Little Muddy Aquifer Computer Model for Water Permit No. 5757

Daniel Smith

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Little Muddy Aquifer Computer Model
for Water Permit No. 5757

Prepared by Daniel Smith
as a Geological Engineering Design Project
for GeoE 485

Geology and Geological Engineering Department
University of North Dakota
May 2009
EXECUTIVE SUMMARY

Water Permit No. 5757 is for a proposed well which would discharge water from the Little Muddy Aquifer in the Little Muddy Management Area (LMMA) in Williams County, North Dakota. The extraction of water in this well could adversely affect the water levels in the aquifer and the water levels in the previously installed wells. To predict the affect that this well will have on the aquifer, a MODFLOW computer model of the Little Muddy Aquifer was constructed. The purpose of this report is to explain how the model was constructed and what conclusions were drawn from the model output.

- The model represented a land area of just under 90 square miles and was made up of approximately 2700 cells. The input hydraulic conductivity and recharge data were split into zones to best represent the natural aquifer texture of the sediments. Recharge was added to the model where other aquifers discharged into the Little Muddy Aquifer. Surface water was represented either as river cells or general head boundaries.

- The model output data calibrated closely in the southern part of the aquifer when all the wells were not pumping. The model output data were not as close when all the wells were pumping at maximum rate, but the water budget outflows were within 1.5% of the inflows.

- The model was not sensitive to small changes in hydraulic conductivity.

- The installation of Water Permit No. 5757 will not negatively affect Water Permit Nos. 4036 and 4036A, but it will contribute a drawdown of 3-4 ft in Water Permit No. 5004. However, this drawdown will occur in an area of the aquifer where the
saturated thickness is approximately 50 ft thick and is not expected to influence the quantity of groundwater available for Water Permit No. 5004.
# TABLE OF CONTENTS

EXECUTIVE SUMMARY ................................................................. ii  
TABLE OF CONTENTS ...................................................................... iv  
LIST OF FIGURES ............................................................................. vi  
LIST OF TABLES .............................................................................. vii  
ACKNOWLEDGMENTS ....................................................................... viii  
INTRODUCTION ..................................................................................... 1  
PROBLEM DEFINITION ................................................................. 2  
OBJECTIVES ....................................................................................... 2  
BACKGROUND ..................................................................................... 3  
PRELIMINARY ANALYSIS ............................................................. 3  
  Design Constraints ........................................................................ 3  
    Regional Geology ........................................................................ 3  
    Climate ....................................................................................... 6  
    Aquifer Properties ....................................................................... 7  
    Hydrogeology ............................................................................ 8  
    Pumping Wells in Operation ..................................................... 10  
Design Approach ........................................................................... 12  
Design Assumptions ....................................................................... 14  
Preliminary Design Options .......................................................... 16  
Final Design .................................................................................... 17  
  Input ............................................................................................ 17  
  Output .......................................................................................... 26
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Map of 29MC.</td>
<td>1</td>
</tr>
<tr>
<td>2.</td>
<td>Map of distances between proposed well and two closest pumping wells.</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>Potentiometric surface of LMMA.</td>
<td>4</td>
</tr>
<tr>
<td>4.</td>
<td>Early depositional events of 29MC.</td>
<td>5</td>
</tr>
<tr>
<td>5.</td>
<td>Later depositional events of 29MC.</td>
<td>6</td>
</tr>
<tr>
<td>6.</td>
<td>Precipitation for 29MC.</td>
<td>7</td>
</tr>
<tr>
<td>7.</td>
<td>Map of pumping test location and Water Permit No. 5757.</td>
<td>8</td>
</tr>
<tr>
<td>8.</td>
<td>Hydrograph of four wells in LMMA.</td>
<td>10</td>
</tr>
<tr>
<td>9.</td>
<td>MODFLOW image of Little Muddy Aquifer and its discretization.</td>
<td>18</td>
</tr>
<tr>
<td>10.</td>
<td>MODFLOW image of ground surface elevation.</td>
<td>19</td>
</tr>
<tr>
<td>11.</td>
<td>MODFLOW image of aquifer base elevation.</td>
<td>20</td>
</tr>
<tr>
<td>12.</td>
<td>MODFLOW image of hydraulic conductivity zones.</td>
<td>21</td>
</tr>
<tr>
<td>13.</td>
<td>MODFLOW image of recharge zones.</td>
<td>23</td>
</tr>
<tr>
<td>14.</td>
<td>MODFLOW image of river cells and general head boundaries.</td>
<td>25</td>
</tr>
<tr>
<td>15.</td>
<td>MODFLOW image of pumping wells.</td>
<td>26</td>
</tr>
<tr>
<td>16.</td>
<td>MODFLOW image of calibrated heads without wells pumping.</td>
<td>28</td>
</tr>
<tr>
<td>17.</td>
<td>MODFLOW image of calibrated heads with hydraulic conductivity values doubled</td>
<td>29</td>
</tr>
<tr>
<td>18.</td>
<td>MODFLOW image of calibrated heads with permitted wells pumping.</td>
<td>30</td>
</tr>
<tr>
<td>19.</td>
<td>MODFLOW image of calibrated heads with permitted wells pumping.</td>
<td>33</td>
</tr>
<tr>
<td>20.</td>
<td>MODFLOW image of calibrated heads with wells pumping.</td>
<td>33</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Details of Water Permit No. 5757</td>
<td>10</td>
</tr>
<tr>
<td>2.</td>
<td>Details of thirty-five existing wells</td>
<td>11</td>
</tr>
<tr>
<td>3.</td>
<td>Hydraulic conductivities for various sediments</td>
<td>14</td>
</tr>
<tr>
<td>4.</td>
<td>Water budget output for model with all permitted wells pumping</td>
<td>31</td>
</tr>
</tbody>
</table>
ACKNOWLEDGMENTS

I would like to personally thank both Dr. Scott Korom and Dr. Lance Yarbrough for their assistance with this project. Dr. Korom has been a very helpful advisor and Dr. Yarbrough helped me by using ArcGIS to determine the thickness values of the aquifer. I would also like to thank the North Dakota State Water Commission for providing the opportunity to work on this project. I especially would like to thank Andrew Nygren and Bob Shaver who have both assisted me in the matter.
INTRODUCTION

The Little Muddy Aquifer (LMA) is located in Williams County, North Dakota. There are two separate areas for the aquifer: 13-Mile Corner (13MC) and 29-Mile Corner (29MC) (Nygren, 2007) (Figure 1).

Figure 1. Location of 13MC and 29MC areas in Williams County in northwest North Dakota. The red box shows the approximate area of the LMMA and the green box shows the approximate area of the SBMA (Nygren, 2007).

13MC refers to the area of the aquifer where U.S. Highway 85 and U.S. Highway 2 intersect each other and 29MC refers to the area of the aquifer where U.S. Highway 85 and State Highway 50 intersect each other 29 miles north of Williston. 29MC is subdivided into the Little Muddy Management Area (LMMA) (Figure 1), where water is pumped from the Little Muddy Aquifer, and the Smoky Butte Management Area (SBMA) (Figure 1), where water is pumped from the Smoky Butte Aquifer. An application for Water Permit No. 5757 has been submitted to the North Dakota State Water Commission (NDSWC) to discharge water from the LMMA.
PROBLEM DEFINITION

There are currently 35 pumping wells in operation in the LMMA (Nygren, 2007). With Water Permit No. 5757 awaiting review, it must be determined whether or not the installation and use of the new well will adversely affect the water levels in the two closest wells: Water Permits Nos. 5004 and 4036A. Figure 2 displays the distances from Water Permit No. 5757 to the two closest wells. To determine the water levels in these two wells as the proposed well is pumping, a model of the aquifer will be constructed using Visual MODFLOW [Schlumberger Water Services (SWS), 2008].

OBJECTIVES

The computer model of the LMMA will be used in two ways. First it will be made with realistic physical data and calibrated to match known heads of the aquifer levels. Then it will be run to predict how Water Permit No. 5757 will affect the water levels in the two closest wells.
Water Permit No. 5757 is located in the extreme southern portion of the model. Therefore, it is more important to calibrate the model more precisely in the southern part of the aquifer.

**BACKGROUND**

MODFLOW (Harbaugh and McDonald, 2000) is a computer program that solves three-dimensional groundwater flow problems. It uses the finite-difference method to compute the equations of groundwater flow (Fetter, 1994). Since the creation of MODFLOW (Harbaugh and McDonald, 2000) in 1984, it has since been modified and enhanced with different packages and versions of MODFLOW (Harbaugh and McDonald, 2000). Visual MODFLOW (SWS, 2008) is one of a few commercial preprocessors available for MODFLOW (Harbaugh and McDonald, 2000). It aids the user in creating the model, running the simulations, and visualizing the results. Figure 3 displays the area of the aquifer modeled with Visual MODFLOW (SWS, 2008).

**PRELIMINARY ANALYSIS**

**Design Constraints**

*Regional Geology*

The development of the Little Muddy Aquifer can be traced back to preglacial times. The uplift of the Rocky Mountains, Big Horn Mountains, and the Black Hills caused a northeasterly drainage in Williams County. The preglacial Yellowstone and Little Missouri Rivers drained north through Williams County and eventually northeast into Hudson Bay. As glaciers moved up these valleys approximately 10000 – 12000 years ago, they blocked the flow of these rivers which formed proglacial lakes. The lakes deposited lacustrine silt and clay over the fluvial deposits that were formed from the
Little Missouri and Yellowstone Rivers. As the glaciers advanced through Williams County, they left till deposits over the lacustrine silt and clay (Figure 4). The melting glaciers left fluvial outwash deposits above the till (Nygren, 2007).

Figure 3. Map of LMA showing potentiometric surface lines and wells represented by the blue circles. The outline of the aquifer shows the modeled area (Nygren, 2007).
After these events, glaciers again proceeded to enter the area in the late Wisconsinan (Figure 5). The Appam end moraine in 29MC shows the furthest advance of this glacier. Meltwater from this glacier developed the West Wildrose Channel. This channel joined up with the Little Muddy channel near Zahl. Another glacial advance occurred leaving the Smoky Butte end moraine just north of the Appam end moraine. The meltwater from this glacier flowed around the Appam end moraine and deposited outwash to the north and west of it. Since that time period, there has been continued erosion and deposition which has helped to form the drainage network found today in 29MC (Nygren, 2007).

Figure 4. Early depositional events of the 29MC area. (a) Fluvial deposits from early rivers, (b) lacustrine deposits from a proglacial lake, (c) till deposits from overlaying glacier, and (d) fluvial deposits from post-glacial rivers (Nygren, 2007).
The northern portion of the aquifer consists predominately of gravel and coarse sand, especially the parts of the aquifer which are closest to the surface. This is a result of the glacial outwash that occurred towards the northern fringe of the Little Muddy Aquifer. The material gets finer and consists of more sand to the south and with depth in the aquifer. The coarse grained material that is present near the surface of the aquifer has an average thickness of 43 ft in the upper zone of the aquifer. Many lenses of silt and clay cause the aquifer to have high and complex heterogeneity (Armstrong, 1969).

Figure 5. Later depositional events of the 29MC area. (a) Fluvial deposits and development of Appam End Moraine, (b) fluvial deposits and development of Smoky Butte End Moraine, (c) development of Little Muddy River (Nygren, 2007).

Climate

The closest National Climate Data Center (NCDC) to 29MC is located 13 miles west at the Grenora station. The climate is described as being semi-arid. The high temperatures of 29MC range from approximately 18° F in January to 83° F in July.
Approximately 70% of the annual precipitation falls on 29MC during the growing season of April to September. The annual average precipitation (Figure 6) is $14.90 \pm 3.62$ in. (± one standard deviation) while the winter precipitation averages $4.36 \pm 1.37$ in. (Nygren, 2007). The standard deviation in the summer is larger than the winter because summer precipitation is usually caused by localized thunderstorms while winter precipitation is predominately regional snow showers.

![Figure 6](image)

Figure 6. Annual, winter, and summer recorded precipitation in the 29MC area along with the 5 year moving average (Nygren, 2007).

**Aquifer Properties**

In the 29MC area, the LMA is composed of glacial outwash of coarse sand and gravel and in some places it is overlain by glacial till. The northern portion of the aquifer has glacial drift overlaying it, while the central portion of the drift was eroded by the West Wildrose outwash channel. This central portion is the thickest part of the aquifer, usually in excess of 100 ft thick. Just to the south, the confined Ray Aquifer discharges
into the Little Muddy Aquifer. The layer that confines Ray Aquifer is eroded by outwash and therefore is not present above the Little Muddy Aquifer. This southern portion of the aquifer is not as thick as the central part, ranging in thickness from 30 to 80 ft (Nygren, 2007).

The overall average thickness of the LMA is 76 ft, based on 132 different test holes done throughout the LMMA. The maximum thickness is 161 ft thick while the minimum is zero ft as the aquifer pinches out at the edges.

In the 29MC area, the properties of the aquifer were determined from a single test at the well associated with Water Permit No. 1403. This well is approximately 3.3 miles northeast of the proposed well (NDSWC, 2009) (Figure 7). The measured hydraulic conductivity (K) was 420 ft/day and the specific storage was $9.6 \times 10^{-6}$ ft$^{-1}$ (Nygren, 2007).

Figure 7. Aquifer properties were tested at Water Permit No. 1403 which is approximately 3.3 miles northeast of the proposed well (No. 5757).

**Hydrogeology**

In the 29MC area, the Little Muddy Aquifer is recharged by infiltration from precipitation, inflow from the Ray, West Wildrose, and Smoky Butte aquifers, and
recharge from surface runoff. Discharge from the aquifer occurs by evapotranspiration to plants, discharge to wetlands, discharge to the Little Muddy River, and discharge to pumping wells. During the spring and during other high water events, the Little Muddy River turns into a recharge zone for the aquifer, but during the rest of the year when the water levels are lower, it is a discharge zone for the aquifer. The groundwater moves from areas of recharge to areas of discharge, and follows a southerly direction, like the Little Muddy River (Nygren 2007) (Figure 5).

Since the first water permit for the LMMA was approved in 1966 there has been a steady increase in the amount of permits approved for the LMMA through 2004, after which no new permits have been approved. Year 2005 saw the highest reported water use of 5,400 acre-ft. During the drought of 1988, an average of 24.9 in. of water per acre were applied. The average in. applied per year since 1977 was 13.9 in./acre (Nygren, 2007).

Each year, the water levels in observation wells tend to be highest in the spring right after the thaw (Figure 8). During the growing season irrigation lowers the aquifer levels 1-3 ft.
Pumping Wells in Operation

Thirty-five pumping wells have already been approved and are in place in the LMMA. The proposed discharge rate and requested acre-ft for Water Permit No. 5757 are listed in Table 1. Each of the approved wells irrigates a different amount of acreage and therefore has been approved to discharge a certain amount of water from the aquifer in acre-ft (Table 2).

Table 1. Details about proposed well for Water Permit No. 5757 (Nygren, 2007).
Table 2. Details of the thirty-five wells which are currently installed in the LMMA (Nygren, 2007).

<table>
<thead>
<tr>
<th>Permit No.</th>
<th>Name</th>
<th>Priority Date</th>
<th>Use Type</th>
<th>Status</th>
<th>Approved Acme Feet</th>
<th>Approved Acreage</th>
<th>Approved Rate, gpm</th>
<th>POD</th>
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</thead>
<tbody>
<tr>
<td>1403</td>
<td>HELGESON, TOBY</td>
<td>11/9/86</td>
<td>IR</td>
<td>P</td>
<td>218.4</td>
<td>109.2</td>
<td>807.8</td>
<td>15810017AB</td>
</tr>
<tr>
<td>1564</td>
<td>GUNLIKSON, DONALD AND ROGER</td>
<td>8/23/66</td>
<td>IR</td>
<td>P</td>
<td>205.5</td>
<td>135</td>
<td>1200</td>
<td>15810124DA</td>
</tr>
<tr>
<td>2251</td>
<td>GUNLIKSON, DONALD AND ROGER</td>
<td>4/27/5</td>
<td>IR</td>
<td>P</td>
<td>203</td>
<td>153</td>
<td>800</td>
<td>15910028CB</td>
</tr>
<tr>
<td>2325</td>
<td>DRAGSETH, RICHARD</td>
<td>10/17/75</td>
<td>IR</td>
<td>P</td>
<td>202</td>
<td>134</td>
<td>925</td>
<td>15910026DB</td>
</tr>
<tr>
<td>2390</td>
<td>DRAGSETH, DONNA MAE</td>
<td>3/8/76</td>
<td>IR</td>
<td>P</td>
<td>250</td>
<td>165</td>
<td>1150</td>
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<td>3159</td>
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<td>P</td>
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<td>133</td>
<td>1000</td>
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<td>3313</td>
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<td>P</td>
<td>201</td>
<td>134</td>
<td>540</td>
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<td>3554</td>
<td>SMITH, DARYN D.</td>
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<td>P</td>
<td>151</td>
<td>107.3</td>
<td>621</td>
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<td>3675</td>
<td>SOURRETT, BENARD</td>
<td>1/10/64</td>
<td>IR</td>
<td>P</td>
<td>366</td>
<td>234</td>
<td>1700</td>
<td>15810112B</td>
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<td>3954</td>
<td>DRAGSETH, MICHAEL and KELVIN</td>
<td>8/27/90</td>
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<td>P</td>
<td>254</td>
<td>132</td>
<td>600</td>
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<td>P</td>
<td>205.5</td>
<td>137</td>
<td>850</td>
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<td>650</td>
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<td>4331</td>
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<td>P</td>
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<td>70</td>
<td>500</td>
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<td>IR</td>
<td>P</td>
<td>220</td>
<td>135</td>
<td>1000</td>
<td>15910031A</td>
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</table>
Design Approach

The approach for the model was to have the entire LMMA modeled in Visual MODFLOW (SWS, 2008). Once the grid had been developed in the model, the next step was to determine which cells would be active and which would not. To get an accurate representation of the aquifer a map had to be imported into Visual MODFLOW (SWS, 2008). Figure 3 is the map that was imported into Visual MODFLOW (SWS, 2008) so the boundaries of the aquifer could be easily determined in the model. Any cell
that had less than half its area filled by the aquifer was designated as an inactive cell and therefore was not used in any of the MODFLOW (Harbaugh and McDonald, 2000) calculations.

The elevation and thickness of the aquifer was the next property to be imported into the model. The model had only one layer, so only one set of aquifer thicknesses had to be determined. The elevation of the model was interpolated from a topographic map of the area and then imported manually into the model. The thickness of the aquifer was determined by a number of steps. First, the thicknesses at all the observation and pumping wells were determined from the lithologic data from the NDSWC website (NDSWC, 2009). With the help of Dr. Lance Yarbrough, a professor at the University of North Dakota, this information was imported into ArcGIS (ESRI, 2004) and was then smoothed for the entire aquifer. Dr. Yarbrough then created a grid file of the thicknesses which correlated directly with the model in Visual MODFLOW (SWS, 2008).

Inputting the properties and boundary conditions of the aquifer was the next step in the modeling process. The recharge varied throughout the model depending on soil texture. The inflow from neighboring aquifers was also modeled as recharge. The hydraulic conductivity data were interpolated using information from one hydraulic conductivity test performed in the south-central portion of the aquifer along with general hydraulic conductivity data from Table 3.
Table 3. Approximate hydraulic conductivities for various sediments in Williams County, North Dakota (Armstrong, 1969)

<table>
<thead>
<tr>
<th>Material</th>
<th>Permeability (gpd per ft²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravel</td>
<td>2,500 - 4,000</td>
</tr>
<tr>
<td>Sand and gravel</td>
<td>2,000 - 2,500</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1,500</td>
</tr>
<tr>
<td>Medium sand</td>
<td>1,000</td>
</tr>
<tr>
<td>Fine sand</td>
<td>500</td>
</tr>
<tr>
<td>Silty sand</td>
<td>100 - 200</td>
</tr>
<tr>
<td>Silt</td>
<td>50</td>
</tr>
</tbody>
</table>

The Little Muddy River was modeled using the River Package of MODFLOW (Harbaugh and McDonald, 2000). The river was modeled in small segments so the elevation could be more accurate. The cells which contained the lakes and wetlands of the model were assigned as general head boundaries. This allowed the water level to fluctuate and not stay constant as it would with a constant head boundary.

Finally, the location, screened interval, and pumping rate for all the current pumping wells had to be imported into the model. The well data for Permit No. 5757 were also imported into MODFLOW (Harbaugh and McDonald, 2000) but the well was not turned on when the model was run for the initial calibration simulation.

**Design Assumptions**

The main assumptions that MODFLOW (Harbaugh and McDonald, 2000) uses in all groundwater flow problems are the Dupuit Assumptions. The two Dupuit Assumptions are: the hydraulic gradient is equal to the slope of the water table and for
small water-table gradients, the streamlines are horizontal and the equipotential lines are vertical (Fetter, 1994).

Many assumptions had to be made during the modeling process of the Little Muddy Aquifer. Many of the inputs did not have sufficient field data, so assumptions had to be made to interpolate between the data points.

The land elevation values for the aquifer were interpolated from a topographic map. The elevation values had to be averaged because only one value could be assigned to each 1000-ft by 1000-ft section of the grid. The thickness of the aquifer was determined by using the thicknesses from 115 well sites and smoothing the data between these points.

Only one hydraulic conductivity test had been performed in the aquifer. This value and knowledge of the sediment textures were used to create hydraulic conductivity zones. Knowing that the aquifer was generally made up of coarser sediments in the northern part of the aquifer, the hydraulic conductivity was estimated to have its highest value in the north and the lowest value in the south.

The average precipitation in the region is 14.9 inches/year (Nygren, 2007). The recharge was estimated as a percentage from this precipitation value. The evapotranspiration was included in the calculation for the recharge from precipitation, so a separate value for evapotranspiration did not have to be included in the model. The recharge from each of the three inflowing aquifers was calculated by Darcy’s Law. The gradient, hydraulic conductivity, and cross-sectional area of each aquifer were needed to determine the inflow using Darcy’s Law. Not all of these values were measured directly, which caused the recharge values to be estimates.
When assigning cells as river cells or general-head boundaries, most of the input data were varied to allow the model to calibrate most accurately.

The information from the pumping wells came directly from the North Dakota State Water Commission (NDSWC, 2009). The pumping rates and screened intervals are exact measurements, but because the locations of the wells were put in manually they could have some variation from their exact locations. Water Permit No. 5757 has not yet been installed, so when the model was run with Water Permit No. 5757 pumping, a screened interval had to be assumed. It was also assumed, for the simulations, that all the wells were pumping continuously at their maximum rates.

In the text that follows, some of these design assumptions are described in further detail.

**Preliminary Design Options**

The design of the model could vary in a number of ways. First, the model could either be steady-state or transient. If steady-state was chosen, then the model would have to be run with Water Permit No. 5757 not included and run a second time with it included in the model. This would need to be done to see the difference that Water Permit No. 5757 causes on the surrounding wells. If the transient model was chosen, it would still have to follow these same principles, but changes in the aquifer levels would be observed over time which would differ from the steady-state models.

The other design options occur because of the many options of how to assign properties and boundary conditions. The properties that could vary in this model were hydraulic conductivity and recharge. The hydraulic conductivity values needed to be split into different zones, but the number of zones and what the hydraulic conductivity
value used for each zone determines the different options. The recharge was also split into zones because it varied depending on how coarse the soil was.

The boundary conditions that are assigned to the surface water of the aquifer also allow for different design options. The lake and pond cells could be assigned as either drain cells or general head boundaries. The river cells could be assigned as either drain cells or river cells. All the combinations of these boundary conditions and properties lead to many different design options.

Final Design

Input

The model consisted of a single layer of cells with a represented land area of just under 90 square miles. It had an east-west distance of approximately 8.14 miles and north-south distance of exactly 11 miles. Each cell in the model had the dimensions of 1000 ft by 1000 ft. The aquifer was not rectangular, so even though the model had 2700 cells, more than ¼ of the cells were inactive. With a model this size, it was important to make sure that the cells were discretized correctly. If the cells were too small then the computer would take a long time processing the information. If the cells were too large then the model would make too many interpolations and the output would not be accurate. Even though it would be ideal to have cells smaller than 1000 ft by 1000 ft, this size was judged to be the smallest appropriate with the limited amount of hydrogeological data available.

Once the grid was developed and a map was imported into MODFLOW (Harbaugh and McDonald, 2000), the active and inactive cells were assigned. Figure 9 is
the MODFLOW (Harbaugh and McDonald, 2000) image which has the inactive and active cells with the map of the Little Muddy Aquifer as an overlay.

![MODFLOW Image with Clear Active Cells and Dark Inactive Cells](image)

**Figure 9.** MODFLOW (Harbaugh and McDonald, 2000) image with the clear active cells and dark inactive cells.

The elevation data were determined by topographic maps and then imported into the model manually. Figure 10 is a representation of the elevation created by MODFLOW (Harbaugh and McDonald, 2000). The lowest elevation in the model is 1920 ft and is represented by dark blue. The highest elevation in the model is 2210 ft, which is represented by the dark red. Comparing Figures 9 and 10 it can be seen that the majority of the Little Muddy Aquifer is in the lower elevations of the area and most of the higher elevations are part of the inactive cells in the model.
Figure 10. MODFLOW (Harbaugh and McDonald, 2000) image of ground surface elevation with dark blue representing 1920 ft above sea level and dark red representing 2210 ft above sea level.

Figure 11 represents the elevations of the base of the Little Muddy Aquifer. The lowest elevation is represented by dark blue and is approximately 1813 ft above sea level. The highest elevation is represented by dark red and is approximately 2130 ft above sea level. MODFLOW (Harbaugh and McDonald, 2000) automatically calculates the difference at each node between the elevation of the top of the aquifer and the base of the aquifer to determine the thickness.
The one hydraulic conductivity test that was performed in the Little Muddy Aquifer indicated that the value of hydraulic conductivity should be close to 420 ft/day near the south-central portion of the aquifer. From basic geologic knowledge, it is known that there is a general fining of the sediments as one moves south in the aquifer. From this basic knowledge, four different zones for hydraulic conductivity were created for the MODFLOW (Harbaugh and McDonald, 2000) model. Figure 12 has the four different zones represented by four different colors. The white zone is the zone that included the hydraulic conductivity test and was therefore assigned the value of 420 ft/day. The zone
to the south of the test is represented by dark blue cells and has an estimated hydraulic conductivity value of 300 ft/day assigned to it. The zone to north of the test is represented by green cells and has an estimated hydraulic conductivity value of 550 ft/day, while the farthest north zone represented by turquoise cells is assigned a value of 700 ft/day. All of these zones were assumed to be isotropic, so the hydraulic conductivity values were equal in all directions.

The aerial recharge into an aquifer is usually estimated to be between 5-20% of the precipitation depending on topography, land usage, and soil type (SWS, 2008). The recharge values were split into three zones and varied depending on the sediment texture;
the coarser the sediment, the greater the recharge (Figure 13). The southern zone is 10% the annual precipitation (1.49 in./year), the central zone is 15% the annual precipitation (2.235 in./yr), and the northern zone is 20% the annual precipitation (2.98 in./yr).

Recharge values were also applied to the cells as boundary conditions where the Ray Aquifer, West Wildrose Aquifer, and the Smoky Butte Aquifer discharge into the Little Muddy Aquifer. In Figure 13, the cells acquiring recharge from the Ray Aquifer are represented by the dark blue cells in the east-central portion of the map. The cells acquiring recharge from the West Wildrose Aquifer are represented by the green cells located in the northeast portion of the map. The cells acquiring recharge from the Smoky Butte Aquifer are represented by the turquoise colored cells in the northwest portion of the map.

The Ray Aquifer contributes an inflow of 7.34 ft³/sec to the Little Muddy Aquifer. This discharge is calculated using Darcy’s Law and a gradient of 0.002 ft/ft, an average cross-sectional area of 1584000 ft², and a hydraulic conductivity of approximately 200 ft/day (Armstrong, 1969). Once converted, the total inflow is equivalent to 2780 in/year. There are 17 cells in the model which the Ray Aquifer contributes water to, so each cell has a recharge of approximately 163.5 in/year. Once the 1.49 in/year of recharge from direct precipitation was added, the recharge value for each of the dark blue cells is 165 in/year. This was the value that was used in the MODFLOW (Harbaugh and McDonald, 2000) model.
The West Wildrose Aquifer contributes 0.416 ft³/sec to the Little Muddy Aquifer. No gradient information was known about the aquifer, so it was assumed to have the same as that of the Ray Aquifer which was 0.002 ft/ft. The aquifer is made up of sand to medium gravel, so from Table 3 an approximate converted value for hydraulic conductivity would be 200 ft/day. The calculated cross-sectional area for the aquifer is 89,700 ft² (Armstrong, 1969). The discharge value is equivalent to a recharge value of 158 in/year. The aquifer inflows into five cells in the model, which means each cell
would be assigned a value of 31.5 in/year plus the recharge from direct precipitation of
1.49 in/year. Each cell was assigned a value of 33 in/year in the MODFLOW (Harbaugh
and McDonald, 2000) model.

No specific information was given about the Smoky Butte Aquifer, so it was
assumed that it had the same discharge as that of the West Wildrose Aquifer. The total
discharge was assigned to be 0.416 ft$^3$/sec which converts to 158 in/year. Only four cells
in the model receive inflow from the Smoky Butte Aquifer, so the recharge value
assigned to each of those cells, including the 1.49 in/year of direct precipitation recharge,
was 40.9 in/year.

All the cells containing surface water that was in the Little Muddy Aquifer had to
have boundary conditions applied to them. The boundary conditions could be general
head boundaries, constant head boundaries, drain cells, or river cells. These cells were
very important in the calibration of the model, because these boundary conditions could
easily be changed until the model converged. Constant head boundaries were never
considered for any of the surface water because none of the bodies of water were big
enough to be held constant no matter the elevation of the water table. Therefore, only
general head boundaries, river cells, and drain cells were used at some point during the
calibration process. Even though drain cells were used at some point during the
calibration process, it was determined that general head boundaries and river cells
worked best for the model, so drain cells were not used in the final model design.

Figure 14 has the boundary conditions used for the calibrated model. The dark
blue cells represent river cells. The river cells were assigned in small groups so that the
river stage could be assigned more accurately. The green cells represent general head
boundaries. The three groups of general head boundaries represent three lakes and ponds which cover at least 1000-ft by 1000-ft. The general head boundary in the south represents the flow that is exiting the model through the Little Muddy Aquifer.

Figure 14. MODFLOW (Harbaugh and McDonald, 2000) image with the river cells in dark blue and the general head boundary cells in dark green.

Figure 15 is the image from the MODFLOW (Harbaugh and McDonald, 2000) model with the 32 pumping wells represented. Even though there are currently 35 pumping wells in the LMMA, only 31 of them were used in the model. The other four wells were either located in an inactive cell area, or there were insufficient data for the wells on the NDSWC website. The proposed well, Water Permit No. 5757, is also
included on Figure 15. The wells can be individually turned on and off so that different scenarios can be accounted for with the same model.

![Figure 15. MODFLOW (Harbaugh and McDonald, 2000) image with all 32 of the pumping wells represented.](image)

**Output**

The model was run in numerous ways with different conditions to make sure that the heads calibrated accurately and that the water budget balanced. Many different boundary conditions, recharge values, and hydraulic conductivity values were used in the calibration process to determine which combination of values represented the aquifer best while also calibrating accurately. Throughout the calibration process, the different input
options indicated the sensitivity of the model. Once an acceptable final design was developed, different forms of output were used to fully analyze the model.

Figure 16 has the output of water levels compared to the actual water levels in the background. This output is from a model run when all of the pumping wells were turned off. Having all the wells turned off represents the winter months when no irrigation takes place. The other extreme, having all wells pumping at maximum rate, is represented in Figure 17. In the southern part of the aquifer in Figure 16, the calibrated heads are very close to the actual heads. The more north and east in the aquifer, there is a greater discrepancy between calculated and actual heads. This is cause of some concern, but Water Permit No. 5757 is located in the extreme south-central portion of the aquifer, so it is most important that the heads are accurate in this region.
Figure 16. MODFLOW (Harbaugh and McDonald, 2000) image of the output of the calibrated heads with four-foot contour intervals and all the pumping wells off.

Figure 17 is the output of the calibrated heads with hydraulic conductivity values twice as large as were used in the other model runs. This was done to determine how sensitive the model was to changes in hydraulic conductivity. The hydraulic conductivity values for the four zones were, from south to north, 600 ft/day, 840 ft/day, 1100 ft/day, and 1400 ft/day. The model does not appear to be too sensitive to small changes in hydraulic conductivity. Comparing Figures 16 and 17 it can be seen that the contours are more spread out in the north and east when hydraulic conductivities are doubled. Very little changes can be seen in the southern portion of the aquifer where Water Permit No. 5757 is located. Based on the pumping tests and geologic knowledge of the area, the
hydraulic conductivities of 300 ft/day, 420 ft/day, 550 ft/day, and 700 ft/day are used throughout the final model runs.

Figure 17. MODFLOW (Harbaugh and McDonald, 2000) of output heads after the hydraulic conductivity values had all been doubled. The contour intervals are four feet and all the pumping wells are off.

Figure 18 is also the output of the calibrated heads, but the difference between this and the previous example is that now all the pumping wells are turned on except Water Permit No. 5757. The calibrated heads in this output are not nearly as close, but that is because of maximum pumping. The model was calibrated to the two extremes of no pumping and maximum pumping knowing that most scenarios would occur between these two calibrations.
Figure 18. MODFLOW (Harbaugh and McDonald, 2000) image of the output of the calibrated heads with four foot contour intervals and all the pumping wells on except Water Permit No. 5757.

With respect to calibration, the water budget is one of the most important pieces of output information. Table 4 contains the water budget information for the MODFLOW (Harbaugh and McDonald, 2000) run which had all the wells except Water Permit No. 5757 turned on. The water budget discrepancy was -1.32%, which is low and a good sign for an aquifer model of that size. Also, it shows that there is no inflow from wells and no outflow from recharge, which are both essential parts of the model.
Table 4. Water budget output from the MODFLOW (Harbaugh and McDonald, 2000) model with all the wells on except Water Permit No. 5757.

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<th>CUMULATIVE VOLUMES L**3</th>
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<tbody>
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<tr>
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<tr>
<td>WELLS =</td>
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<tr>
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<table>
<thead>
<tr>
<th>OUT:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
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</tr>
</tbody>
</table>

IN - OUT = -80044.0000

PERCENT DISCREPANCY = -1.32

The final step in the MODFLOW (Harbaugh and McDonald, 2000) model was to predict how the installation and pumping of Water Permit No. 5757 would affect the water levels in the two neighboring wells. Once the model was successfully calibrated, the prediction process could take place. Figures 19 and 20 show zoomed-in views of the output from the Little Muddy Aquifer after predictive simulations. Figure 19 has the head contouring and shading representing the water table when Water Permit No. 5757
was off, but all other wells were pumping at maximum rates. Figure 20 has the head contouring and shading representing the water table when all of the wells, including Water Permit No. 5757, were pumping at maximum rates. The contours are at one foot intervals, with the darkest blue representing 1915 ft above sea level and the darkest red representing 1940 ft above sea level. From the two figures, it can be deduced that the pumping of Water Permit No. 5757 minimally affects the water level of the nearest pumping wells to the northwest, Water Permit Nos. 4036 and 4036A. The two figures suggest that Water Permit No. 5757 does negatively affect the water levels in Water Permit No. 5004. The maximum pumping of Water Permit No. 5757 causes an extra drawdown in Water Permit No. 5004 of three to four ft. At this point the saturated thickness is approximately fifty ft. Even though there is a drawdown of three to four ft, this is not a relatively large amount because of the saturated thickness at that point.

There may be some economic considerations for those individuals who irrigate with Water Permit No. 5004, but because the drawdown is only three to four feet, the economic implications should be minimal.
Figure 19. MODFLOW (Harbaugh and McDonald, 2000) output image with all wells pumping at maximum rate except Water Permit No. 5757 was not pumping. The contours are one foot difference and the dark blue represents 1915 ft above sea level and the dark red represents 1940 ft above sea level.

Figure 20. MODFLOW (Harbaugh and McDonald, 2000) output image with all wells pumping at maximum rate. The contours are one foot difference and the dark blue represents 1915 ft above sea level and the dark red represents 1940 ft above sea level.
Economic Considerations

The only costs for developing a model of an aquifer using Visual MODFLOW (SWS, 2008) is the cost of the license for the program and the time that it takes to develop the model. Compensating someone for their time to develop the model can be a large cost because of the large amount of time it takes to create an accurate model.

The University of North Dakota (UND) Department of Geology and Geological Engineering did not previously own a license for Visual MODFLOW (SWS, 2008). The North Dakota State Water Commission (SWC) agreed to split the cost of the student license. A student license costs $745.00, so UND and the SWC both paid $372.50 to purchase it.

The installation of the proposed well for Water Permit No. 5757 could have economic implications for surrounding wells that are also in use for irrigation. If the proposed well causes water levels to drop in surrounding wells, then it could take more power to pump the same amount of discharge which is now being extracted.

Conclusions

The Visual MODFLOW (SWS, 2008) model was accurately calibrated in the southern portion of the aquifer near the well for Water Permit No. 5757. The prediction model that was run with the well for Water Permit No. 5757 pumping indicated that there was no additional drawdown in wells associated with Water Permit Nos. 4036 and 4036A. The model did indicate that there was an additional drawdown of 3-4 ft at Water Permit No. 5004. The saturated thickness at this point of the aquifer is approximately 50 ft, so this drawdown is believed to not be significant. The well for Water Permit No.
5004 should be able to continue production without major effects from Water Permit No. 5757. Therefore, according to this model, Water Permit No. 5004 should be approved.
REFERENCES


