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Development and Application of Surface-Water Groundwater Flow Model of the Tuul River Basin near Ulaanbaatar, Mongolia

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14. ABSTRACT
The USGS groundwater flow model MODFLOW was used to simulate the effects of groundwater pumping and changes in climate on Tuul River flow and groundwater storage in the Center Area Well Field area immediately to the east of Ulaanbaatar, Mongolia. The model was calibrated in steady-state to August 2015 hydrologic conditions. A transient calibration to April 2015 to April 2016 conditions was also completed. Results of the study indicate that the primary source of recharge to the aquifer system is from the Tuul River. During summer months, groundwater extraction accounts for less than two percent of the flow in the Tuul River. During winter months, pumping withdrawals have a dramatic impact on aquifer storage.

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Executive Summary

The Tuul River watershed, located in north-central Mongolia, includes a catchment area of approximately 6,750 square kilometers above the capitol city of Ulaanbaatar. The water supply of Ulaanbaatar is derived wholly from groundwater pumped from shallow aquifers adjacent to the Tuul River. The USGS (United States Geological Survey) groundwater flow model, MODFLOW was used to simulate the effects of groundwater pumping and changes in climate on streamflow and groundwater storage in the Center Well Field area immediately to the east of Ulaanbaatar. Available data input into the model included: 22 boring logs; hydraulic conductivity tests performed at 88 pumping well locations; and, continuous groundwater elevations from data loggers installed at twelve monitoring wells. The model was calibrated in steady-state to August 2015 hydrologic conditions in the area. A transient calibration to April 2015 through April 2016 groundwater levels and streamflow conditions in the Tuul River was then performed. Results of the model study indicate that the primary source of recharge to the aquifer system is from the Tuul River. Although groundwater extraction accounts for less than two percent of the flow in the Tuul River in a typical August, during winter months pumping increases have a dramatic impact on groundwater levels. Because of the direct interaction between streamflow and groundwater extraction, an expansion of the model domain to include all significant groundwater pumping well fields within the watershed is recommended.

Acknowledgments

The development and application of the Tuul River surface-groundwater flow model was completed by Mr. Jon Fenske of the Institute for Water Resources (CEIWR), Hydrologic Engineering Center (HEC) and Stephen England of the U.S. Army Corps of Engineers (USACE), Philadelphia District (CENAP) in support of the U.S. Pacific Command's (USPACOM) Overseas Humanitarian, Disaster and Civic Aid (OHDACA) Program. Data gathering and valuable assistance with the conceptual model formulation was provided by Nyamaa Mendsaikhan and Dr. Dorjsuren Dechinlhundev of the Fresh Water Institute of Mongolia (FWI). Dr. Michelle Haynes (CEIWR-ICI) provided project management and guidance.

Chapter 1

Introduction

1.1 Background

The Tuul River watershed encompasses an area of approximately 57,800 square kilometers (Altansukh, 2012). The total catchment area of the watershed above Ulaanbaatar is approximately 6,750 square kilometers (HEC, 2013). With 1.3 million citizens, Ulaanbaatar is home to almost half of the population and represents the economic and cultural hub of Mongolia.

Water use, primarily derived from groundwater pumped adjacent to the Tuul River, has grown hand in hand with the demographic and economic boom the city has experienced over the last 25 years. As a result, streamflow and groundwater levels have dropped significantly. During 1945 through 1989, annual mean flow in the Tuul River at Ulaanbaatar averaged approximately 25 cubic meters per second (cms). During 1996 through 2007 the mean annual flow of the Tuul River at Ulaanbaatar decreased to 13.3 cms (Davaa, 2010). In addition to groundwater withdrawal, climate change and a decrease in precipitation on the Upper Tuul Watershed are also considered to be contributing factors for the decreasing flows in the Tuul River.

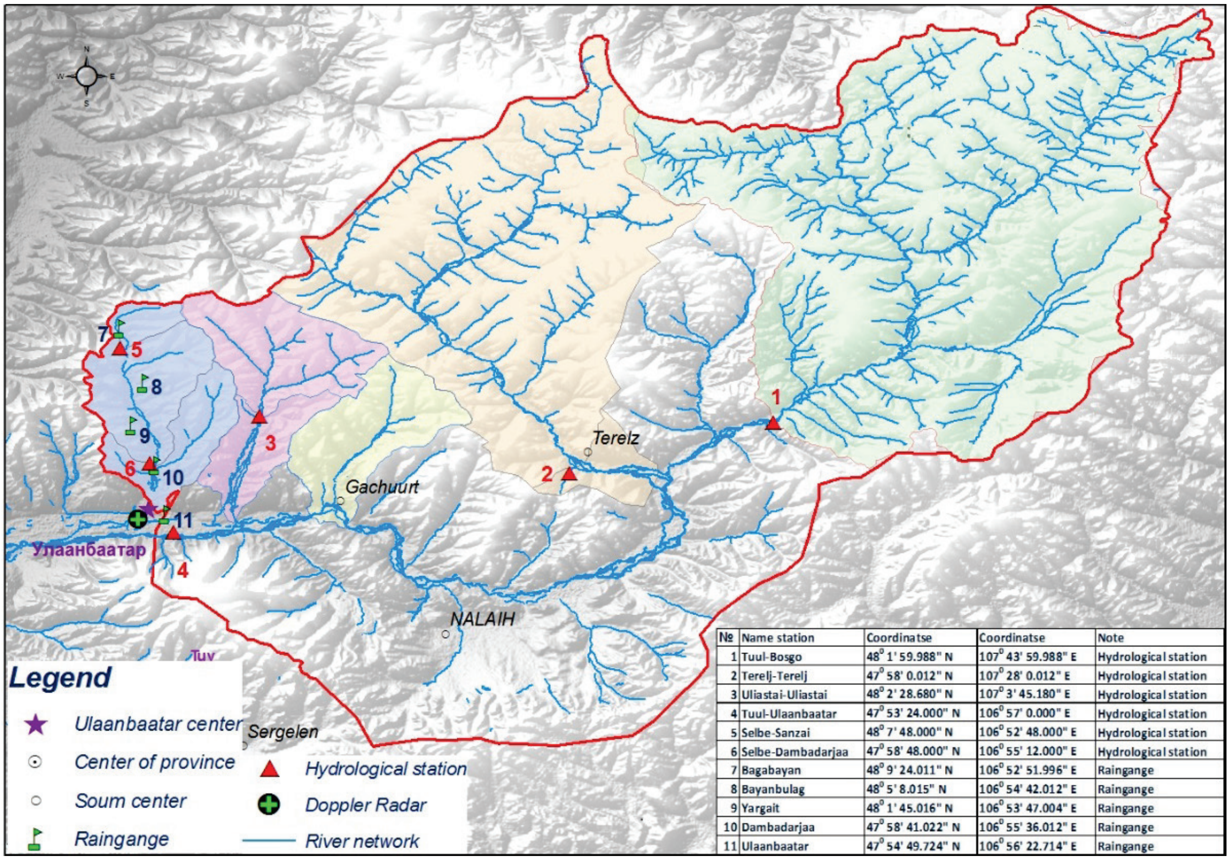
According to estimates by the Mongolian Government (Ganbold, 2010), total water usage for Ulaanbaatar is expected to double between 2010 and 2030. Computer models are needed to better understand the impact of groundwater withdrawal and climate change on the flows of the Tuul River and the water budget of the Tuul River Basin. The models should have the capability to simulate: channel flow; streambed conductance; groundwater flow; stream-aquifer interaction; recharge to the aquifer from precipitation; and, groundwater pumping. The models should provide a better understanding of system interrelationships, and help guide future data collection. The models can also be used for predictive applications within the limitations of the data.

1.2 Past Model Efforts

Previous model studies performed in the region include: HEC-HMS (HEC's Hydrologic Modeling System software) model of the Selbe River watershed (HEC, 2010); an HEC-HMS regional model of the Tuul River watershed (HEC, 2013); an HEC-RAS (HEC's River Analysis System software) channel flow model of the Tuul River (HEC, 2013); a MODFLOW groundwater flow model of the pumping area immediately east of Ulaanbaatar (2014); and a basin-wide MODFLOW model developed by the USGS (2015).

1.3 Study Area

Figure 1 presents the Tuul River watershed above Ulaanbaatar, Mongolia along with hydrologic and meteorologic gage locations. Figure 2 presents the groundwater pumping fields that serve as the primary source of water for Ulaanbaatar. The model domain of the 2016 study encompasses the Center Well Field area as presented in Figure 2. The model grid boundary is dictated by geologic and hydrologic conditions.



№	Name station	Coordinatse	Coordinatse	Note
1	Tuul-Bosgo	48° 1' 59.988" N	107° 43' 59.988" E	Hydrological station
2	Terelj-Terelj	47° 58' 0.012" N	107° 28' 0.012" E	Hydrological station
3	Uliastai-Uliastai	48° 2' 28.680" N	107° 3' 45.180" E	Hydrological station
4	Tuul-Ulaanbaatar	47° 53' 24.000" N	106° 57' 0.000" E	Hydrological station
5	Selbe-Sanzai	48° 7' 48.000" N	106° 52' 48.000" E	Hydrological station
6	Selbe-Dambadarjaa	47° 58' 48.000" N	106° 55' 12.000" E	Hydrological station
7	Bagabayan	48° 9' 24.011" N	106° 52' 51.996" E	Raingange
8	Bayanbulag	48° 5' 8.015" N	106° 54' 42.012" E	Raingange
9	Yargait	48° 1' 45.016" N	106° 53' 47.004" E	Raingange
10	Dambadarjaa	47° 58' 41.022" N	106° 55' 36.012" E	Raingange
11	Ulaanbaatar	47° 54' 49.724" N	106° 56' 22.714" E	Raingange

Figure 1. Tuul River Watershed above Ulaanbaatar (Mongolia Institute of Meteorology and Hydrology, 2012)

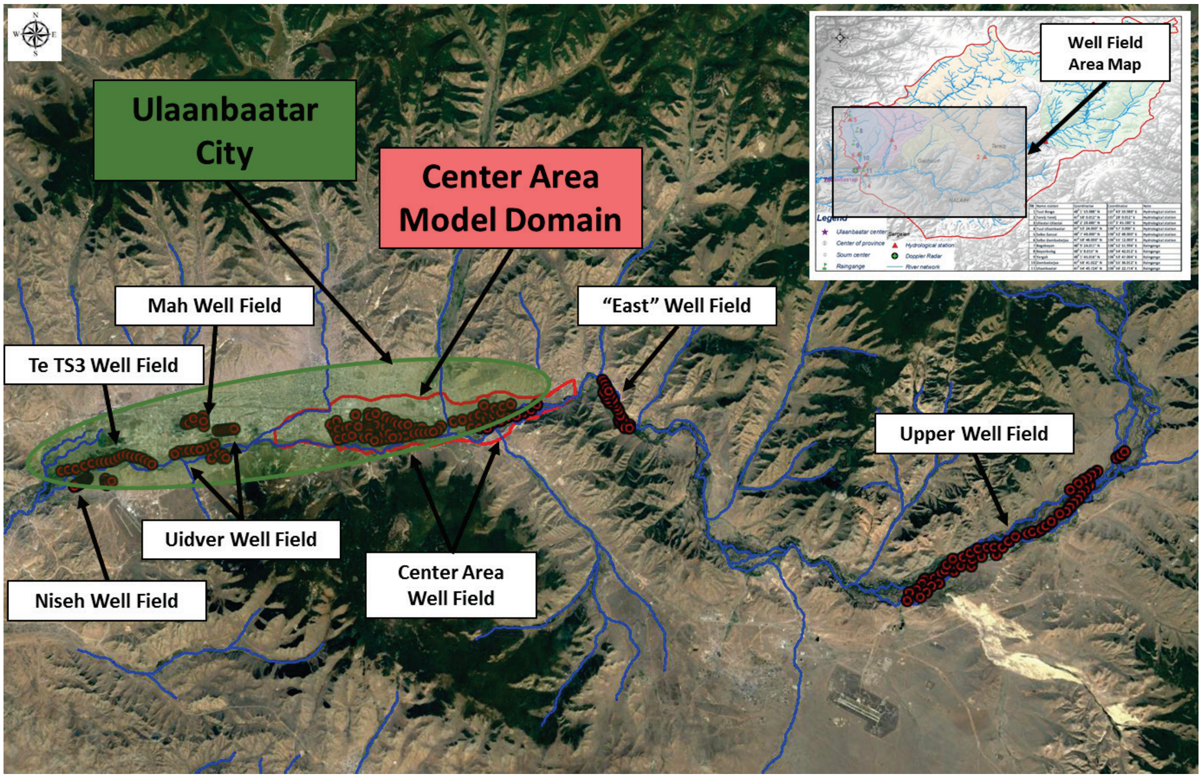


Figure 2. Groundwater Pumping Well Fields and Center Area Model Domain

Chapter 2

Conceptual Model Development

The purpose of a conceptual model is to organize and interpret available information that is known about a site into a framework that can be used to build a numerical model of the site. The conceptual model describes the overall water budget of the project area, the hydrologic and hydrogeologic units that are modeled, and the groundwater and surface water boundary conditions that are imposed. System drivers generally include the boundary of the model domain, various types of source/sink and boundary conditions, subsurface features that convey water or interrupt flow, rainfall and evapotranspiration zones, and site stratigraphy.

The conceptual model should start with the basic components that have the greatest effect on groundwater flow. Once the preliminary conceptual model has been developed, the computational grid used by MODFLOW can be constructed and the desired simulations can be set up to portray the conceptual model. Complexity can be added to the conceptual and computational models as a better understanding of the flow systems is defined. This often is an iterative process where the numerical model results raise questions or confirm answers used to help improve the conceptual model.

When evaluating the results of the numerical model, it is important to have an adequate understanding of the conceptual model so that potential model limitations are fully understood. The following subsections provide a brief description of the features included in the Tuul River Center Area conceptual model and MODFLOW numerical model.

2.1 Model Datum

All datasets used in model development were converted to a common horizontal and vertical datum. The horizontal datum used for this model is meters Universal Transverse Mercator (UTM), Zone 48, World Geodetic System (WGS) 84. The vertical datum used is meters WGS84. Any geographic datasets that were not in the correct coordinate system were converted using the coordinate conversion software, Corpscon, Version 6.0.1, developed by the Topographic Engineering Center (CETEC) of the U.S. Army Corps of Engineers (USACE).

2.2 Topography

In the MODFLOW model, topographic information is used to define the surface of the three-dimensional computational grid. Topographic information for this study is based on two meter contours of the Ulaanbaatar area that were provided, as an ArcGIS® coverage, by the Fresh Water Institute of Mongolia (FWI). This contour data was merged with cross-section data that was input to a previous HEC-RAS model that was developed for the Tuul River (HEC, 2013). Figure 3 illustrates the type of topographic information available in both datasets.

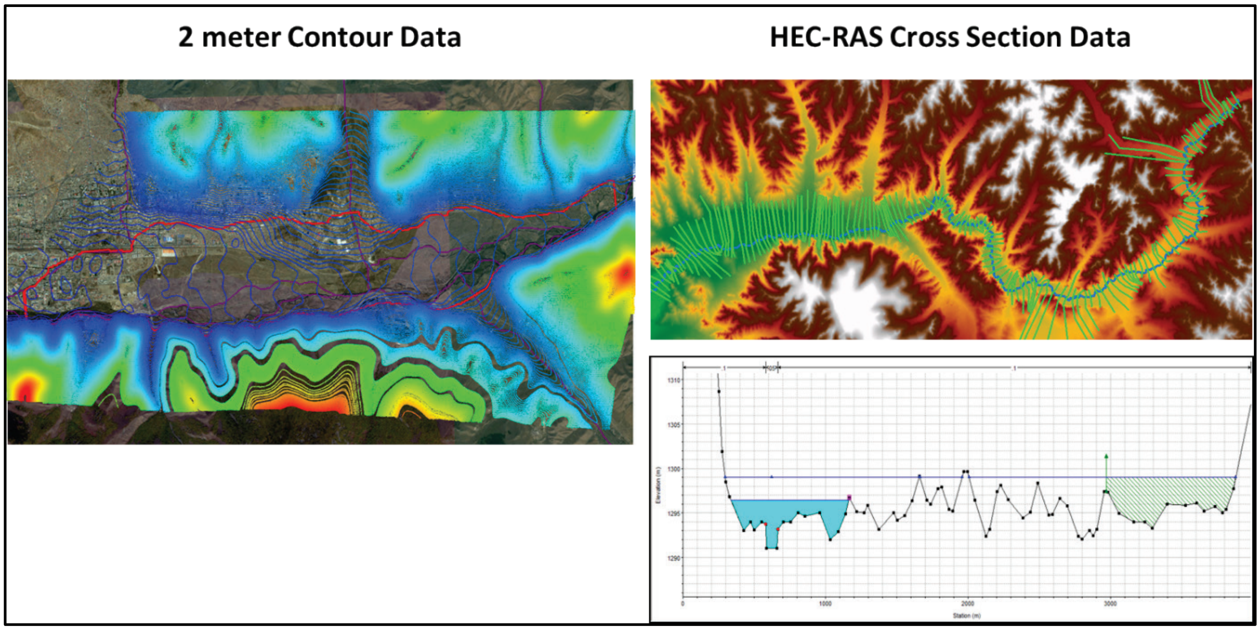


Figure 3. Topographic Datasets

The merged topographic dataset provided good regional coverage across the model domain, while incorporating the smaller scale variations in topography near the Tuul River. Once this combined topographic dataset was reviewed for consistency, the dataset was interpolated to the MODFLOW grid as the top of Layer 1. Figure 4 presents the combined topographic dataset and the interpolated topographic relief across the model domain.

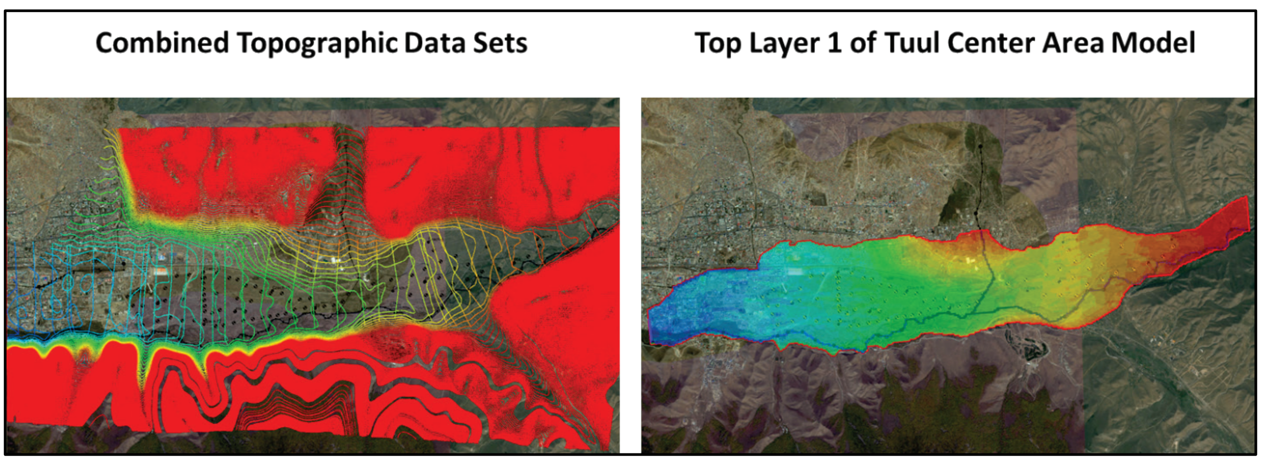


Figure 4. Modeled Topography

2.3 Geology and Hydrogeology

The geology across the Tuul River Center Area model domain is composed of alluvial deposits overlying bedrock. These deposits are comprised of gravel, sand, loam and clay. Several geologic investigations define the alluvial aquifer as a two layer system, with the upper layer having an average thickness of ten meters and the lower layer having an average thickness of up to thirty meters. The current MODFLOW model has two computational layers to replicate this conceptual geologic layering. However, during model development a review of the available boring logs in the Center Area did not indicate a well-defined two layer system. Consequently, the hydraulic properties assigned to both model layers were not varied vertically for this iteration of the model. If additional information becomes available to better define the tw0-layer alluvial geology, revisions can be made to future iterations of the model. The following sub-sections describe how the geologic layering and hydrogeologic properties used in the model were developed.

2.3.1 Geologic Layering

At the edge of the alluvial valley the rock rises steeply along the mountain outcrops. Based on discussions during model development, the underlying rock was assumed to carry minimal flow in comparison to the overlying unconsolidated, alluvial material. The base of the model was assumed to be at the interface between the unconsolidated material and the underlying rock.

The interface between the alluvial aquifer and the underlying bedrock was based on 22 boring logs in the Center Area. Boring log data was provided by FWI. These boring logs indicated the presence of fine grained material (clay, silt, loam) interlaced through the coarser water bearing material (gravels and sands). The presence of conglomerated (potentially non-water bearing) material was also identified within the alluvial beds. The geologic layering appeared to be intermittent based on the depositional environment of the Tuul River and did not form laterally continuous layers. The presence of this lower conductivity material indicates that even surficial deposits may act as semi-confined aquifers. As such, the vertical hydraulic conductivity may be substantially lower than that in the horizontal direction (Kh/Kv anisotropy). As depicted in Figure 5, the 22 boring logs that were available for this modeling study were well distributed across the model domain.

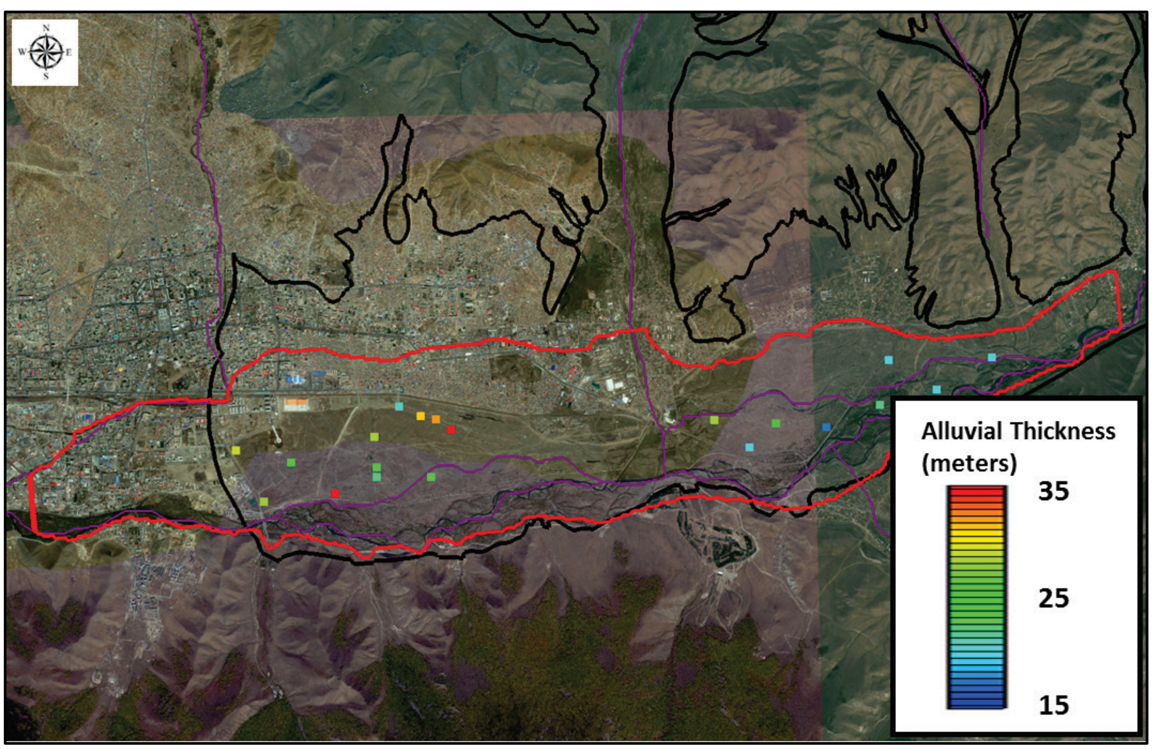


Figure 5. Geologic Boring Locations and Alluvial Thickness

The depth of the alluvial aquifer was determined based on the boring log intersection with substantial clay or sandstone units at the base of the boreholes. An alluvial outcrop ArcGIS® coverage (shown in black on Figure 5) provided by FWI was overlain on the available alluvial depth data to guide the lateral extents of the model domain. Using the alluvial outcrop coverage as a guide, the alluvial thickness was assumed to be negligible along the mountain interfaces. The lateral extent of the alluvial material was modified during model construction to account for significant surface features (river locations, mountain outcrops, etc.) seen from satellite imagery. The depth of the alluvial aquifer system was then interpolated to the MODFLOW grid using a Kriging routine. This Kriging was based on the data from the 22 boring logs and the alluvial outcrop assumptions. A Kriging anisotropy aligned from upstream to downstream along the Tuul River was applied to better reflect the depth variations in the observed data. Overall, the alluvial aquifer appears to thicken moving from upstream to downstream. The Kriged depth was then subtracted from the surface topography to define the elevation of the base of the alluvial aquifer that was used as the bottom of Layer 2 in the MODFLOW model. The Kriged depth used for this model is shown in Figure 6.

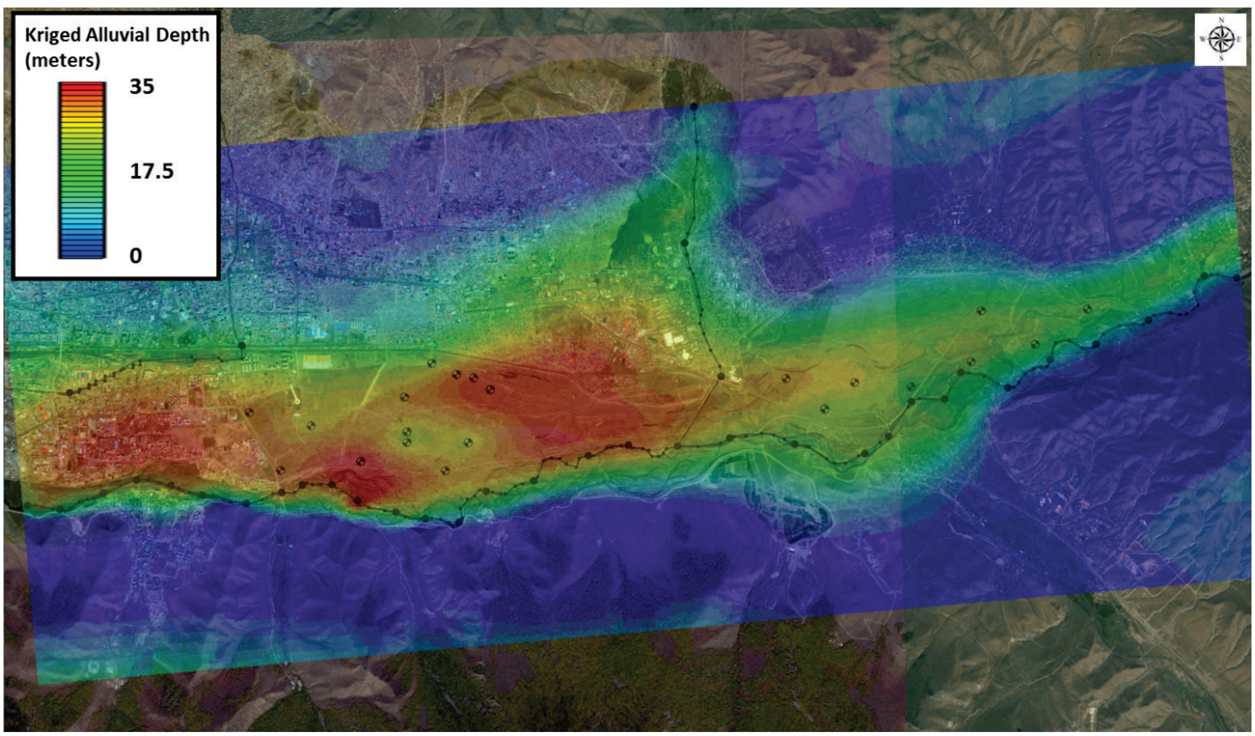


Figure 6. Kriged Alluvial Depth

2.3.2 Hydrogeologic Properties

Hydraulic conductivity testing was performed at 88 well locations in the Center Area. Results from the hydraulic conductivity testing were provided by FWI. As shown in Figure 7, these hydraulic conductivity test locations were uniformly spread across the MODFLOW model domain. A wide range of hydraulic conductivities were seen in the Center Area, varying from a low of 12.0 meters/day to a high of 242.2 meters/day. The average of all of the test data was 61.3 meters/day. This variation is likely due to the heterogeneity of the alluvial material. Although a wide range of hydraulic conductivities were recorded, a review of this data indicated

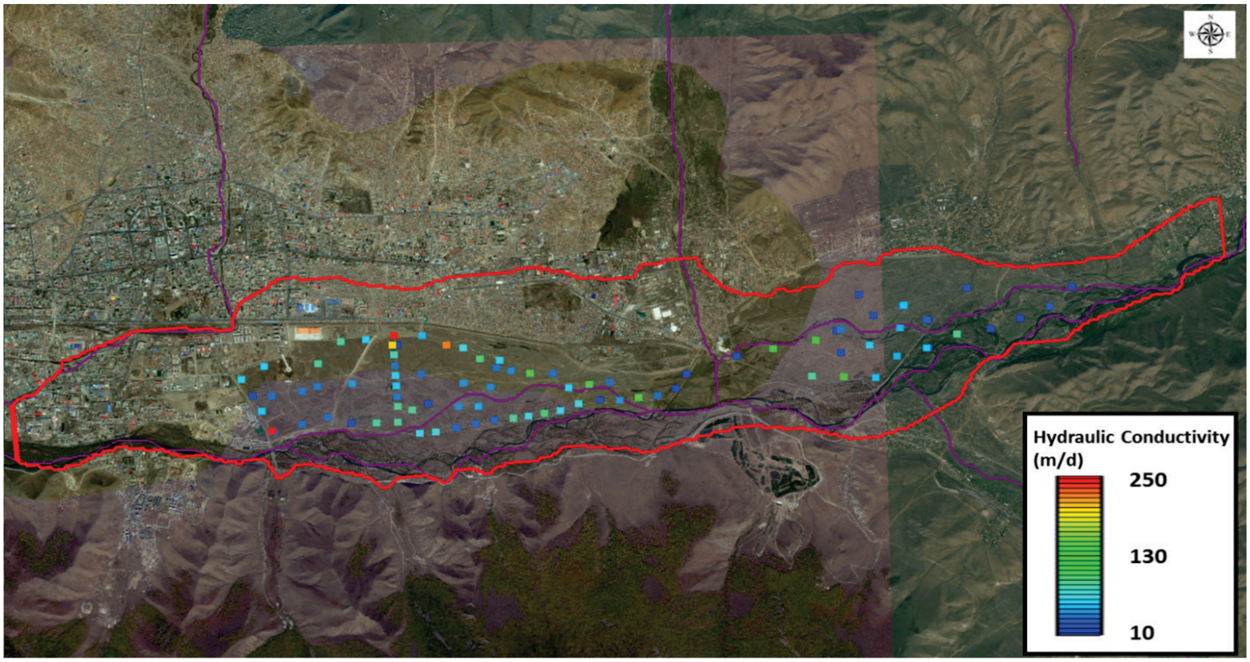


Figure 7. Hydraulic Conductivity Distribution

several distinct trends. These trends were used to develop zones of hydraulic conductivity in the calibrated MODFLOW model. These hydraulic conductivity zones are more fully discussed in Section 3.3.1.

2.4 Groundwater Monitoring Well Data

A variety of water level data was available in and around the Center Area well field in Ulaanbaatar. Much of the historic data was not suitable for model calibration since it consisted of manual water level measurements taken from active pumping wells. These measurements were taken during periods of active pumping as well as under "Static" conditions. However, it was unclear how long each well had been pumping or allowed to recover prior to each measurement being taken.

During discussions concerning the limitations of this water level data for calibration purposes, FWI indicated that continuous water level monitoring was taken at twelve locations in the Center Area. These continuous readings were taken using HOBO (Onset Computer Corporation, Massachusetts, United States) Data Loggers. The HOBO Data Loggers were installed and began recording on or about January 2015 and collected continuous water level measurements every four hours. Figure 8 shows the location of the twelve HOBO Data Loggers.

Seven of the twelve HOBO Data Loggers were installed in dedicated monitoring wells. These dedicated monitoring wells are called Czech-2, Czech-6, Czech-7, Czech-10, Czech-12, Czech-13, and Czech-15. In addition to these dedicated monitoring wells, five additional HOBO Data Loggers were installed at or immediately adjacent to active pumping wells. These locations included Well-23, Well-41a, Well-49a, Well-66a, and Well-69a. The horizontal and vertical location of all twelve HOBO Data Loggers were surveyed so that the water depth readings recorded by the logger could be converted to the water level elevations used for model calibration.

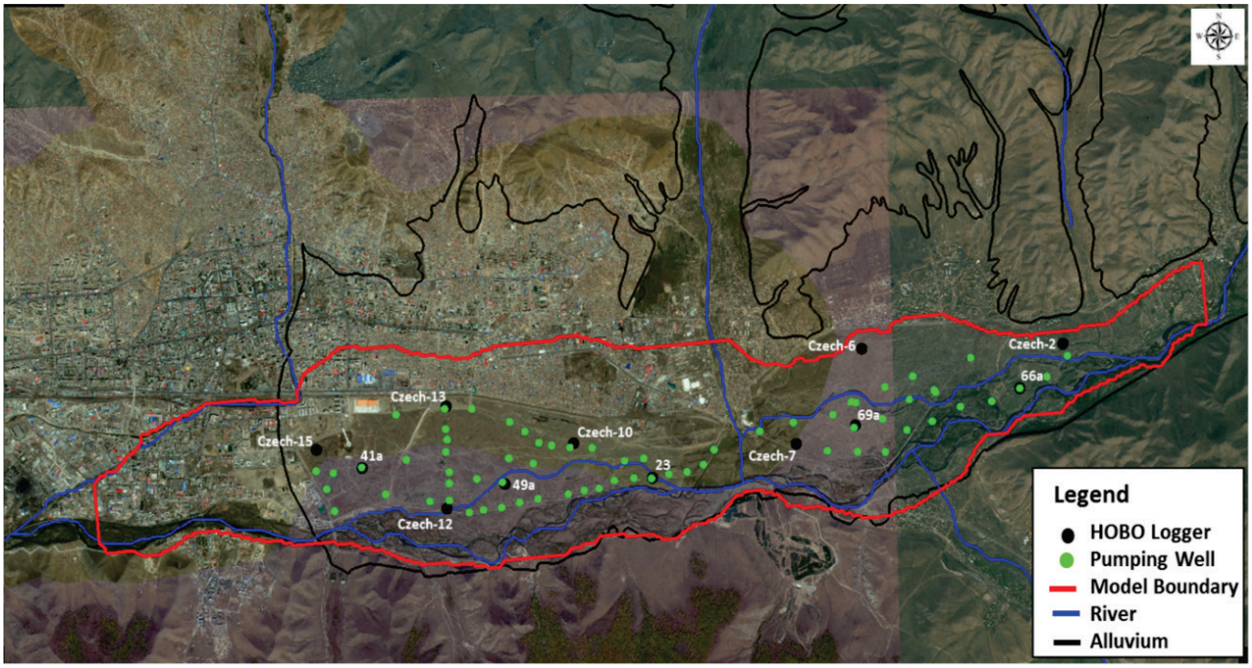


Figure 8. HOBO Data Logger Monitoring Well Locations

2.5 Surface Water

As depicted in Figure 9, the Selbe River is located at the northwestern boundary of the model domain, and the Uliastai River flows into the Tuul River near the center of the study area. The Tuul River flow gage at Ulaanbaatar is located towards the western end of the study area.

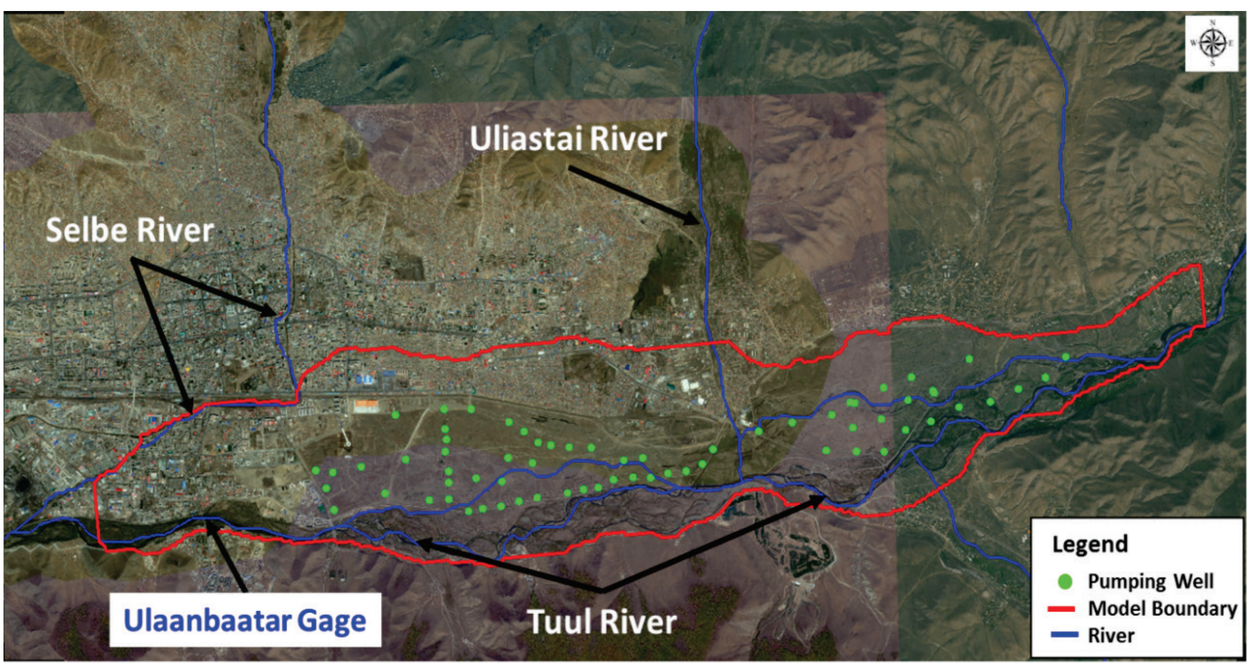


Figure 9. Rivers and Ulaanbaatar Gage Location

2.5.1 River Flows

Figure 10 presents a Google Earth® depiction of the Selbe River. The Selbe River flows southwest from the Khentii Mountains to join the Tuul River at Ulaanbaatar. As shown in Figure 1, there are two streamflow gages located in the Selbe watershed. From the limited data available, flows in the Selbe River generally range between 0.5 and two cms at Ulaanbaatar between May and October (Davaa, 2006), with flood events capable of exceeding 25 cms. Stage and river bed elevation data are not available within the model domain. For model development, stage was based on topography and average river width is derived from Google Earth® measurements.

Figure 10. Selbe River (from Google Earth®) at Northwest Boundary of Model Domain

Figure 11 presents a photograph of the Uliastai River taken in September 2016, approximately one kilometer above the confluence with the Tuul River. There is limited information regarding flow and stage of the Uliastai River. As is the case with the Selbe River, the stage of the Uliastai River is based on topography and average river width is derived from Google Earth® measurements.

Figure 12 presents a photograph of the Tuul River taken in September 2016 at the Ulaanbaatar gage located at the Zaisan Street Bridge in Ulaanbaatar. The average channel width of the Tuul River is 35 to 37 meters during normal flows, depth is 0.8 to 3.5 meters, and velocity is 0.5 to 1.5 m/sec (NAMHEM, 1999). The Ulaanbaatar gage has been in operation since 1945 and is the most reliable and important source of surface water flow data used in the model. From 1945 to 1989, prior to large scale development, the long-term mean annual flow at the Ulaanbaatar gage was approximately 25 cms. However, the annual mean flow decreased to 13.3 cms from 1996 to 2007 (Davaa et al., 2010). Flows recorded at the Ulaanbaatar gage range from zero during winter months to a high of 1,580 cms recorded during the 1966 flood event. The sources of water discharge to the Tuul River can be broken into three components: rainfall runoff; groundwater; and snowmelt. In the year 2000, it was estimated that 56 percent of flow came from rainfall, 37 percent from groundwater, and seven percent from snowmelt (Altansukh, 2008).

Figure 11. Uliastai River September 2016 Approximately One Kilometer (km) above Confluence with Tuul River

Figure 12. Tuul River September 2016 at Ulaanbaatar Gage

Measured flows at the Ulaanbaatar gage in 2015 are presented in Table 1. Note that flows approach or reach zero in winter months when the river is frozen. In April 2015, the average flow increases to 12.0 cms due largely to snowmelt. The peak flow of 76.2 cms measured in August 2015, is largely a product of summer rainfall.

Table 1. Measured Average Monthly Flow Data at Ulaanbaatar Gage, 2015

2015	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Monthly Average (cms)	0.055	"	0.52	12.0	7.61	8.06	12.5	30.4	13.5	8.72	2.48	0.39
Maximum (cms)	0.19	"	3.00	22.8	21.0	17.2	32.7	76.2	17.2	11.8	5.48	0.71
Minimum (cms)	"	"	"	3.44	3.60	4.64	5.66	15.3	10.4	6.34	0.75	0.20

2.5.2 Stream-Aquifer Interaction

The water exchange between a river and groundwater is a function of the relative water elevation, and the streambed conductance of the streambed sediments. The flux (Q) of water exchange is calculated using the following formula:

$$Q = COND\ (Hriv - Hgw) \tag{1}$$

where:

COND is streambed conductance;
Hriv is the river stage;
Hgw is the hydraulic head of the adjacent groundwater.

Streambed conductance (COND) is calculated in MODFLOW using the following formula:

$$COND = KLW/m \tag{2}$$

where:

K is the hydraulic conductivity of the river bed material;
L is the length of the reach;
W is the width of the reach;
m is the thickness of the river bed

The width of rivers were estimated using Google Earth® and from direct field observations made in September 2016. The width of the Selbe River was estimated to average approximately five meters. The width of the Uliastai River was estimated to average approximately three meters, and the width of the Tuul River was estimated to average approximately fifty meters.

From direct field observation, it was determined that the hydraulic conductivity of the river bed material of the Selbe and Uliastai Rivers in the study area is low. Figure 13 presents a photograph of the Uliastai River bed sediments taken in September, 2016. Note sediments tend to be fine in nature and consist mainly of silt and clay. This was verified by taking a hand sample and observing a granular cohesion indicative of clay.

Figure 13. Photo of Uliastai River Bed Sediments, September 2016

Conversely, Figure 14 presents a photograph of Tuul River bed sediments taken in September 2016. Note bed material consists mainly of highly conductive cobbles, pebbles, and gravel. Thus, water exchange between the Tuul River and groundwater is much more robust than in the Selbe and Uliastai Rivers.

Figure 14. Photo of Tuul River Bed Sediments, September 2016

2.5.3 Groundwater Pumping

Figure 15 presents a simplified representation of inflows and outflows into the study area. Inflows into the model domain are represented by the green arrows. Inflow and outflow from the system includes: recharge from precipitation; Tuul River surface flow into the model domain at the upstream river boundary; leakage from the Tuul River; leakage from the Selbe River and the Uliastai River; and subsurface inflows from groundwater. Outflows out of the model domain are represented by the red arrows and include: groundwater pumping; and Tuul River flow out of the model domain at the downstream boundary.

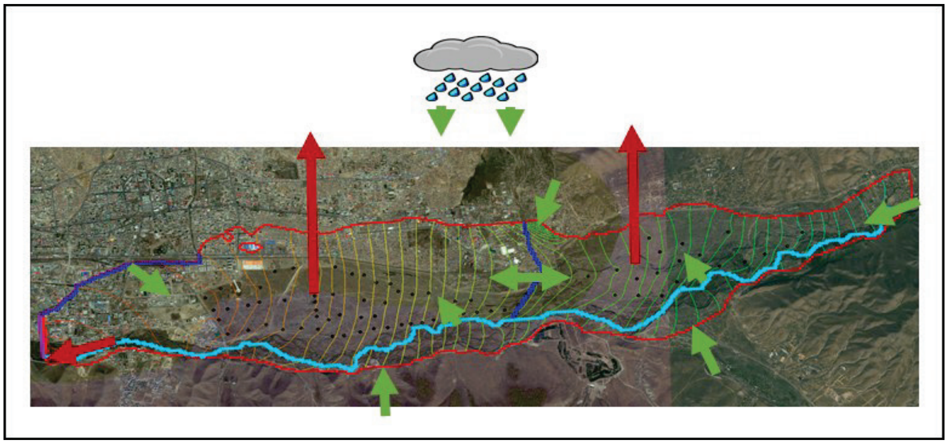


Figure 15. Simplified Representation of Inflows and Outflows

Figure 16 presents an overview of the study area taken from the lower left corner of Figure 15. The location of the western portion of the Center Area Well Field can be seen in the distance.

Figure 16. Tuul River (foreground) September 2016 at Western Ulaanbaatar

The Center Area Well Field is just one of several well fields used to meet the water supply needs in Ulaanbaatar. As shown in Figure 2, well fields are also located in the Tuul River basin both upstream and downstream of the Center Area Well Field. Since this modeling study focused on the Center Area Well Field, potential impacts from the other well fields were not evaluated. However, future model development should expand the model domain to cover these other well fields.

Groundwater pumping is the primary sink to groundwater in the Center Area Well Field. Based on information provided by FWI, 84 active groundwater pumping wells are known to exist in the Center Area Well Field. These active wells have location data as well as pumping capacity information. The available data indicates that the wells in the Center Area Well Field have capacities of between 864 cubic meters/day and 1,987 cubic meters/day, with an average rate of 1,144 cubic meters/day. Figure 17 shows the pumping capacity for each of the 84 wells in the Center Area Well Field.

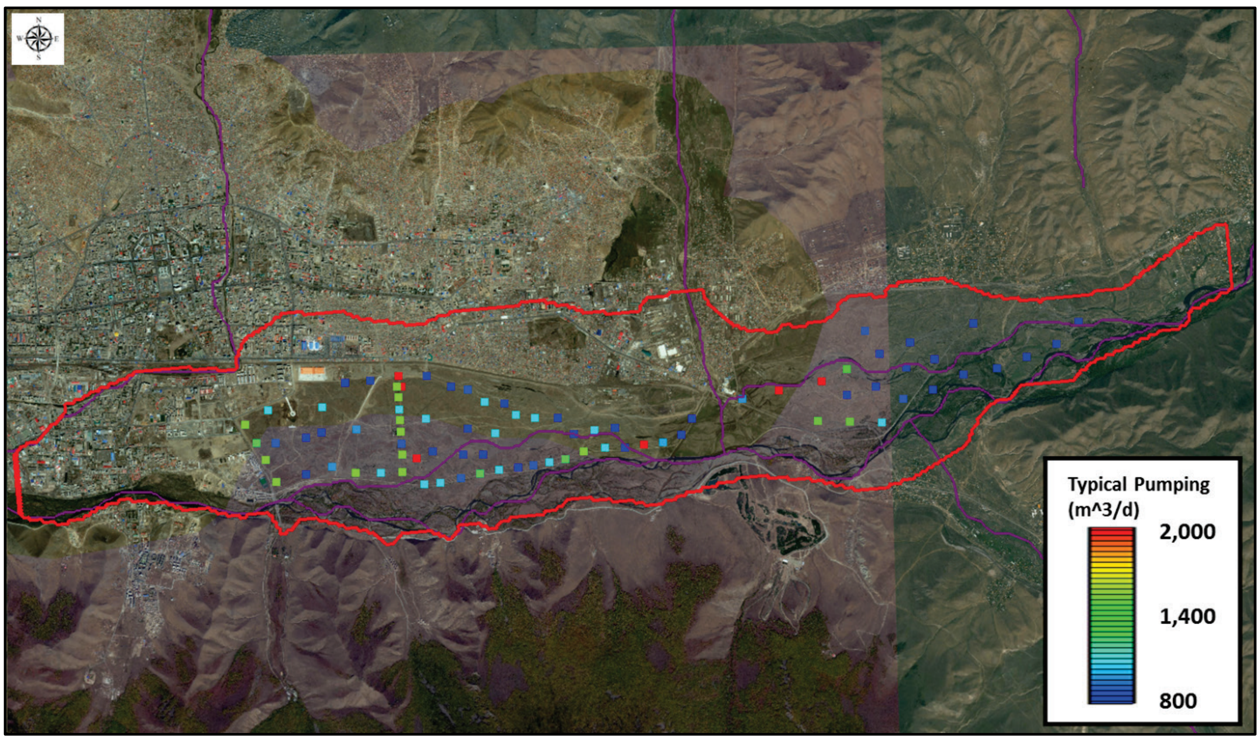


Figure 17. Center Area Well Field Pumping Capacity

In addition to the pumping capacity data at each well, monthly cumulative pumping data for the Center Area Well Field was also provided by FWI. As shown in Figure 18, this monthly data depicts seasonal trends of well field operation as well as a long term decrease in the total amount of water pumped from the Center Area Well Field. During a September 2016 workshop and meetings, several possible reasons for this reduction were discussed, which included augmentation in water supply from adjacent well fields, and the need to reduce excessive drawdown in wells. Current operational regulations in Mongolia require that pumping be reduced if drawdown exceeds fifty percent of aquifer thickness.

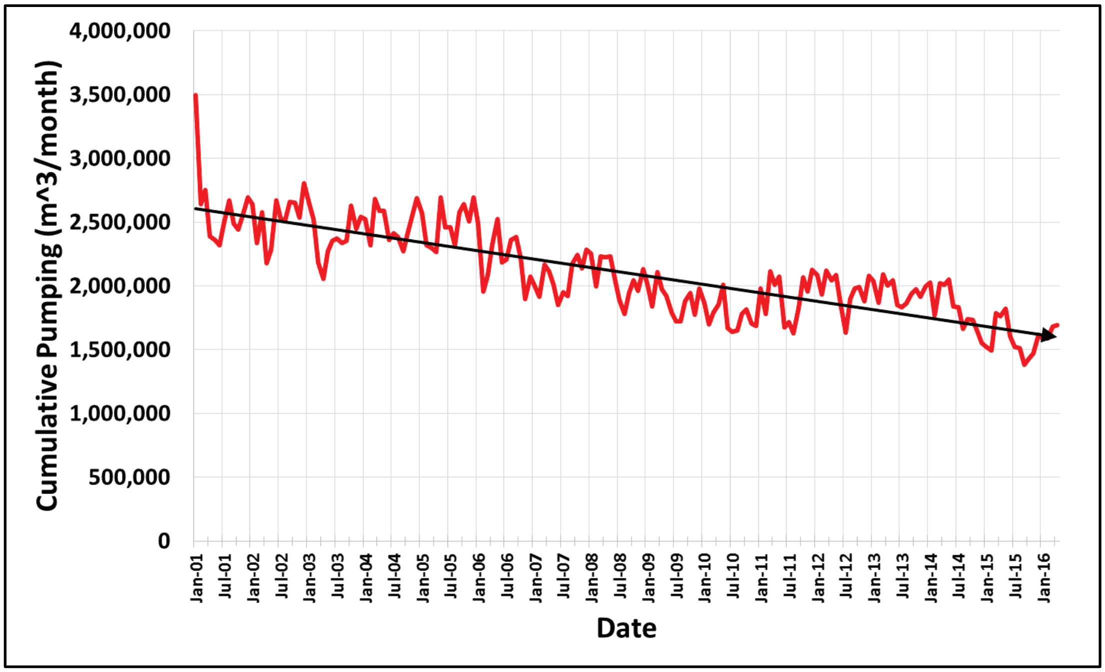


Figure 18. Center Area Well Field Cumulative Pumping

Since pumping rates at individual wells were not available on a monthly basis, a methodology for distributing the cumulative pumping needed to be developed. First, the pump capacity information was used to develop a weighted average of the relative flow that each well contributed to the total pumping from the Center Area Well Field. This weighted contribution factor was multiplied by the cumulative pumping recorded each month to determine the anticipated flow from each well per month. The methodology for deriving a monthly pump distribution from each well is a coarse assumption; however, this was the most defensible methodology available at the time the model was constructed. During the September 2016 workshop, the methodology was discussed and the operators of the well fields indicated that the additional seasonal constraints to pumping at selected wells may occur. Refinements to the pumping distribution methodology based on these operational constraints will be incorporated in subsequent iterations of the model.

2.6 Groundwater Recharge

In addition to surface-subsurface interaction along the Tuul River, the alluvial aquifer in the Center Area Well Field is recharged via both precipitation and groundwater inflow from the surrounding mountains. Long term monthly precipitation data was available for the Ulaanbaatar area from 1969 to present. This precipitation data shows distinct seasonal trends, including minimal precipitation during the winter months and peak precipitation typically between July and August. This peak precipitation during July and August generally ranges from seventy to 150 millimeters per month. Based on discussions with USGS in April 2016, the average infiltration of this precipitation into the groundwater system is approximately six percent. However, this groundwater infiltration rate likely varies due to seasonal variations in runoff due to moisture content in the soil and snow cover, as well as climatic factors such as the intensity of rainfall and evapotranspiration. As such, a reasonable range for general aerial groundwater recharge during model calibration was considered to be between zero and ten percent of the precipitation.

In addition to this aerial groundwater recharge, discussions with the FWI indicted that groundwater inflows from the mountains to the north and south of the Center Area Well Field could be influential on observed groundwater flow patterns. As such, drainage basins contributing to selected areas on the northern and southern model boundaries were defined as mountain recharge areas for the model. Flow from these mountain recharge areas was applied to the model boundaries based on the contributing basin size, monthly precipitation and lateral extent of the area where a recharge boundary was applied to the model. Figure 19 identifies the location and extent of the recharge areas across the Center Area Well Field model domain.

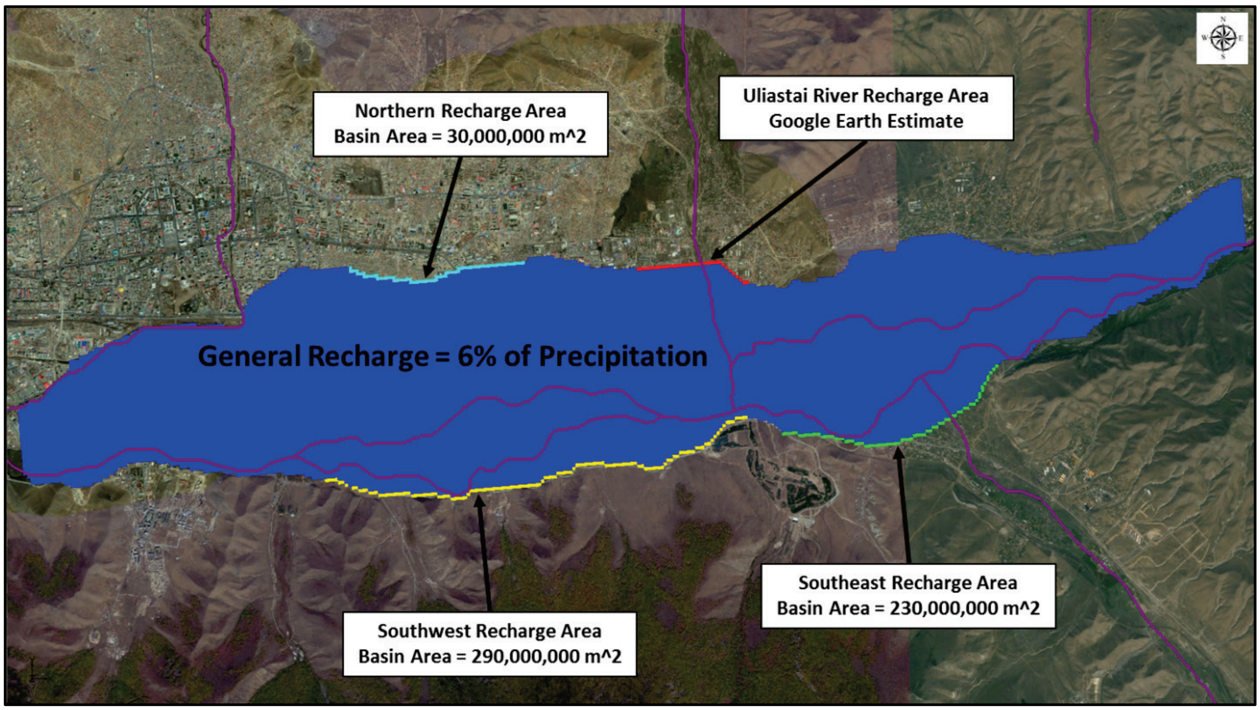


Figure 19. Recharge Areas

Chapter 3

Numerical Model Development

In saturated groundwater, a combination of continuity (mass conservation) and Darcy's Law leads to the following mathematical description of groundwater flow:

$$\frac{\partial}{\partial x}\left(K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z\frac{\partial h}{\partial z}\right) - W = S\frac{\partial h}{\partial t} \quad (3)$$

In this equation, the dependent variable is the hydraulic head, *h*, which is defined in the traditional (x, y, z) Cartesian coordinate system. The horizontal and vertical hydraulic conductivities (K_x, K_y, and K_z) and storage coefficient (S) are specified. Water exchange from sources such as wells and rivers is represented by W. Boundary conditions and initial head conditions must also be specified to solve Equation 3. The boundary conditions may be defined by: specified head (Dirichlet), specified flux (Neumann), or, head-dependent flux (Cauchy).

The USGS groundwater flow modeling software MODFLOW-2000 (USGS, 2000) provides a means to solve Equation 3 for *h* in a chosen domain, with specified values for hydraulic conductivity and storage coefficient and specified boundary conditions. MODFLOW uses the finite-difference (FD) method to approximate the groundwater flow equation as a set of algebraic equations in a discretized three-dimensional grid of rectangular cells.

3.1 Model Design

3.1.1 Model Grid

The model grid was rotated five degrees from a north-south orientation (Figure 20) in order to follow the general alignment of the Tuul River. At the west end of the model, the grid extends from the base of the southern highlands in the south to the Selbe River located approximately 2,000 meters to the north. The rest of the model generally extends from the base of the southern highlands to a location far enough to the north where any influence from pumping wells is insignificant. In the east-west direction, the model domain extends from a location 2,400 meters upgradient from the nearest pumping well in the east to 1,800 meters downstream from the Ulaanbaatar gage in the west.

Model cell size was specified as fifty meters square to conform to the approximate width of the Tuul River as discussed in Section 2.5.2. The finer grid relative to previous models also allows for a more precise simulation of groundwater flow conditions, as well as boundary condition locations such as rivers and pumping wells.

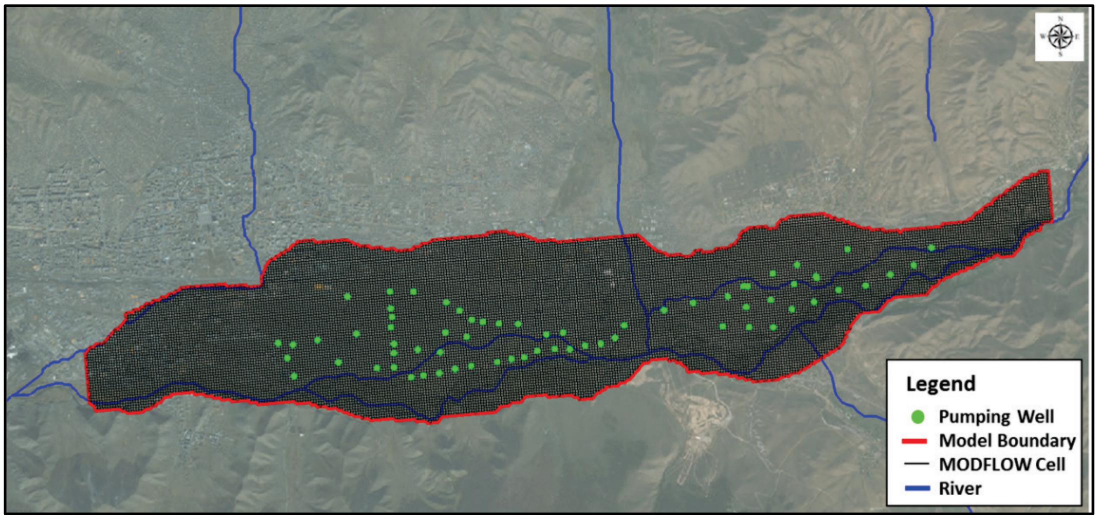


Figure 20. Active MODFLOW Grid

3.1.2 Model Layers

The numerical model was discretized vertically to allow for a more accurate representation of stream depth, pumping well screened interval, and site geology. The model was divided into two layers that generally varied in thickness between ten to twenty meters. Rivers were located in Layer 1, all monitoring wells were located in Layer 2, and pumping wells were assumed to be equally screened in both layers. Layer 2 was utilized in the Center Area Well Field of the model to simulate the effects of pumping wells and leakage from the rivers. Layer 2 was converted to Layer 1 along the north and south model boundaries where the thickness of the aquifer thinned substantially.

3.2 Boundary Conditions

Boundary conditions are specified values of flow or head that allow for the numerical solution of the groundwater model. MODFLOW has numerous algorithms called "Packages" that simulate different hydrologic processes. The MODFLOW Packages used to simulate boundary conditions are presented in Figure 21.

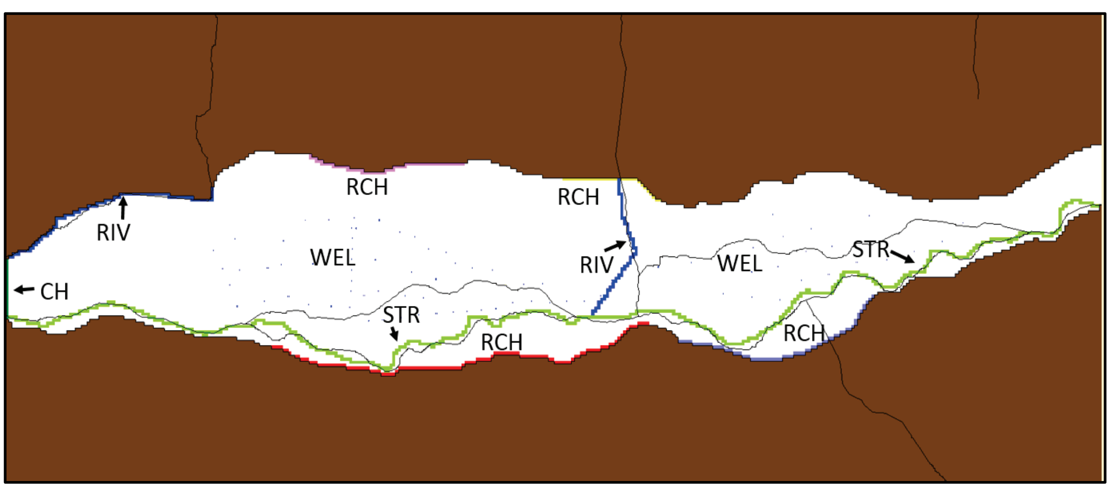


Figure 21. MODFLOW Boundary Conditions used in Model

The finite-difference structure of MODFLOW requires that a model cell represents homogeneous values of aquifer properties and stresses. Thus, MODFLOW assumes all stresses from pumping or water exchange between a river and groundwater are applied equally throughout a cell and groundwater elevations are computed at the cell center. Post-processors for MODFLOW, which were used in this model, commonly employ an algorithm that will interpolate head at specific monitoring well locations.

3.2.1 Pumping Wells

Section 2.6 provides an overview of groundwater pumping in the study area. The MODFLOW Well (WEL) Package was used to simulate pumping stresses at a total of 82 wells in the numerical model (Figure 17). As discussed in Section 2.6, individual well pumping data was not available. However, good data describing the cumulative monthly volume of water pumped from the Center Area Well Field was available. Pumping values were distributed to each well as a function of the relative capacity of each well as provided by FWI (email, May 2016). The extraction rate for each pumping well was divided equally between Layers 1 and 2.

3.2.2 Selbe and Uliastai Rivers

The MODFLOW River (RIV) Package was used to simulate the Selbe and Uliastai Rivers (Figure 21). Parameters input into RIV include river stage and streambed conductance. RIV does not allow for the simulation of streamflow, rather the modeler specifies stage and water exchange between the river and groundwater, which is calculated as a function of the relative water elevation, and the streambed conductance of the streambed sediments (Section 2.5.2). River stage of both the Selbe and Uliastai Rivers were based on topography.

As discussed in Section 2.5.2, fine-grained bed sediments were observed in field visits to the Selbe and Uliastai Rivers in October 2016. The width of the Selbe River was estimated as averaging about five meters from field observations. The length of the reach is equivalent to the cell size of fifty meters. A low hydraulic conductivity of 0.1 m/day to 0.2 m/day and bed thickness of approximately one meter was specified for the bed sediments. An initial streambed conductance of approximately 35 m^2/day was calculated according to Equation 2 (Section 2.5.2) and entered into the numerical model. The width of the Uliastai River was estimated as averaging about three meters from field observations. The length of the reach is equivalent to the cell size of fifty meters. A low hydraulic conductivity of 0.05 m/day to 0.15 m/day and bed thickness of approximately one meter was specified for the bed sediments. An initial streambed conductance of approximately 10 m^2/day was calculated according to Equation 2 (Section 2.5.2) and entered into the numerical model. These low values of streambed conductance resulted in limited water exchange between the groundwater and the Selbe and Uliastai Rivers.

3.2.3 Tuul River

The MODLFOW Stream (STR) Package employs Manning's equation to simulate flow and stage in the Tuul River (Figure 21). Parameters input in STR include stream slope and geometry, streambed conductance, and inflow at the upstream reach.

Elevation of the river bottom and slope were defined by the thalweg from a previous HEC-RAS model (HEC, 2013) of the Tuul River. The Manning's friction coefficient "n" was set equal to 0.03 based upon field observation. The average width of the river was specified as fifty meters, the width of a model cell. Initial stream stage was set as a function of measured values at the Ulaanbaatar gage (Section 2.5.1). River inflows entered for the upstream side of the model were set equivalent to flows observed at the Tuul River Ulaanbaatar gage. This assumption results in uncertainty in the model which could be reduced if additional gaging is installed.

As discussed in Section 2.5.2, values of streambed hydraulic conductivity for the Tuul River is much greater than in the Selbe or Uliastai rivers by a factor of at least ten. Values of streambed conductance were initially estimated to be between 700 m^2/day and 5,000 m^2/day and were varied within this range during model calibration.

3.2.4 Recharge

The MODFLOW Recharge (RCH) Package simulates recharge from precipitation or from subsurface inflow (Figure 21). As discussed in Section 2.7, recharge to the groundwater system can occur from infiltrating precipitation or snowmelt, and subsurface inflows into the model domain. As depicted in Figure 19, RCH was applied universally on the top of Layer 1 to simulate infiltration from rainfall to the water table. As depicted in Figures 19 and 21, RCH was additionally applied in Layer 1 to simulate subsurface inflow at four locations, the mountain recharge areas.

3.2.5 Constant Head Boundary Condition

The Constant Head (CH) Boundary Condition allows for the specification of head in a model cell which remains constant over a stress period. A CH boundary condition was applied adjacent to the downstream boundary of the model (Figure 21). This CH boundary condition allowed for groundwater outflow from the model domain. During model calibration, it was concluded that a CH boundary condition was not needed at the upstream boundary of the model. An assumption that the water table gradient is relatively flat and flows across the upstream model boundary is minimal was used.

3.3 Steady-State Analysis

The development of the steady-state model included: developing zones of hydraulic conductivity; identifying calibration targets; model calibration; and, model application.

The steady-state model employed boundary conditions discussed in Section 3.2 and was calibrated to August 2015 conditions. August 2015 was selected as representative of long-term average summer precipitation and streamflow conditions. The July to August 2015 precipitation measured at Ulaanbaatar was 150.3 mm, with July being wetter than average. The average long-term (1938-2006) precipitation measured at Ulaanbaatar for the months of July to August is 123.4 mm. The average August streamflow measured at the Ulaanbaatar gage in August 2015 is 30.4 cms. The average flow measured on August 15, between 1996 and 2011 is 30.9 cms.

Average pumping and precipitation-recharge data for the month of August 2015 was entered into the model. It was assumed that six percent of rainfall in August recharges to groundwater (USGS, phone conversation, April 2016). Streamflow data from the Ulaanbaatar gage was averaged over the month of August and a value of 30.4 cms was entered as inflow into the model domain. Tuul River flows at the Ulaanbaatar gage were assumed to be equal to the inflow at the upper end of the model domain.

3.3.1 Development of Hydraulic Conductivity Zones of Homogeneity

Section 2.3.2 provides an overview of groundwater pump test data for hydraulic conductivity (K) at a total of 88 wells. Field values of hydraulic conductivity average 61 m/day, and range between twelve m/day and 242 m/day. As illustrated in Figure 7 (Section 2.3.2), there is a general patterning of hydraulic conductivity that shows distinct trends. Values tend to be higher over the western half of the model domain, and lowest in the Center Area Well Field adjacent to the Uliastai River and at the eastern end of the model domain.

Because of the uncertainty inherent in the data and the relative heterogeneity of the hydrogeology, the principle of appropriate complexity was applied in determining the number of hydraulic conductivity zones to be used in the model, i.e., the complexity of the model should be commensurate with the ability of the data to represent the system. Several different zone scenarios were tested during an initial calibration phase. Measured water levels were also taken into account during the initial calibration. Figure 22 presents the zones of homogenous hydraulic conductivity used in the 2016 model. Four zones of hydraulic conductivity (K) were delineated based upon pump test data and initial calibration. The first zone of 20 to 40 meters/day represents a medium sand. The second zone of 60 to 90 meters/day represents a coarse sand. The third zone of 15 to 25 meters/day represents a fine sand. The fourth zone of 30 to 45 meters/day represents a medium sand. Vertical hydraulic conductivity is simulated as 1/10 to 1/20 of horizontal hydraulic conductivity based on the depositional environment common in alluvial plains where strata of fine grained silt material separates coarser deposits.

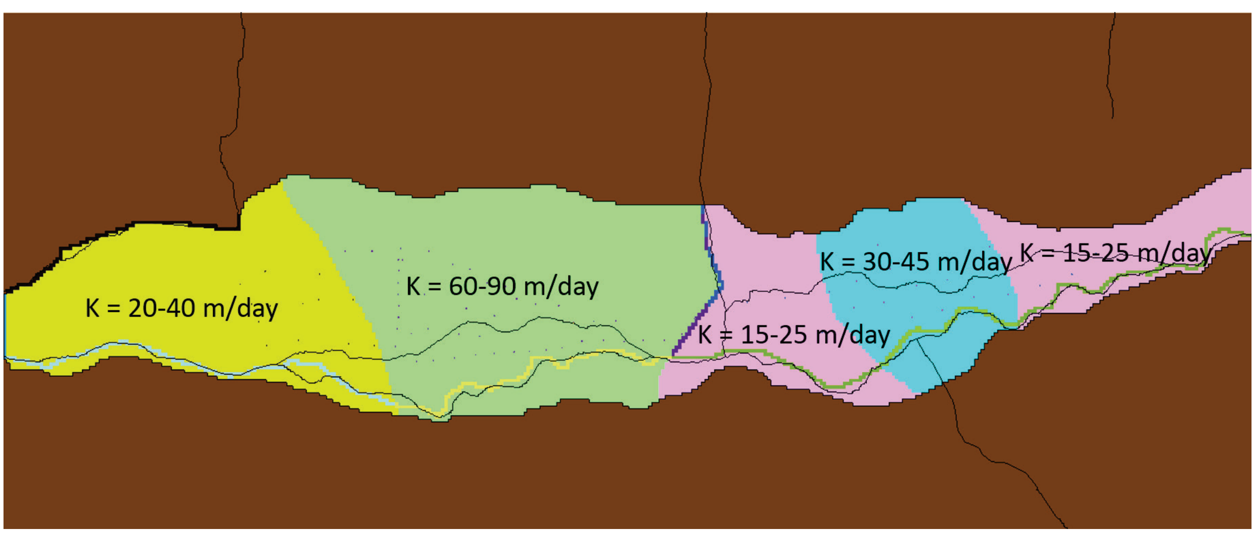


Figure 22. Zones of Homogenous Hydraulic Conductivity

3.3.2 Steady-State Calibration

The steady-state calibration used the monthly average groundwater elevations measured at twelve HOBO Data Loggers in August 2015 (Section 2.4, Figure 8). Groundwater level variations were minor during this month. Calibration consisted of manually adjusting values of hydraulic conductivity and streambed conductance through a range of reasonable values until a good match between observed and simulated water levels was attained. This process also included the formulation of new conceptualizations that were tested during model simulations. Several hundred model runs were required for the steady-state calibration.

Figure 23 presents the locations and measured versus simulated residuals at the twelve water levels used during the calibration process. Calibration focused on attaining a good spatial distribution of positive and negative residuals and minimizing the overall Residual Mean and Absolute Residual Mean. Steady-state calibration statistics are presented in Figure 24. Figure 25 presents the steady-state model groundwater elevation contours.

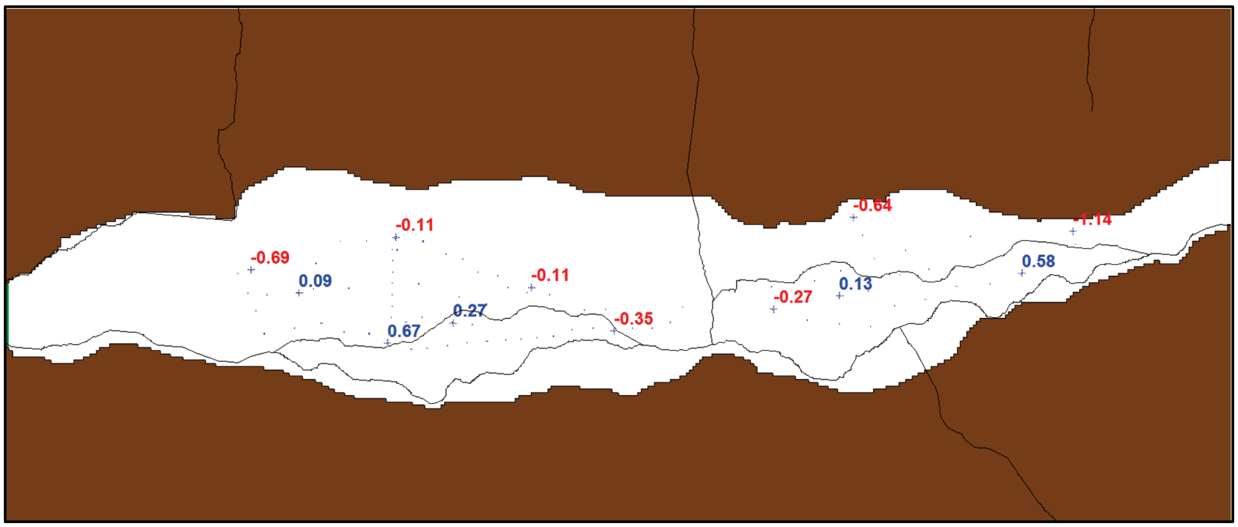


Figure 23. Groundwater Elevation Measured versus Simulated Residuals

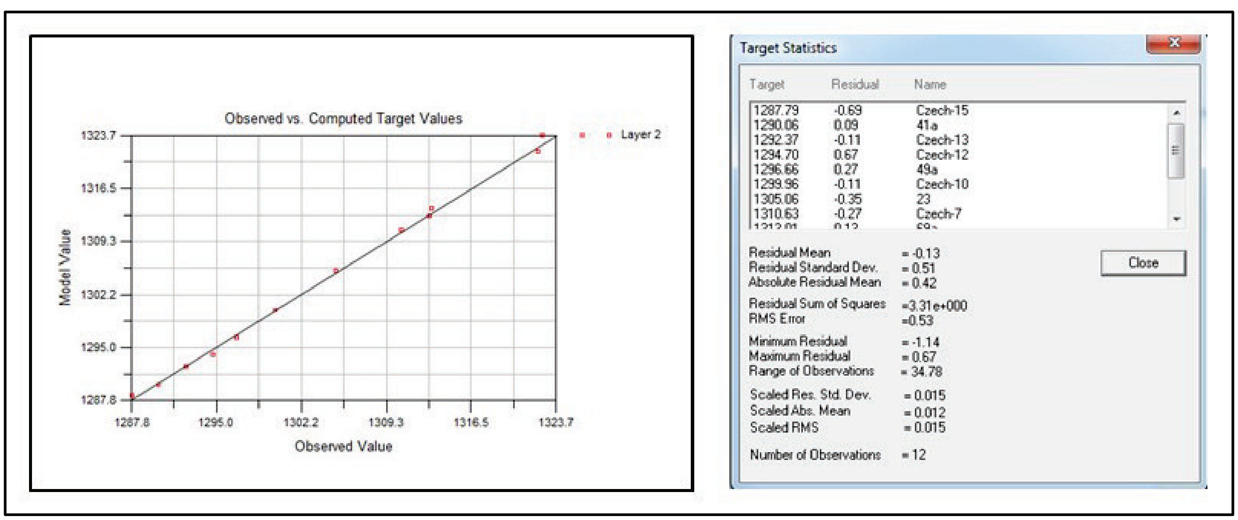


Figure 24. Steady-State Model Calibration Statistics

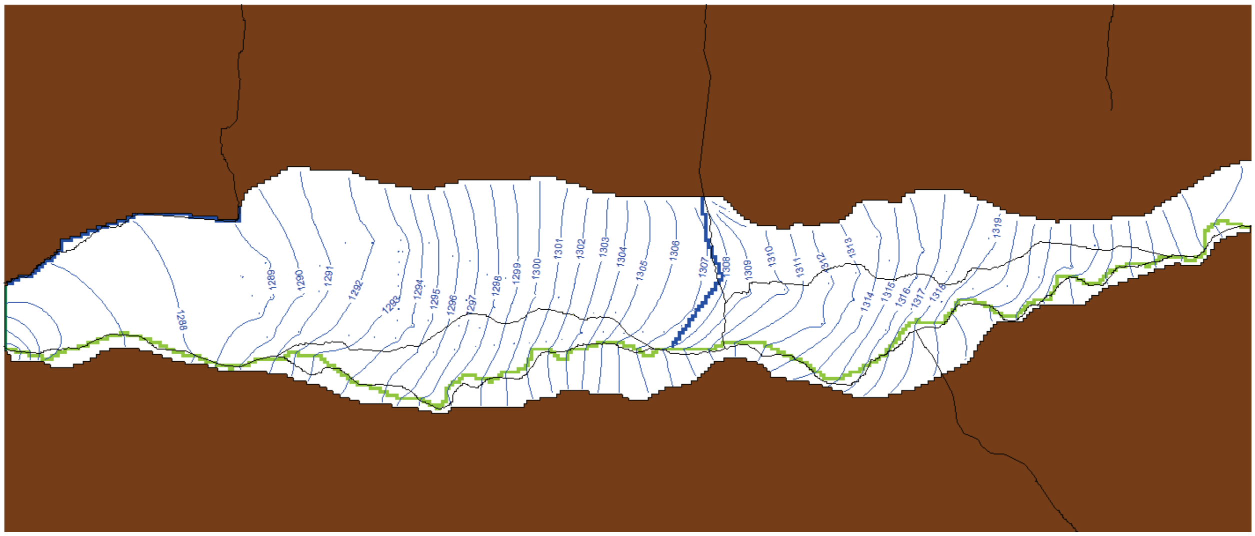


Figure 25. Steady-State Model Groundwater Elevation Contours

3.3.3 Steady-State Flow Budget

The volumetric output flow budget for the calibrated steady-state model is presented in Figure 26. The water exchange between the Tuul River and groundwater is represented by STREAM LEAKAGE in the volumetric budget (Figure 26). Note that STREAM LEAKAGE (IN) to groundwater exceeds STREAM LEAKAGE (OUT) from groundwater to the stream by 37,543 m^3/day or 0.43 m^3/sec (Figure 26). Thus, the steady-state model simulates the Tuul River as a slightly losing reach in the model domain during average summer conditions.

```
  VOLUMETRIC BUDGET FOR ENTIRE MODEL AT END OF TIME STEP   1 IN STRESS PERIOD    1
  ------------------------------------------------------------------------------

     CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
     ------------------                 ------------------------

           IN:                                      IN:
           ---                                      ---
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =         873.8565         CONSTANT HEAD =         873.8565
               WELLS =           0.0000                 WELLS =           0.0000
       RIVER LEAKAGE =        1713.7952         RIVER LEAKAGE =        1713.7952
            RECHARGE =        9467.0000              RECHARGE =        9467.0000
      STREAM LEAKAGE =       44036.3984        STREAM LEAKAGE =       44036.3984

            TOTAL IN =       56091.0508              TOTAL IN =       56091.0508

          OUT:                                     OUT:
          ----                                     ----
             STORAGE =           0.0000               STORAGE =           0.0000
       CONSTANT HEAD =         910.8310         CONSTANT HEAD =         910.8310
               WELLS =       48647.0000                 WELLS =       48647.0000
       RIVER LEAKAGE =          42.0118         RIVER LEAKAGE =          42.0118
            RECHARGE =           0.0000              RECHARGE =           0.0000
      STREAM LEAKAGE =        6493.1396        STREAM LEAKAGE =        6493.1396

           TOTAL OUT =       56092.9844             TOTAL OUT =       56092.9844

            IN - OUT =          -1.9336              IN - OUT =          -1.9336

 PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```

Figure 26. Volumetric Flow Budget of Steady-State Model

Groundwater pumping is represented by WELLS (OUT) in the volumetric budget (Figure 26). The monthly averaged rate of groundwater withdrawal is 48,647 m^3/day. Thus, leakage from the Tuul River is the source of 77 percent of groundwater pumped under average summer conditions. This conclusion is supported by a study performed by Tsujimura (2013) of groundwater contribution sources in the study area using isotopic analysis. River leakage into groundwater from the Selbe and Uliastai Rivers is represented by RIVER LEAKAGE (IN) in Figure 26. The model simulates a net of 1,672 m^3/day of leakage into groundwater. This value is relatively small mainly due to low conductance of the streambed materials. Thus, the Tuul River accounts for 96 percent of the leakage to groundwater in the model. Subsurface recharge and infiltrating rainfall into the groundwater system is represented by RECHARGE (IN) in Figure 26. The model simulates 9,467 m^3/day of leakage into groundwater. This represents the source of nineteen percent of groundwater pumped from the system under average summer conditions.

3.4 Transient Analysis

Upon completion of the steady-state model calibration to August 2015 conditions, a transient calibration was performed. The transient model employed the zones of homogenous hydraulic conductivity derived during steady-state model development as discussed in Section 3.3.1 in model calibration.

3.4.1 Transient Model Development

The transient calibration period selected for this model was from August 2014 to April 2016. This time period was selected for transient calibration since it encompasses the seasonal variation collected between April 2015 and April 2016 using the HOBO Data Loggers. This transient calibration period also contains a nine month spin-up period from August 2014 to April 2015. By including this model spin up period, potential errors resulting from inaccurate initial water levels will be minimized. The transient calibration period used for this study, allows the model to be calibrated to observed data from both rising and falling trends during annual groundwater level variations. The goal of this transient calibration was to match average seasonal water level trends. As such, a monthly stress period was selected with four time steps per month.

Total monthly groundwater pumping data was available for each month of the calibration period. All 84 extraction wells were assumed to be operational for the transient calibration. As discussed in Section 2.6, pumping from these wells was assumed to be uniformly distributed for each monthly stress period based on pump capacities.

Stage variations on the Uliastai and Selbe Rivers were assumed to be minimal within the model domain. As discussed in Section 2.5, the river bed conductance of the Uliastai and Selbe Rivers is assumed to be low, thus, limiting interaction with groundwater. Conversely, the Tuul River has a much more robust interaction with groundwater. Specified inflows into the Tuul River at the upstream end of the model domain were set equal measured values at the Ulaanbaatar gage for each monthly stress period.

3.4.2 Transient Model Calibration

During transient calibration, adjustments were made to the model input parameters. Parameters of hydraulic conductivity and river bed conductance were varied within reasonable ranges as defined by the steady-state calibration. A combination of manual and automated parameter estimation was used to match observed water level data. Areal groundwater recharge during the calibration period was varied between four and nine percent of the precipitation as discussed in Section 2.7. Recharge from the mountain faces were kept consistent with those used in the steady-state model; however, snowmelt inflow from these mountain areas was assumed to be at a rate of four times normal in May 2015 when the spring thaw occurs.

Results from the transient calibration indicated a slightly higher Tuul River bed conductance upstream of the confluence with the Uliastai River than downstream. This higher conductance may be the result of minor sedimentation downstream of the confluence. Calibrated values of hydraulic conductivity were within the same ranges as defined by the steady-state model in Section 3.3.1. The calibrated value of the storage coefficient parameter was 0.04. This value is indicative of semi-confined hydrogeologic conditions and provides further evidence of intermixed strata of fine and coarse grained material noted in Section 2.3.1.

3.4.3 Calibration Results

Figure 27presents the final transient model calibration across the Center Area Well Field model domain. On each of these plots the blue line shows the observed water level from the HOBO Data Loggers, while the red and green lines show the computed water levels assuming a high (green line) or low (red line) initial water table elevation. In all of the plots the red and green lines converge by April 2015, after the initial start-up period. This convergence illustrates that

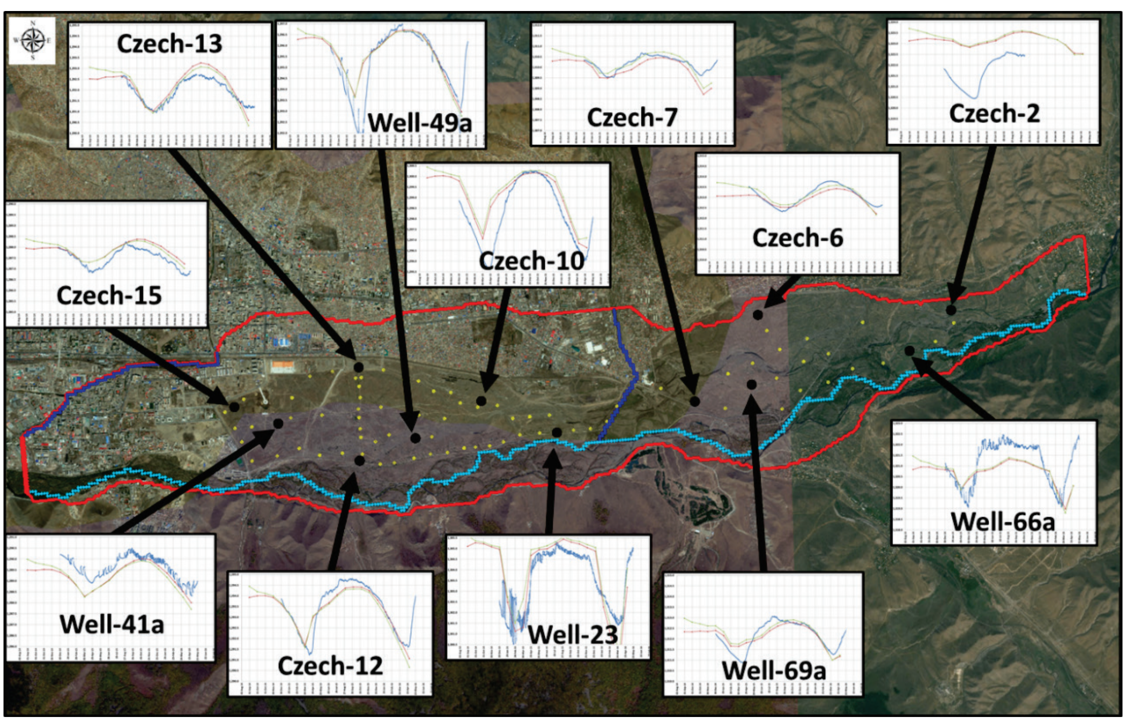


Figure 27. Transient Model Calibration

the model is relatively insensitive to the initial water table condition during the primary calibration period between April 2015 and April 2016. Each of the plots on Figure 27 uses a five meter vertical scale to provide a sense of the magnitude of water level variation at the well. Detailed plots for each well are provided in Appendix A.

Substantial short term variation (up to one meter over a several hour period) can be seen in several of the monitoring wells, such as Well 23, 41a, 49a, 66a. As mentioned in Section 2.4, the HOBO Data Loggers at these locations were placed either in or adjacent to the active pumping wells. These rapid water level changes are the result of the pump cycling on and off at these pumping wells. Since the goal of the transient calibration was to replicate the seasonal water level variations and well cycling information was not available, no attempt was made to calibrate to these high frequency short duration variations in water levels.

Overall the model shows good correlation between the computed and observed transient water levels, although there is more discrepancy in the calibration on the east end of the model domain. Well 41a and Czech-15 are the two most downstream monitoring locations. Both of these wells have a smooth seasonal transition of approximately 1.5 meters, which is being replicated in the model. Czech-12 and Czech-13 are located in a good alignment to evaluate the groundwater variations near the Tuul River (Czech-12) and away from the river (Czech-13). Czech-12 is located in close proximity to Tuul River and has a seasonal head variation of three to four meters, with a sharp rise in water level after the spring thaw in May 2015. This variation in observed water level is muted to less than two meters in Czech-13, which is located approximately 2,500 meters north of the river. Both of these trends are replicated well in the model. Well-49a, Czech-10 and Well-23 are located in the heart of the Center Area Well Field, downstream of the Uliastai River. These three wells have observed seasonal water level variations of five meters or more and appear to be heavily influenced by well field operations. The magnitude and timing of these variations are reasonably simulated in the model. Upstream of the Uliastai River the observed water level variations are much less pronounced. The seasonal water level variations in Czech-7, Czech-6 and Well-69a only vary between one and two meters, with very smooth seasonal transitions. Again the model does a good job at reproducing these seasonal changes. At the eastern edge of the model, the model has the difficulty matching the distinct trends in water level variations at Well-66a and Czech-2. As discussed during the September 2016 workshop in Ulaanbaatar, improvements to the conceptual model, pumping distribution, and incorporation of the influence of well fields upstream of the current model domain may help improve model calibration in this area.

In addition to model calibration to observed water level data, the simulated flow from the MODFLOW River (RIV) package at the Tuul River flow gage in Ulaanbaatar was evaluated. The simulated and observed flow at this gage is presented in Table 2. The simulated flow is the combined flow in the Tuul River based on the inflow at the upstream end of the model and the combined inflows/losses resulting from surface-subsurface interaction along the Tuul River. These computed flows are reasonable in comparison to the observed data given the limitations and uncertainties inherent in this model.

Table 2. Simulated and Measured Flow at Ulaanbaatar Gage

	Simulation Flow (cms)	Average Measured Flows (cms)
Jan-15	0.00	0.55
Feb-15	0.00	0.00
Mar-15	0.00	0.52
Apr-15	11.19	12.00
May-15	7.32	7.61
Jun-15	7.41	8.06
Jul-15	12.16	12.50
Aug-15	30.37	30.40
Sep-15	13.23	13.50
Oct-15	8.37	8.72
Nov-15	2.07	2.48
Dec-15	0.01	0.39
Jan-16	0.00	0.05
Feb-16	0.00	0.00
Mar-16	0.00	0.00
Apr-16	0.00	0.04

3.5 Sensitivity Analysis

Sensitivity analysis is used to measure uncertainty in the calibrated model resulting from uncertainty in input parameters. A sensitivity analysis was performed using the transient model. Parameters of storage coefficient, hydraulic conductivity, and Tuul River streambed conductance were varied systematically one parameter at a time by a factor of 2.0 and 0.5. Model results are presented (detailed the following sections) at monitoring well Czech-12, located approximately 750 meters to the north of the Tuul River (Figure 27).

3.5.1 Sensitivity Analysis of Storage Coefficient

Sensitivity analysis of the storage coefficient is presented in Figure 28. The blue hydrograph (Observed Water Level) represents measured field values. The green hydrograph (Figure 28) is the results for the Computed Water Level (storage coefficient times 2.0). While the red hydrograph (Figure 28) is the results for the Computed Water Level (storage coefficient times 0.5). Note that the slope and shape of the simulated hydrographs are sensitive to a storage coefficient. A higher storage coefficient results in a muted response to stresses, while a lower storage coefficient value results in a more amplified response.

3.5.2 Sensitivity Analysis of Hydraulic Conductivity

Sensitivity analysis of hydraulic conductivity is presented in Figure 29. The blue hydrograph (Observed Water Level) represents measured field values. The green hydrograph (Figure 29) is the results for the Computed Water Level (hydraulic coefficient times 2.0). While the red hydrograph (Figure 29) is the results for the Computed Water Level (hydraulic coefficient times 0.5). Note that the elevation of the hydrograph is sensitive to hydraulic conductivity. A higher

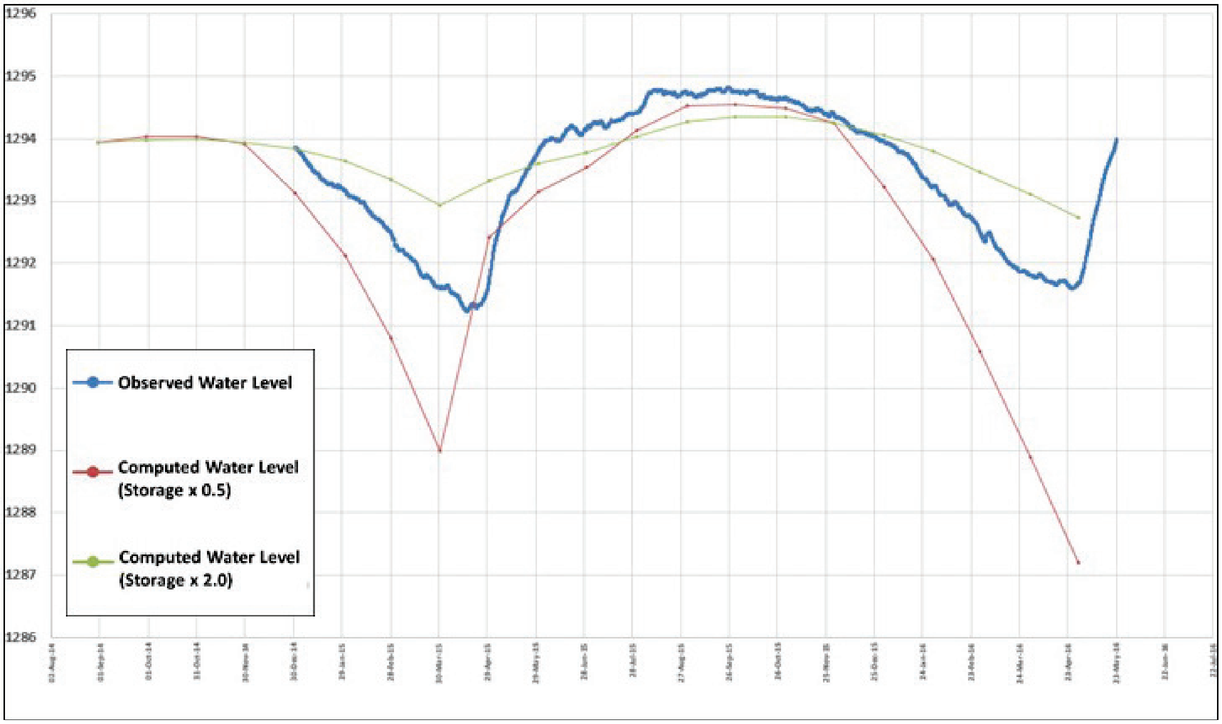


Figure 28. Sensitivity Analysis of Storage Coefficient

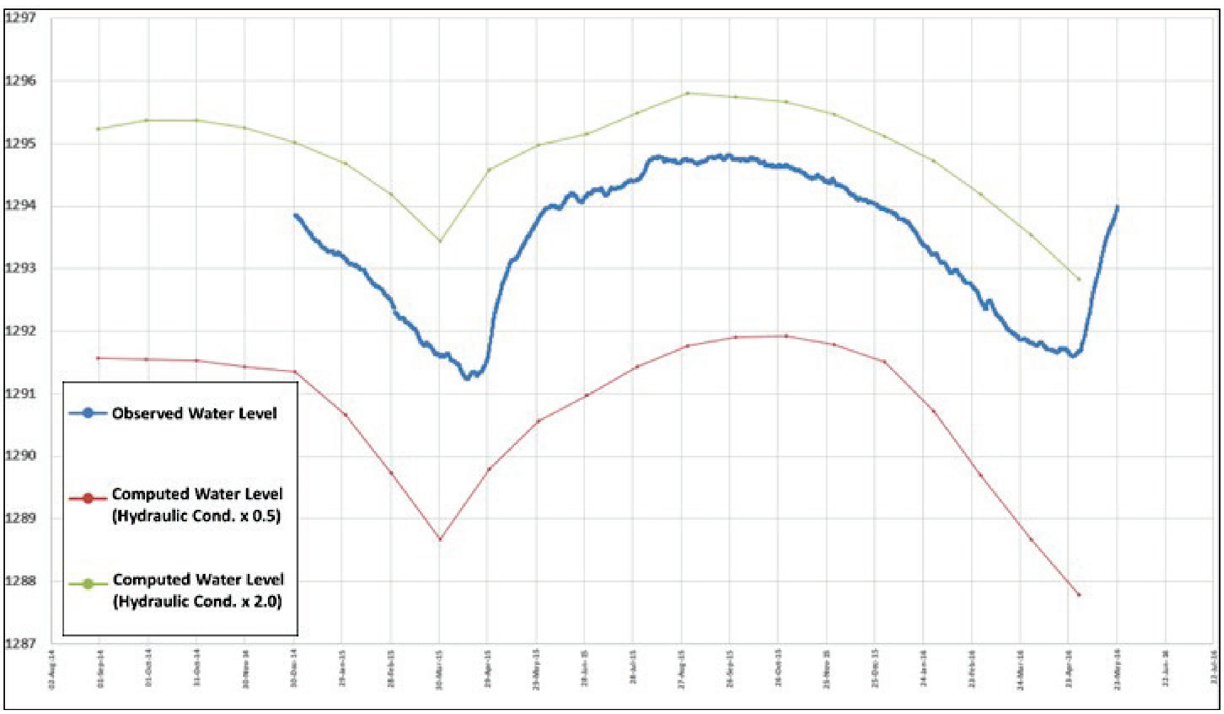


Figure 29. Sensitivity Analysis of Hydraulic Conductivity

hydraulic conductivity results in a higher starting and ending simulated groundwater elevation, while a lower hydraulic conductivity value results in a lower starting and ending simulated groundwater elevation.

3.5.3 Sensitivity Analysis of Tuul River Streambed Conductance

Sensitivity analysis of Tuul River streambed conductance is presented in Figure 30. The blue hydrograph (Observed Water Level) represents measured field values. The green hydrograph (Figure 30) is the results for the Computed Water Level (streambed conductance times 2.0). While the red hydrograph (Figure 30) is the results for the Computed Water Level (streambed conductance times 0.5). Note that the transient model is not as sensitive to streambed conductance as storage coefficient or hydraulic conductivity. The location of monitoring well Czech-12 is approximately 750 meters from the Tuul River. Monitoring wells further from the river will have a less pronounced response to changes in streambed conductance.

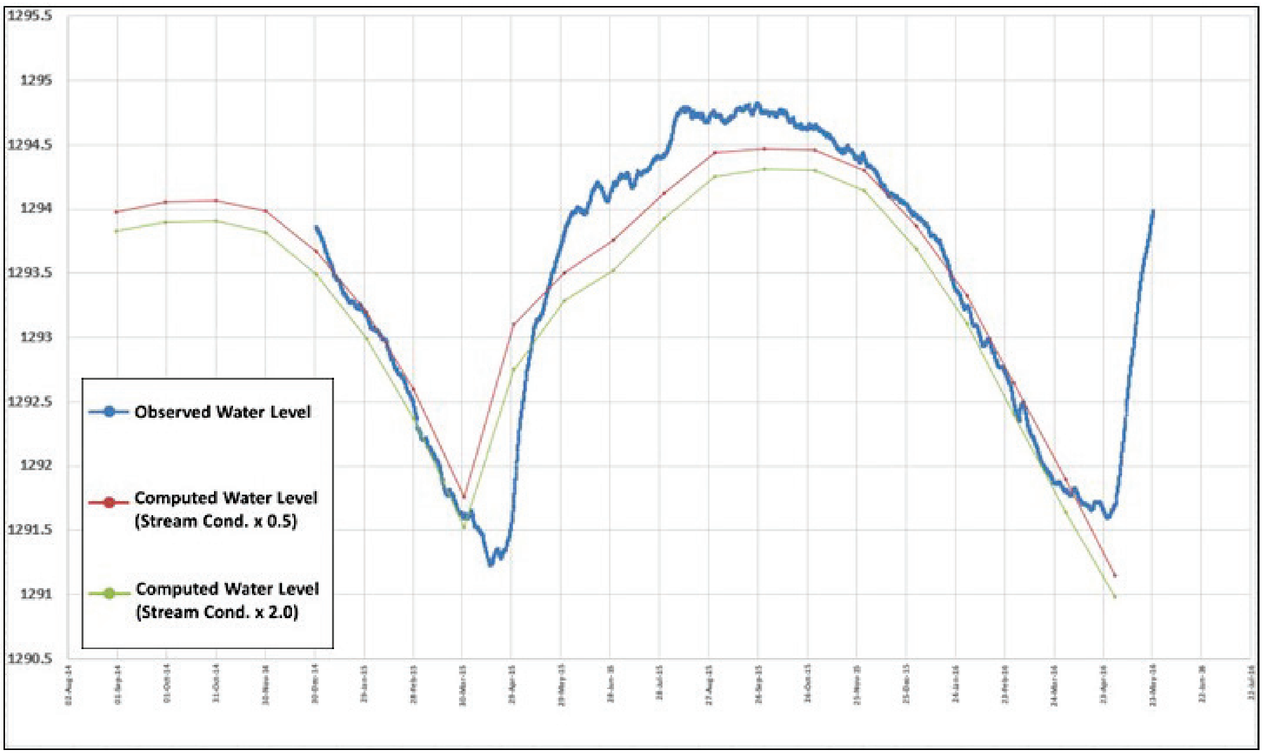


Figure 30. Sensitivity Analysis of Tuul River Streambed Conductance

Chapter 4

Numerical Model Predictive Simulations

The calibrated steady-state and transient flow models were applied under several scenarios to assess the potential effects of groundwater pumping and climate change on the hydrologic system.

4.1 Steady-State Model Applications

Steady-state models are developed under the assumption that hydrologic conditions are fairly stable and there is no change in aquifer storage, pumping, recharge, or streamflow. The 2016 steady-state model was calibrated to August 2015 observed data, which is assumed to be generally representative of average summer conditions. Thus, model output is applicable to summer conditions.

4.1.1 No Pumping

Steady-State Application 1 (Figure 31) specifies that groundwater pumping is set equal to zero. Note that drawdown is zero. This application represents base conditions for relative simulated drawdown in subsequent applications, and, also represents predevelopment conditions of the model area. Without groundwater pumping, the simulated flow at the Ulaanbaatar gage is 30.8 cms.

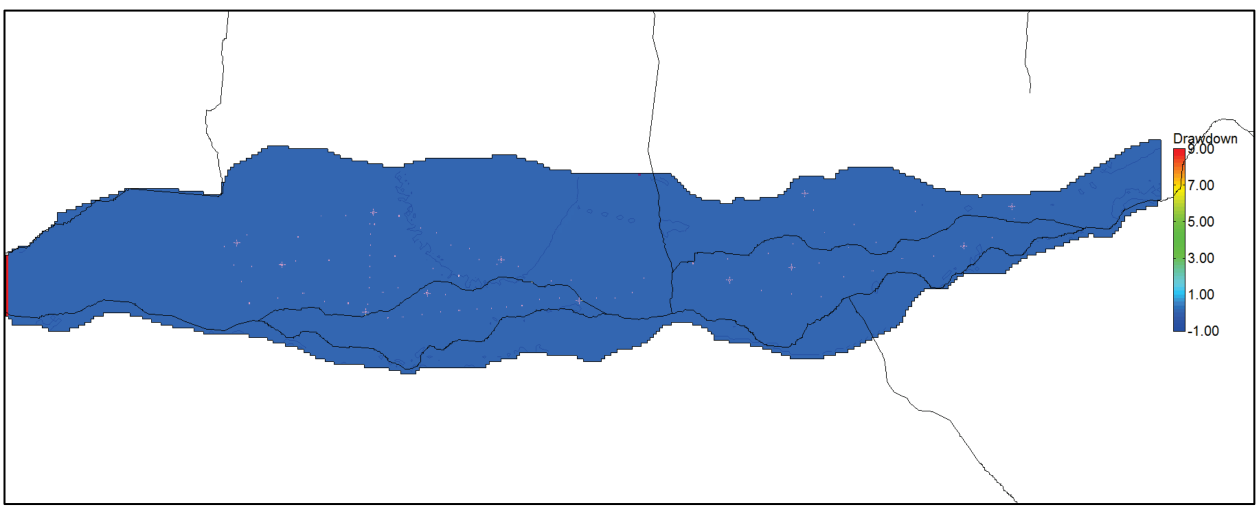


Figure 31. Steady-State Application 1 - Pumps Turned Off (drawdown is zero)

Figure 32 presents the volumetric flow budget from Steady-State Application 1. Note, with pumps turned off, flow from groundwater (TOTAL (OUT)) to the stream, exceeds flow from the stream (TOTAL (IN)) to groundwater (Figure 32). Thus, the Tuul River is simulated as gaining in this area in the absence of pumping.

```
    CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
    ------------------                 ------------------------

          IN:                                   IN:
          ---                                   ---
             STORAGE =           0.0000            STORAGE =           0.0000
       CONSTANT HEAD =         837.2538      CONSTANT HEAD =         837.2538
       RIVER LEAKAGE =        1162.1394      RIVER LEAKAGE =        1162.1394
            RECHARGE =        9468.5000           RECHARGE =        9468.5000
      STREAM LEAKAGE =       14403.9531     STREAM LEAKAGE =       14403.9531

            TOTAL IN =       25871.8477           TOTAL IN =       25871.8477

         OUT:                                  OUT:
         ----                                  ----
             STORAGE =           0.0000            STORAGE =           0.0000
       CONSTANT HEAD =         951.0814      CONSTANT HEAD =         951.0814
       RIVER LEAKAGE =        1339.7388      RIVER LEAKAGE =        1339.7388
            RECHARGE =           0.0000           RECHARGE =           0.0000
      STREAM LEAKAGE =       23580.9434     STREAM LEAKAGE =       23580.9434

           TOTAL OUT =       25871.7637          TOTAL OUT =       25871.7637

            IN - OUT =       8.3984E-02           IN - OUT =       8.3984E-02

 PERCENT DISCREPANCY =             0.00  PERCENT DISCREPANCY =             0.00
```

Figure 32. Volumetric Budget under No-Pumping Scenario

4.1.2 Current Conditions

Steady-State Application 2 (Figure 33) replicates August 2015 averaged pumping rates. This results in a maximum sustained drawdown of approximately six meters. Simulated flow at the Ulaanbaatar gage is 30.3 cms.

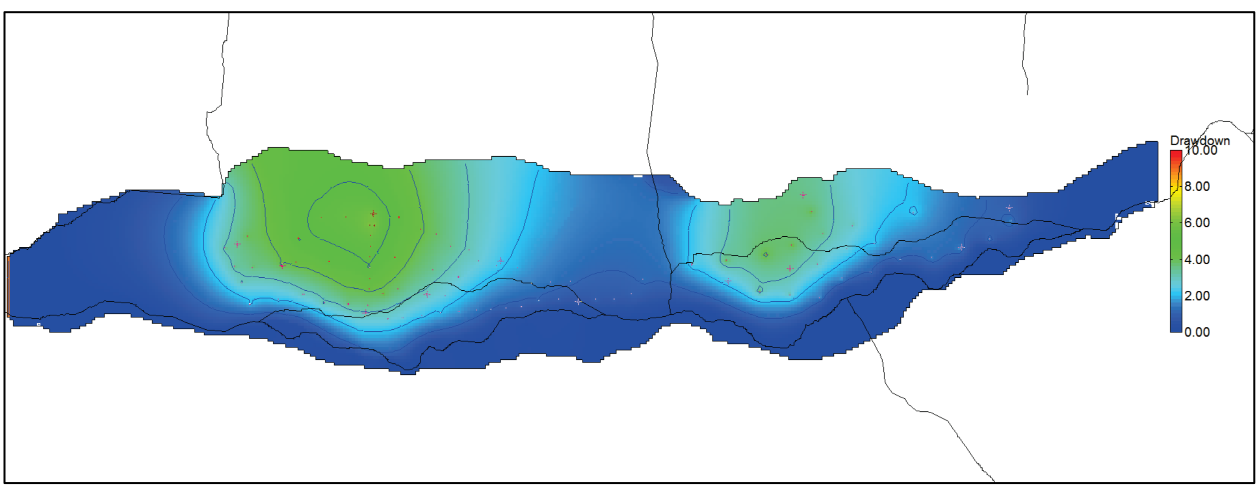


Figure 33. Steady-State Application 2 - Drawdown using August 2015 Conditions

Figure 34 presents the volumetric flow budget from Steady-State Application 2. Note that the total groundwater pumping is 48,647 cubic meters/day, or 0.56 cms. The reduction in simulated streamflow at the Ulaanbaatar gage as a result of pumping is approximately 0.5 cms. Thus, the source of the majority of groundwater pumped in this simulation is from the Tuul River.

```
  CUMULATIVE VOLUMES      L**3       RATES FOR THIS TIME STEP      L**3/T
  ------------------                 ------------------------

        IN:                                   IN:
        ---                                   ---
          STORAGE =           0.0000            STORAGE =           0.0000
    CONSTANT HEAD =         873.8565      CONSTANT HEAD =         873.8565
            WELLS =           0.0000              WELLS =           0.0000
    RIVER LEAKAGE =        1713.7952      RIVER LEAKAGE =        1713.7952
         RECHARGE =        9467.0000           RECHARGE =        9467.0000
   STREAM LEAKAGE =       44036.3984     STREAM LEAKAGE =       44036.3984

         TOTAL IN =       56091.0508           TOTAL IN =       56091.0508

       OUT:                                  OUT:
       ----                                  ----
          STORAGE =           0.0000            STORAGE =           0.0000
    CONSTANT HEAD =         910.8310      CONSTANT HEAD =         910.8310
            WELLS =       48647.0000              WELLS =       48647.0000
    RIVER LEAKAGE =          42.0118      RIVER LEAKAGE =          42.0118
         RECHARGE =           0.0000           RECHARGE =           0.0000
   STREAM LEAKAGE =        6493.1396     STREAM LEAKAGE =        6493.1396

        TOTAL OUT =       56092.9844          TOTAL OUT =       56092.9844

         IN - OUT =          -1.9336           IN - OUT =          -1.9336

PERCENT DISCREPANCY =           0.00     PERCENT DISCREPANCY =           0.00
```

Figure 34. Volumetric Budget under Current Conditions Scenario

4.1.3 Pumping Increased by Fifty Percent

Steady-State Application 3 (Figure 35) increases groundwater pumping to a level fifty percent above the August 2015 pumping rates. Aquifer thickness is approximately 25 meters in the valley center. Increasing the pumping rate fifty percent above the August 2015 pumping rates results in a maximum sustained drawdown of approximately nine meters. Simulated flow at the Ulaanbaatar gage is 30.0 cms.

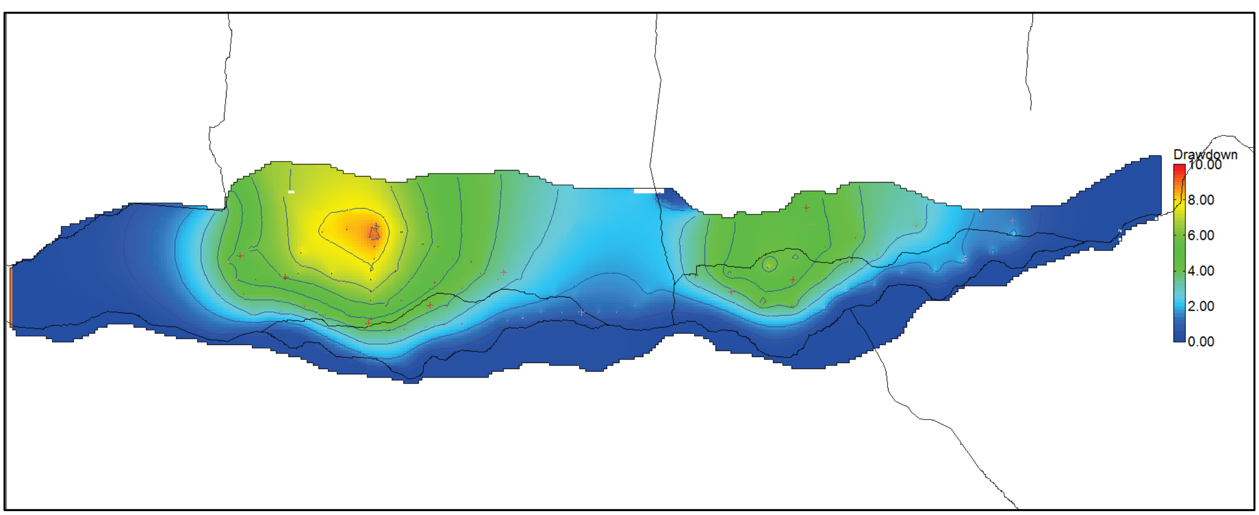


Figure 35. Steady-State Application 3 - Drawdown with Pumping Increased Fifty Percent

4.1.4 Pumping Increased by One Hundred Percent

Steady-State Application 4 (Figure 36) increases groundwater pumping to a level one hundred percent above the August 2015 pumping rates. Aquifer thickness is approximately 25 meters in the valley center. Increasing the pumping rate one hundred percent above the August 2015 pumping rates results in a maximum sustained drawdown of approximately eleven meters. Simulated flow at the Ulaanbaatar gage is 29.8 cms.

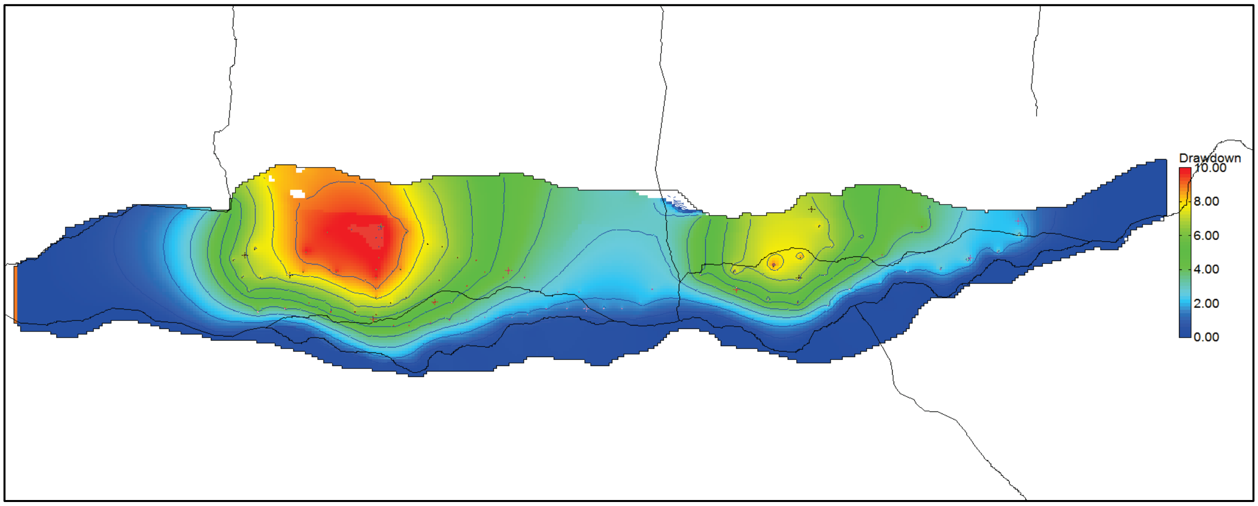


Figure 36. Steady-State Application 4 - Drawdown with Pumping Increased One Hundred Percent

4.1.5 Climate Change

Steady-State Application 5 (Figure 37) uses the August 2015 average monthly pumping rates and attempts to simulate drought conditions. Recharge from precipitation is decreased by fifty percent, recharge from subsurface inflow is decreased by fifty percent, and inflow into the model domain at the Tuul River is decreased fifty percent. This resulted in a maximum sustained drawdown of approximately seven meters. Simulated flow at the Ulaanbaatar gage is 14.8 cms.

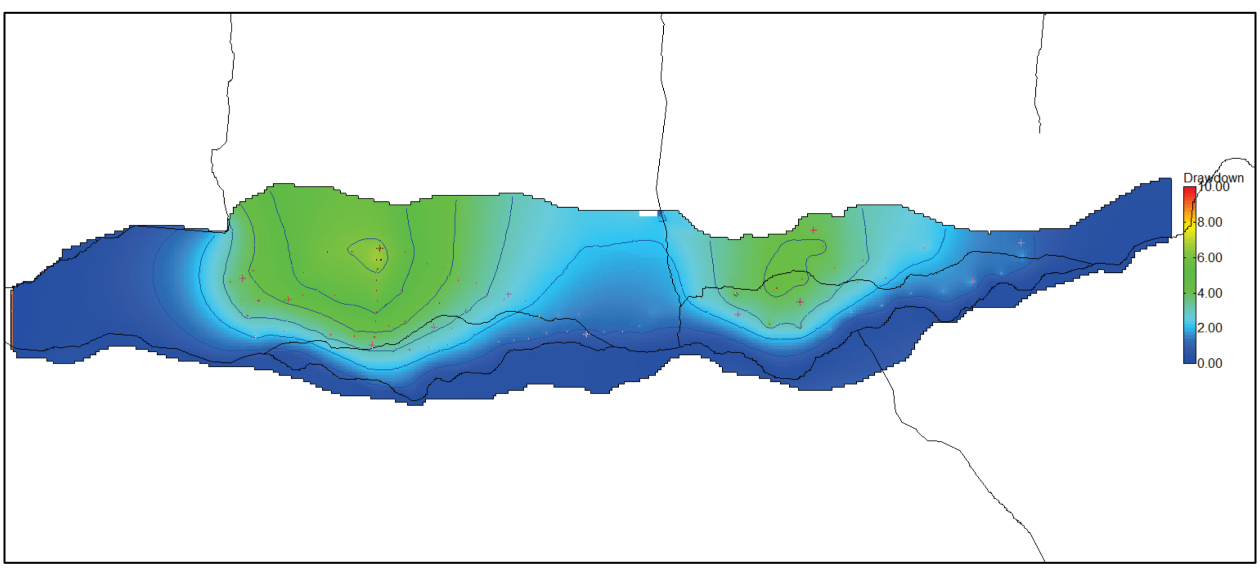


Figure 37. Steady-State Application 5 - Recharge and Tuul River Flow Decreased by Fifty Percent

4.1.6 Sustainable Yield

Steady-state analysis provides information on sustainable yield for specified, long-term, seasonal conditions. The steady-state model simulated a reduction in Tuul River flow that closely matches any increase in groundwater pumping. Thus, the Tuul River is the primary source of groundwater extracted. The volume of groundwater extracted in the model domain averages approximately 0.5 cms in August, and the total groundwater extraction accounts for less than two percent of the flow in the Tuul River.

Sustainable yield of groundwater extraction during summer months is dependent on maintaining flows in the Tuul River. The sustainable yield from groundwater during winter months and other periods can be inferred from the long-term application of the transient model.

4.2 Transient Model Application

Transient models are developed to evaluate water table and groundwater flow fluctuations over time in response to various system stresses. The transient calibration seasonal period of April 2015 to April 2016 represented relatively average hydrologic conditions based on the historical precipitation and river flow data. For the transient model applications, this seasonal cycle was repeated for 25 years. For these predictive simulations, individual parameters such as pumping rate, recharge, and river flow were varied for each simulation and the long term impacts were evaluated.

4.2.1 Current Conditions

Figure 38 presents the computed groundwater contours during the summer at the end of the 25 year simulation, assuming no changes in pumping, recharge or river flow. These computed water levels are similar to those computed in the steady-state predictive simulation. In both the steady-state and transient simulations, distinct depression cones are observed downstream of the confluence between the Tuul and the Uliastai Rivers due to the large amount of pumping in this area. These areas of decreased head also result in more water flowing from the Tuul River into the alluvial aquifer as shown (Figure 38) by the bending of the groundwater contours along the Tuul River.

By comparison, Figure 39 shows the computed water levels in the summer after 25 years of no pumping. Under these conditions, flow downstream of the Uliastai River is essentially parallel to the Tuul River. In order to better illustrate the effects of the current pumping on water levels in the Center Area Well Field alluvial aquifer, Figure 40 shows the computed water level variations under current and no pumping conditions over the 25 year simulation at Well-41a. This well was selected as representative since it is located in close proximity to both the Tuul River and the majority of the Center Area Well Field pumping wells. In Figure 40, the green line represents the computed water levels under no pumping conditions. Under these condition, minimal variation (approximately 0.5 meters) in aquifer water level are observed in response to seasonal flow changes in the Tuul River. In Figure 40, the blue line represents the computed water level under current condition pumping over 25 years. The blue line shows a much larger aquifer water level variation (approximately two meters) and an overall depression in the water

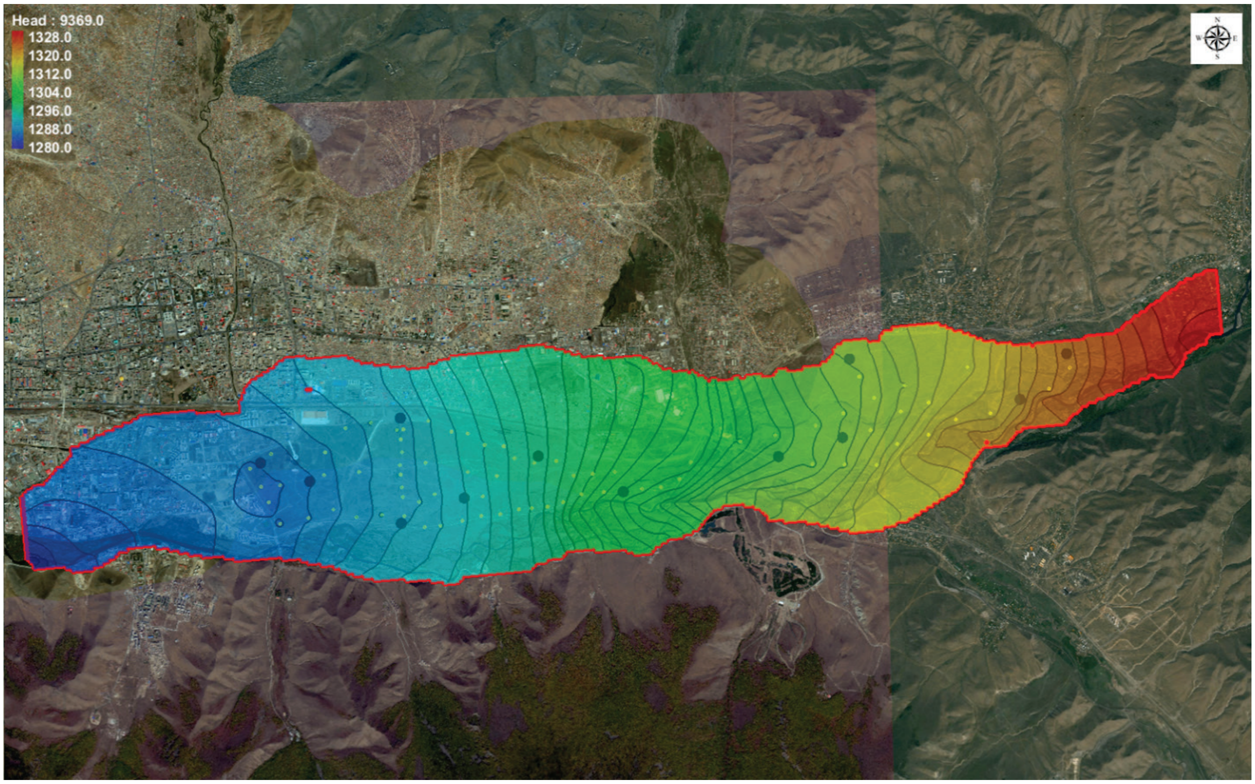


Figure 38. Water Levels based on Current Conditions Projected 25 Years

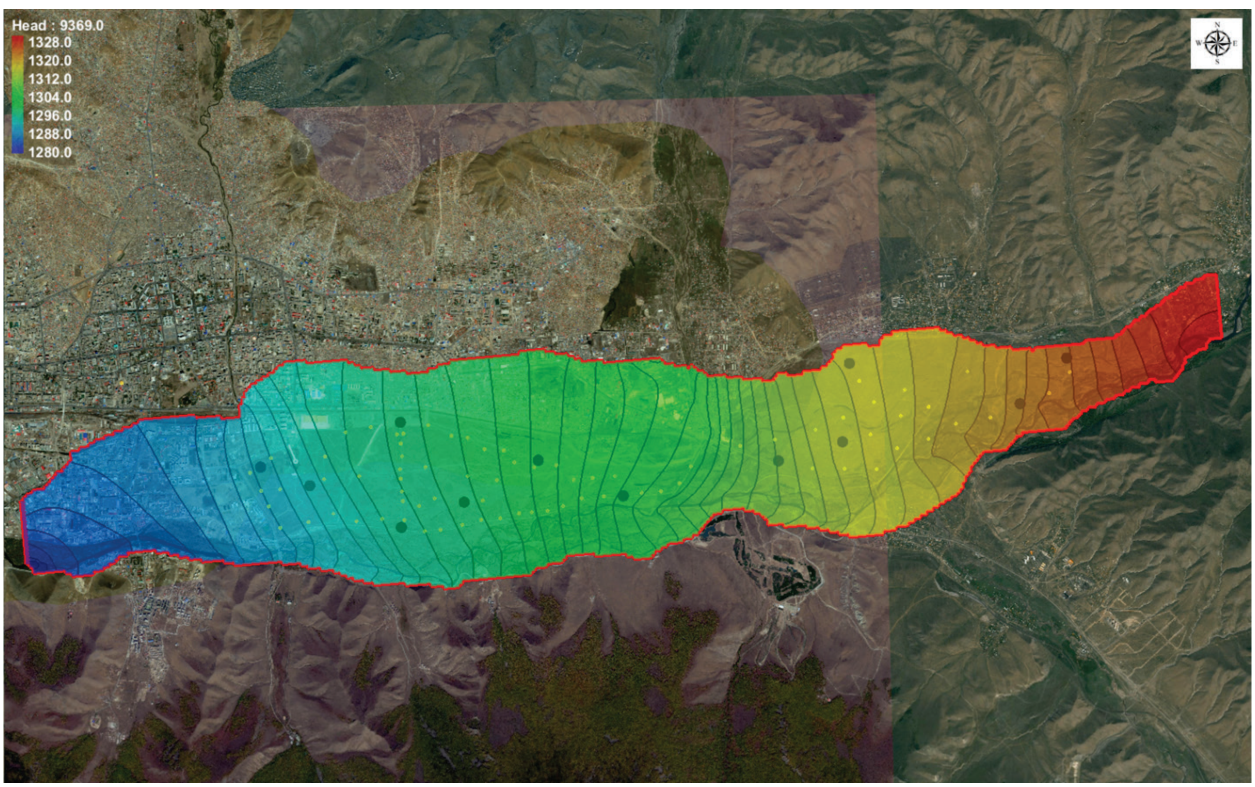


Figure 39. Water Levels based on No Pumping Conditions Projected 25 Years

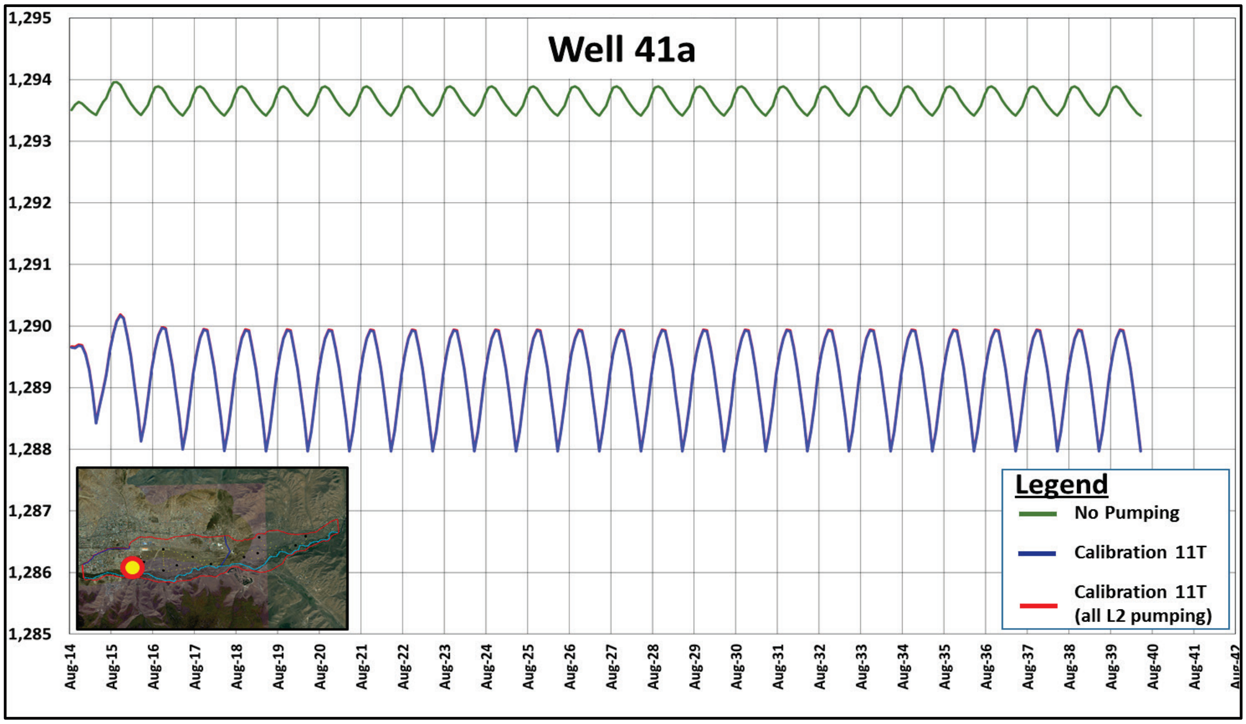


Figure 40. Water Level Variations at Well-41a

table of approximately 4.5 meters. In Figure 40, the blue line represents the simulation where the pumping was evenly distributed between model Layers 1 and 2. The red line (which is imperceptible due to it plotting below the blue line) represents a simulation where all of the pumping is from model Layer 2 only. Insignificant differences are observed between these two simulations indicating that the model is relatively insensitive to the model layer where the pumping is applied.

4.2.2 Increased Pumping

In addition to evaluating the long term impacts of the current pumping conditions, the model was also used to evaluate potential increases in pumping. Initial simulations increased the current pumping rate by 100 percent. However, these simulations failed to converge, since more water was being removed from the model domain that could be sustainably supported during the winter months. Consequently, the increase in pumping was reduced to fifty percent and evenly distributed across the Center Area Well Field. Figure 41 shows the computed drawdown resulting from an average fifty percent increase in pumping rate. Substantial drawdown of ten meters or more are observed at the end of the 25 year simulation, with significant areas of the alluvial aquifer north of the well field drying out. Note that this computed drawdown represents the average aquifer drawdown for each fifty meter square MODFLOW cell, and does not account for well losses. As such, the actual drawdown observed at individual well heads may be significantly more than that computed in the model. Sustainable yield targets for each well were discussed during the September 2016 workshop in Ulaanbaatar. During these discussions, the well field operators indicated that individual well were not allowed to operate if drawdown exceeded fifty percent of aquifer thickness. Discussion about operational variations in pumping at individual wells to account for seasonal constraints were held. These seasonal operational constraints and near well field effects will be more fully evaluated in future modeling efforts.

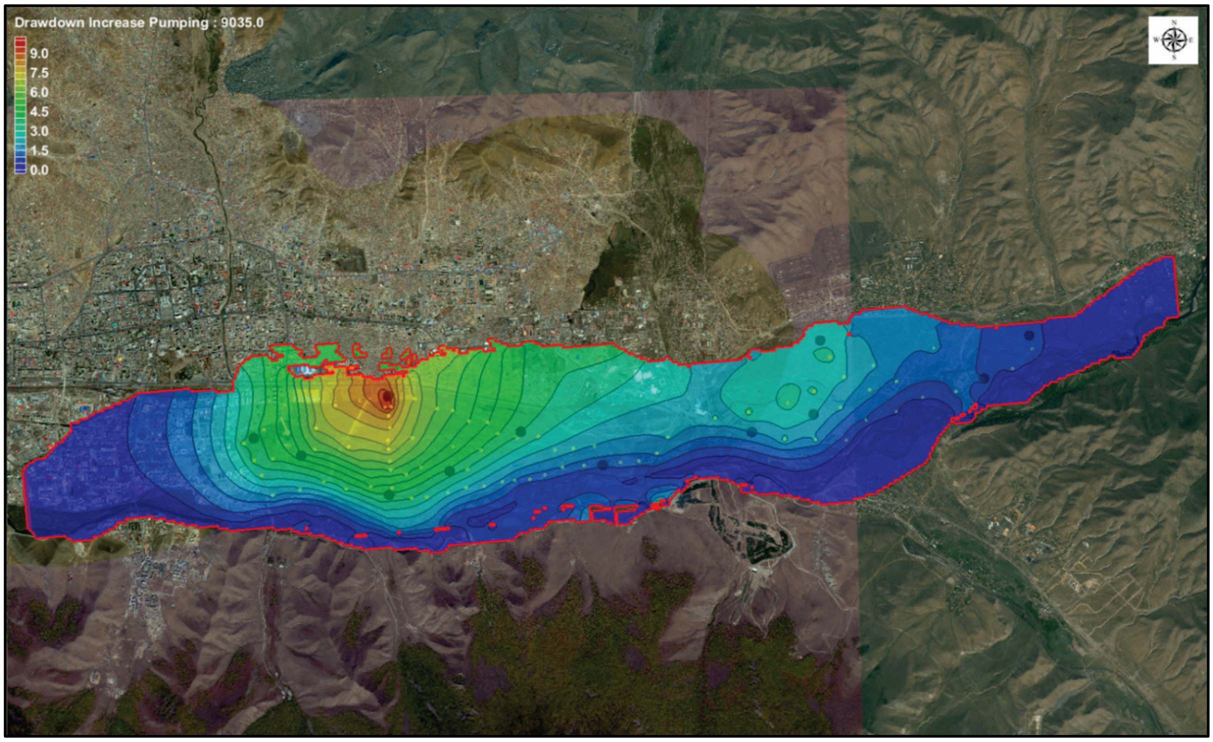


Figure 41. Drawdown with Fifty Percent Pumping Increase at the End of a 25 Year Simulation

In addition to the increased total drawdown, the magnitude of computed aquifer water level variation increases substantially as the pumping is increased. Figure 42 shows the computed water level at Well-41a under both current conditions (blue line) and with the fifty percent increase in pumping (red line).

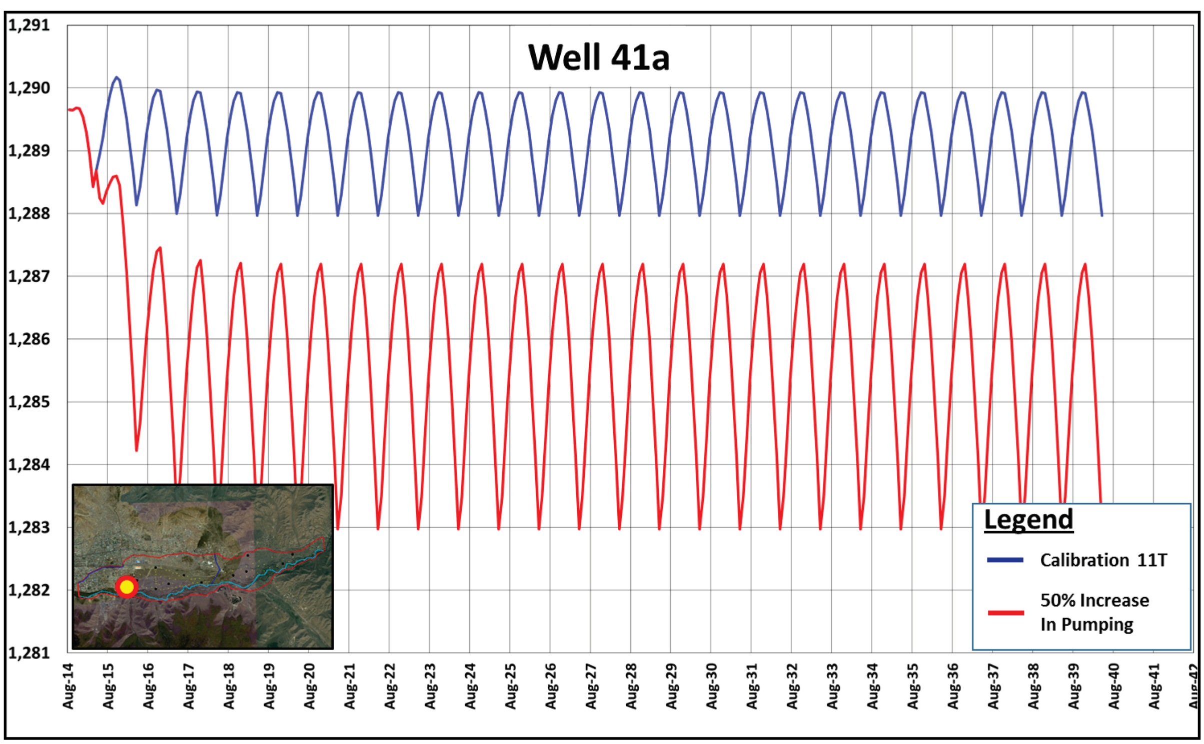


Figure 42. Water Level Variations at Well-41a with Pumping Increase of Fifty Percent

4.2.3 Climate Change

In order to perform a preliminary evaluation of climate change on the sustainability of the Center Area Well Field, two 25-year simulations were performed. The first simulation assumed that the flow in the Tuul River was reduced by fifty percent and the second assumed that the groundwater recharge was reduced by fifty percent. Both simulations assumed that the groundwater pumping remained unchanged from current conditions. Figure 43 shows the reduction in groundwater heads resulting from decreases in Tuul River flow. The largest magnitude changes are noted in April at the end of the 25-year simulation, with changes centered on the confluence of the Tuul and Uliastai Rivers. Variations in aerial and mountain recharge had minimal impacts on water levels within the Center Area Well Field. These predictive simulations tend to support the conceptual understanding that the alluvial aquifer recharge in the Center Area Well Field is primarily from the Tuul River and not surface recharge.

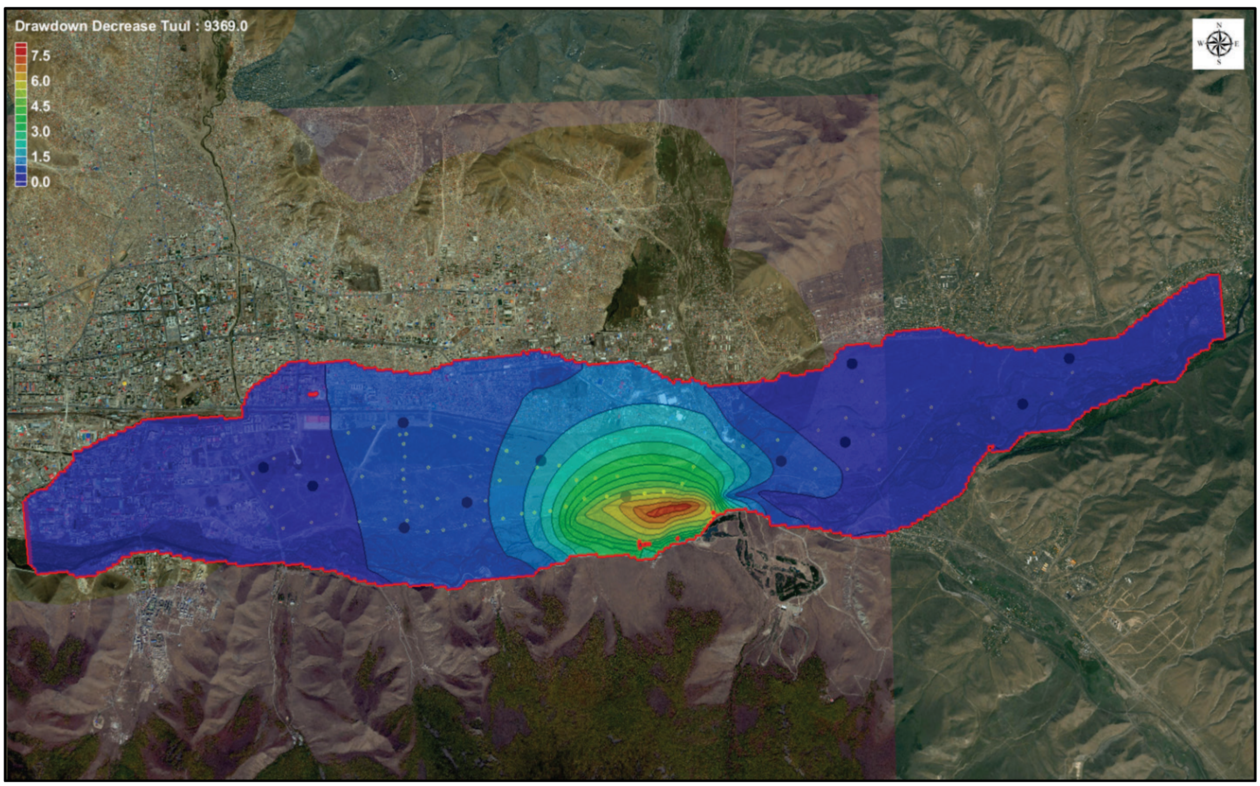


Figure 43. Groundwater Head Reduction due to Fifty Percent Decrease in Tuul River Flow

Chapter 5

Model Sources of Uncertainty

5.1 Numerical Model Uncertainty

The accuracy of the model is dependent on the ability of the data to represent the system being modelled. The current Tuul River Basin groundwater model should be considered a first step in the modeling process. As more data becomes available, the complexity of the model in terms of parameter zonations and applications can be increased. During model development and sensitivity analysis, several areas of model uncertainty and needs for future data gathering were identified. Areas of uncertainty to address and addition data to gather, include groundwater pumping, streamflow, and groundwater level data.

5.2 Recommendations for Future Data Gathering

Groundwater pumping is a very important model parameter. The current model uses monthly averaged pumping rates. These rates are based on cumulative pumping values which are distributed to individual wells as a function of relative pumping capacity. Data on groundwater pumping rates at specific wells was not available. Logs of power usage for individual wells over time would provide for a more accurate distribution of groundwater pumping in the model domain. More information on seasonal adjustment in pumping within certain areas of the well field would be helpful. Finally, the potential impact of pumping from well fields adjacent to the Center Area Well Field on groundwater levels within the model domain should be addressed by expanding the model domain to include all significant well fields illustrated in Figure 2.

The only streamflow data available for the model is from the Tuul River Ulaanbaatar gage located at the downstream end of the model domain. The model assumed Tuul River inflow into the model domain was equal to the measured value at the Ulaanbaatar gage. The installation of additional stream gages along the Tuul River above Ulaanbaatar would provide very useful information on the impacts of hydrologic stresses on streamflow, and allow for a more accurate quantification of model inflows. Additionally, there is no flow or stage information available for the Selbe and Uliastai Rivers in the model domain. The model used topographic survey information to specify stage values as equal to land surface elevation. More accurate data on the Selbe and Uliastai Rivers would allow for a more accurate understanding of the water balance in the study area.

Several monitoring wells used in model calibration were impacted by the near field effects of groundwater pumping. Additional data loggers in dedicated monitoring wells not directly influenced by individual pumping wells would provide valuable data on the groundwater flow regime.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

The 2016 Tuul River Basin steady-state and transient model calibrations were able to successfully replicate measured groundwater levels and streamflow in the Tuul River Basin. Model results indicated: recharge to the aquifer system is primarily from the Tuul River; snowmelt impacts are localized and of short duration; pumping increases have a significant impact on groundwater water levels; and, the aquifer is semiconfined containing intermixed strata of fine and coarse grained material.

6.2 Recommendations

Model recommendations include additional simulations using the existing model and the next steps in model development. The existing model can be used in a more detailed analysis of sustainable yield and winter drawdowns in the Center Area Well Field. During the September 2016 workshop in Ulaanbaatar, well field operators indicated that individual wells were not allowed to operate if drawdown exceeded fifty percent of aquifer thickness, which is an important issue during the dry winter months when the Tuul River freezes. Operational variations in pumping at individual wells to account for seasonal constraints were also discussed. The current transient model can be used to assist seasonal operations and evaluate winter drawdowns at individual wells under different water use and climate scenarios. Operational constraints to available groundwater storage will be more fully evaluated in future modeling efforts.

The annual mean flow of the Tuul River decreased by approximately fifty percent from 1950 to 2007 (Davaa, 2010). This decrease in streamflow was primarily the result of the growth of Ulaanbaatar and the corresponding increase in groundwater pumping adjacent to the Tuul River. According to estimates by the Mongolian Government (Ganbold, 2010), the total water usage of Ulaanbaatar is expected to double between 2010 and 2030. As illustrated in Figure 2, the Center Area Well Field is only one of several well fields that supply water to Ulaanbaatar. The Center Area Well Field is not an isolated system. The Tuul River and adjacent well fields are an interconnected system where water use activities in one area may have effects throughout the system. Because of this interrelationship, a more complete understanding of the hydrologic system is necessary. The expansion of the current groundwater flow model to include all major pumping areas will provide a more complete and holistic understanding of the effects of groundwater pumping on streamflow, aquifer storage, and sustainable yield. This new model will serve as a water resource management tool to assist in operations. The model can also be used to predict the future effects of potential water use and changes in climate on water resources as well as the potential impacts of proposed reservoirs on the groundwater system.

The eventual step in model development should include the expansion of the model to include the entire watershed above Ulaanbaatar. The existing HEC-HMS watershed model (HEC, 2013) could be used for simulating effects of precipitation and climate change on the upper watershed. Precipitation and snowmelt can be routed overland and through the subsurface to contributing streams. Output from the HEC-HMS model can be directly transferred to the existing HEC-RAS model of the Tuul River (HEC, 2013). The HEC-RAS model can be directly coupled with the expanded MODFLOW model on a time-step basis using RAS-MODFLOW. An HMS-RAS-MODFLOW application would be able to simulate the impacts of climate change, water use, reservoirs, and development on groundwater and surface water resources throughout the entire Tuul River watershed above Ulaanbaatar.

Chapter 7

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Appendix

Transient Calibration Hydrographs

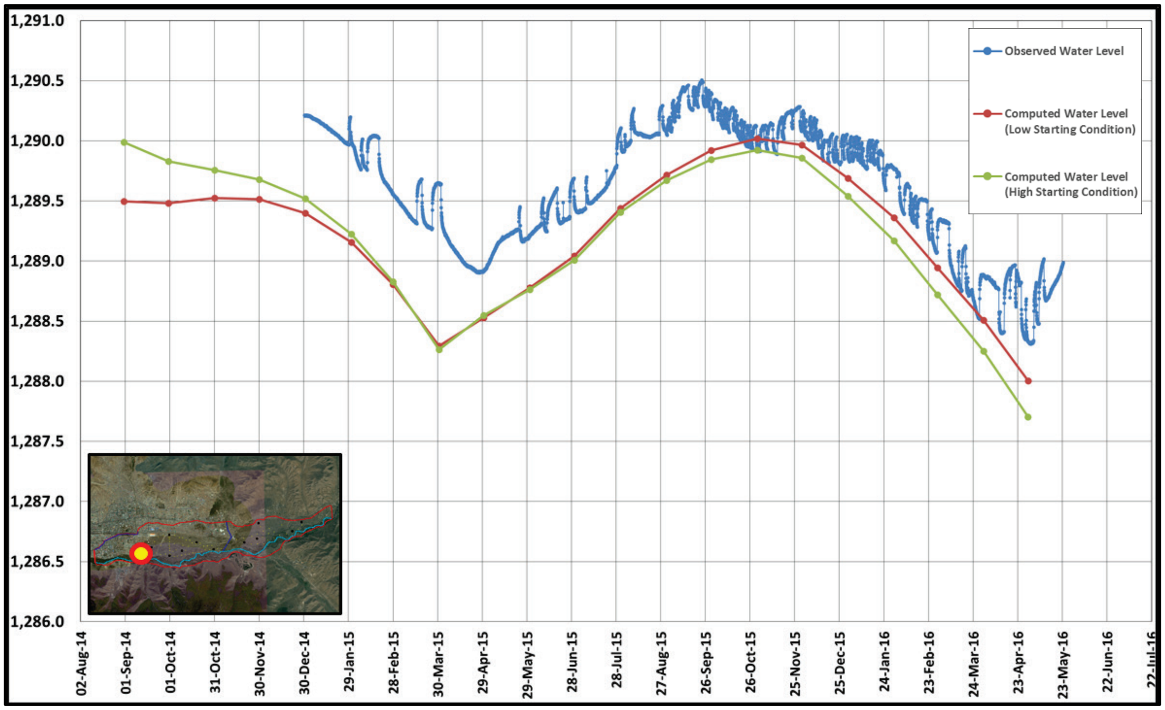

Figure 44. Monitoring Well Czech-15 Transient Calibration

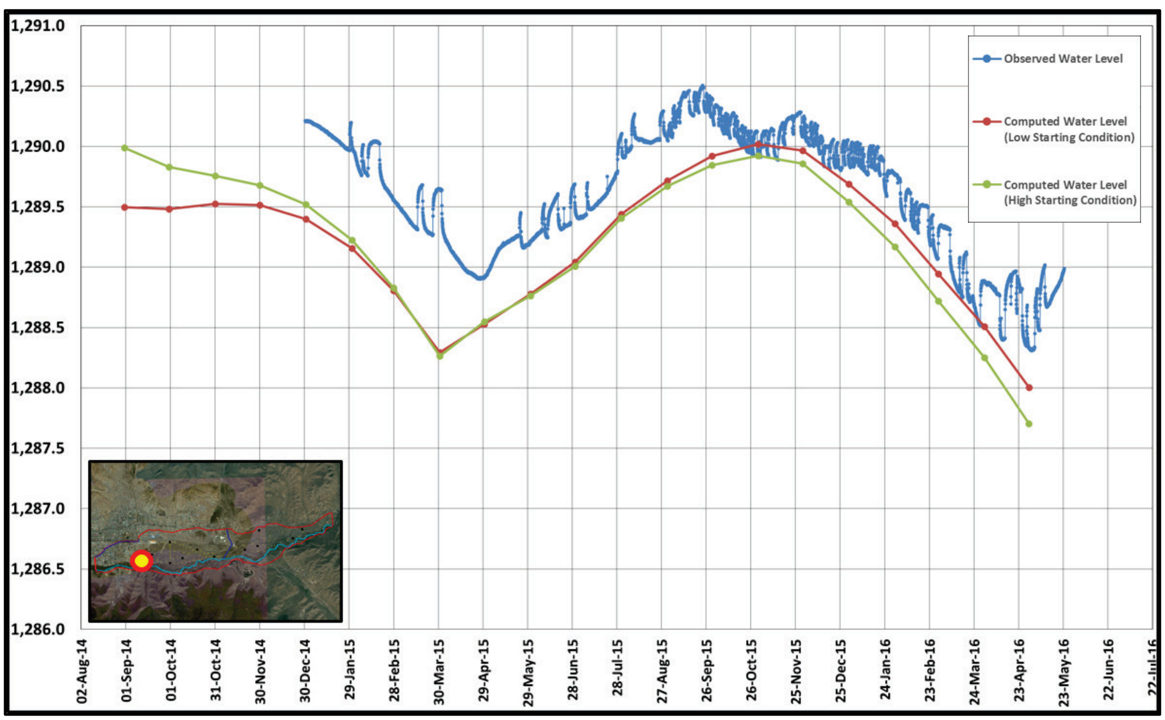

Figure 45. Monitoring Well 41a Transient Calibration

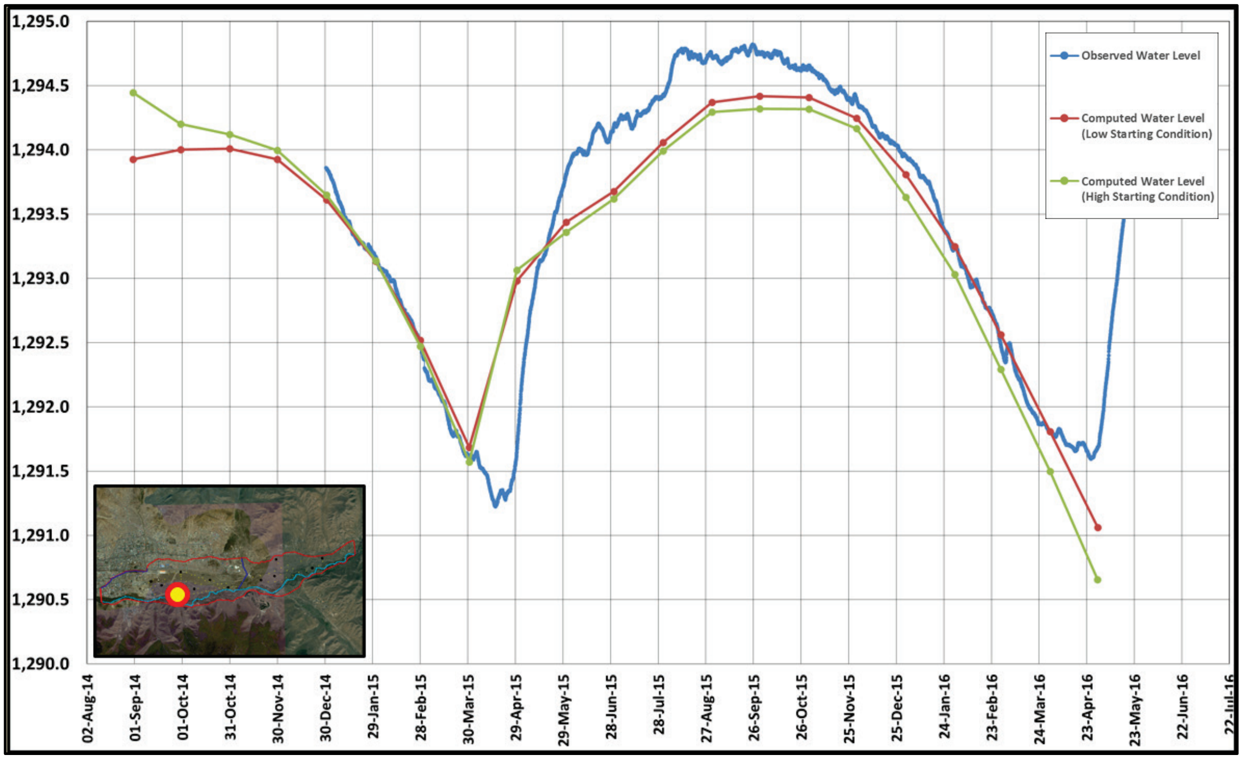

Figure 46. Monitoring Well Czech-12 Transient Calibration

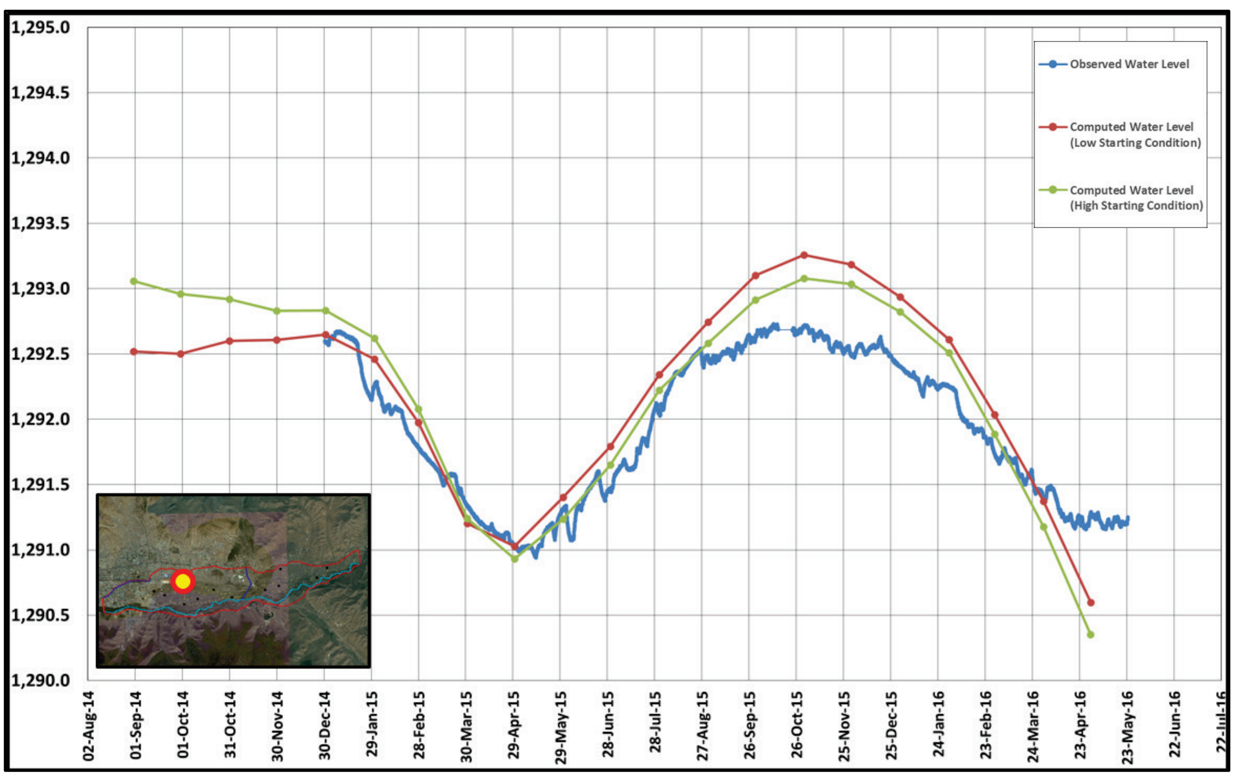

Figure 47. Monitoring Well Czech-13 Transient Calibration

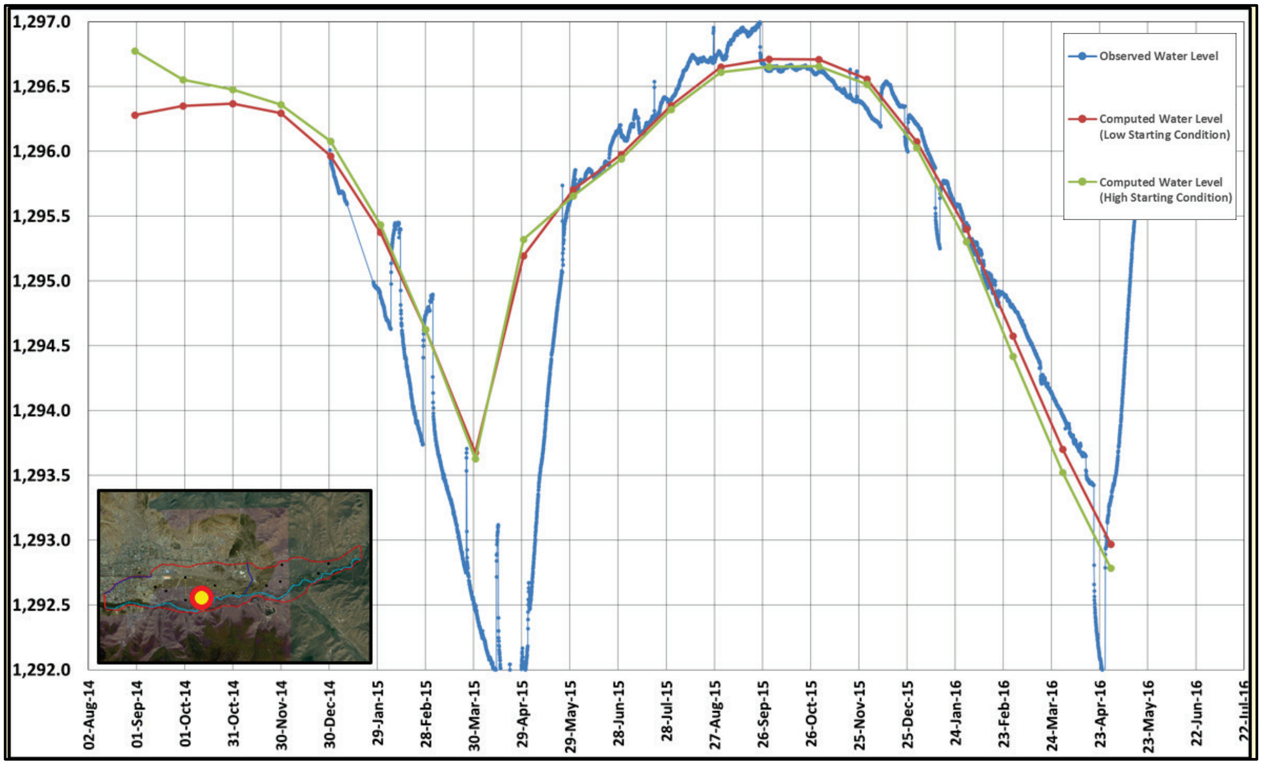

Figure 48. Monitoring Well 49a Transient Calibration

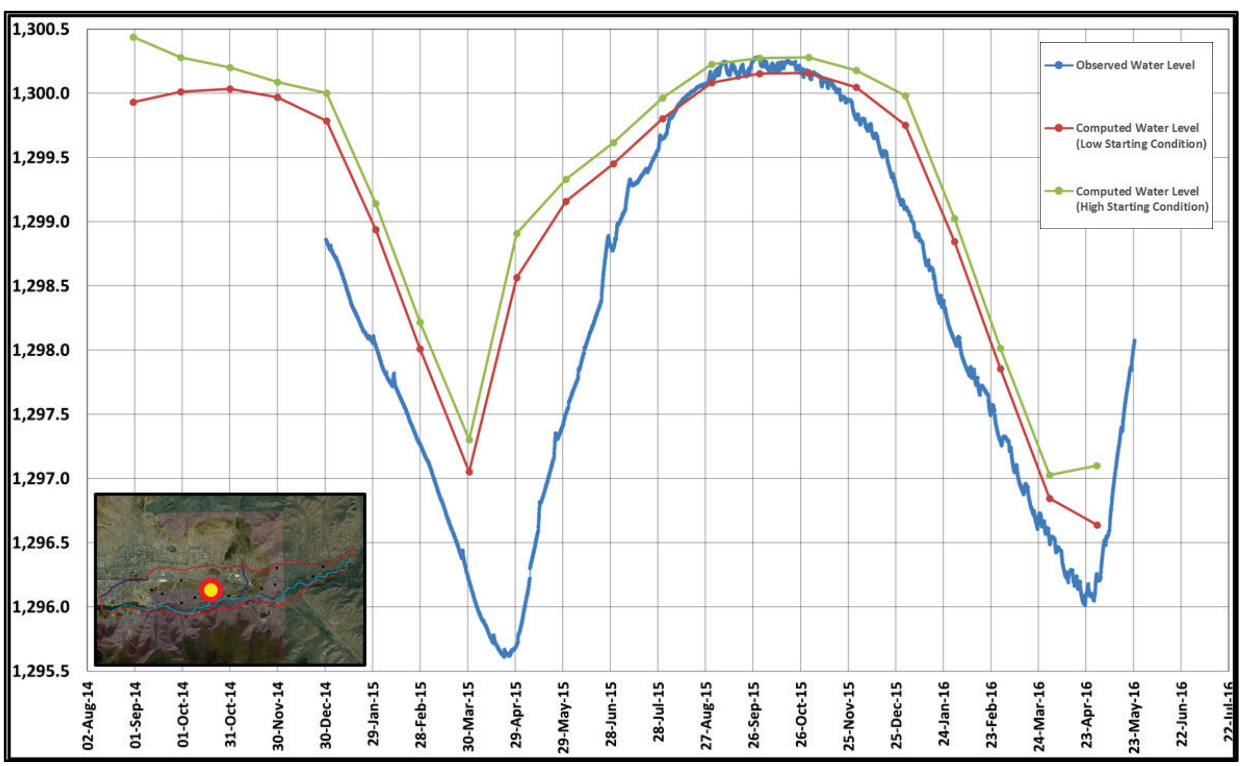

Figure 49. Monitoring Well Czech-10 Transient Calibration

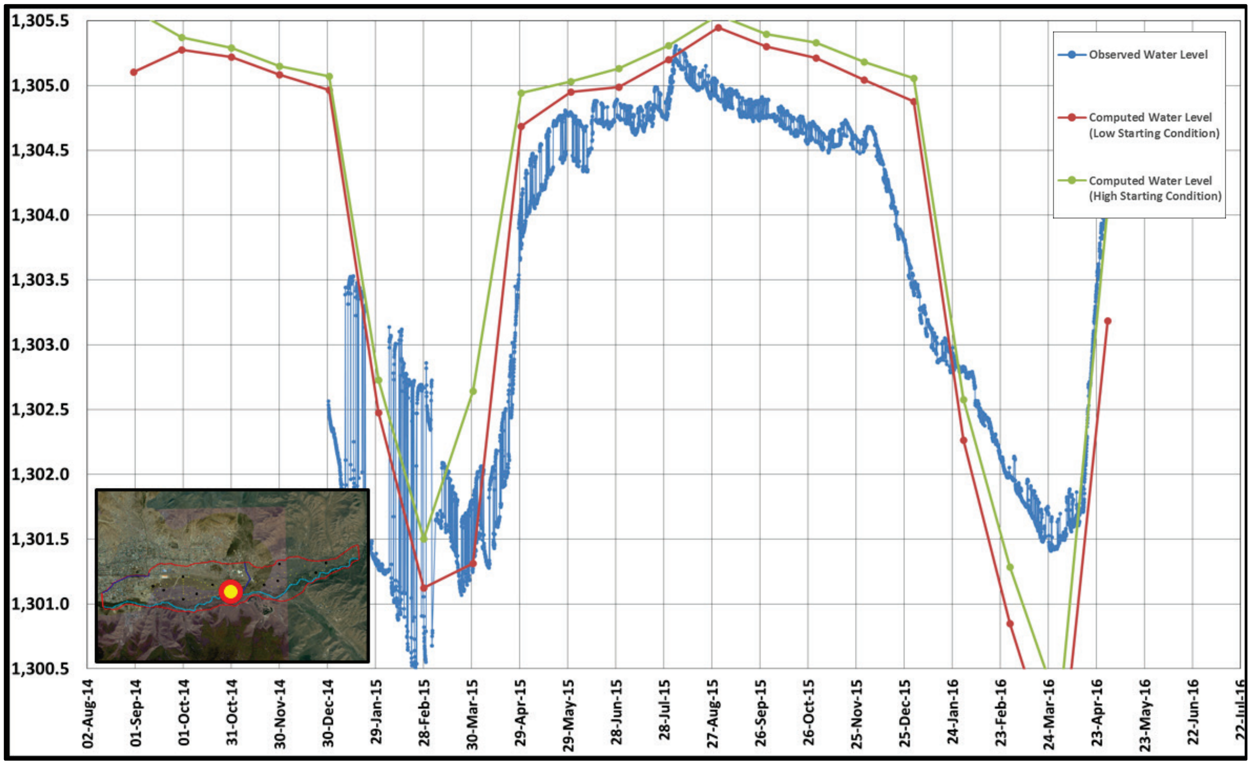

Figure 50. Monitoring Well 23 Transient Calibration

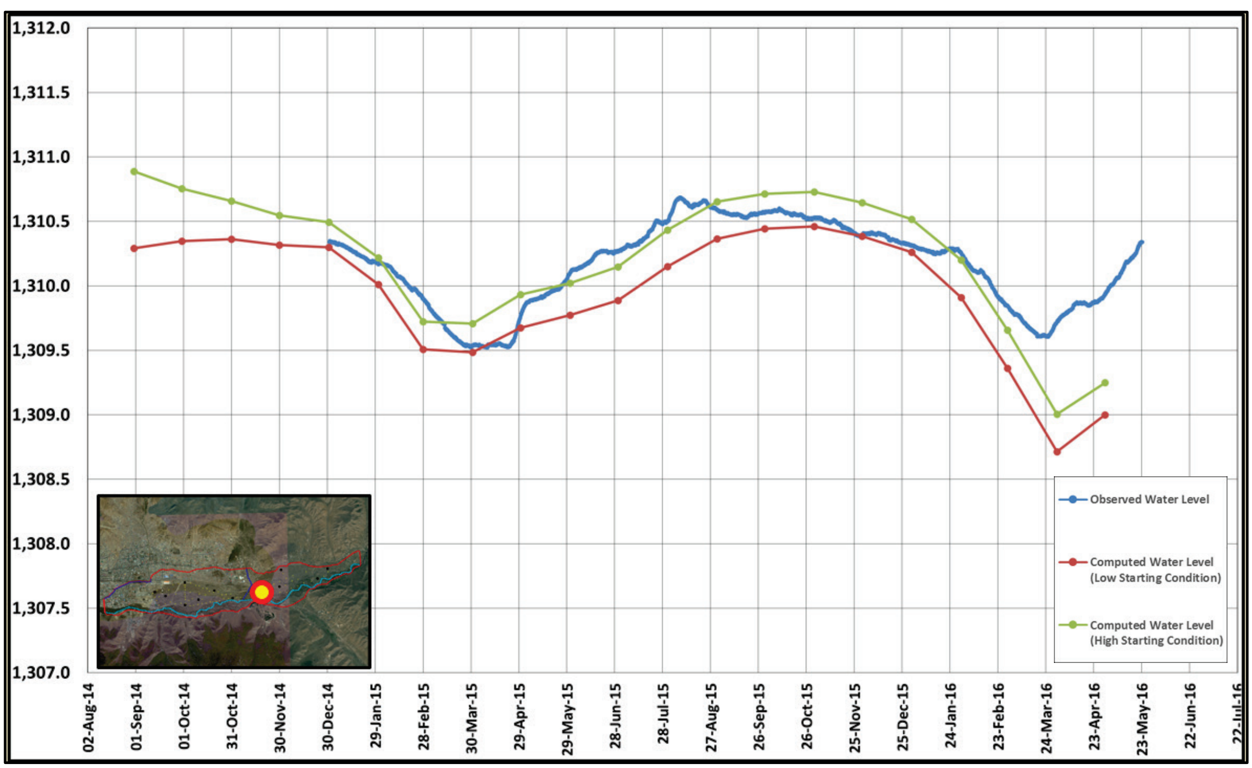

Figure 51. Monitoring Well Czech-7 Transient Calibration

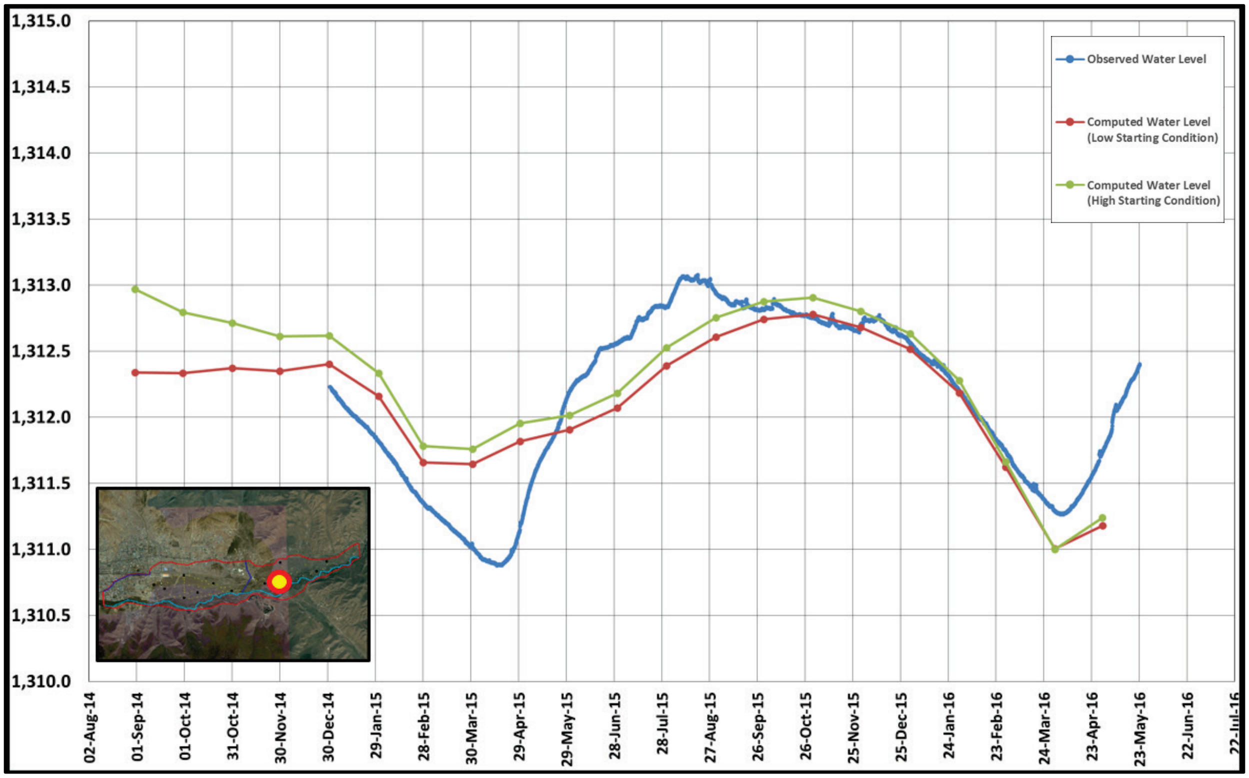

Figure 52. Monitoring Well 69a Transient Calibration

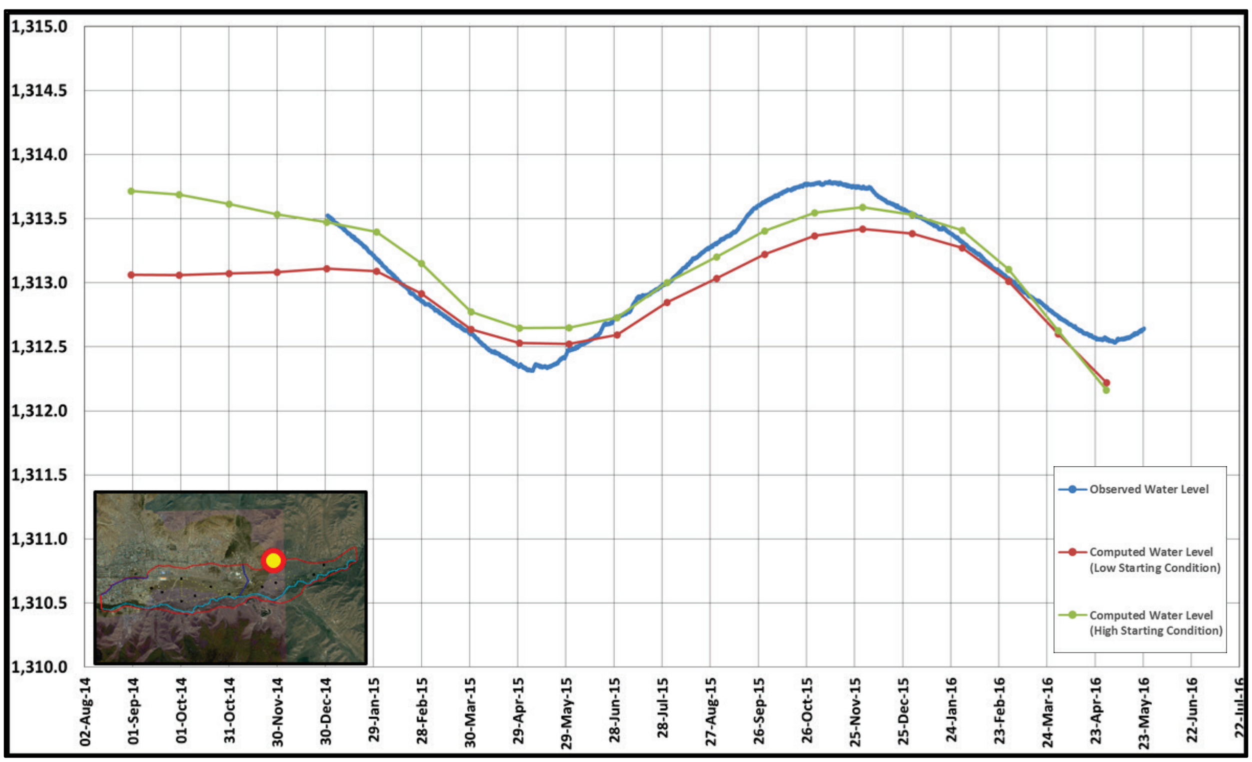

Figure 53. Monitoring Well Czech-6 Transient Calibration

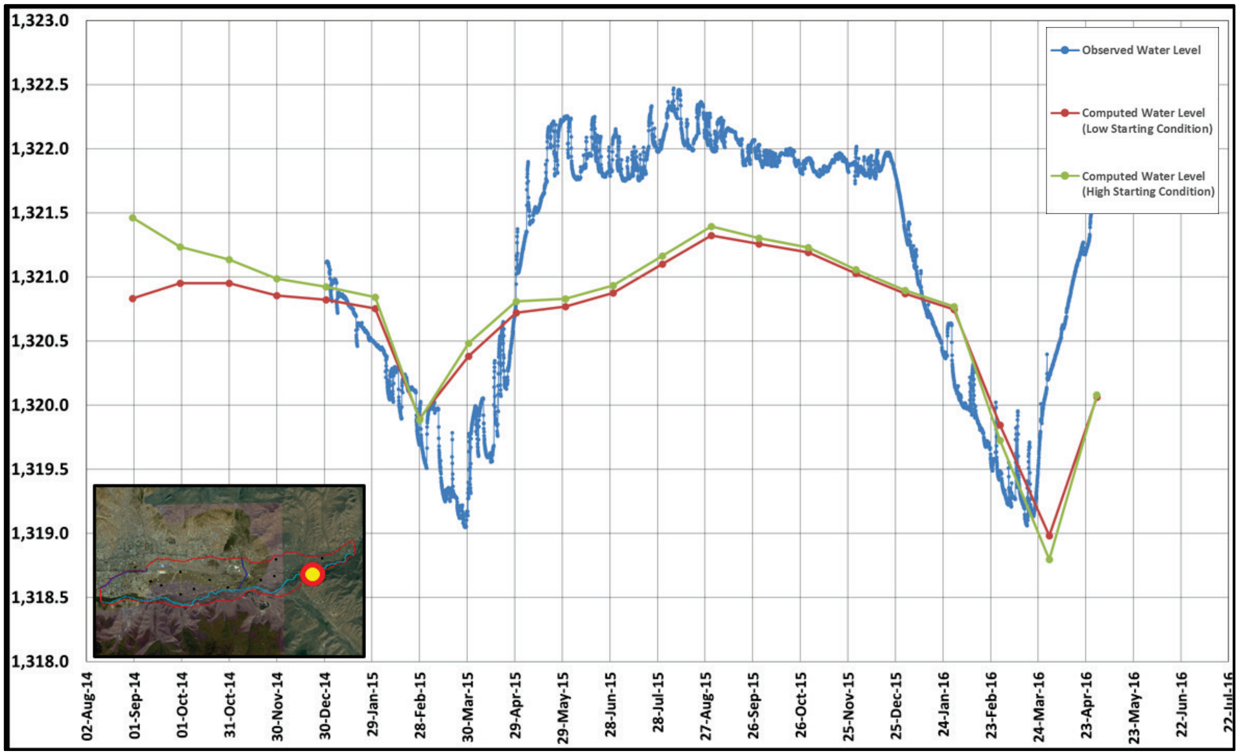

Figure 54. Monitoring Well 66a Transient Calibration

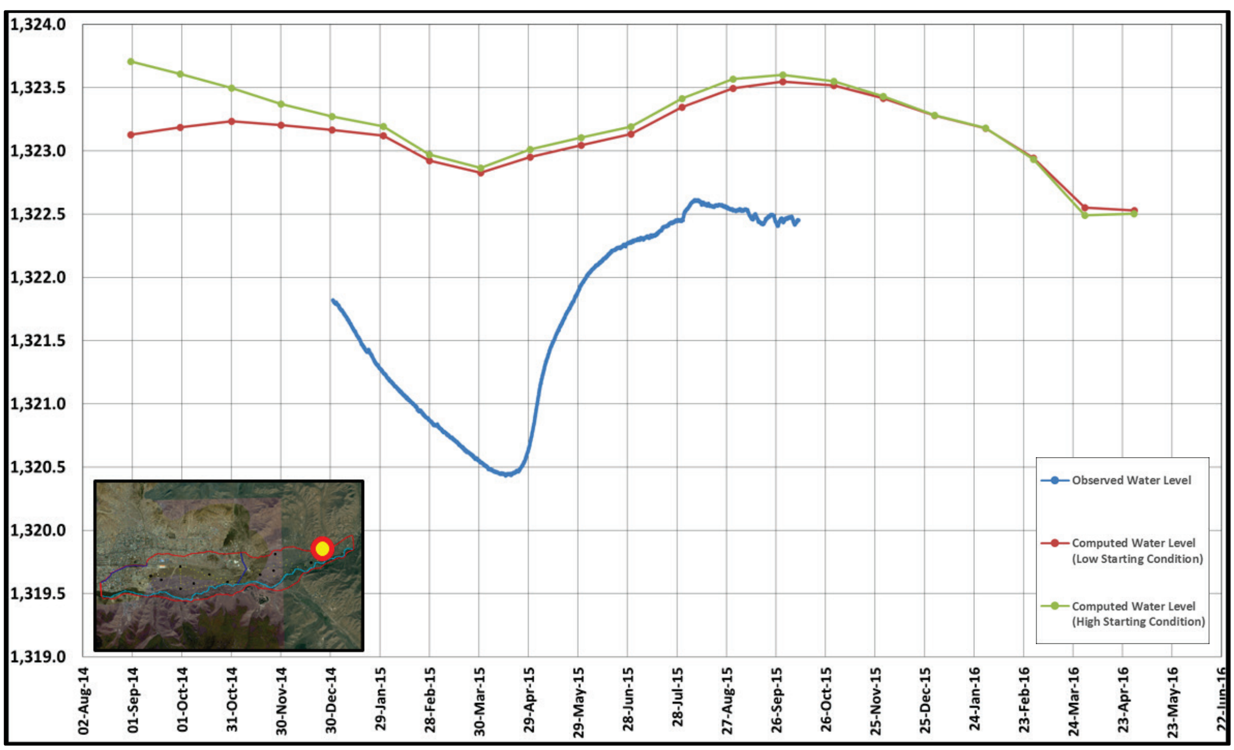

Figure 55. Monitoring Well Czech-2 Transient Calibration