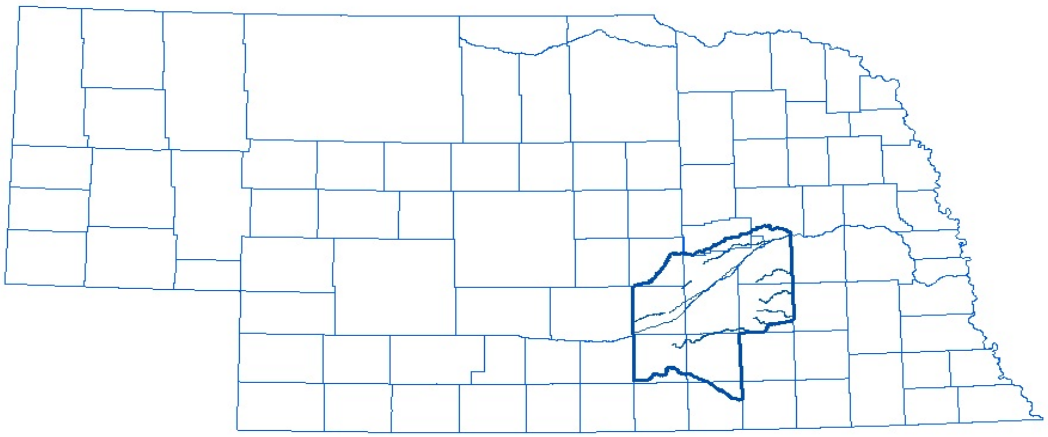
A GROUNDWATER MODEL TO DETERMINE THE AREA WITHIN THE UPPER BIG BLUE NATURAL RESOURCES DISTRICT WHERE GROUNDWATER PUMPING HAS THE POTENTIAL TO INCREASE FLOW FROM THE PLATTE RIVER TO THE UNDERLYING AQUIFER BY AT LEAST 10 PERCENT OF THE VOLUME PUMPED OVER A 50-YEAR PERIOD



Prepared By
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Upper Big Blue Natural Resources District
September 2005

ACKNOWLEDGMENTS

The following persons provided assistance with inputs and reviews that were incorporated into the model and final report:

Courtney Hemenway, P.E., Hemenway Groundwater Engineering, Inc., provided a peer review of the model development, model inputs, model application, and report to ensure that these components are developed in accordance with acceptable standards.

Duane Woodward, Hydrologist, Central Platte Natural Resources District, reviewed the model and inputs for consistency with COHYST standards. Duane also assisted with evaluating recent river bed conductance data that was incorporated into the model.

Steve Peterson, Hydrologist, U.S. Geological Survey, assisted with implementation of the EMSI[1] GMS[2] modeling techniques.

Jim Cannia, Nebraska Department of Natural Resources, reviewed the model and model inputs regarding suitability for determining hydrologic connectivity of streams with the aquifer.

Marie Krausnick, Upper Big Blue Natural Resources District, provided assistance with GIS mapping.

Xun Hong Chen, Ph.D. and *Mark Burhach, Ph.D.*, University of Nebraska Conservation and Survey Division, provided Geoprobe electric logging, permeameter testing, and pump tests to estimate aquifer hydraulic conductivity and river bed conductance on the Platte River and Big Blue River.

Larry Cast, Geologist, reviewed test hole and irrigation well drilling logs to determine geologic and hydrologic properties of the layers used to define the aquifer.

Rich Kern, P.E., Hydrologist / Programmer, Nebraska Department of Natural Resources, provided computer programming of utilities to assist with database management, grouping geologic layer parameters, retrieving data from the DNR databases, and analysis of GMS - MODFLOW outputs.

COHYST Modelers[3], developed the COHYST Eastern Regional groundwater model from which this sub-regional model is derived.

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[1] EMSI is an acronym for "Environmental Modeling Systems, Inc."

[2] GMS is an acronym for "Groundwater Modeling System".

[3] COHYST is an acronym for " Cooperative Hydrology Study".

AUTHORIZATION

The groundwater model discussed in this report was commissioned by the Upper Big Blue Natural Resources District for the purpose of estimating the location of areas within the Natural Resources District that have the potential to be hydrologically connected to base-flow streams. The groundwater model and modeling results, shown in this report, have been presented to the Natural Resources District Board, and have been approved for submittal to the Nebraska Department of Natural Resources.

HGE
Hemenway Groundwater Engineering, Inc.

September 29, 2005

NE-0010-05

Mr. Jay Bitner
District Engineer
Upper Big Blue Natural Resources District
105 Lincoln Avenue
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Dear Jay:

Subject: Groundwater Model Review for the Upper Big Blue Natural Resources District (UBBNRD)

As you requested, Hemenway Groundwater Engineering, Inc. (HGE) is pleased to submit this letter documenting the consulting services provided for the UBBNRD regarding your ongoing groundwater model development. HGE's Scope of Work (SOW) for consulting services was related to the review of the current groundwater computer model for the UBBNRD. The model is a sub-regional model of the area covered by the Eastern Model Unit (EMU) developed by the Nebraska Cooperative Hydrology Study (COHYST). The model utilizes the Groundwater Modeling System (GMS) pre- and post-processor modeling system and the United States Geological Survey (USGS) finite difference model MODFLOW 2000. The grids in the model are 1,320 feet by 1,320 feet or 40 acres per model grid, which is a refinement of the COHYST EMU model grid size of 2,640 feet by 2,640 feet. The focus of the UBBNRD model is to determine the depletion to the Platte River from wells, which represents 10 percent flow from the river after 50 years of well pumping. To determine the depletions, a baseline transient model was run without any wells pumping. Following the baseline run, the model was run numerous times with one well pumping at a new location at each model run. The depletions were calculated after each model run as a function of the distance of the well from the Platte River, and the 10 percent depletion line was mapped.

The services provided by HGE included reviewing the current UBBNRD groundwater model for "fatal flaws" and providing recommendations for improving and modifying the model to meet the intended purposes by the UBBNRD. HGE's recommendations were accepted and implemented by UBBNRD in the current groundwater model. The UBBNRD provided additional studies and information, model refinements, and improvements to the current COHYST EMU groundwater model. With these revisions and improvements, the current UBBNRD groundwater model meets the industry standards for groundwater modeling practices.

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HGE looks forward to the opportunity to work with you and the UBBNRD in the future. If you have any questions regarding this letter or HGE's review of the UBBNRD groundwater model, please do not hesitate to contact me.

Sincerely,

Hemenway Groundwater Engineering, Inc.

Courtney Hemenway
President

HGE/UBBNRDGWMODELREVLET

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INTRODUCTION

This report discusses development and application of a groundwater model for a region that lies within the boundary of the Cooperative Hydrology Study (COHYST) eastern regional groundwater model[4] in Nebraska. The geographic area modeled is shown on Figure 1 and includes all, or portions of, Platte, Polk, York, Nance, Merrick, Hamilton, Clay, Nuckolls, Howard, Hall, and Adams Counties. The modeled area overlays portions of the Upper Big Blue, Central Platte, and Little Blue Natural Resources Districts. The total land surface within the model boundary is approximately 7,520 square miles (4.8 million acres).

PURPOSE

The purpose of this model is to provide a method for calculating the potential increase in the rate of flow from the Platte River to the underlying aquifer due to groundwater pumping near the Platte River within the Upper Big Blue Natural Resources District. The model is used to define a boundary encompassing the area within which a well pumping groundwater could increase flow from the Platte River to the underlying aquifer by an amount equal to, or greater than, 10 percent of the volume pumped over a period of 50 years. For purposes of determining whether or not a river basin is *fully appropriated* [5], the Nebraska Department of Natural Resources considers that wells within the 10 percent / 50-year boundary are hydrologically connected to the river.

CONCEPTUAL MODEL

The model boundaries are defined with a series of *fixed flow* arcs that specify flow into or out of the model, depending upon the direction and slope of the groundwater gradient at the boundary. The Platte River is defined with a series of *river* arcs which specify the river bed conductance, river bed thickness, and river stage. The model cells intersected by the river arcs are defined by the model as a series of point source river cells, each with its own conductance value. The model cells intersected by the fixed flow boundary arcs are defined by the model as a series of wells that are either source (injection) or sink (withdrawal), depending on whether the

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[4] S. M. Peterson, *Groundwater Flow Model of the Eastern Model Unit of the Nebraska Cooperative Hydrology Study (COHYST) Area*, 2005.

[5] Nebraska Department of Natural Resources, Proposed Rule pursuant to Neb. Rev. Stat. §46-713.

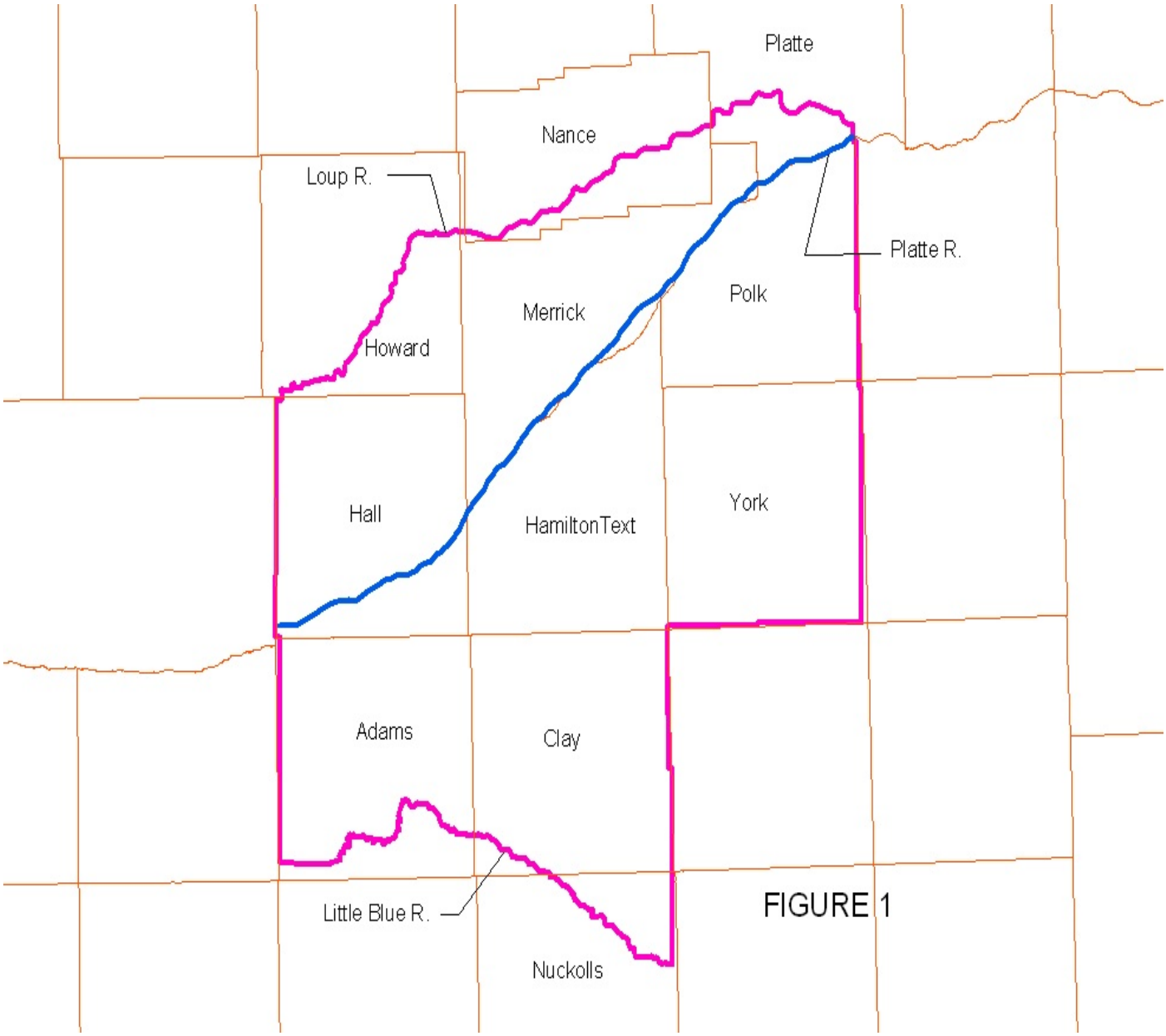
Platte
Nance
Loup R.
Platte R.
Polk
Merrick
Howard
Hall
HamiltonText
York
Adams
Clay
Little Blue R.
Nuckolls

FIGURE 1

boundary flow is into or out of the model at that point. The amount of river to aquifer flow induced by pumping is tested with a single well, which is moved from cell to cell parallel to the Platte River, at varying distances from the river. Other streams within the model boundary, such as the Big Blue River and its tributaries, including the West Fork Big Blue River, Lincoln Creek, and Beaver Creek, are not included in the model. The bed conductances of these rivers and streams are very low, approximately 0.0079 ft^2/day, and have minimal connectivity to the underlying aquifer[6] and the Platte River. Areal sources and sinks included in this model are recharge from precipitation, and evapotranspiration from rooted plants located in wet meadows near the Platte River. The model geology is represented by five unconfined layers. The numerical flow model is based on the following basic assumptions:

- At the scale in which this model is constructed, flow in the aquifer obeys Darcy's Law and mass and energy are conserved.
- Since the modeled fluid is groundwater, having a temperature in the range of 50 degrees Fahrenheit, the density and viscosity of water are constant over time and space.
- Parameters are uniform within each cell, and represent an estimate of their average value within the cell.
- The interchange of water between the aquifer and Platte River can be adequately simulated as one-dimensional flow through a discrete streambed layer. This conceptualization is appropriate over the scale at which this model is constructed.
- Hydraulic conductivity in the horizontal plane is isotropic; however, hydraulic conductivity in the vertical direction is not equal to hydraulic conductivity in the horizontal direction. The horizontal to vertical anisotropic ratio is assigned a value of 10 (i.e. horizontal hydraulic conductivity is ten times greater than vertical hydraulic conductivity), unless otherwise noted.

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[6] Xun Hong Chen, *River Bed Conductance Studies - West Fork Big Blue River and Platte River in Nebraska*, University of Nebraska Conservation and Survey Division, 2005.

GEOLOGIC AND HYDROSTRATIGRAPHIC UNITS

The model has five unconfined geologic layers. The layer definitions are consistent with those documented in the COHYST aquifer characterization report[7]. The model layers consist primarily of Quaternary deposits of Pleistocene alluvium, Pleistocene and Holocene loess, Holocene dune sand, and Holocene valley fill. Valley fill deposits are found along the Platte River and consist of gravel, sand, and silt. Alluvial deposits, which typically support high capacity wells, are found throughout the model area. In topographic bedrock highs these deposits are generally thinner, and produce lower yielding wells. Loess deposits are found throughout the model area, and the thickest deposits are located along the Platte River bluffs. The deposits become thinner as they approach the Platte River north of the loess bluffs. The Platte River bed contains a low permeability loess layer at about 10 to 20 feet below the current streambed surface[8]. The bedrock formation at the bottom of Layer 5 consists of shale, chalk, limestone, siltstone, and sandstone of Cretaceous age. These bedrock materials transmit very little water, and for modeling purposes are considered to be impermeable.

The model layers are numbered 1 through 5. Unit 1 is the top layer, and Unit 5 is the bottom layer. The layers used in this model are described as follows:

- Layer 1 — Top layer consisting of upper Quaternary age silt and clay with some sand and gravel
- Layer 2 — Middle Quaternary age sand and gravel
- Layer 3 — Lower Quaternary age silt and clay with some sand and gravel
- Layer 4 — Upper Tertiary age silt and clay with some sand and gravel
- Layer 5 — Middle Tertiary age sand and gravel underlain with bedrock materials consisting of shale, chalk, limestone, siltstone, and sandstone

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[7] J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report, November 2004.

[8] See geoprobe electric logs shown in Appendix B

MODEL DESCRIPTION

The groundwater model is a three-dimensional finite difference computer model developed around the MODFLOW[9], Version 2000, groundwater modeling software enclosed within EMSI GMS[10], Version 5.1. The GMS software includes a pre-processor to read input data and place it in the model according to MODFLOW format requirements. GMS also does some post-processing of output in both graphical and numerical forms. The units of measure used in this model include feet for linear measure, days for time, feet per day for velocity, cubic feet for volume, and cubic feet per day for flow rate.

Model Grid

The model grid has 120,330 cells per layer. Each cell measures 1,320 feet per side, and covers an area of approximately 40 acres. Model feature locations are geo-referenced in the horizontal plane to the Nebraska State Plane Coordinate System, NAD 83 - feet. Top and bottom elevations of each layer are referenced to USGS mean sea level datum.

Modules

The MODFLOW software is modular in the sense that various modules (packages) can be activated for any particular modeling situation. The modules used in this model include river, well, recharge, and evapotranspiration.

River Module

The Platte River is simulated in this model as a series of arcs, connected at their upstream and downstream ends at nodes, with a combined length of 87.8 miles. Attributes associated with the arcs and nodes specify the river bed conductance, bottom of river bed elevation, and river stage. The hydrologic properties (K, S_y) of model cells identified as river cells (cells crossed by river arcs), and located in Layer 1, are adjusted to match the hydrologic properties of the underlying cell in Layer 2. In this way there is a direct connection of the Platte River bed to the aquifer, and the only limitation on inter-connectivity between the river bed and underlying

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9 M. G. McDonald and A.W. Harbaugh, *Modular Three-Dimensional Finite-Difference Groundwater Flow Model*, U.S. Geological Survey, 1984.

10 *Groundwater Modeling System (GMS)*, Environmental Modeling Systems, Inc. (EMSI), Park City, Utah.

aquifer is river bed conductance. River bed conductance is a function of river bed length, width, bed thickness, and hydraulic conductivity. MODFLOW uses the following equation[11] to calculate bed conductance:

EQ. 1 $$C = (k \times L \times W) / M$$

For each river arc "n":

C_n = streambed conductance ($ft^2/d/ft$)

k_{vn} = vertical hydraulic conductivity of the streambed (ft/d)

L_n = length of the streambed (ft)

W_n = width of streambed (ft)

M_n = thickness of streambed (ft)

For this model, the value of river bed conductance at each river arc is set at the same value as used in the COHYST Eastern Regional Model, except where detailed testing indicates the value should be different. The values established by testing were determined based on geoprobe and permeameter tests conducted by the University of Nebraska Conservation and Survey Division. Geoprobe electric logs, hydraulic conductivities, and bed conductance calculations are shown in Appendix B of this report. Platte River bed conductances used in this model are set at 11 $ft^2/d/ft$ in reaches where testing is completed. River bed conductances in the remaining reaches vary from 20 $ft^2/d/ft$ to 30 $ft^2/d/ft$.

Well Module

The potential increase in induced flow from the Platte River to the underlying aquifer, due to groundwater pumping near the Platte River, is tested with this model by placing a simulated pumping well at alternate cell locations, operating the model for a 50-year period at each location, and calculating the change in the water budget when compared with the baseline condition. The initial baseline condition is simulated with no pumping well.

For these simulations, pumping is assumed to be from Layer 2, the volume of water

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[11] *Documentation of a Computer Program to Simulate Stream-Aquifer Relations Using a Modular, Finite Difference, Groundwater Flow Model*, U.S. Geological Survey, Open-File Report 88-729, 1989.

pumped is set at 160 acre-feet per year, and the pumping rate is set to be continuous at 19,094.79 cubic feet per day. This volume of groundwater is approximately the average amount of water pumped in one year to irrigate a quarter section of crop. A gravity irrigated system would pump slightly more volume on average, and a pivot irrigated system would pump slightly less volume on average, based on the District's records of irrigation water use. Although irrigation systems typically operate at a higher pumping rate, are operated on an intermittent pumping schedule, and only operate for a few months per year, a continuous lower pumping rate is used to simplify the modeling process. The volume of water pumped per year would be the same with either continuous or transient pumping schedules. The continuous pumping schedule is not expected to give significantly different results than a transient pumping schedule would yield. Some comparisons of continuous and transient pumping were made to confirm this conclusion.

Recharge Module

Recharge is modeled as an areal source of inflow to the aquifer, and includes the amount of precipitation that percolates from the surface through Layer 1 into Layer 2. The recharge rate used in this model, in feet per day, is interpolated from the COHYST Eastern Model, pre-development period, scatter point data set. The scatter point file is derived from the COHYST EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is imported to the MODFLOW model recharge array. The recharge point of application option is set to the highest active layer at each grid cell. For this model, the minimum recharge rate is 0.000222 feet per day (0.97 inches per year), and the maximum rate is 0.000557 feet per day (2.44 inches per year). The mean rate is 0.000222 feet per day (0.972 inches per year). The recharge rate is held constant throughout the modeled time period, and does not vary from stress period to stress period.

Evapotranspiration Module

Evapotranspiration (ET) is modeled as the amount of groundwater extracted from the aquifer by rooted vegetation, and then evaporated from the plant canopy to the atmosphere external from the model. For this model ET is considered to be an areal sink; i.e., outflow from the model space. The ET rate data set used in this model is interpolated from the COHYST Eastern Model pre-development data set. A scatter point file is produced from the COHYST

EMU model and interpolated to this model's 2-dimensional grid. The 2D data set is then imported to the MODFLOW model ET array. The point of ET withdrawal is the top of Layer 1, and the extinction depth is set at a specified depth (nominally 7 feet) below the top of Layer 1. For this sub-regional model, the minimum ET rate is 0.00 feet per day, and the maximum rate is 0.002993 feet per day (13.1 inches per year). The rate of evapotranspiration is held constant throughout the modeled time period, and does not vary from stress period to stress period.

Wetland areas, mostly located near the Platte River, are treated as groundwater sinks, where groundwater can be removed from the model space by plant evapotranspiration. The evapotranspiration rate, extinction depth, and active ET layer are interpolated to the model 2D grid from COHYST EMU scatter point data sets. Areas that have potential for significant evapotranspiration are selected using 1997 land use mapping data for wetlands (Dappen and Tooze, 2001), and also by defining areas where the depth to groundwater is on average 7 feet or less below land surface, according to USGS long-term depth to water data (U.S. Geological Survey National Water Information System, 1999).

Boundary Conditions

The model is bounded vertically by land surface at the top of Layer 1 and bedrock at the bottom of Layer 5. The model is bounded horizontally by fixed flow boundaries. A fixed flow boundary is a boundary where the flow is specified prior to the simulation and held constant throughout the simulation (McDonald and Harbaugh, 1988). At fixed flow boundaries the simulated water level can change, but flow across the boundary does not change. The northern model boundary is aligned with the Loup River and the southern boundary is aligned with the Little Blue River and southern boundary of Adams County. The eastern model boundary is aligned with the eastern boundaries of York and Polk Counties, and the western boundary is aligned with the western boundaries of Hall and Adams Counties, as shown on Figure 1. The rate of flow through each model boundary, in cubic feet per day, is calculated using the Darcy Equation.

EQ. 2 $$Q_n = k_n \times i_n \times A_n$$

For each boundary arc "n"

Q_n = fixed rate of flow through the boundary, ft^3/d

k_n = weighted horizontal hydraulic conductivity, ft/d

i_n = gradient of the 1950 groundwater surface perpendicular to the boundary flow plane, ft/ft

A_n = cross sectional area of the flow plane at the boundary, ft^2

Each layer's thickness determines the relative weight given to each layer's hydraulic conductivity for this calculation. The calculated boundary flow is distributed evenly over the saturated thickness between the groundwater level and the base of the aquifer at each boundary arc. Appendix A contains calculations and supporting documents used to compute boundary fixed flows. A boundary flow is not computed for Layer 1, since it is a silty clay layer generally representing the unsaturated zone which overlays the saturated zone.

Model Flow Simulation

The MODFLOW software has several packages (BCF, LPF, and HUF) available for calculating conductance coefficients and groundwater storage parameters to be used in the finite-difference equations that calculate flow between cells. The Layer Property Flow (LPF) package is selected as the internal flow calculation methodology for this model. The LPF package reads input data for hydraulic conductivity and global top and bottom elevation data for each cell (layer). Transmissivity is calculated for each cell at the beginning of each iteration of the flow equation matrix solution process. The LPF package calculates leakance between layers using the vertical hydraulic conductivity, based on estimated anisotropic ratio K_x/K_z, and distance between nodes obtained from global elevation data.

Flow Equation Solver

The MODFLOW software has several linear differential equation "solver" packages (SIP1, PCG2, SCR1, and GMG) available. For this model, the pre-conditioned conjugate-

gradient[12] (PCG2) package is selected to solve the linear finite difference equation matrix. For a transient groundwater model, the solution matrix is expressed as shown in EQ. 3, where [A] is the coefficient matrix, [x] is a vector of hydraulic heads, and [b] is a vector of defined flows, associated with head-dependent boundary conditions and storage terms at each grid cell.

EQ. 3 $$[A] \bullet [\vec{x}] = [\vec{b}]$$

The matrix is solved iteratively until both head-change and residual convergence criteria are met. The convergence criteria are too large if the global groundwater flow budget discrepancy is unacceptably large. In general, a global budget discrepancy less than one percent is considered acceptable. Convergence criteria for this model, specified in the input options for the PCG2 module, are 0.5 foot for heads and 10.0 ft^3/d for flow residual. The iteration parameters are not specified, but rather are calculated internally.

Aquifer Characteristics

Aquifer properties are input for each layer, including horizontal hydraulic conductivity (K_x), vertical anisotropic ratio (K_x/K_z) or vertical hydraulic conductivity K_z, horizontal anisotropic ratio (K_x/K_y), Specific Storage (S_s), and specific yield (S_y). The procedures used to estimate parameter values for each layer are described in the COHYST hydrostratigraphic Units Characterization Report[13].

Hydraulic Conductivity K_x

Test well logs, interpreted by Reed and Piskin[14], are the basis for horizontal hydraulic conductivity values used in this groundwater model and the COHYST eastern regional model. The interpreted values for each layer are weighted according to layer thickness, and the weighted average value of K_x is then determined for each model layer at each test well location. The

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12 P. Concus, G. H. Golub, and D. P. O'Leary, A Generalized Conjugate Gradient for the Numerical Solution of Elliptical Partial Differential Equations, Academic Press, 1976.

13 J. C. Cannia, D. Woodward, L. Cast, and R. L. Luckey, *Cooperative Hydrology Study COHYST Hydrostratigraphic Units and Aquifer Characterization Report*, November 2004.

14 E. C. Reed and R. Piskin, unpublished report, University of Nebraska Conservation and Survey Division.

process used to weight the values is written in a computer code called *Geoparm*[15]. A 2D data set is then created by interpolating the computed values. The 2D data set is then used to set the MODFLOW array of values for each layer.

Anisotropic Ratios

As described previously in this report, the vertical anisotropic ratio, K_x/K_z , is estimated to be 10.0 for all layers at each grid cell, unless pump testing indicates a different ratio, and the horizontal anisotropic ratio, K_x/K_y, is estimated to be 1.0.

Specific Yield S_y

Data compiled by USGS, and summarized by Reed and Piskin, is the basis for specific yield values used in this groundwater model and the COHYST eastern regional model. As discussed in the Hydrostratigraphic Units Report, specific yield values are interpreted for each layer material classification. The interpreted values are then weighted using the Geoparm program to establish specific yield for each model layer at each test well location. The computed values are then interpolated to the model's 2D grid for each model layer. The 2D data sets are then used to set the MODFLOW array values for each layer.

Specific Storage Ss

All layers in this model are considered to be unconfined; however, the LPF simulation options available in MODFLOW are either confined or convertible. The convertible option is selected for all layers, and the specific storage for all layers, except Layer 1, is set to $2.1e^{-3}$; this value is based on discussions with UNL Conservation and Survey[16] and takes into account low potential for changes in aquifer storage due to height of overburden or changes in hydraulic head. The specific storage for Layer 1 is set to 0.16, the estimated specific yield, since this layer is always unconfined, and cannot be converted to confined.

Specific storage is the volume of water per unit volume of *confined* saturated aquifer that is absorbed, or expelled, due to changes in pressure within the aquifer. Overburden tends to

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15 R. Kern, *Nebraska Cooperative Hydrology Study Computer Program Documentation GeoParam - Hydraulic Conductivity from Well Logs*, Nebraska Department of Natural Resources.

16 Personal communication with Xun Hong Chen, University of Nebraska, Conservation and Survey Division.

consolidate the aquifer (reduce storage volume), and hydraulic pressure head tends to offset consolidation (increase storage volume).

Storativity for a *confined* layer is equal to the product of specific storage and layer thickness. Storativity for an *unconfined* layer is equal to the specific yield plus the product of groundwater depth and specific storage.

PRE-DEVELOPMENT PERIOD

Geologic and hydrogeologic layer parameters used in this model are derived from calibrated COHYST eastern regional model (EMU) data. The EMU was calibrated for the pre-groundwater development period by varying and adjusting evapotranspiration, recharge, hydraulic conductivity, properties at horizontal flow boundaries, and streambed conductances. For this model the evapotranspiration, recharge and horizontal hydraulic conductivity are interpolated from EMU scatter point files. Streambed conductances and vertical hydraulic conductivities are adjusted at some locations based on recent testing conducted by the University of Nebraska Conservation and Survey. Fixed flows at boundaries are computed for each boundary arc as previously described. Observed water levels, measured between 1946 and 1955, are used to establish the starting head values.

Observed water levels used to establish starting heads are from a period of relatively stable conditions. Observation points were selected as being representative of pre-groundwater development, and only the most reliable data within 4-mile by 4-mile grid cells were selected (by COHYST modelers) for EMU calibration. This selection process prevents a cluster of closely spaced observation wells from dominating the calibration process. After screening values in all of the 4 by 4-mile cells, a few points that appeared to have large errors in location or land-surface elevation were excluded from the calibration data set. The starting heads file for this model is based on a sub-set of the EMU calibration data set that contains 209 of the observation points.

The ability of this model to represent a 50-year period of pre-groundwater development conditions is evaluated by comparing the percent discrepancy in global groundwater flow budget, as well as the mean difference, mean absolute difference, and root mean square of the differences between observed pre-development groundwater levels at the beginning and end of a 50-year computer run without well development.

Mean Difference

The mean difference (MD) of observed and simulated water levels is defined in EQ.4. The variable h_0 is the observed water level and h_s is the simulated water level at each of the n observation points. The mean difference is used here as a measure of overall bias in calibration, and as such should be close to zero at calibration.

EQ.4 $$MD = \frac{1}{n}\sum_{i=1}^{n}\left(h_0 - h_s\right)_i$$

Mean Absolute Difference

The mean absolute difference (MAD) of observed and simulated water levels is defined in EQ.5. The MAD is used here to evaluate the overall model calibration, since positive and negative differences do not cancel each other. All differences are given an equal weight, so a few measurements with large differences will not dominate the result.

EQ.5 $$MAD = \frac{1}{n}\sum_{i=1}^{n}\left|h_0 - h_s\right|_i$$

MODFLOW calculates the water level changes as draw-downs, therefore positive changes are declines and negative changes are rises.

Root Mean Square Difference

The root mean square difference (RMSD), also referred to as the quadratic mean, is defined in EQ. 6. This statistic is the standard deviation of the differences between observed groundwater levels and groundwater levels produced by the model, for the pre-development period. Assuming that the differences between observed and modeled water levels are normally distributed about the mean difference, the standard deviation gives a measure for determining the range within which the differences can be expected to occur. Statistically, 68.27% of the differences are expected to occur within MD ± RMSD, and 95.45% of the differences are expected to occur within MD ± (2)(RMSD).

EQ. 6 $$RMSD = \left[\frac{1}{n}\sum_{1}^{n}\left(h_s - h_0\right)_i^2\right]^{0.5}$$

PRE-DEVELOPMENT MODEL - WITHOUT PUMPING

Starting heads for the pre-development model are obtained by interpolating the observed pre-development water levels to the model 2D grid, which is then imported to the MODFLOW model starting head data set. The observation data points are also imported to the model so that heads computed by the model can be compared to the starting heads for the purpose of evaluating groundwater level changes over the 50-year period. Figures 2 and 3 show the locations of water level observation points, water level contours, and statistical variation at each observation point for the starting heads and 50-year model run. Statistical variations are shown in 10 feet increments; green indicates variation from 0 to 10 feet, yellow indicates variation from 10 to 20 feet, and red indicates variation from 20 to 30 feet. If the indicator is above the line, the computed water level is higher than observed, and if the indicator is below the line the computed water level is lower than observed at that observation point. The mean difference between observed and interpolated water levels, for both starting heads and 50-year model run, is 0.240 feet, the mean absolute difference is 1.376 feet, and the root mean square difference is 2.235 feet. Statistically it can be expected that approximately 95% of the differences between observed and computed water levels will occur within ± 2.235 feet of the mean difference.

The global groundwater inflow and outflow budgets, without well development, are shown in Tables 1 and 2 for the 50-year model run.

TABLE 1

MODEL INFLOW VOLUMETRIC BUDGET

Inflow From	Inflow Volume (KAF)	Inflow Rate (KAF / Yr.)	Percent of Inflow (%)
Storage	19,088	382	52.1
Fixed Flow Boundary	2,324	46	6.4
Platte River	4,388	88	12.0
Recharge	10,781	216	29.5
Total Inflow	36,580	732	100

TABLE 2

MODEL OUTFLOW VOLUMETRIC BUDGET

Outflow From	Outflow Volume (KAF)	Outflow Rate (KAF / Yr.)	Percent of Outflow (%)
Storage	22,196	444	60.7
Fixed Flow Boundary	5,599	112	15.3
Platte River	106	2	0.3
Evapotranspiration	8,681	174	23.7
Total Outflow	36,582	732	100

For the 50-year no well development scenario, the model calculates flow from the Platte River to the underlying aquifer at an average rate of 86 acre-feet per year within the model boundaries. This river to aquifer flow, without pumping, is the baseline for computing induced river to aquifer flow due to groundwater pumping. The global groundwater flow budget discrepancy is less than 0.01 percent.

HYDROLOGICALLY CONNECTED AREA

The portion of the Upper Big Blue Natural Resources District that is considered to be "hydrologically connected" to the Platte River, is that area contained between the Platte River, the Upper Big Blue NRD boundary, and the 10% / 50 year line. Groundwater pumping wells contained within this area are determined by the model to have the potential for inducing additional flow from the Platte River to the underlying aquifer by an amount of at least 10 percent of the volume pumped over a 50-year period. The increase in flow from the river to the aquifer is presented in terms of the "global" model volumetric budget; i.e., the water pumped from the well causes an increase in the mass of water moving from the river to the aquifer, but does not address the transport issues, such as source path or age of water pumped.

A baseline model run, without a pumping well, establishes the volume of water moving from the river to the aquifer due to non-pumping gradients. Independent model runs are then made for each new location of the single pumping well. The well is placed at the center of a grid

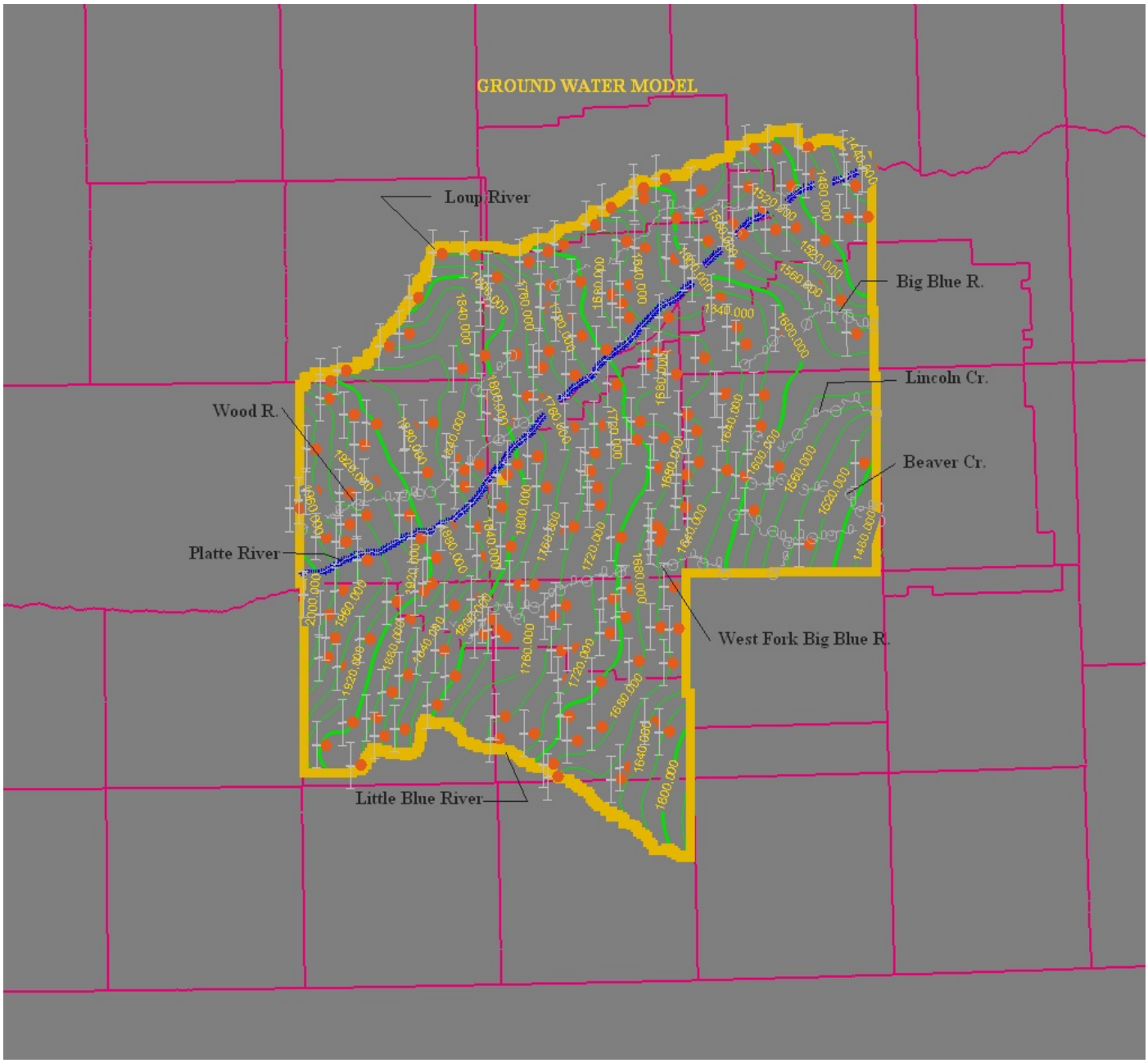


FIGURE 2

PRE-DEVELOPMENT G.W. LEVELS

STARTING HEADS

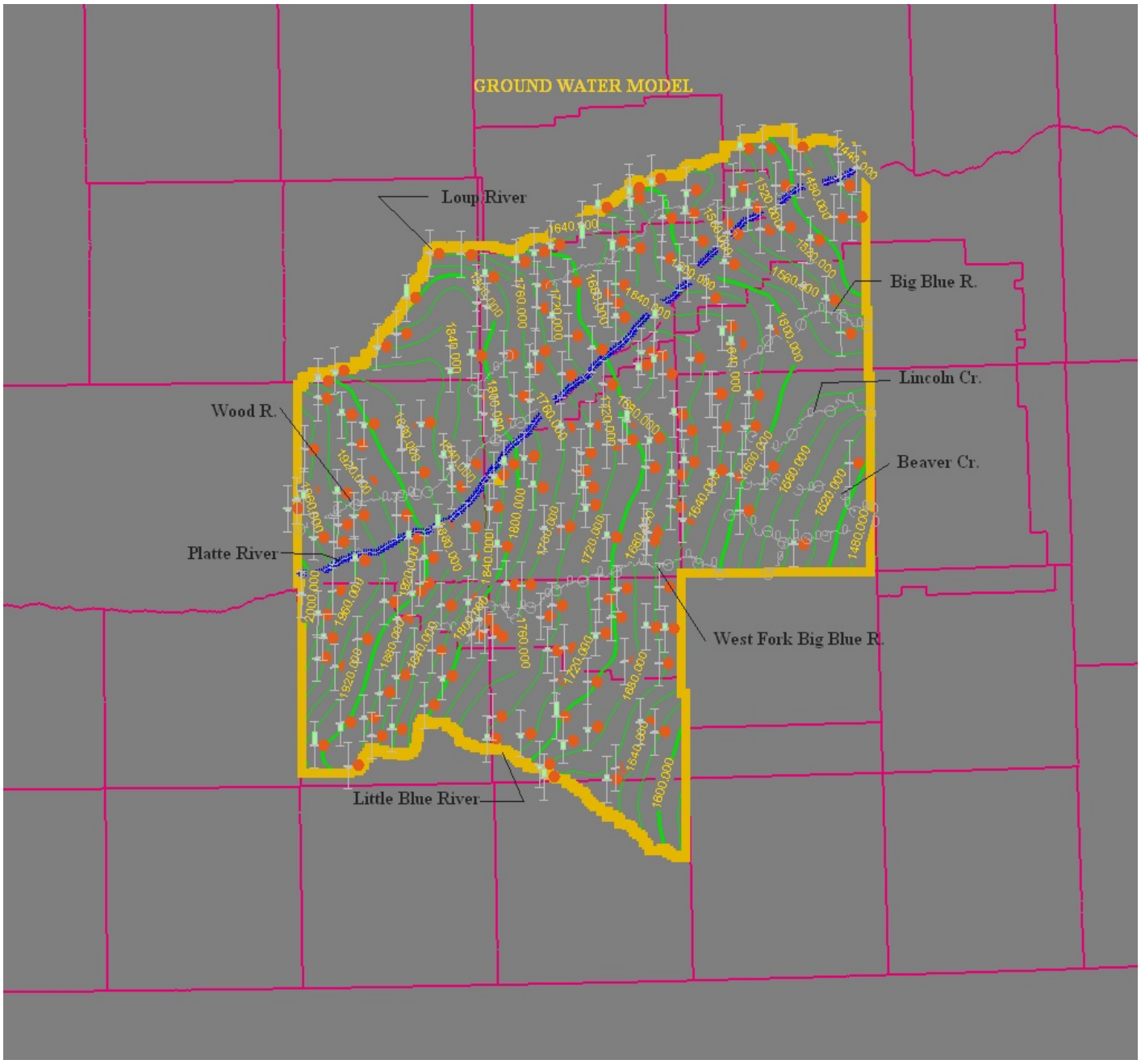


FIGURE 3

FIFTY YEAR MODEL G.W. LEVELS

CHANGES AT OBSERVATION WELLS

cell, and the well screen is assumed to be in Layer 2 for each run. The global volumetric budgets at the end of the 50th stress period are compared with and without pumping, and the difference in river flow into the model is used to determine the volume of water induced from the river to the aquifer due to pumping.

10% / 50-Year Boundary Determination

The 10% / 50-year boundary is determined by evaluating groundwater pumping along transects, spaced approximately 1 mile apart and perpendicular to the Platte River. Transect cells that lie on either side of the boundary line are interpolated linearly to determine the actual coordinates[17] of the boundary line on each transect. Table 3 is a summary of coordinates used to establish the 10 / 50 boundary line within the Upper Big Blue NRD. Figures 4 and 5 are graphical representations of the 10% / 50-year boundary line location.

TABLE 3

10% / 50-YEAR BOUNDARY WITHIN THE UPPER BIG BLUE NRD

STATE PLANE COORDINATES

Easting	Northing
2115914.5307	368243.7495
2119524.3678	373861.1446
2122067.5150	377912.3125
2124670.4467	383220.1545
2128158.4452	387639.9242
2132229.2680	391476.8695
2135624.8026	395989.1030
2139012.1417	400512.5376
2140957.5416	402519.5190
2145105.3989	406279.4298
2149493.4078	411118.6532
2153212.8089	415307.0203

[17] Coordinate system is North American Datum, 1983, Nebraska State Plane, Feet.

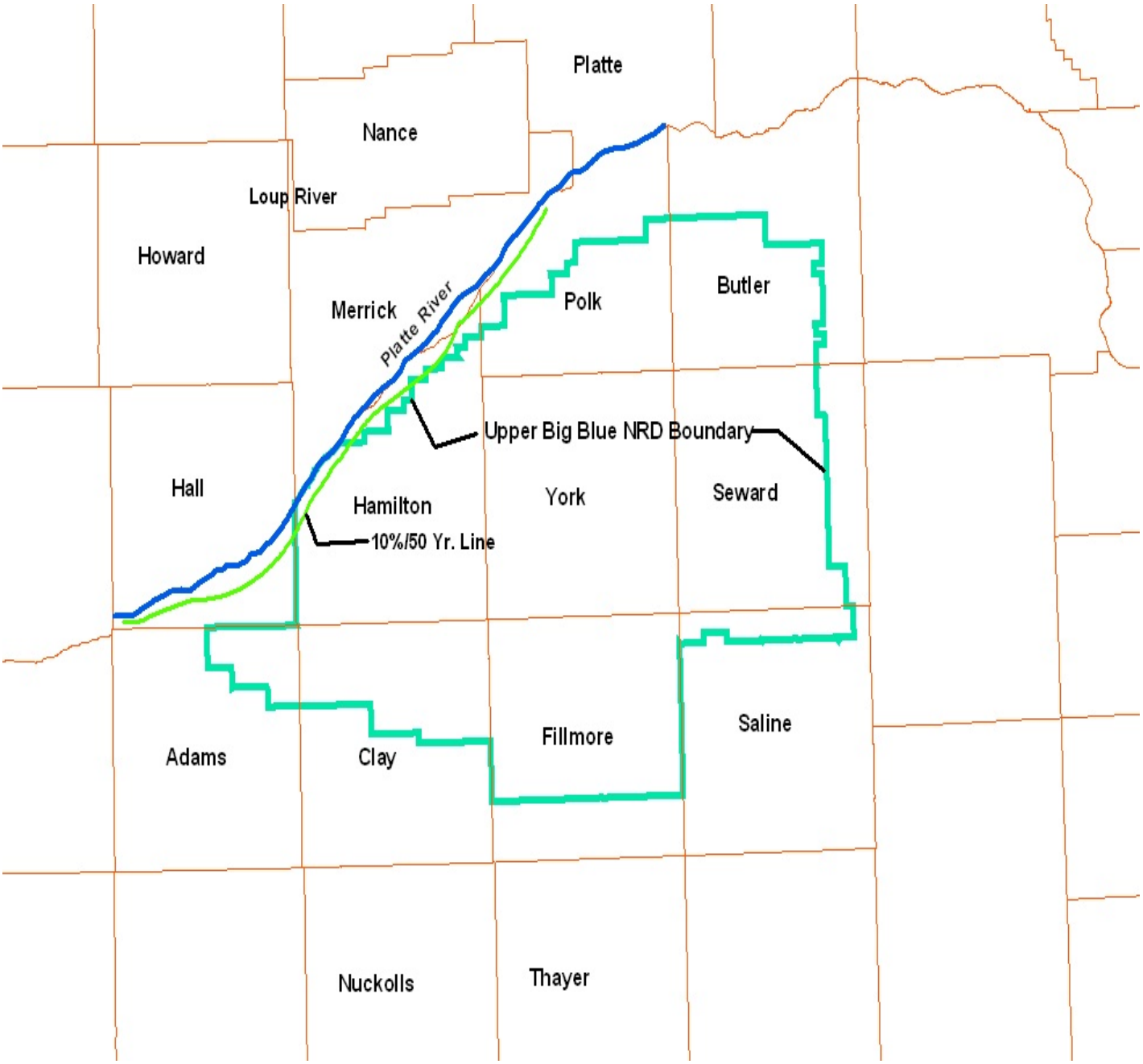


FIGURE 4

10% / 50-YEAR LINE PLATTE RIVER

HALL, HAMILTON AND POLK COUNTIES

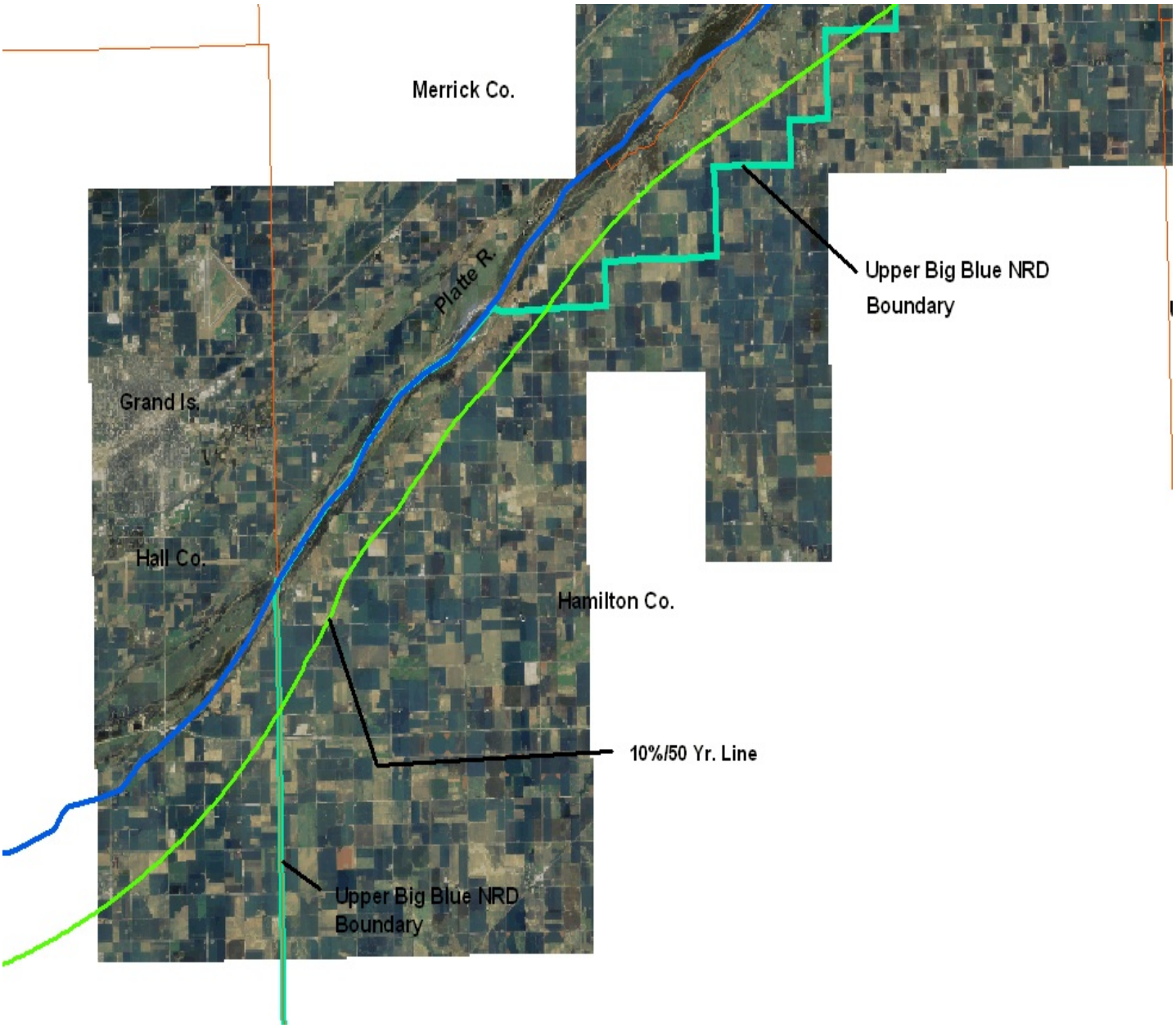


FIGURE 5

10% / 50-YEAR LINE PLATTE RIVER

WITHIN THE UPPER BIG BLUE NRD BOUNDARY

APPENDIX A

MODEL BOUNDARY

FIXED FLOW CALCULATIONS

Ground Water Model
Fixed Flow Boundary Estimates
Southern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
80	-0.000869	90	0.000000	44.3	0.000	1880.0	1660.4	219.6	46,017	10,105,333	0
38	-0.00208	90	0.000000	69.6	0.000	1833.0	1589.0	244.0	28,340	6,914,960	0
39	-0.00208	0	-0.002080	54.4	-0.113	1805.0	1557.6	247.4	27,847	6,889,348	-779,543
82	-0.00129	90	0.000000	59.8	0.000	1775.0	1551.3	223.7	41,096	9,193,175	0
23	-0.00089	90	0.000000	109.5	0.000	1740.0	1587.2	152.8	16,903	2,582,778	0
40	-0.000968	90	0.000000	84.0	0.000	1728.0	1600.4	127.6	30,987	3,953,941	0
41	-0.002924	72	-0.000904	144.8	-0.131	1680.0	1575.0	105.0	24,486	2,571,030	-336,384
1	-0.002000	35	-0.001638	192.1	-0.315	1650.0	1566.5	83.5	24,920	2,080,820	-654,872
42	0.001481	24	0.001353	93.3	0.126	1660.0	1562.9	97.1	35,838	3,479,870	439,268
43	0.002000	33	0.001677	82.0	0.138	1632.0	1467.0	165.0	35,201	5,808,165	798,866
36	0.002105	67	0.000822	94.2	0.077	1600.0	1410.6	189.4	31,263	5,921,212	458,766

Total Estimated 1950 Boundary Flow = -73,898

Ground Water Model
Fixed Flow Boundary Estimates
Northern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
79	-0.002609	54	-0.001534	34.9	-0.054	1910.0	1698.3	211.7	64,788	13,715,620	-734,063
66	-0.001696	49	-0.001113	178.6	-0.199	1735.0	1687.3	47.7	30,975	1,477,508	-293,616
67	-0.001885	70	-0.000645	54.3	-0.035	1790.0	1635.3	154.7	46,543	7,200,202	-252,062
78	-0.002924	0	0.000000	36.2	0.000	1775.0	1608.3	166.7	9,834	1,639,328	0
49	-0.002924	0	0.000000	19.3	0.000	1765.0	1611.0	154.0	10,939	1,684,606	0
50	-0.002924	26	-0.002628	11.1	-0.029	1750.0	1605.0	145.0	18,572	2,692,940	-78,557
75	-0.002924	26	-0.002628	18.7	-0.049	1730.0	1598.7	131.3	14,537	1,908,708	-93,803
68	-0.002924	26	-0.002628	35.5	-0.093	1715.0	1593.3	121.7	37,939	4,617,176	-430,767
69	-0.002827	29	-0.002473	69.4	-0.172	1670.0	1596.3	73.7	33,140	2,442,418	-419,107
70	-0.002827	29	-0.002473	121.3	-0.300	1630.0	1544.3	85.7	37,584	3,220,949	-966,028
71	-0.002827	29	-0.002473	175.5	-0.434	1595.0	1505.0	90.0	36,660	3,299,400	-1,431,717
77	-0.002310	63	-0.001049	121.7	-0.128	1585.0	1468.7	116.3	51,693	6,011,896	-767,292
72	-0.002310	63	-0.001049	53.8	-0.056	1505.0	1430.3	74.7	40,925	3,057,098	-172,485
37	-0.002310	63	-0.001049	17.7	-0.019	1480.0	1417.5	62.5	3,374	210,875	-3,914
74	-0.001571	51	-0.000989	21.5	-0.021	1475.0	1409.0	66.0	31,526	2,080,716	-44,228
73	-0.001571	51	-0.000989	18.9	-0.019	1445.0	1365.7	79.3	27,643	2,192,090	-40,961

Total Estimated 1950 Boundary Flow = -5,728,601

Ground Water Model
Fixed Flow Boundary Estimates
Eastern Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
27	-0.001333	34	-0.001105	13.3	-0.015	1440.0	1323.2	116.8	11,533	1,347,054	-19,799
1	-0.001097	59	-0.000565	23.8	-0.013	1443.0	1318.4	124.6	9,800	1,220,753	-16,415
5	-0.001296	81	-0.000203	22.8	-0.005	1455.0	1304.0	151.0	15,820	2,388,820	-11,042
2	-0.001296	81	-0.000203	14.0	-0.003	1480.0	1298.4	181.6	23,550	4,276,680	-12,139
3	-0.002455	41	-0.001853	12.8	-0.024	1487.0	1302.1	184.9	26,940	4,981,206	-118,134
4	0.002261	0	0.000000	20.7	0.000	1555.0	1260.0	295.0	51,610	15,224,950	0
6	-0.002665	75	-0.000690	21.4	-0.015	1570.0	1207.1	362.9	33,086	12,006,909	-177,230
19	-0.001964	50	-0.001262	31.6	-0.040	1505.0	1206.0	299.0	26,280	7,857,720	-313,468
18	-0.001399	29	-0.001224	35.8	-0.044	1485.0	1210.9	274.1	34,070	9,338,587	-409,073
17	-0.001399	29	-0.001224	52.3	-0.064	1473.0	1191.8	281.2	8,860	2,491,432	-159,436
25	-0.001399	29	-0.001224	32.8	-0.040	1465.0	1267.9	197.1	24,300	4,789,530	-192,222
16	-0.001565	74	-0.000431	24.3	-0.010	1472.0	1318.6	153.4	18,560	2,847,104	-29,844
15	-0.001565	74	-0.000431	62.0	-0.027	1500.0	1318.3	181.7	19,950	3,624,915	-96,949
14	-0.001565	74	-0.000431	124.9	-0.054	1520.0	1310.1	209.9	13,430	2,818,957	-151,881
13	-0.001565	74	-0.000431	131.8	-0.057	1540.0	1308.8	231.2	12,850	2,970,920	-168,911
12	-0.001565	74	-0.000431	138.2	-0.060	1552.0	1328.8	223.2	10,080	2,249,856	-134,127
11	-0.001565	74	-0.000431	100.4	-0.043	1570.0	1371.8	198.2	13,820	2,739,124	-118,631
10	-0.001565	74	-0.000431	52.5	-0.023	1590.0	1409.6	180.4	8,470	1,527,988	-34,604
9	-0.001565	90	0.000000	45.2	0.000	1600.0	1425.0	175.0	5,450	953,750	0
8	-0.001565	90	0.000000	35.1	0.000	1615.0	1449.2	165.8	12,070	2,001,206	0
7	-0.001565	90	0.000000	22.4	0.000	1630.0	1489.1	140.9	9,460	1,332,914	0
26	-0.001399	90	-0.001399	23.4	-0.033	1638.0	1512.3	125.7	18,456	2,319,919	-75,946
20	-0.001399	90	-0.001399	72.3	-0.101	1640.0	1471.9	168.1	28,943	4,865,318	-492,116
21	-0.001399	90	-0.001399	30.0	-0.042	1647.0	1506.0	141	30,370	4,282,170	-179,723
22	-0.001794	41	-0.001354	77.2	-0.105	1595.0	1388.6	206.4	52,830	10,904,112	-1,139,751
23	-0.001696	22	-0.001573	117.6	-0.185	1577.0	1314.5	262.5	14,429	3,787,613	-700,430
24	-0.001555	7	-0.001543	109.1	-0.168	1575.0	1364.0	211	35,841	7,562,451	-1,273,411

Total Estimated 1950 Boundary Flow = -6,025,283

Ground Water Model
Fixed Flow Boundary Estimates
Western Boundary
1950 G.W. Level - Layer 5
Updated 07/18/05

Boundary Arc No.	Gradient Crossing Boundary (ft./ft.)	Gradient Angle At Boundary (deg)	Gradient Perpendicular To Boundary (ft./ft.)	Weighted Hyd. Cond. At Boundary (ft./d)	Weighted G.W. Velocity At Boundary (ft./d)	1950 Groundwater Elevation (ft.>msl)	Bottom Layer 5 Elevation (ft.>msl)	Saturated Thickness At Boundary (ft.)	Boundary Arc Length (ft.)	Boundary Flow Area (ft.2)	Boundary Flow (ft.3/d)
1	0.000891	0	0.000891	29.5	0.026	1902.0	1745.3	156.7	10,227	1,602,571	42,123
2	0.001382	45	0.000977	56.5	0.055	1903.0	1782.5	120.5	12,141	1,462,991	80,776
4	0.003388	26.5	0.003032	50.5	0.153	1920.0	1812.4	107.6	9,090	978,084	149,762
12	0.002875	18.4	0.002728	45.0	0.123	1932.0	1811.7	120.3	12,930	1,555,479	190,952
3	0.002964	26.5	0.002653	48.5	0.129	1930.0	1784.8	145.2	13,060	1,896,312	243,961
13	0.002341	34.5	0.001929	54.1	0.104	1955.0	1720.3	234.7	26,130	6,132,711	640,096
5	0.002145	19.3	0.002024	51.6	0.104	1985.0	1694.7	290.3	25,910	7,521,673	785,727
6	0.001969	17.6	0.001877	50.0	0.094	2008.0	1768.2	239.8	40,530	9,719,094	912,056
7	0.001607	45	0.001136	40.7	0.046	2003.0	1818.3	184.7	35,491	6,555,188	303,166
14	0.001786	45	0.001263	31.9	0.040	1982.0	1797.9	184.1	11,750	2,163,175	87,146
8	0.001684	0	0.001684	17.6	0.030	1972.0	1759.4	212.6	34,700	7,377,220	218,649
9	0.001684	0	0.001684	10.0	0.017	1978.0	1731.2	246.8	14,990	3,699,532	62,300
10	0.001752	27.6	0.001553	9.2	0.014	1978.0	1722.8	255.2	10,340	2,638,768	37,693
11	0.001906	56.9	0.001041	19.2	0.020	1960.0	1713.6	246.4	19,299	4,755,274	95,033

Total Estimated 1950 Boundary Flow = 3,849,440

APPENDIX B

RIVER BED CONDUCTANCE

PLATTE RIVER

Platte River
Average Bed Conductance
Between Hwy. 34 And Chapman Bridges
Based On Permeameter Tests and Geoprobe Borings
UNL Conservation and Survey - August 2005

Transect	Site	K_{v1} (ft/d)	K_{v2} (ft/d)	Ecbase (mS/m)	M_1 (ft)	M_2 (ft)	K_v (ft/d)	L (ft)	W (ft)	M (ft)	C (ft^2/d/ft)
A1	NC	78.7	0.056	35	13.8	6.8	0.169	1	1	20.6	0.0082
A2	MC	78.7	0.056	35	15.9	6.9	0.185	1	1	22.8	0.0081
A3	SC	78.7	0.056	35	12.4	13.3	0.108	1	1	25.7	0.0042
B1	NC	109.7	0.056	35	21.6	1.7	0.763	1	1	23.3	0.0327
B2	MC	109.7	0.056	35	10.8	9.5	0.120	1	1	20.3	0.0059
B3	SC	109.7	0.056	35	8.5	8.1	0.115	1	1	16.6	0.0069

Average Unit C = 0.0110 ft^2/d per foot of river reach per foot of river width
Total Conductance C 11.0 ft^2/d per foot of river reach (using a river bed with of 1,000 ft.)

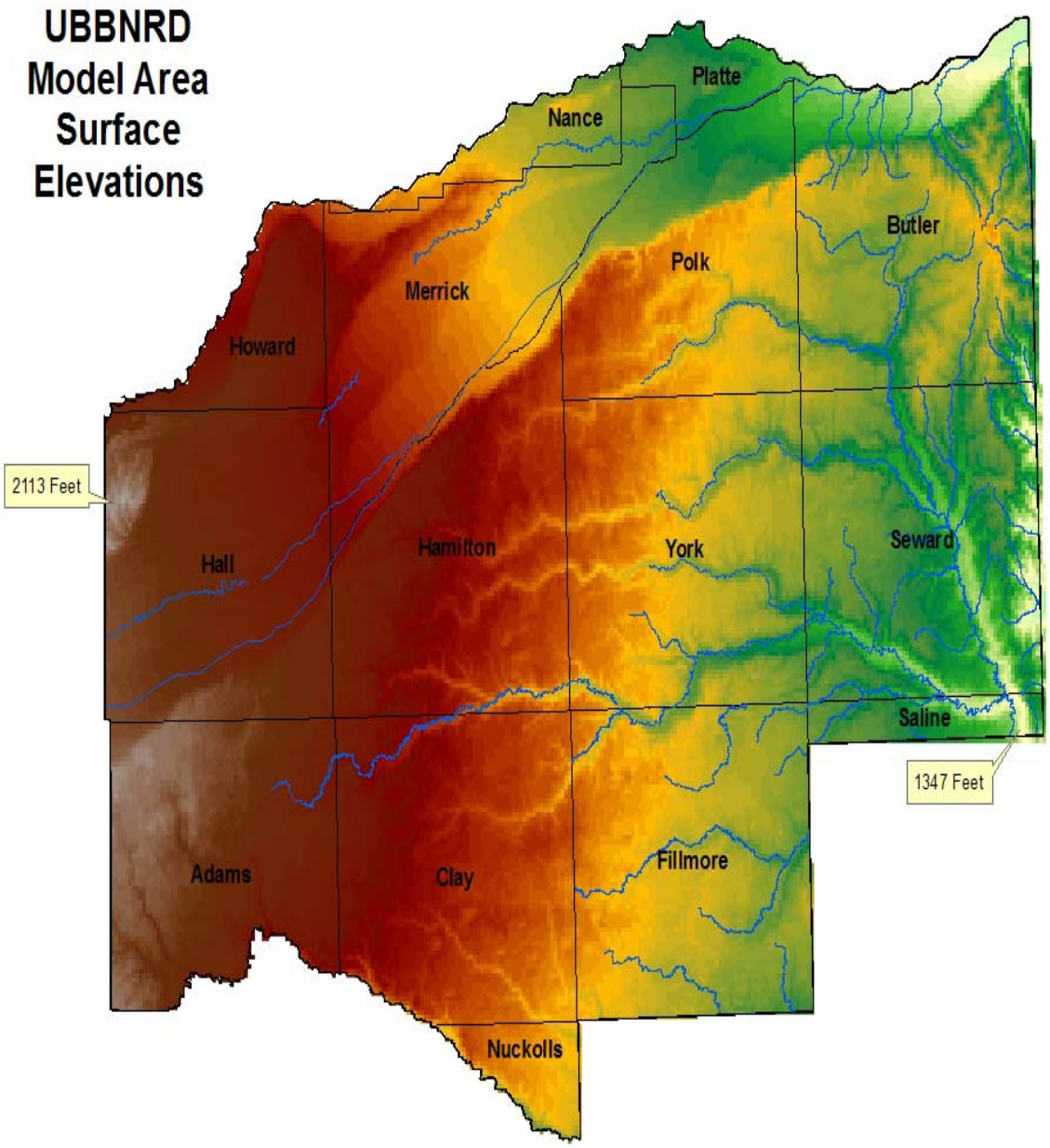
NOTES:
1. NC = North Channel
2. MC = Middle Channel
3. SC = South Channel
4. Site A is located in Sec 29, Twp 11N, Rng 8W, and is upstream from the BNSF railroad bridge over the Platte River near Grand Island
5. Site B is located in the NW^4 Sec 11, Twp 11N, Rng 8W, and is near the upstream from the Chapman Bridge near the intersection of 5th and B Streets
6. K_{v1} = vertical hydraulic conductivity of river bed material with EC log < 35 mS/m
7. K_{v2} = vertical hydraulic conductivity of river bed material with EC log >= 35 mS/m
8. K_v = wighted vertical hydraulic conductivity for total river bed thickness M
9. L = river reach length (use 1.0 ft. for this calculation)
10. W = river bed width (use 1.0 ft. to compute the unit condutance.
    Apply total river bed width of 1,000 ft. to determine total bed conductance per linear foot of river reach between Hwy. 34 bridge and Chapman bridge
11. M1 = thickness of the river bed material with EC log < 35 mS/m)
    (based on CSD geoprobe resistivity log)
12. M2 = thickness of the river bed material with EC log >= 35 mS/m)
    (based on CSD geoprobe resistivity log)
13. M = total river bed thickness ($M_1 + M_2$)
14. Equation for computing river bed conductance

$$C = \frac{K_v \times L \times W}{M}$$

15. Equation for weighting vertical hydraulic conductivity:

$$Kv = \frac{M}{(M_1/K_{v1}) + (M_2/K_{v2})}$$

APPENDIX C
GROUNDWATER LEVEL MAPS
DEPTH TO GROUNDWATER


UBBNRD
Model Area
Surface
Elevations
Platte
Nance
Butler
Polk
Merrick
Howard
2113 Feet
Hall
Hamilton
York
Seward
Saline
1347 Feet
Adams
Clay
Fillmore
Nuckolls

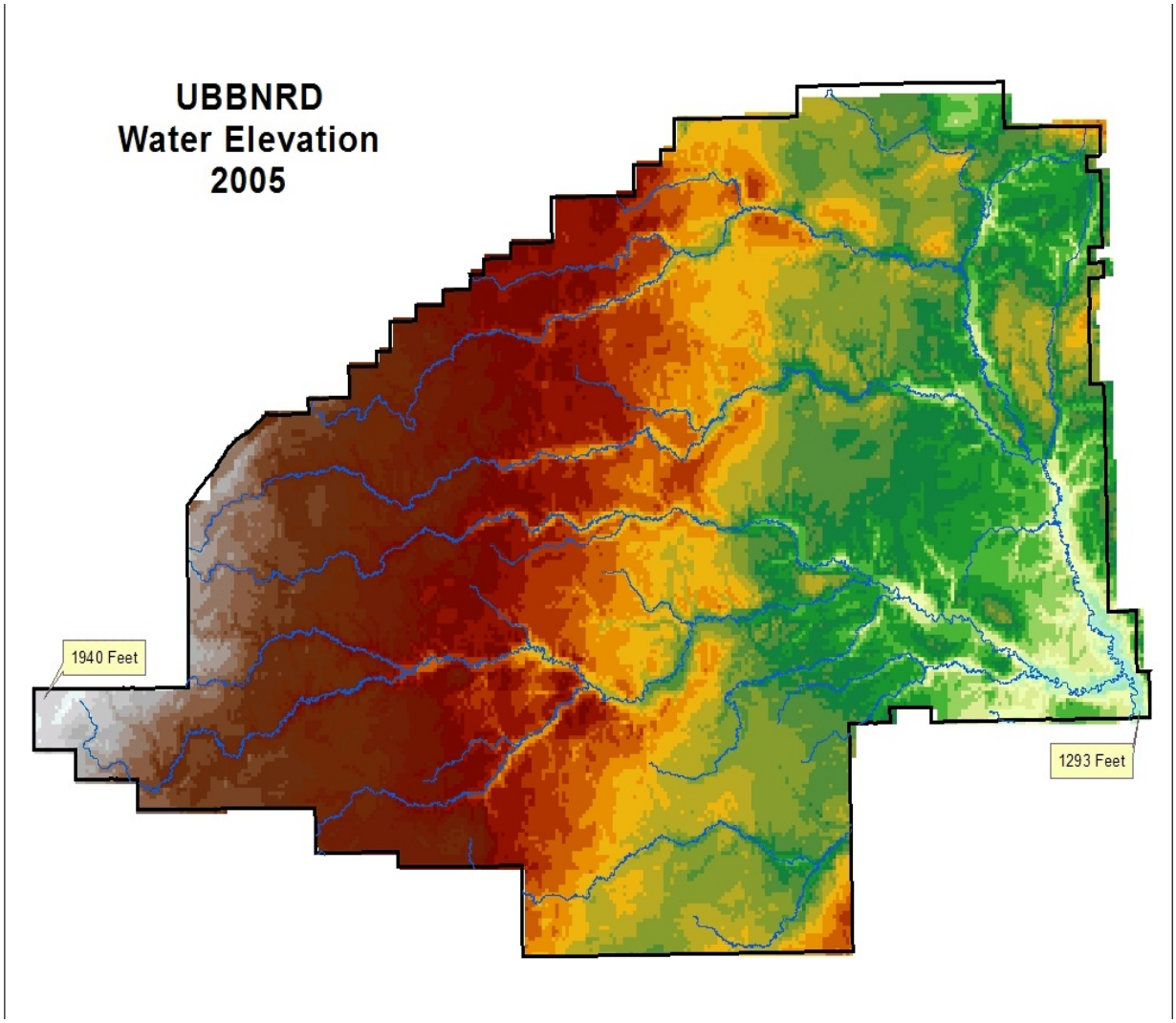


FIGURE 7

GENERAL GROUNDWATER ELEVATION MODEL

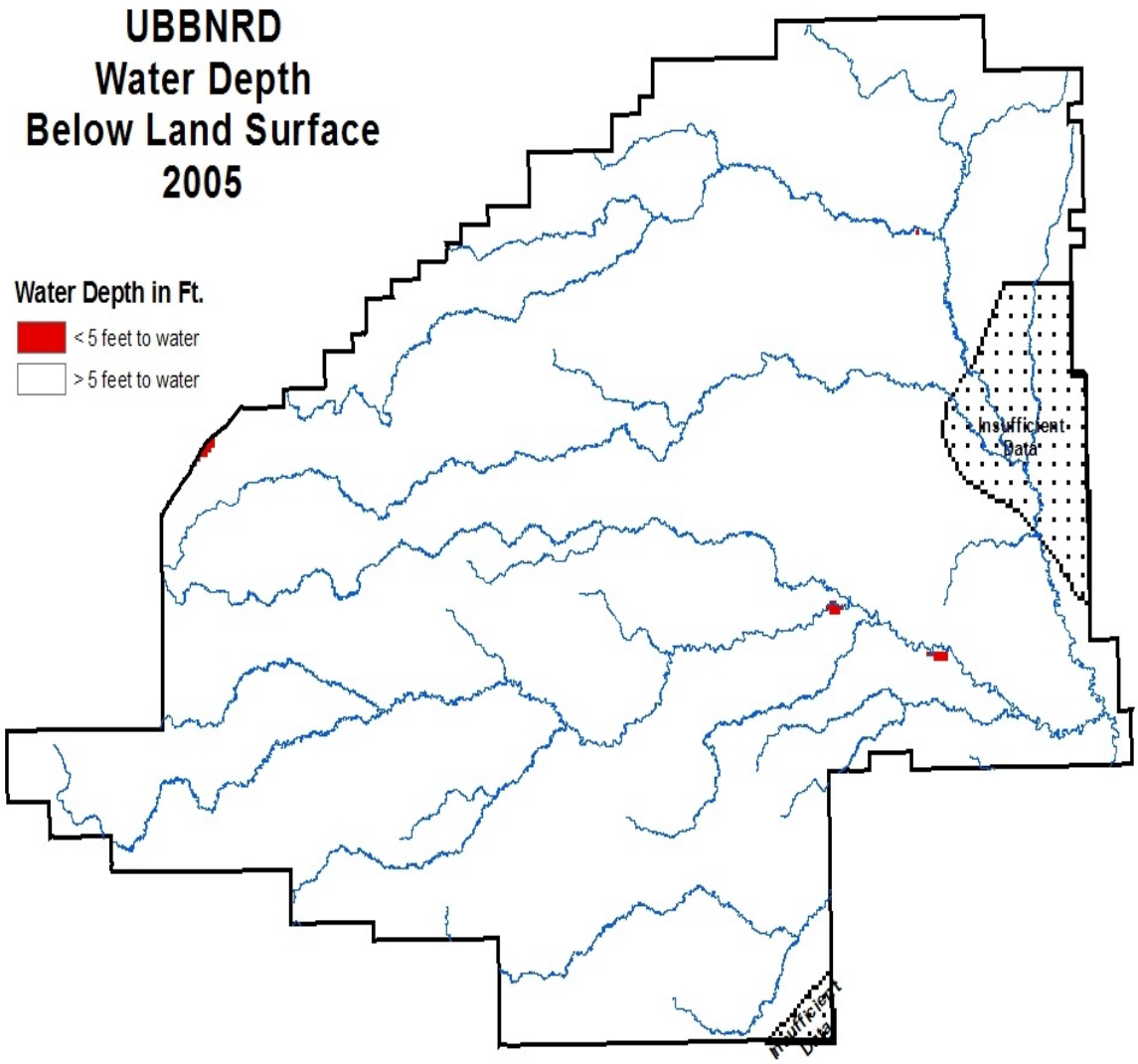


FIGURE 8

GENERAL DEPTH OF GROUNDWATER BELOW LAND SURFACE