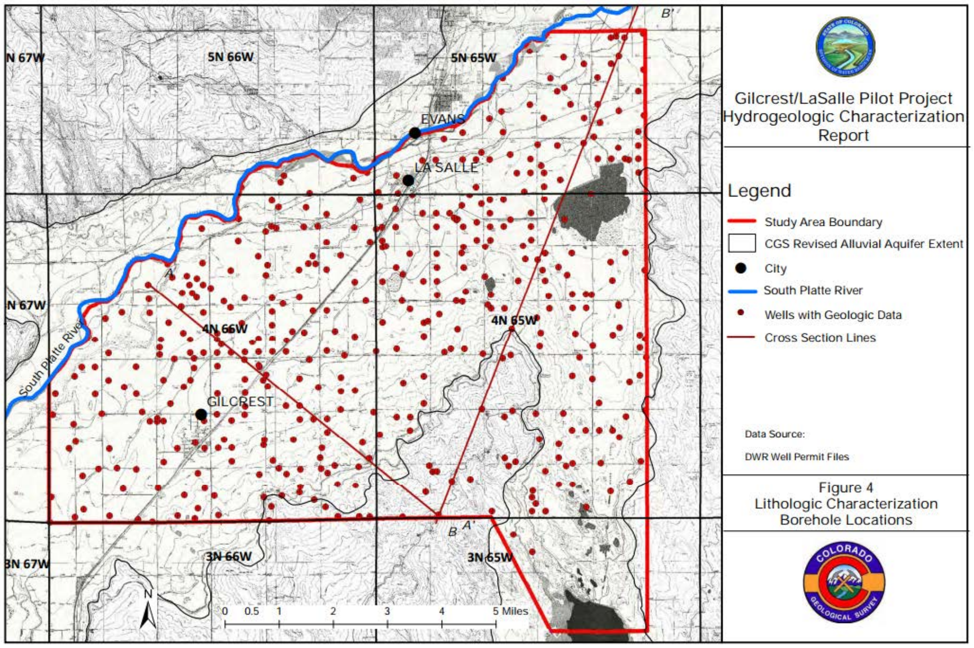


Figure 20. Location of boreholes in LaSalle/Gilcrest area. Data from these boreholes are used to create 3D maps of hydraulic conductivity for the refined MODFLOW model of the area.

Table 1. K value for different soil types

Soil Type	K	unit
clay	1.56E-05	ft/day
silt and clay	8.57E-05	ft/day
silt	1.56E-04	ft/day
sand and clay	7.80E-03	ft/day
sand and silt	7.87E-03	ft/day
sand	1.56E-02	ft/day
sand and gravel	715.57	ft/day
gravel	1431.13	ft/day

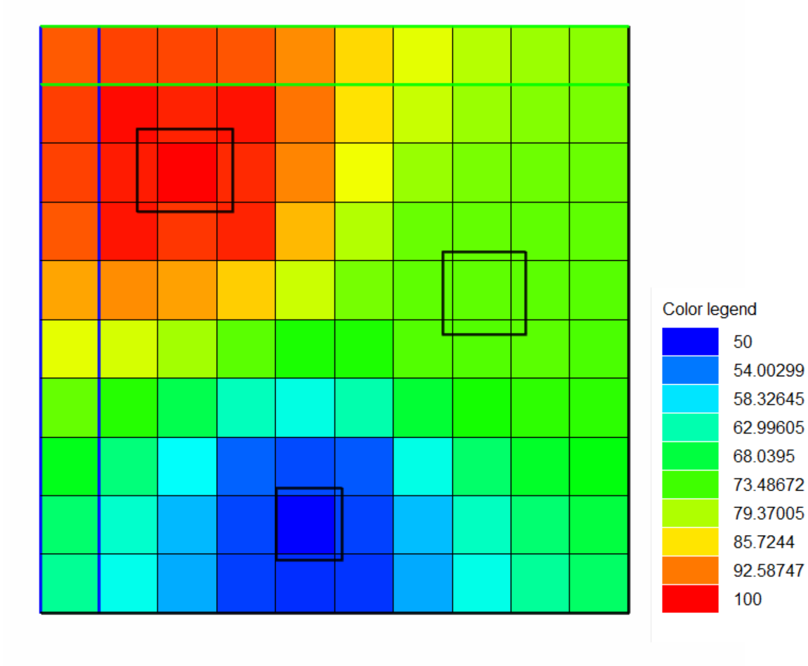


Figure 21. The Natural Neighbor method used in interpolation

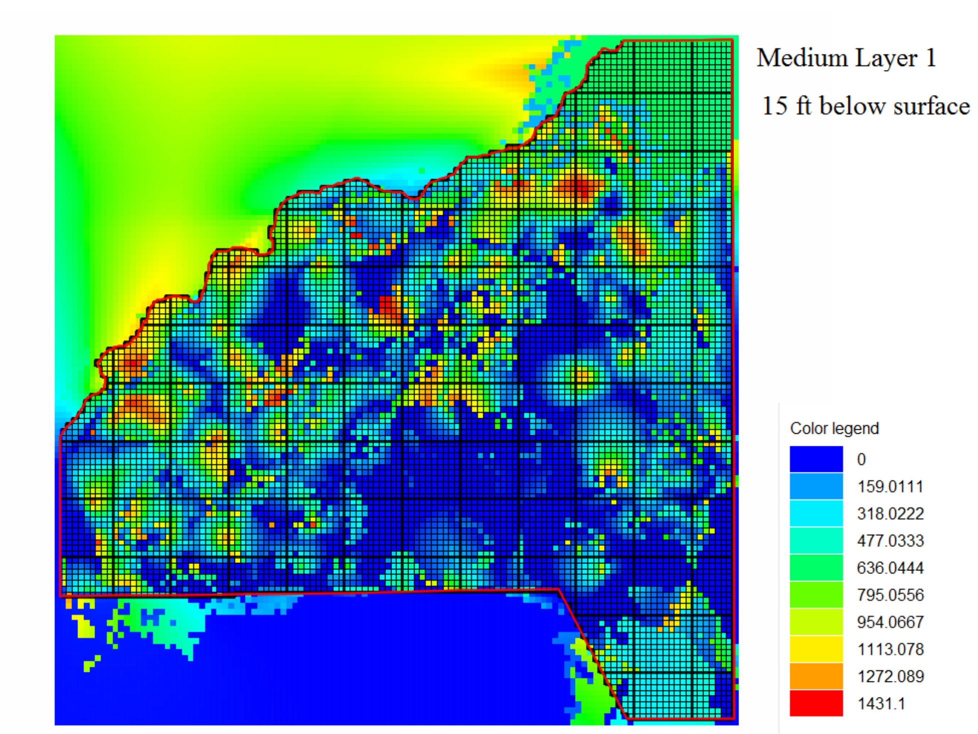


Figure 22. Hydraulic conductivity map of medium layer 1

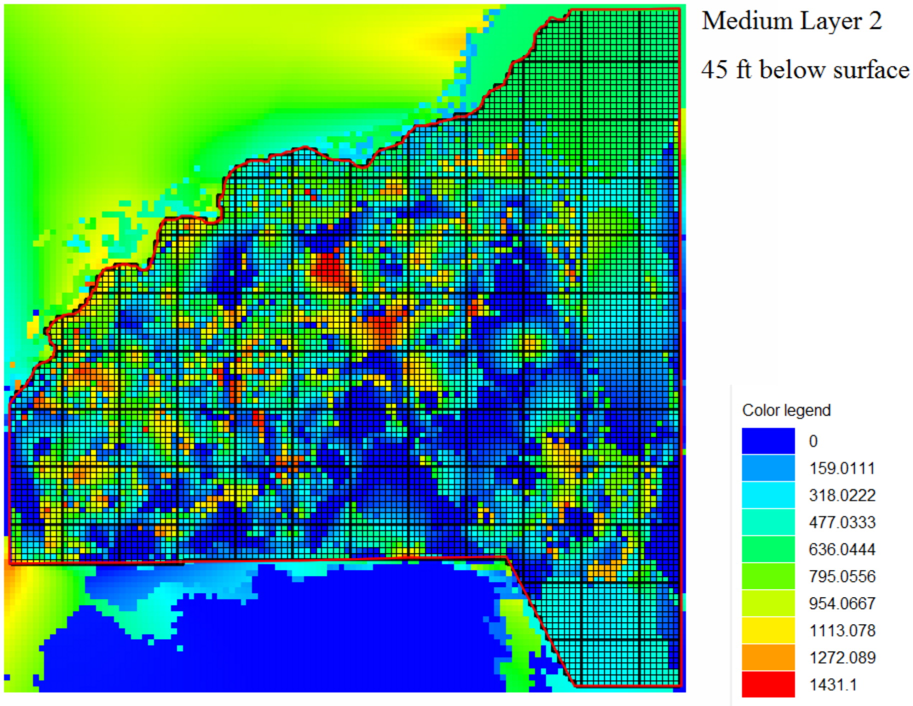


Figure 23. Hydraulic conductivity map of medium layer 1

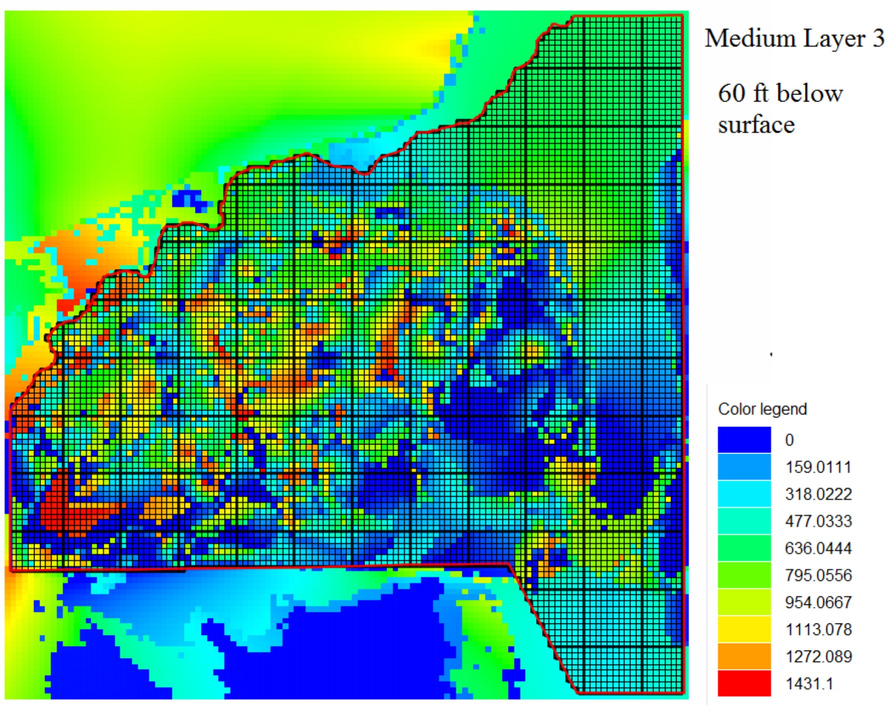


Figure 24. Hydraulic conductivity map of medium layer 1

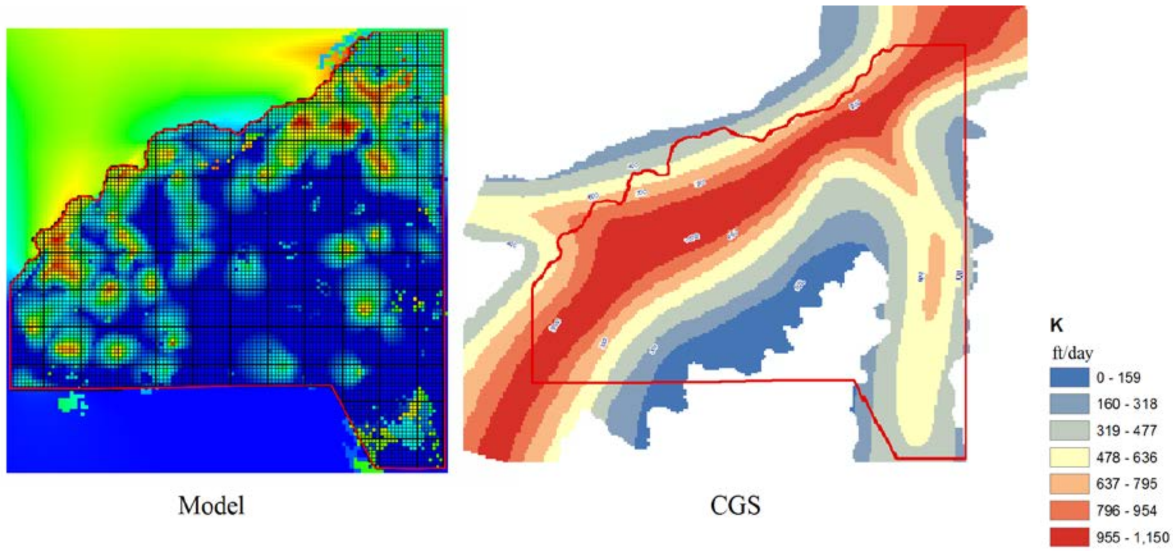


Figure 25. Comparison of hydraulic conductivity map of the new model and the map from the Colorado Geological Survey.

Next Steps

In the project for the current year (2016-2017), the following data will be collected and included in the MODFLOW model for the LaSalle/Gilcrest area: well pumping rates, Crop ET and crop distribution, rainfall, canal seepage, recharge pond inflow rates, etc. Model results will then be compared with historical monitoring well data through 2012, and also water table elevation data from recently installed monitoring wells in the Gilcrest area.