An Investigation of the Impacts of High Capacity Wells in the Northwestern Region of the Central Wisconsin Sand and Gravel Aquifer for 2016 by Use of FREEWAT and the MODFLOW-NWT Formula

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Geography 578: GIS Applications

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Capstone Statement:

Overall, the goal of this research is to investigate the impacts of high-capacity wells on a Northwestern region of the Central Wisconsin Sand and Gravel Aquifer (CWSGA) and to the impacts of high-capacity wells. To accomplish this goal the change in hydraulic head across the aquifer will used as a proxy to assess the change in aquifer volume per unit area. The year 2016 will be modeled for this region using the MODFLOW-NWT based tool FREEWAT.

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1. Introduction

An aquifer is a layer of permeable, saturated rock and soil that exists below the water table, which can store or transmit groundwater. The groundwater in Wisconsin is held in four primary aquifers (listed shallowest to deepest): the sand and gravel aquifer, eastern dolomite aquifer, sandstone and dolomite aquifer, and crystalline bedrock aquifer (Kassulke & Chern, 2006). As seen in Figure 1, aside from parts of the southwest region, Wisconsin's sand and gravel aquifer covers the majority of the state. This layer of sand and gravel material was deposited within the past million years as the glacial sheets covering North America melted. Therefore, these deposits in the sand and gravel aquifer are categorized as glacial outwash. As the dominant surface material in Wisconsin this aquifer is the most susceptible to human and natural influences.

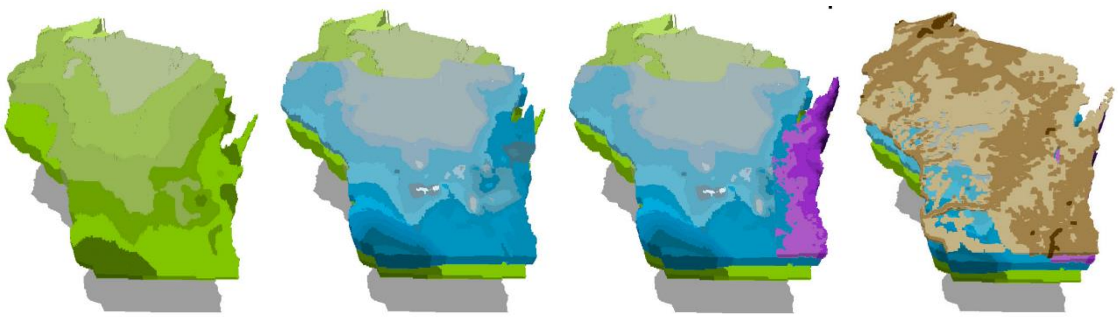


Figure 1. Wisconsin Aquifers: the crystalline bedrock aquifer (green), sandstone and dolomite aquifer (blue), eastern dolomite aquifer (purple), and sand and gravel aquifer (brown). Images from Wisconsin Geological & Natural History Survey (Wisconsin Geologic and Natural History Survey, 2013).

One highly influenced region of the Wisconsin sand and gravel aquifer is the Central Wisconsin Sand and Gravel Aquifer (CWSGA). The CWSGA area, as defined by the Wisconsin DNR, is the "contiguous area east of the Wisconsin River with sand and gravel surficial deposits greater than 50 feet deep" (Wisconsin DNR, "High Capacity Wells", 2017). A visual showing the CWSGA boundaries is shown below in Figure 2. This area consists of approximately 1.75 million acres and spans over portions of several counties, including: Adams, Marathon, Marquette, Portage, Shawano, Waupaca, Waushara, and Wood.

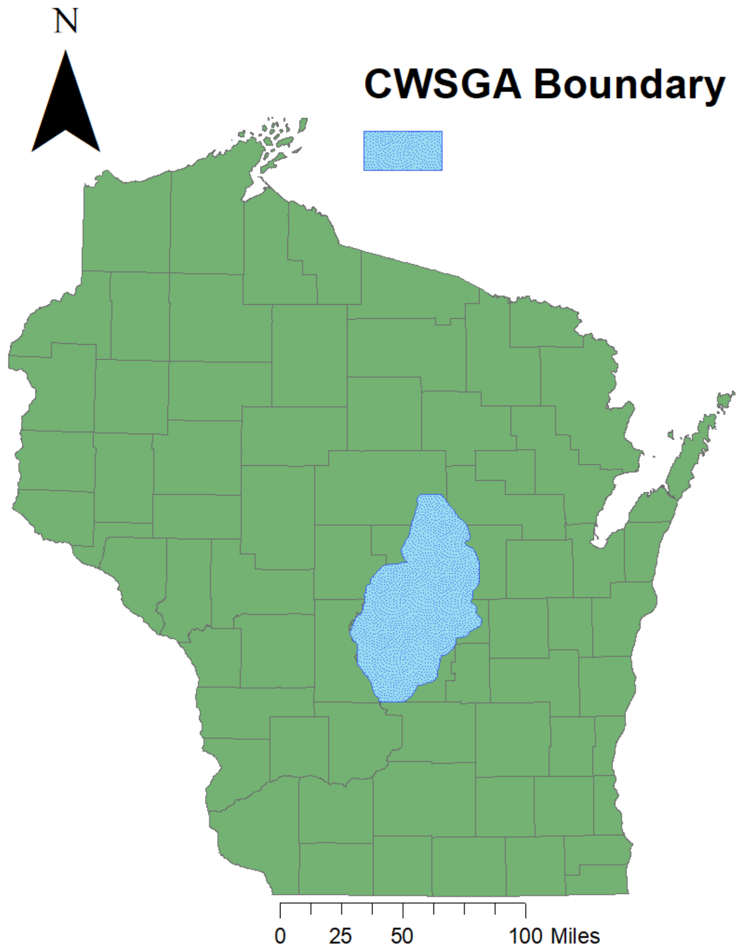
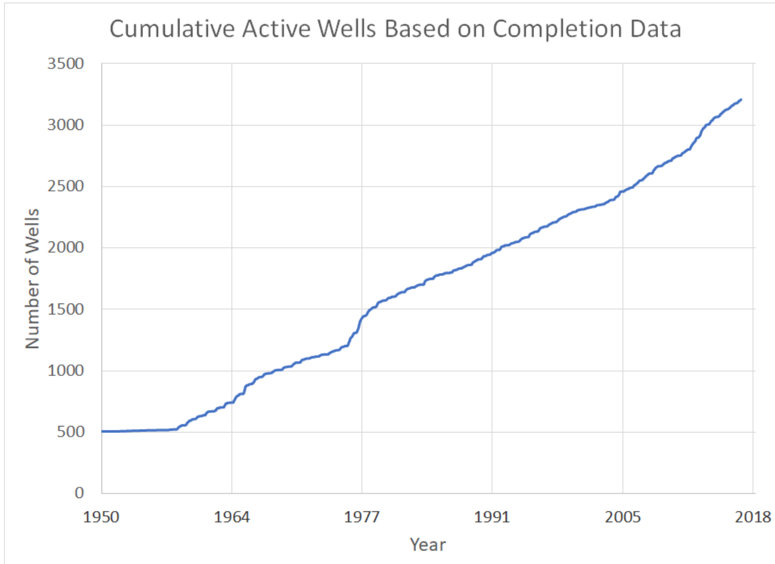


Figure 2. Central Wisconsin Sand and Gravel Aquifer (CWSGA) Boundary.

The CWSGA is largely responsible for Wisconsin's agricultural success and plays a key role in producing the state's potatoes, green beans, sweet corn peas, and carrots (Helsel, Ken, & Fienen, n.d.). Besides agriculture, the CWSGA also draws in outdoor tourism from its impressive "800 miles of trout stream and 300 lakes" (Wisconsin DNR, "High Capacity Wells", 2017). Although this aquifer's true value is immeasurable, it has been estimated to have a multibillion-dollar economic impact and is responsible for maintaining tens of thousands of jobs per year (Helsel, Ken, & Fienen, n.d.).

In the past several decades the number of active high-capacity wells in the CWSGA has increased dramatically. A plot of cumulative active high-capacity wells in the CWSGA since 1950 is shown below in Figure 3, where an example of a high-capacity well in Central Wisconsin is also shown. According to information shared by the DNR, the CWSGA currently contains half of all irrigation wells in Wisconsin. This number of high-capacity irrigation wells counts more than 2000 in total (Helsel, Ken, & Fienen, n.d.).

Figure 3. Active high-capacity wells in the CWSGA. Data provided by the Wisconsin Department of Natural Resources (WI DNR). Example of high-capacity well in Central Wisconsin. Image from Fox11 (LaCombe & FOX, 2016).



The Wisconsin DNR defines a high capacity well (HCW) as "a well that has the capacity to withdraw more than 100,000 gallons per day, or a well that, together with all other wells on the same property, has a capacity of more than 100,000 gallons per day" (Wisconsin DNR, 2017). In the past, the ability to obtain permits for HCW in Wisconsin was regulated in a way that prevented the installation and use of HCW if it caused unreasonable harm to another landowner, direct and substantial effect on a stream or lake, or if it was not for a "beneficial use" (Johnson, 2014). In 2004, the definitions for impacts to surface and ground water were decreased to allow for more pumping. Rather than protecting the impacts to private land owners nearby, it was revised to "not adversely impact or reduce the supply of water to any public water utility" (Johnson, 2014). Since June 1, 2017 these laws have seen substantial change with the passing of Senate Bill 76 (Verburg & Wisconsin State Journal, 2017).

The most significant changes in these regulations have to do with the approval of repairs, replacements, and renewal of permits, as well as the usage limits. In the past, the DNR was allowed to consider the impact of another well on the cumulative impact of high-capacity wells on the water budget (Verburg & Wisconsin State Journal, 2017). The permits are now issued and addressed based on case-by-case impacts, rather than addressing their cumulative influence. The new regulation also allows for current permit holders to make changes (e.g. drilling deeper, fully replacing a well, etc.) or transfer their permit to someone else without approval from the DNR (Ferral, 2017). Permits were also nearly doubled from their initial pumping capacity of 1.3 billion gallons to 2.4 billion gallons within a 30-day period (Verburg & Wisconsin State Journal, 2017).

Recently, there have been visual signs of disturbances to the CWSGA's water budget. For example, stretches of the Little Plover River have run dry, which is a major clue the aquifer has been stressed. There is public debate whether the CWSGA has been mismanaged or if these stressors to the aquifer have been caused by natural impacts. A heat map of Wisconsin's high capacity wells is shown below in Figure 4. It may be noticed that the area of the CWSGA clearly contains the densest quantity of high-capacity wells in Wisconsin.

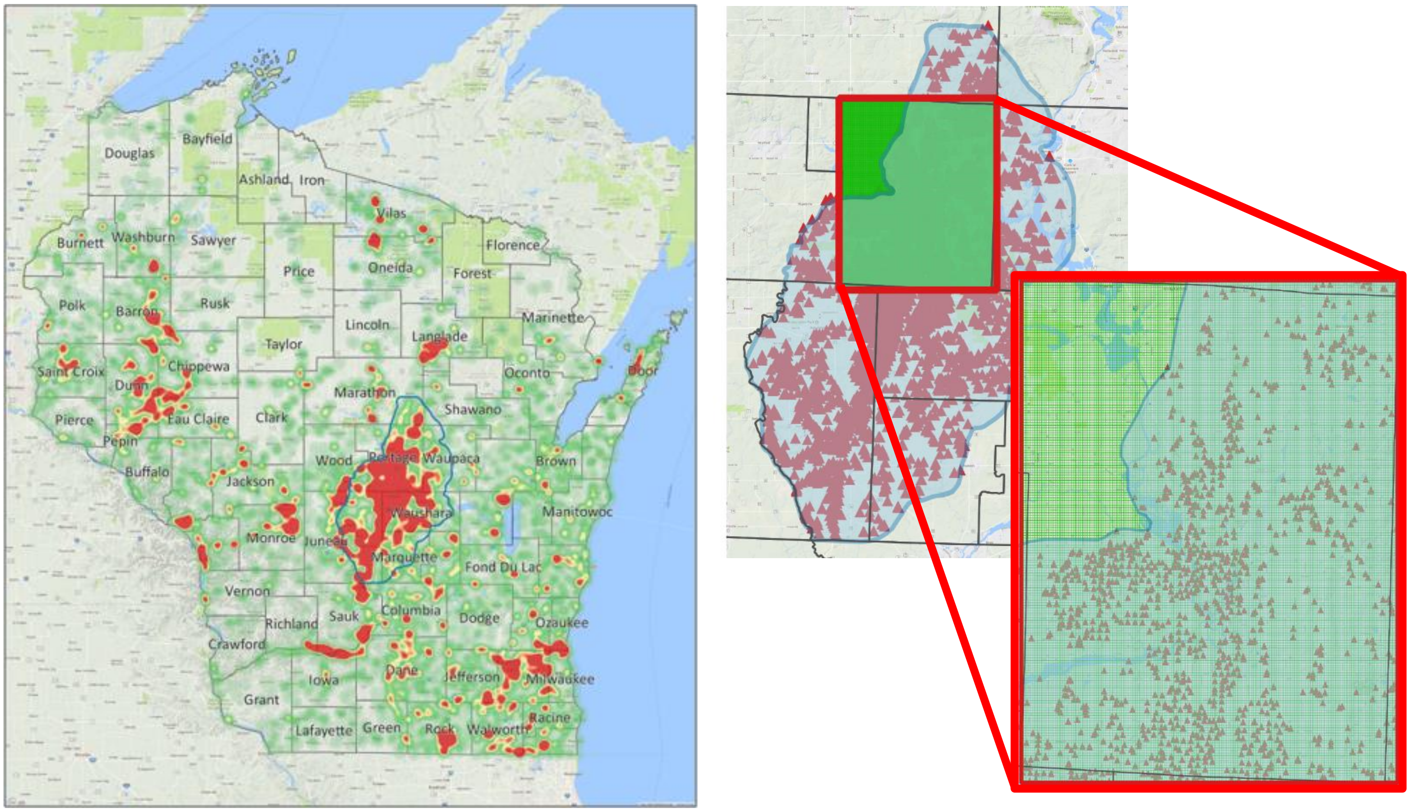


Figure 4. (Left) High-capacity well heat map showing spatial density variations across Wisconsin. The CWSGA boundary is outlined in blue. (Right) Delineation of study domain, defined as the northwestern region of the CWSGA. The domain includes the majority of Portage County.

The objective of this research will be to model the spatial variation of recharge and discharge in the northwest region of the CWSGA, which, in turn, will include the hydrologic budget and high-capacity wells for the region. The overall mission is to assess the sensitivity of the aquifer to high-capacity wells' influence and define areas of concern. Hopefully these results can help guide policy makers' and water shed managers' decisions about effective aquifer management strategies. All-in-all this project aims to help ensure this invaluable natural resource remains sustainable and resilient for future generations.

2. Background

In 1580 A.D. Bernard Palissy was imprisoned as a heretic in the Bastille for asserting the idea that rainfall alone was insufficient for the maintenance of rivers. For this, he is often credited for the discovery of what we now refer to as the "Water Cycle" (Wikipedia, "Bernard Palissy", 2018). There are roughly 14 distinct processes that make up the entire water cycle: precipitation, canopy interception, snowmelt, runoff, infiltration, subsurface flow, evaporation, sublimation, deposition, advection, condensation, transpiration, percolation, and plate tectonics (Wikipedia, "Water cycle", 2018). Modeling these processes has never been easy, especially since water is in a constant state of flux (Kotwicki, 2009). Modern day hydrologists have simplified the water balance equation to the following:

$$P = R - ET - \Delta S$$

where,

P = Precipitation

R = Runoff

ET = Evapotranspiration

ΔS = Change in Storage

Each of the 14 processes listed above can fall under one of these four variables, but the model remains complex (Wikipedia, "Water Balance", 2017). Thanks to modern advancements in remotely sensed imagery, climate sensors, and powerful computing power, the water budget model has improved in accuracy and has become spatially easier to visualize. One example, an international standard used for groundwater flow modeling, is the U.S. Geologic Survey (USGS) finite-difference model called MODFLOW. This model was initially created in the early 1980's but has since been revised multiple times and remains relevant in groundwater modeling today (Harbaugh, 2005).

In a state that relies heavily on an economy of agriculture, it is easy to see the necessity of high capacity wells. All politics aside, concerns about groundwater will affect growers, private landowners, municipalities, and wildlife alike. Accurate water budget models can help regulators and managers to make the most informed decisions for preserving and sustaining this invaluable natural resource.

3. Methodology

All methodology utilized an open source MODFLOW graphical user interface (GUI) called FREEWAT. MODFLOW is a public domain three-dimensional finite-difference groundwater simulation code created by the U.S. Geological Survey (USGS). This code was adopted into a QGIS GUI plugin (FREEWAT) to help the user visualize and manipulate model inputs and outputs.

The USGS' MODFLOW model functions by discretizing the model domain both spatially and temporally. Spatially, the model is divided into grid cells and model layers. The grid cells define the Easting (X) and Northing (Y) boundaries, or columns and rows, while the model layers define the elevation (Z) boundary of each layer. A visual of this discretization is shown below in Figure 5.

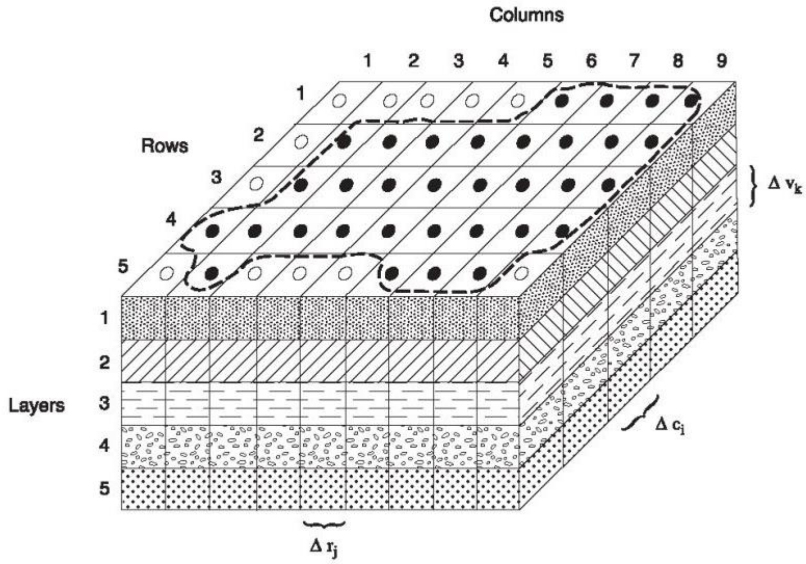


Figure 5. MODFLOW discretization – divided into columns (X), rows (Y), and layers (Z) (Harbaugh, 2005).

The overall goal of this project is to assess how and where high-capacity wells are impacting the Central Wisconsin Sand and Gravel Aquifer (CWSGA). Therefore, there is one key concept that will be used to assess the aquifer: the change in aquifer storage. It is difficult to spatially map the changes in aquifer storage in a two-dimensional format, therefore, the changes in the hydraulic head throughout the aquifer will be used as a proxy to assess the aquifer through cartographic figures and analyses. In an unconfined aquifer, such as the CWSGA, hydraulic head is assumed to be representative of the water table elevation in the aquifer (Hemond, 2015). Therefore, using changes of hydraulic head as a proxy for changes to aquifer storage should be valid for this assessment.

If available, input parameters chosen for this model were based on the year 2016 aquifer and climate conditions. Therefore, model outputs should be representative of 2016, which was chosen because of its nearness to the present and data availability.

3.1. Conceptualization

The MODFLOW based QGIS Plugin FREEWAT conceptualization will be based on the model inputs (operational variables) and the model output (key concept). Inputs were divided into four key components: groundwater flow, surface flow, recharge, and discharge. The groundwater flow variables affect the key internal flow process of the aquifer, while all other key components in this conceptualization involve variables that affect external stressors on the aquifer (whether flow is in, out, or through the aquifer). Model parameters pertaining to each respective key component will be described in detail in the following Conceptualization sections. A linearized conceptualization map is shown on the next page (Figure 6).

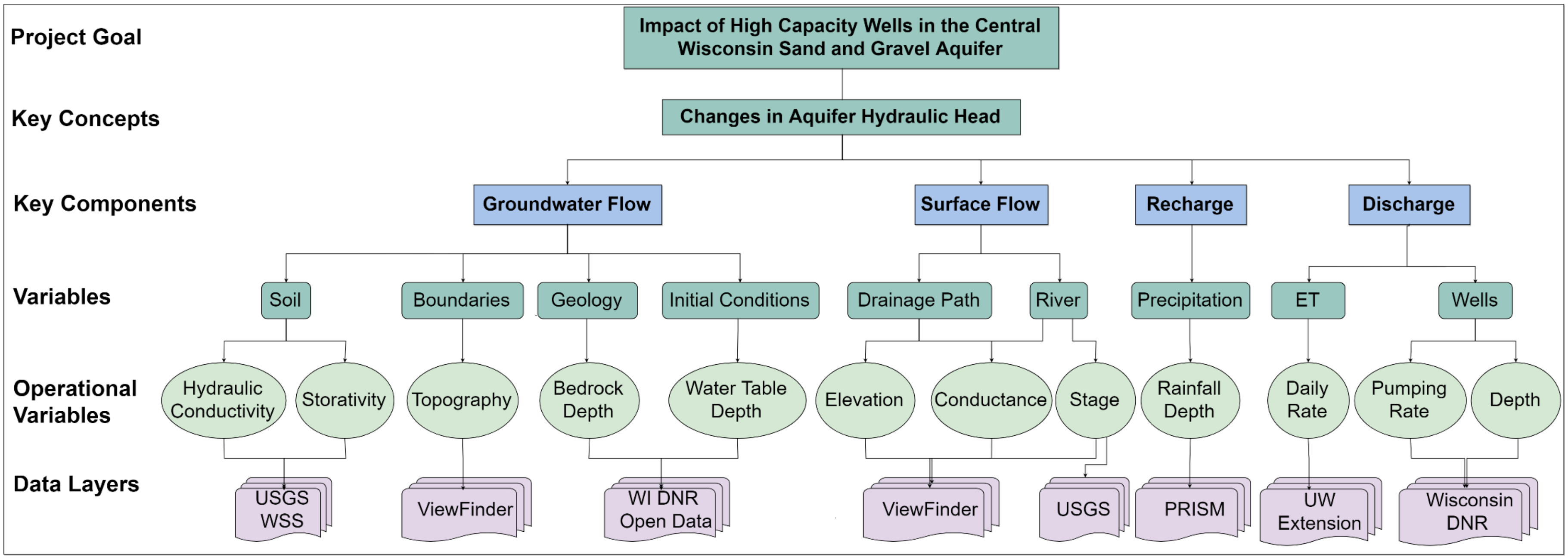


Figure 6. Project conceptualization for the Impacts of High Capacity Wells on the Central Wisconsin Sand and Gravel Aquifer.

3.1.1. Conceptualization: Groundwater Flow

Soils were classified by their hydraulic conductivity and storativity. Hydraulic conductivity is a one-dimensional flux property representing the ease with which fluid can pass through aquifer (Wikipedia, "Hydraulic Conductivity", 2018). The hydraulic conductivity was defined similarly for the X and Y (horizontal) directions using the saturated hydraulic. The Z directional hydraulic conductivity (K_z) was defined as a function of the horizontal (K_x and K_y) hydraulic conductivities. Specifically, K_z was defined as one-tenth (1/10) of the horizontal conductivities (Todd, 1980). Horizontal hydraulic conductivities were gathered through the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service's (NRCS) Web Soil Survey (WSS) data on saturated hydraulic conductivities (K_{sat}). All soil data gathered through the WSS was collected as a shapefile containing polygons with the average K_{sat} value weighted by each polygon's respective soil layer thickness.

Storativity (S) is a measurement of the volume of water released from storage per unit surface area of the aquifer per decline in hydraulic head (Wikipedia, "Specific Storage", 2017). Storativity is a function of two model inputs necessary to successfully run a MODFLOW model: specific yield (S_y) and specific storage (S_s). This relationship is defined as the following (Specific Storage, 2017):

$$S = S_y + b*S_s$$

where,

S = Storativity

S_y = Specific Yield

b = Thickness of Aquifer

S_s = Specific Storage

In an unconfined aquifer the primary drainage force is due to gravity, and therefore, the storativity is regarded to be approximately equivalent to the S_y (Ferris et al., 1962). Data on S_y was available on the WSS and was gathered similarly to the K_{sat} values. Since S_y was assumed to be approximately equal to the storativity it is reasonable to assume S_s is significantly smaller the S_y. Therefore, S_s values were defined as two orders of magnitude smaller (1/100) than their spatially respective S_y values.

Boundaries must be defined for an aquifer when using a MODFLOW based groundwater model. The elevation boundaries of the aquifer were defined using the topography of the study domain. Topography was defined using a raster file containing elevation data (DEM) available through the Viewfinder Panoramas.

Geologic conditions involving the statigraphy of bedrock was necessary to build a representative groundwater model. Bedrock was assumed to be an impervious layer when building this model. Therefore, bedrock data was used to define active and inactive groundwater flow zones throughout the aquifer. Information regarding the depth from the surface to bedrock was available through the Wisconsin Department of Natural Resources (WI DNR) GIS Open Data Portal. This data was available in a polygon shapefile and defined with bedrock depth groupings providing a range for each polygon. The middle value of each group's range was selected to represent the bedrock depth of each respective polygon.

When simulating groundwater flow using a MODFLOW based model it is necessary to input an initial state of hydraulic head throughout the aquifer. Water table depths were used to define this starting state while beginning the simulation. Information on water table depth is available through the WI DNR Groundwater Retrieval Network (GRN) in the form of monitoring wells across the state of Wisconsin. Historic and current data was retrieved for several monitoring wells in and around the study domain.

3.1.2. Conceptualization: Surface Flow

There are two key surface flow variables through the aquifer that were determined crucial to include in this model: a river and drainage path. The river included in this model was the Wisconsin River, while the drainage path was defined as the Little Plover River. The Little Plover River in the study domain has a significantly lower flowrate when compared to the Wisconsin River, which was why it was modeled as a drainage path instead of a river.

Elevation and conductance information is required for both the river and drainage path variables. The elevation data was gathered from the same DEM file used to determine the topography of the domain (Ferranti, 2014). The conductance for each surface flow variable was determined by estimating a single hydraulic conductivity (K) value for each variable and solving the following relationship (GMS: Conductance, 2016):

$$C = K^* \Delta H$$

where,

C = Conductance

K = Hydraulic Conductivity

ΔH = Change in Hydraulic Head

The change in hydraulic head (ΔH) was extracted from the elevation information relevant to each variable.

The river variable also required the river stage elevation at the beginning and end of the river segment through the domain. Streamflow measurements, specifically water-level gage height data, is available for the Wisconsin River through the USGS National Water Information System. Data was collected at one upstream and one downstream point relative to the study domain – specifically, at Rothschild and Wisconsin Rapids gage locations, respectively.

3.1.3. Conceptualization: Recharge

The only external recharge stressor included in this model was precipitation. Precipitation data was gathered for each month of the year modeled (2016), which was available in a raster format describing the monthly rainfall depth across the aquifer. These spatial datasets were available on the PRISM Climate Group's website, which is supported by the USDA Risk Management Agency. Rainfall depth values were converted to a daily average rainfall depth for each month of 2016.

3.1.4. Conceptualization: Discharge

Two discharge variables were identified as necessary to create a complete groundwater flow model that can achieve the overarching goal of this project. These external discharge stressors include evapotranspiration (ET) and wells pumping from the aquifer. ET data was chosen to be included in the model to ensure a groundwater flow model that includes all aspects of the aquifer's hydraulic budget. Well information is necessary to achieve the overarching objective of analyzing the impacts of high-capacity wells on the CWSGA.

All ET data included in this model was extracted from the UW Extension Ag Weather database, which provides historical hindcasted estimates of ET throughout Wisconsin. Since the year being modeled is 2016, any ET data used in this model was from this respective year, which was available as a daily average. ET data estimates from this source are respective to specifically defined coordinates, therefore, a central point of the domain was selected to represent an average rate of ET for each month under inspection.

Well data was provided by the WI DNR in the format of a point shapefile with monthly pumping rates for 2016. Each month's respective pumping rate for each well was used, but first converted to the month's daily average pumping rate. Depths of the pumping wells were also provided in this data set, which is important to define for the well model package. If well depth data was missing the average well depth in the domain was assumed to be a reasonable estimation.

3.2. Implementation

In general, MODFLOW based models function by discretizing space into grid cells and model layers, which divides the model in three-dimensions (X, Y, and Z). Groundwater flow variables are assigned to each three-dimensional cell based on the variables discussed in the Conceptualization: Groundwater Flow section (3.1.1). In addition, external variables (surface flow, recharge, or discharge) are input into the model via separate model packages. Each package is defined by its own model layer with the external stressor parameters assigned to its model cells. The model uses the inputs for each cell to simulate how the groundwater will flow under the specific model conditions.

MODFLOW also discretizes time into stress periods, which are defined by the user. Inputs for stress periods include the duration of the period and the number of time-steps to complete for the assigned duration. These stress periods can also be defined to run the model under steady-state or transient conditions. Under steady-state conditions the model's initial conditions will be the same as its ending conditions (i.e. hydraulic head throughout the aquifer will remain the same), which should not imply there is no movement of water during the simulation. Conversely, under transient conditions the model's conditions in the aquifer will change through the time (i.e. hydraulic head at the start and end of the simulation will not be the same).

This implementation section will discuss what and how model parameters were input into the FREEWAT model. A brief discussion of the stress periods modeled for this domain will be discuss in the results section.

3.2.1. Implementation: Groundwater Flow

All variables that fall within the Groundwater Flow Key Component are implemented by performing a spatial selection – either vector or raster – and then copying the relevant parameters to each cell of the model.

Operational variables under the Soil variable (hydraulic conductivity and storativity) were determined for each polygon of their respective shapefiles (see 3.1.1. Conceptualization: Groundwater Flow for details). Initially, values from each shapefile layer were input into the FREEWAT model by copying from a vector layer. This method proved to be an intensive process that required ample computing power. Therefore, each polygon layer was converted to a raster file and then a spatial average over then entire domain was calculated for each soil parameter using the Zonal Statistics tool in ArcGIS. These mean parameters were then copied to each model layer and used in the FREEWAT model.

The topography DEM files were clipped to the model domain and used to define the model layer's top and bottom boundaries. First, layer thicknesses were chosen based on bedrock depths. Then the layer thickness was subtracted from the DEM file to define the tops and bottoms for each layer. For example, the original DEM was used to define the top of model layer 1. Then, using raster math, the determined thickness of model layer 1 was subtracted from the initial DEM to create a new DEM. This new DEM file was used to define both the bottom of model layer 1 and the top of model layer 2. This process of subtracting the model layer thicknesses from their respective top DEM boundary was repeated until all model layers contained a top and bottom boundary.

As stated in the previous paragraph the bedrock information was used to determine each model layer's thickness. In addition, bedrock data was used to define active (flow) and inactive (no-flow) zones in each model layer. For example, if model layer 2 extended from a depth of 10 feet to 20 feet any zones with bedrock less than 10 feet deep were assumed to be impervious, and therefore, were inactivated to simulate a no-flow zone. Similar polygons were dissolved together to simplify the bedrock shapefile. The dissolved shapefile was then used to define active and in-active zones in each model layer by selecting cells within each zone and activating or deactivating the cells depending on the bedrock depth and model layer boundaries.

Water table conditions throughout the aquifer were used to define an initial state of the aquifer for each simulation. Water table information for 2016 at several wells in and around the model domain was gathered and then georeferenced into a point shapefile. Water table depths over then entire model domain were interpolated using the monitoring well shapefile and an inverse distance weighting interpolation method. This output was in the form of a raster file and could be copied via raster to each model layer.

3.2.2. Implementation: Surface Flow

The surface flow variables were built in two separate model packages with their own model layers and assigned values. Both the river and drainage path packages were created by first defining the flow paths. Orthographic images were traced with line shapefiles to define the path length and location for each variable. The Wisconsin River was traced for the river variable and the Little Plover River was traced for the drainage path. These shapefiles were use do define the active cells for each of the surface flow packages.

Parameters at the start and end of each flow path was required for each of the surface flow packages and were input using a CSV file. These parameters were interpolated across the flow path by FREEWAT and included: elevation, conductance, and stage (river package only). Elevation at the start and end of each flow path were extracted from the topographic DEM file. As stated in section 3.1.2 the conductance is a function of the change in head over the flow path and the hydraulic conductivity. To solve for the conductance at the beginning and end of each flow path the hydraulic conductivity was extracted from the original polygon shapefiles. The river stage parameters were added to the elevation parameters to solve for the hydraulic head at the start and end points of the river (see section 3.1.2. Conceptualization: Surface Flow for details).

3.2.3. Implementation: Recharge

The only variable included in the recharge package was precipitation. The model layer for this package was created by copying from a raster file containing rainfall depth over the model domain. The initial raster files were downloaded as monthly rainfall depths over the entire U.S. from the PRISM Climate Group. These rasters were clipped to the model domain and converted to each respective month's daily average.

3.2.4. Implementation: Discharge

Two key model packages were created that simulate external discharge from the model domain. Evapotranspiration (ET) rates were determined for each month of 2016 by selecting a single central point of the domain and assuming this rate was reasonable for the entire domain. For future models ET rates should be selected at multiple points in and around the model domain and interpolated across the region. This should create more accurate ET rates across the study domain.

The well model package was created by selecting cells that contained points representing wells and then copying relevant well parameters. Well parameters and their selection are described in more detail in section 3.1.4. Conceptualization: Discharge.

4. Results

All results are compiled in section A. Appendix: Results. Results include the monthly change in head for the months April through August during the year 2016, which should be representative of the growing season for the region under inspection. In total, there are 10 outputs – two for each month, which correspond to their model layers 1 and 2 (model layer 1 being the shallower layer).

These results consist of a raster file produced by subtracting the initial hydraulic head conditions from the final hydraulic conditions after the model has finished simulating the month under inspection. Therefore, a negative change in hydraulic head corresponds to a drop in hydraulic head, and conversely, a positive change in hydraulic head corresponds to an increase in hydraulic head.

5. Discussion

As discussed above, MODFLOW can be a useful and accurate way of modeling groundwater flow and is considered an industry standard. With the release of FREEWAT in 2017 as an open source way of accessing MODFLOW in a GIS GUI (QGIS 2.18), this project aimed to use the new interface for the model. Due to time constraints and data availability, results were always dependent on the execution of the FREEWAT program.

Even with most of the data and parameters for 2016 already gathered and compiled, executing the program was a trial and error process. One key factor in getting a model to run for the finite differences in an unconfined aquifer was troubleshooting the nature of the program to fail from cells running dry in the model before it could complete all iterations of stress periods. The solution was the MODFLOW-NWT, a Newton Formulation for MODFLOW-2005. This program is intended to solve models that involve drying and rewetting or unconfined groundwater flow, ideal for modeling the CWSGA (Hunt & Feinstein, 2012). These methods could be applied to the same study area, or one of similar size for a highly calibrated groundwater flow model.

Overall, the MODFLOW based GIS tool FREEWAT proved to be a complete tool for modeling groundwater activity, but inherently groundwater modeling is a complex process that requires a firm knowledge of hydrological processes. The GIS platform it was developed for bridges the gap between hydrologists and the rest. Creating spatially referenced outputs of model outputs can help policy makers and other shareholders make more informed decisions when choosing how to manage their aquifers.

6. Conclusions

Modeling spatially varying water budgets is a complex process that has only recently become a truly accurate process thanks to toolsets and software such as ArcGIS and QGIS. Impacts of high capacity wells on the CWSGA can already be seen through witness accounts of wells running and rivers running dry (Ferral, 2017). The accuracy of this model, as well as future models, can help regulators, well users, and private land owners see how and why the aquifer is affected by these high capacity wells. Hopefully the decisions made thereafter will be well informed and used in a way that can benefit all who depend on the CWSGA.

7. Future Work

In the future, instead of modeling the northwestern region of the aquifer, it should be a goal to create a model of the entire CWSGA. This would require more intensive processing power than was available for this project. Data collection and cleaning was a crucial part of this project. Ensuring data is a correct and consistent format for the entire aquifer would be the first step in creating a model of the entire CWSGA. In general, it would give a better understanding of problem areas within the aquifer.

In addition, more time should be allotted to calibrating the model. This proved to be the most time-consuming process throughout the project and should be expected as such. A better calibrated model should produce more accurate results compared to the ground-truth. This could be completed by comparing measured hydraulic head data to the simulated hydraulic head data. Then, once properly calibrated, the model could be used to forecast and hindcast hydraulic head conditions throughout the aquifer and potentially identify when and where wells could begin to run dry.

An analysis of how wells affect the change in hydraulic head should be considered as well for future work. Comparing the average change in hydraulic head of cell that contain aquifers versus cells that do not contain aquifers could yield interesting results. Or analyzing cells within a specific radius of wells by creating a buffer around well points could be another approach. An analysis of how changes in hydraulic head is affected by the density of wells may also be an interesting approach to analyzing this data produced by the FREEWAT model.

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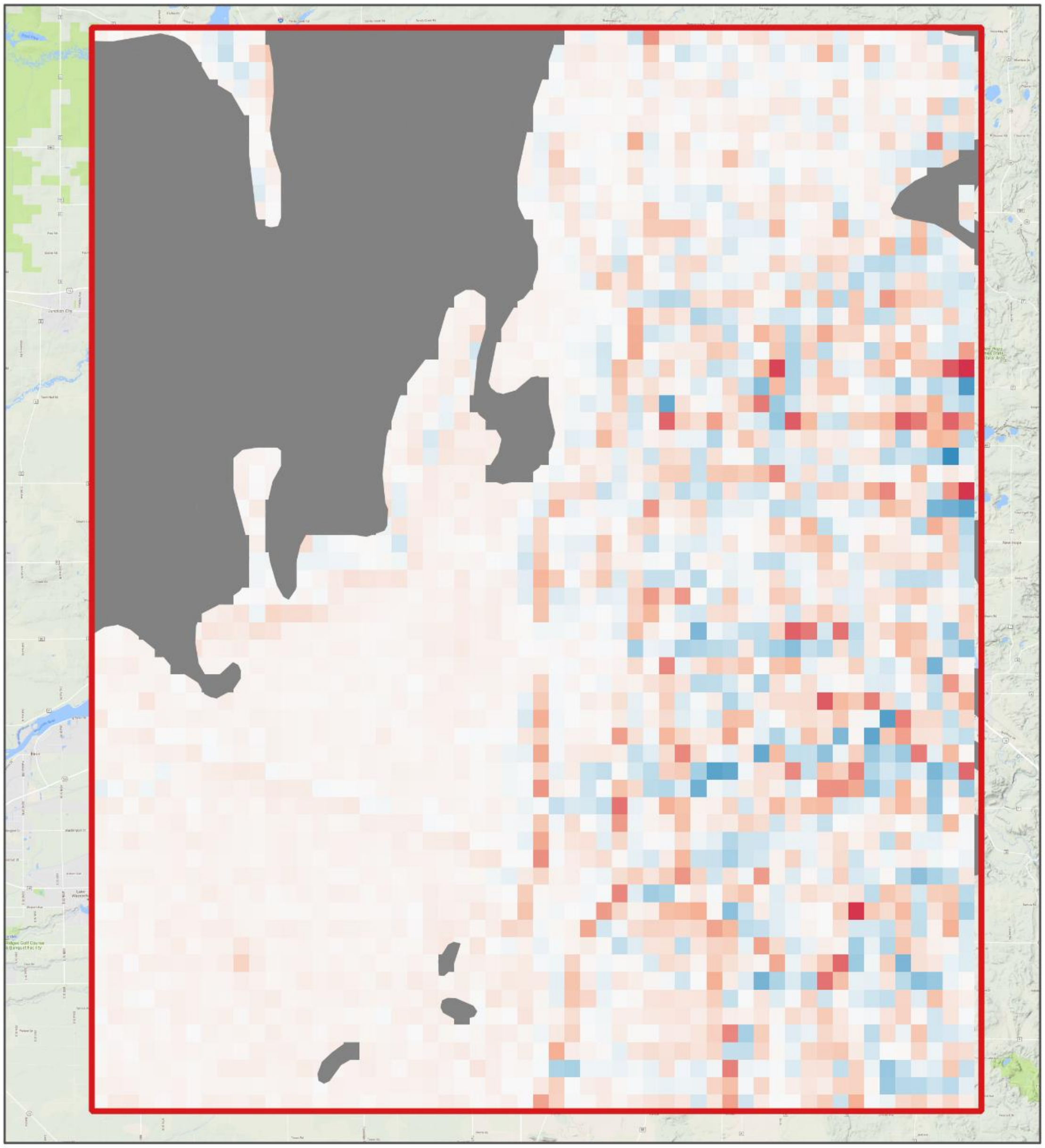
A. Appendix: Results

Appendix A contains the monthly change in hydraulic head in the model domain for the year 2016. There are two outputs for each month, which represent the model layer 1 and model layer 2. Figure titles are denoted by a letter corresponding to a month in 2016 and numeric value denoting whether the figure represents model layer 1 (1) or model layer 2 (2).

A: January	B: February	C: March	**D: April**
E: May	**F: June**	**G: July**	**H: August**
I: September	J: October	K: November	L: December



No Flow Zone (bedrock within 10m)

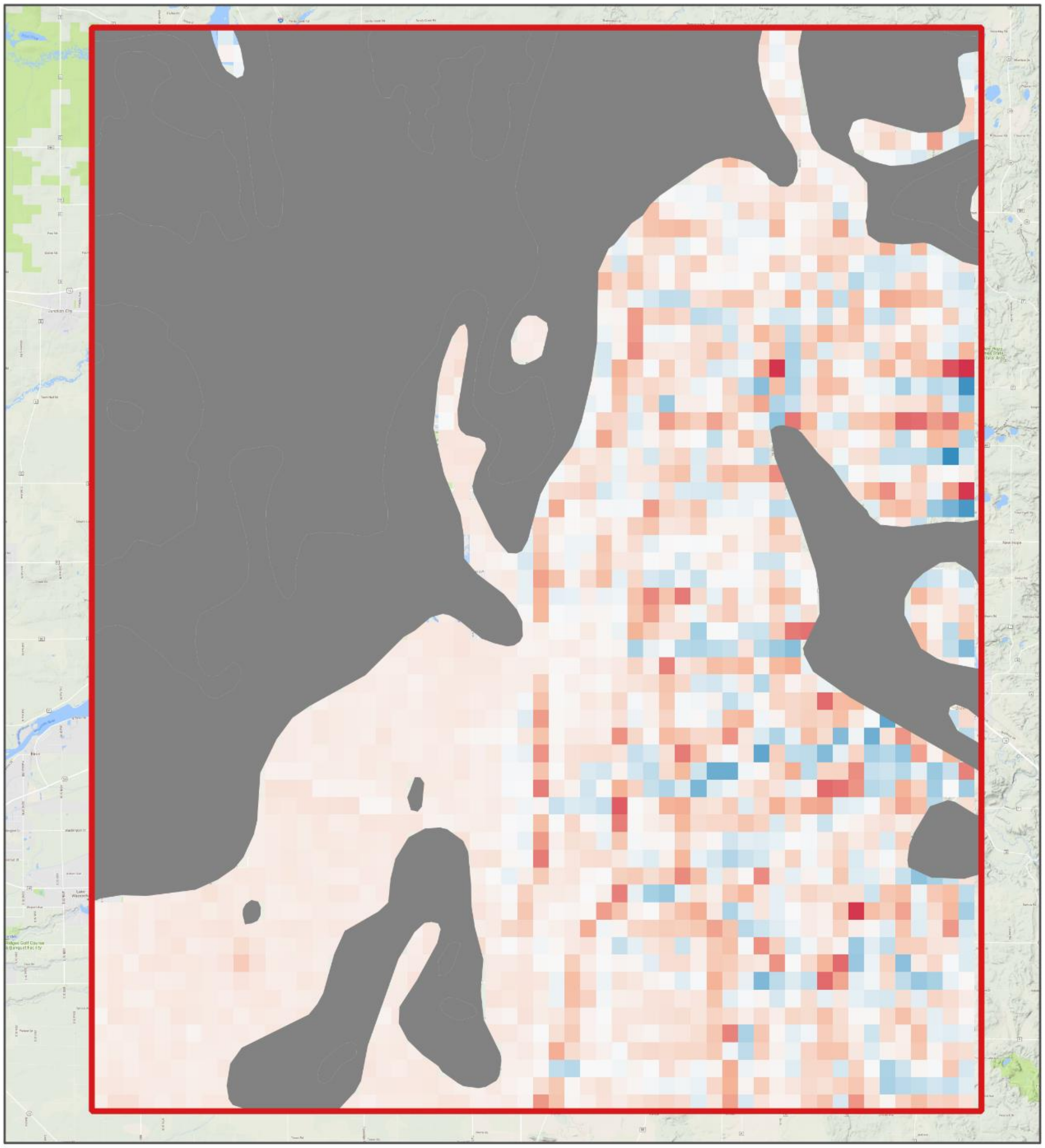
Change in Head (m)

- -18.5
- -8.98
- 0.58
- 10.1
- 19.7

N

Figure D-1. April 2016 Change in Head Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone (bedrock within 30m)

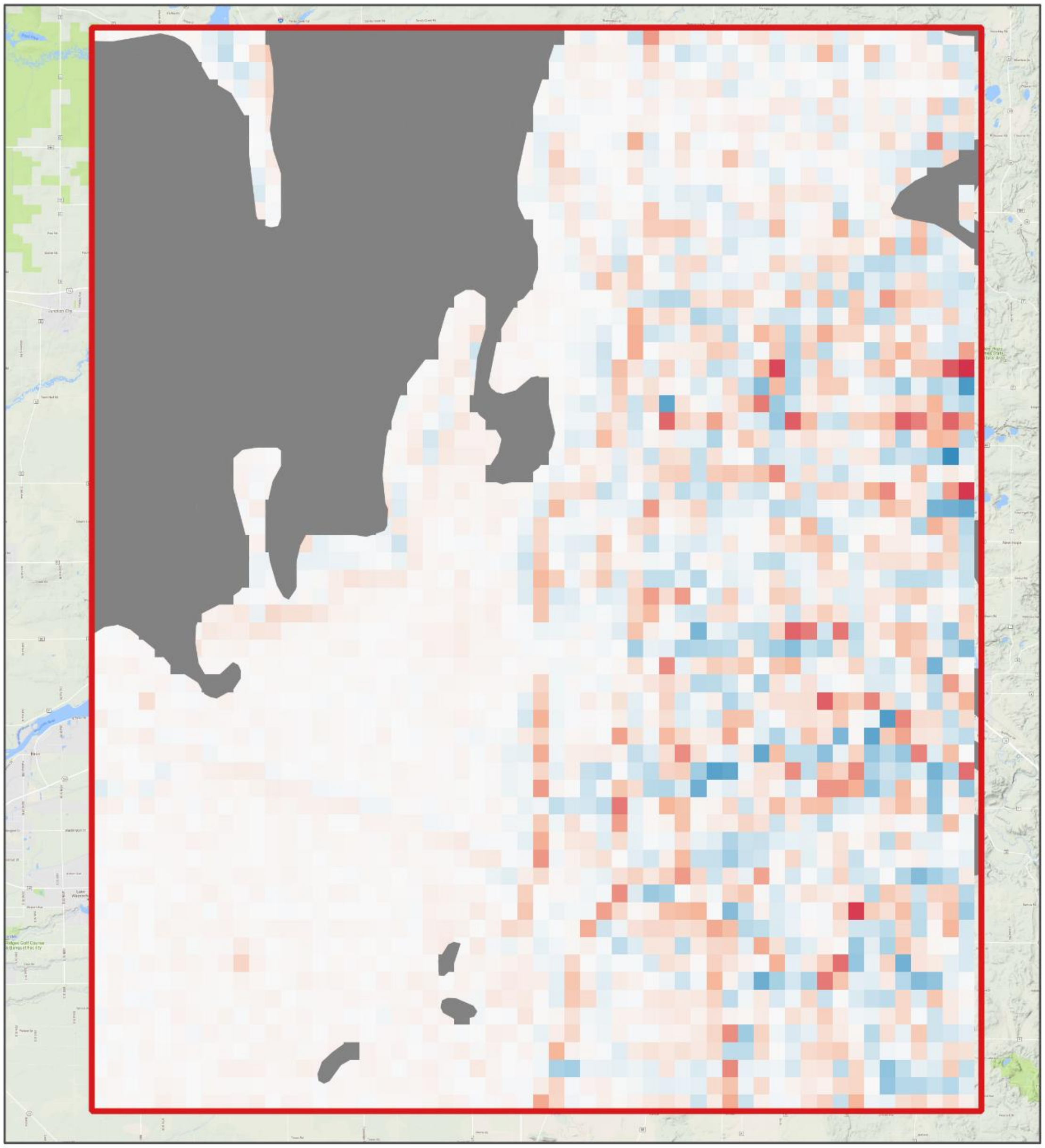
Change in Head (m)

- -13.4
- -6.08
- 1.23
- 8.54
- 15.9

N

Figure D-2. April 2016 Change in Head Model Layer 2

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone (bedrock within 10m)

Change in Head (m)

- -19.1
- -9.63
- -0.139
- 9.35
- 18.8

N

Figure E-1. May 2016 Change in Head Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source

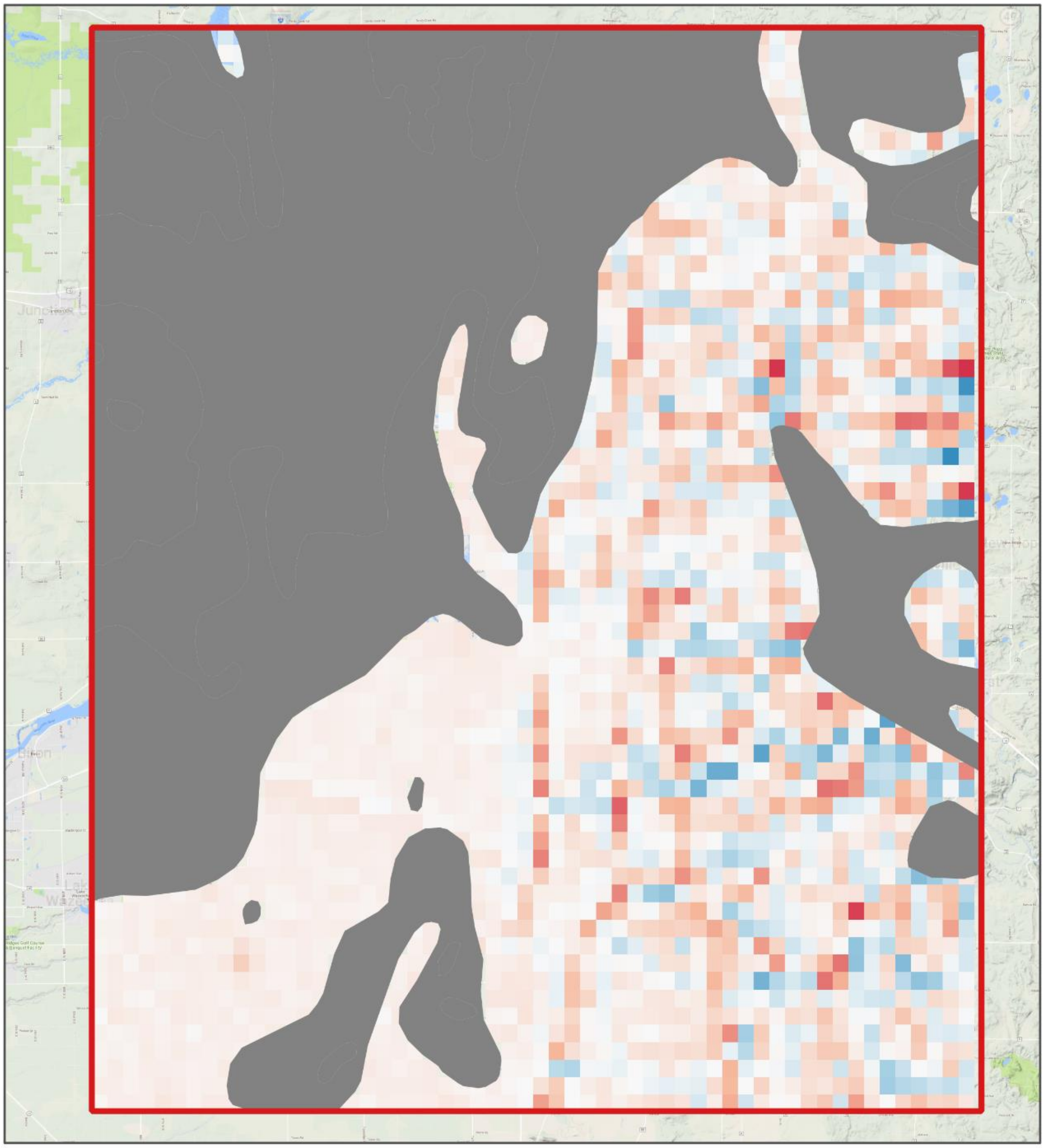
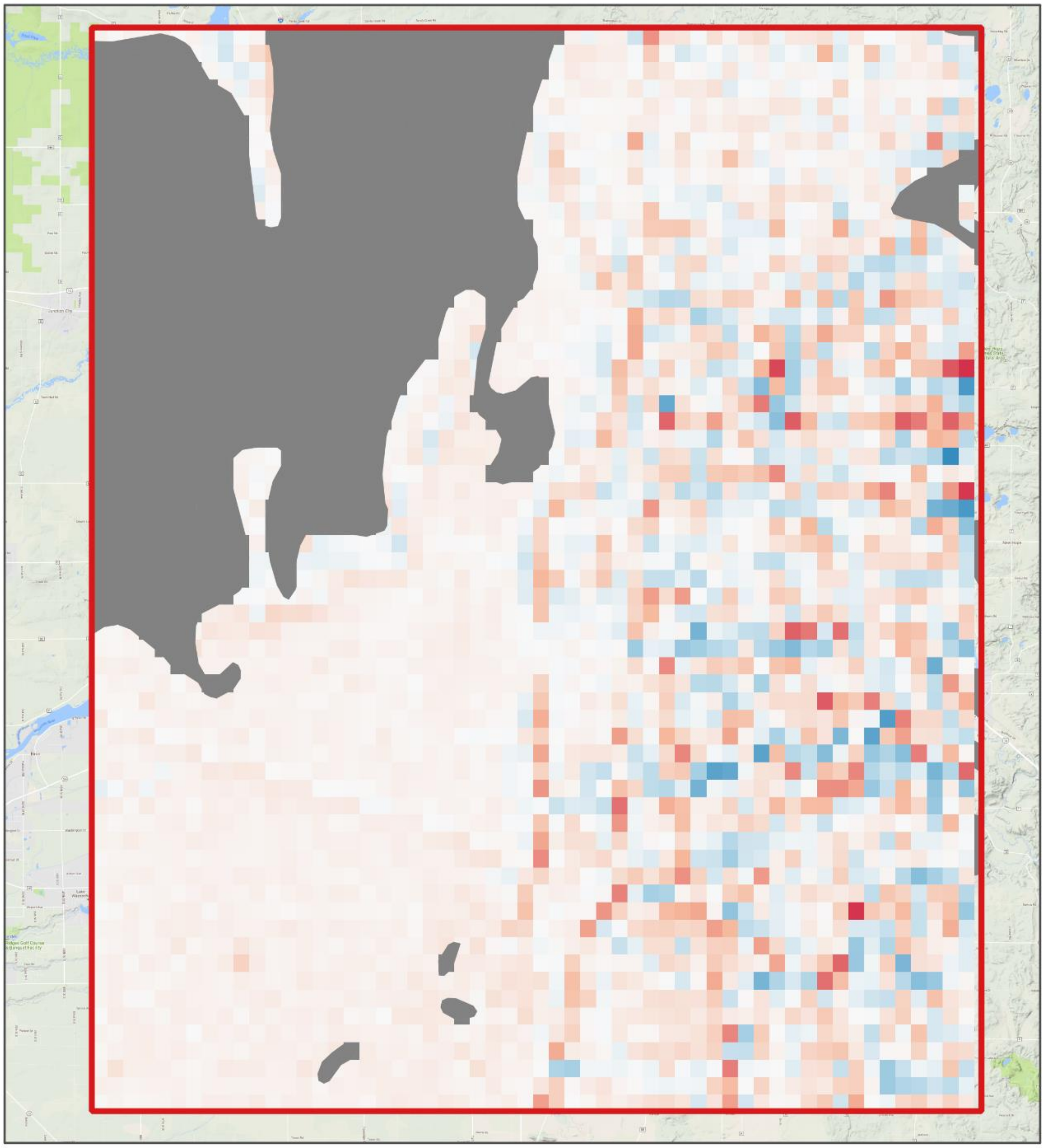


Figure E-2. May 2016 Change in Head Model Layer 2

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone (bedrock within 10m)

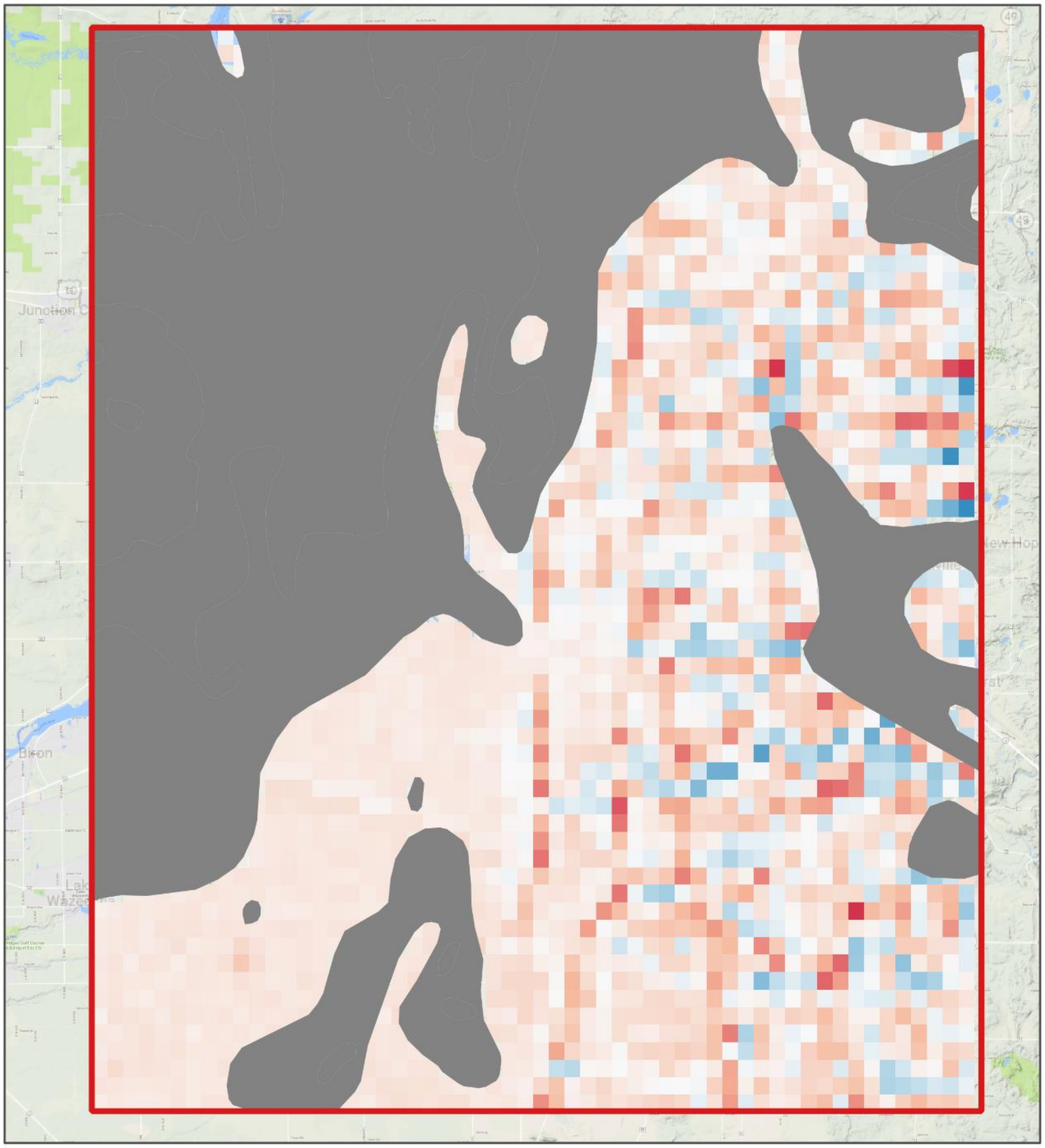
Change in Head (m)

- -17
- -7.36
- 2.25
- 11.9
- 21.5

N

Figure F-1. June 2016 Change in Head Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone
(bedrock within 30m)

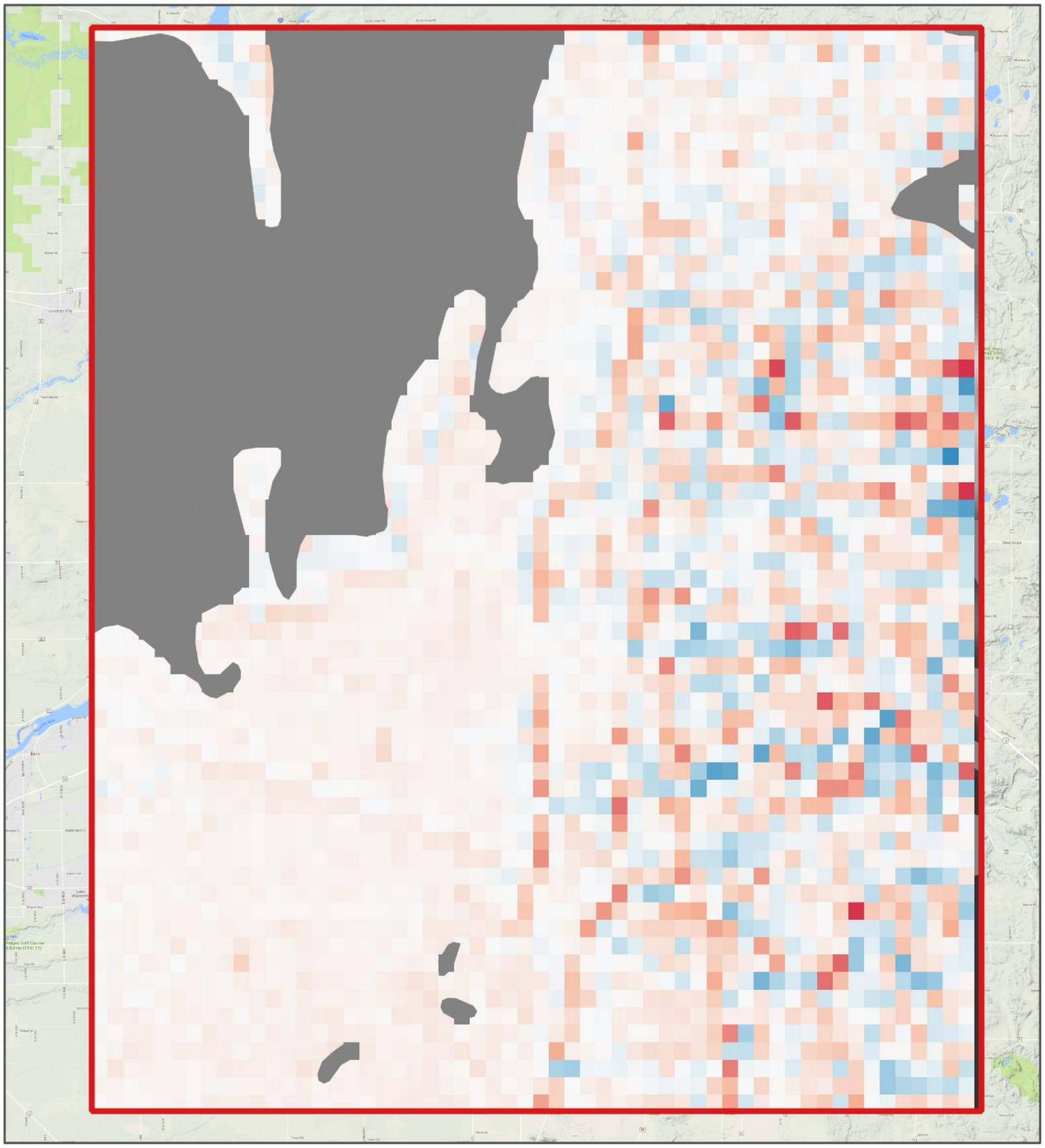
Change in Head (m)

- -11.8
- -4.33
- 3.13
- 10.6
- 18.1

N

Figure F-2. June 2016 Change in Head Model Layer 2

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone (bedrock within 10m)

Change in Head (m)

- -17.3
- -7.69
- 1.89
- 11.5
- 21.1

N

Figure G-1. July 2016 Change in Head Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source

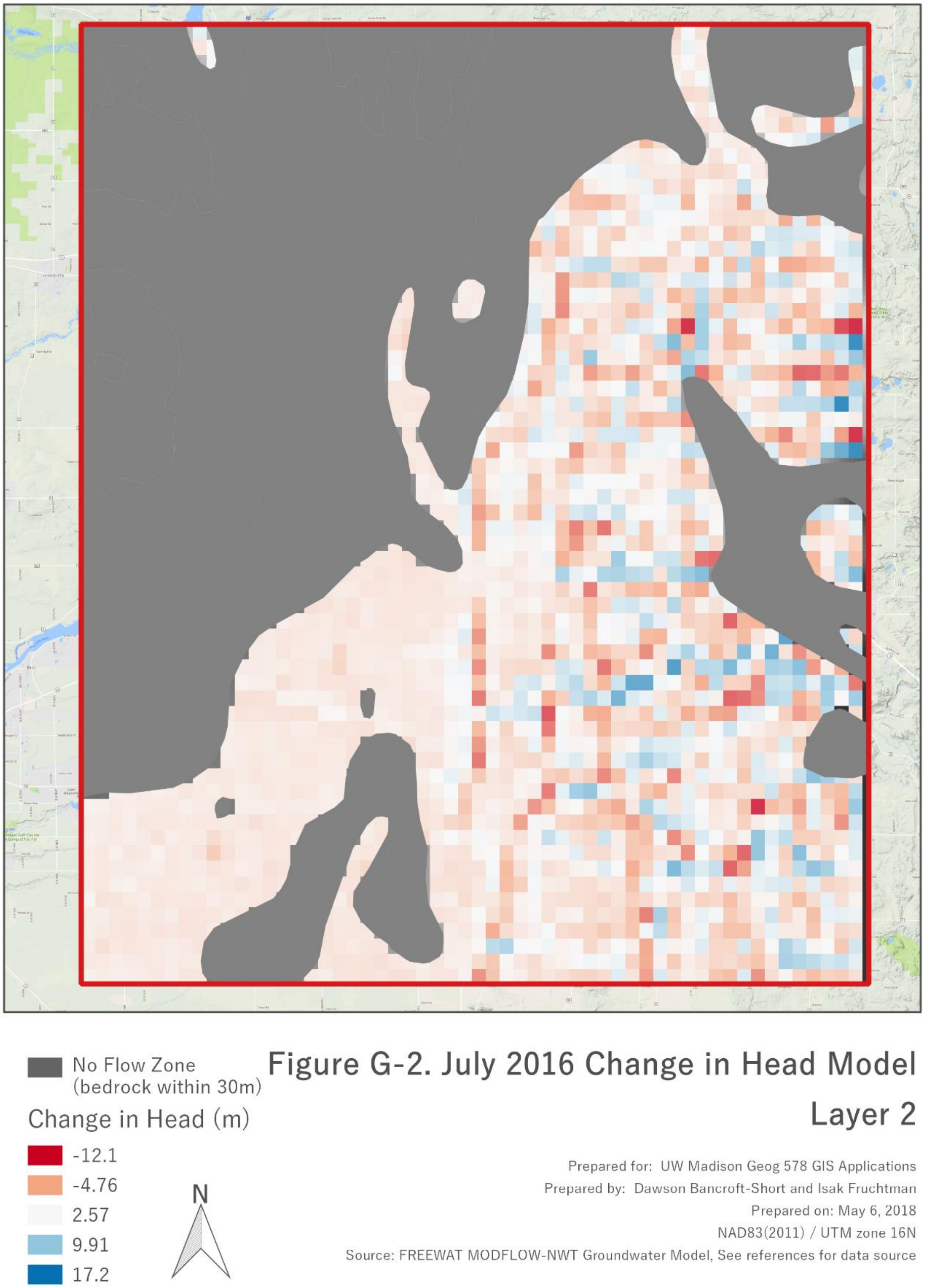
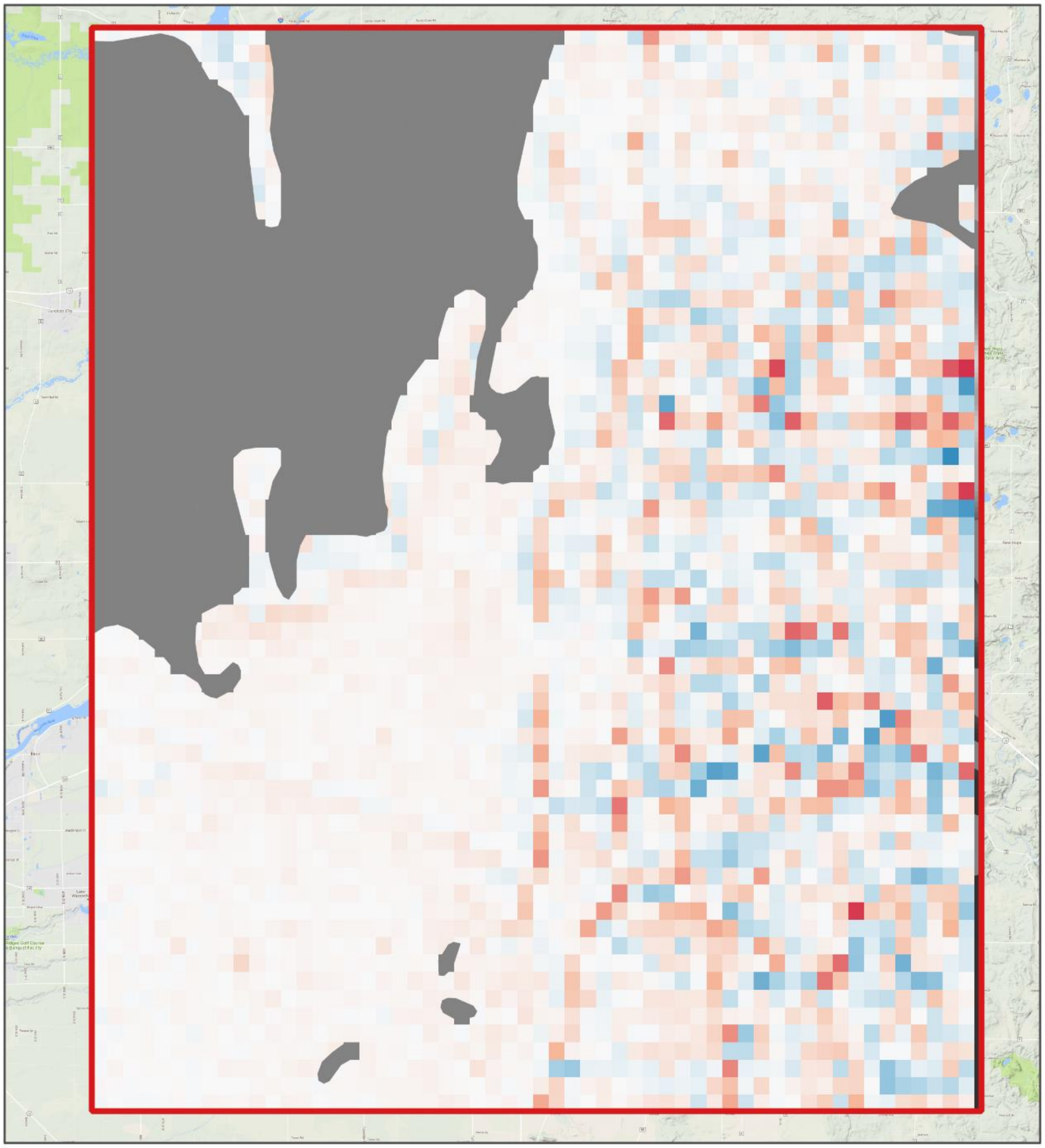


Figure G-2. July 2016 Change in Head Model Layer 2

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone
(bedrock within 10m)

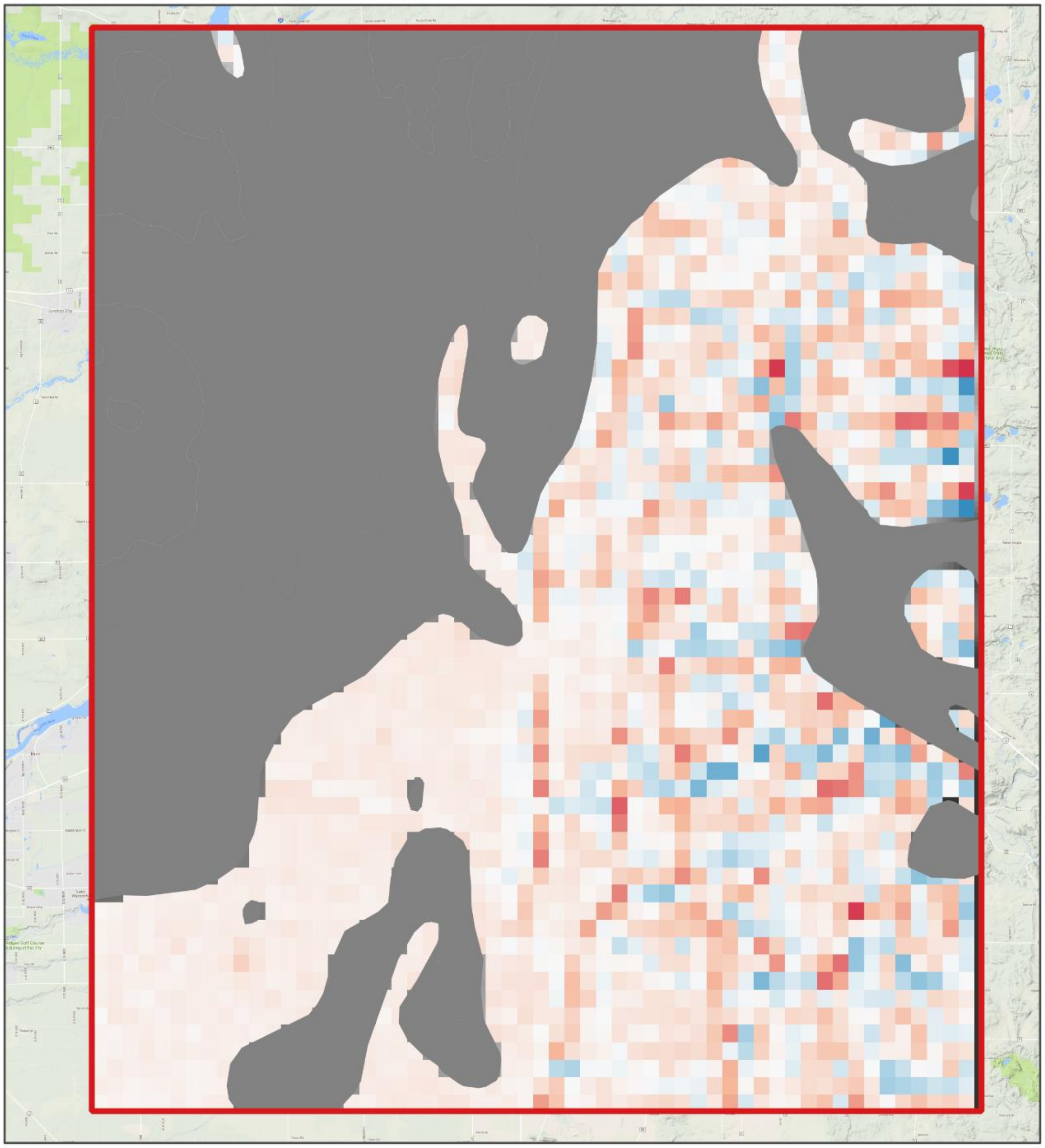
Change in Head (m)

- -17.8
- -8.25
- 1.32
- 10.9
- 20.4

N

Figure H-1. August 2016 Change in Head
Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source



No Flow Zone (bedrock within 30m)

Change in Head (m)

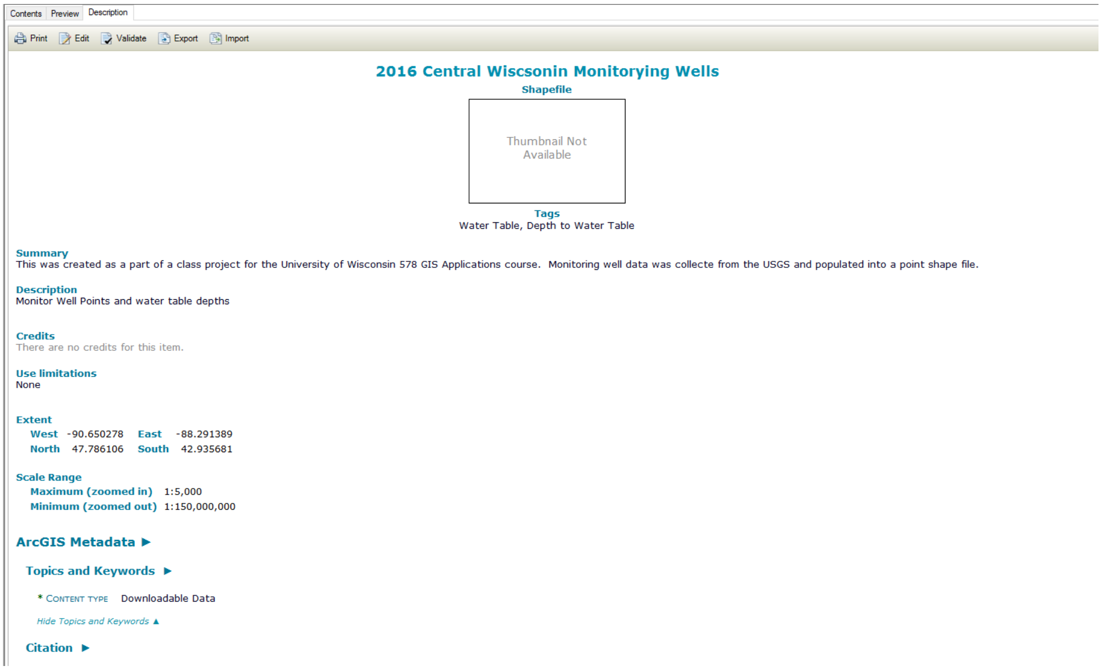
- -12.6
- -5.2
- 2.24
- 9.67
- 17.1

N

Figure H-1. August 2016 Change in Head Model Layer 1

Prepared for: UW Madison Geog 578 GIS Applications
Prepared by: Dawson Bancroft-Short and Isak Fruchtman
Prepared on: May 6, 2018
NAD83(2011) / UTM zone 16N
Source: FREEWAT MODFLOW-NWT Groundwater Model, See references for data source

B. Appendix: Metadata



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