



2005

Assessing recharge and discharge across the prairie pothole landscape: application of spatial hydrological data and statistical analysis in a groundwater flow model

Christopher D. Laveau
University of North Dakota

Follow this and additional works at: <https://commons.und.edu/theses>

 Part of the [Geology Commons](#)

Recommended Citation

Laveau, Christopher D., "Assessing recharge and discharge across the prairie pothole landscape: application of spatial hydrological data and statistical analysis in a groundwater flow model" (2005). *Theses and Dissertations*. 173.
<https://commons.und.edu/theses/173>

This Thesis is brought to you for free and open access by the Theses, Dissertations, and Senior Projects at UND Scholarly Commons. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of UND Scholarly Commons. For more information, please contact zeinebyousif@library.und.edu.

ASSESSING RECHARGE AND DISCHARGE ACROSS THE PRAIRIE POTHOLE
LANDSCAPE - APPLICATION OF SPATIAL HYDROLOGICAL DATA AND
STATISTICAL ANALYSIS IN A GROUNDWATER FLOW MODEL

by

Chris D. Laveau
Bachelor of Science, University of North Dakota, 2002

A Thesis

Submitted to the Graduate Faculty

of the

University of North Dakota

in partial fulfillment of the requirements

for the degree of

Master of Science

Grand Forks, North Dakota

May
2005

This thesis, submitted by Chris D. Laveau in partial fulfillment of the requirements for the Degree of Master of Science from the University of North Dakota, has been read by the Faculty Advisory Committee under whom the work has been done and is hereby approved.

Chairperson

This thesis meets the standards for appearance, conforms to the style and format requirements of the Graduate School of the University of North Dakota, and is hereby approved.

Dean of the Graduate School

Date

PERMISSION

Title Assessing Recharge and Discharge Across the Prairie
 Pothole Landscape - Application of Spatial
 Hydrological Data and Statistical Analysis in a
 Groundwater Flow Model

Department Geology

Degree Master of Science

In presenting this thesis in partial fulfillment of the requirements for a graduate degree from the University of North Dakota, I agree that the library of this University shall make it freely available for inspection. I further agree permission for extensive copying for scholarly purposes may be granted by the professor who supervised my thesis work or, in his absence, by the chairperson of the department or the dean of the Graduate School. It is understood that any copying or publication or other use of this thesis or part thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of North Dakota in any scholarly use which may be made of any material in my thesis.

Signature _____

Date _____

TABLE OF CONTENTS

LIST OF FIGURES	v
LIST OF TABLES	vi
ACKNOWLEDGEMENTS	vii
ABSTRACT	viii
CHAPTER	
I. INTRODUCTION	1
Hydrologic Framework	2
Groundwater Model	4
Site Characterization	7
II. METHODOLOGY	8
GIS Environment	8
Model Design & Application	26
III. RESULTS	29
Sensitivity Analysis	29
Reference Grids	34
IV. DISCUSSION	40
IV. CONCLUSIONS	42
APPENDIX: MODEL CODE	44
REFERENCES	54

LIST OF FIGURES

Figure	Page
1. Filter Neighborhood & Weight	10
2. Contoured DEM Before Filtering	11
3. Contoured DEM After Filtering	12
4. Hillshade of DEM	14
5. Hydraulic Conductivity Map of the Watershed	22
6. Sensitivity Analysis for Specific Yield	31
7. Sensitivity Analysis for Hydraulic Conductivity	33
8. Sensitivity Analysis for Depth to Water Table	35
9. Reference Grid Comparison Data	37
10. Comparison of Model Output to Hydric Soils Grid	38
11. Model Flux With Respect to Wetland Distribution	39

LIST OF TABLES

Table	Page
1. DEM Elevation Statistics	13
2. Soil Symbol Substitutions	16
3. Hydraulic Conductivity Values	18
4. Svea-Buse Loam Example	19
5. Watershed Soils Data	20
6. Verification of Correlation	28
7. Specific Yield Sensitivity Data	30
8. Hydraulic Conductivity Sensitivity Data	32
9. Water Table Sensitivity Data	34
10. Reference Grid Comparison Data	36

ACKNOWLEDGMENTS

I would like to thank my committee members Phil Gerla, Scott Korom and Richard LeFever for their insightful contributions and review of this work. I would also like to thank the North Dakota Water Resources Research Institute and the University Of North Dakota Biocomplexity Research Group for affording me the opportunity to explore a scientific interest. Finally, I would like to express my appreciation to my wife, Michelle, for her patience and support during this project.

Opportunity is missed by most people because it is dressed in overalls and looks like work.

-Thomas A. Edison (1847 - 1931)

ABSTRACT

Quantifying the spatial and temporal dynamics between groundwater recharge, discharge, and wetlands is a necessary step to develop effective water management strategies. Wetlands in the northern Great Plains play a role in flood control, water supply, and regional ecology. The water budget of a wetland in the northern prairies is often an unequal balance between moisture input and output in which the permanence of a wetland depends on its groundwater budget. Identifying and quantifying groundwater recharge and discharge zones has applications in predicting the spatial and temporal distribution of wetlands.

The current work involved the application of a groundwater model to the watershed of the North Branch of the Turtle River in Nelson County, North Dakota. The model identified the spatial distribution of recharge and discharge zones by estimating the local configuration of the water table. Model input parameters were developed using geographic information systems (GIS). The model was modified to integrate a statistical component to spatially correlate the modeled configuration of the water table with observed water table conditions. The statistical package compared the model output arrays indicating shallow water table with the spatial distribution of observed wetlands and hydric soils. Within the watershed, recharge and discharge zones were

mapped, the configuration of the water table was estimated, and areas with a shallow water table identified. Model output was found to be strongly controlled by the initial topographic profile of the landscape. The magnitude of groundwater flux was considered less reliable than the pattern of flux due to the difficulty in accurately quantifying and discretizing the physical parameters that control the rate of groundwater movement. The model and methods presented provide a means to model the groundwater hydrology of prairie pothole wetlands.

CHAPTER I

INTRODUCTION

In landscapes characterized by isolated depressions such as the Prairie Pothole Region, the hydrologic continuum in space is defined by the groundwater system. In the northern prairie, wetlands are surficially isolated and groundwater maintains the hydrologic connection among wetlands. This connection, together with a negative water balance with respect to the atmosphere (Winter 1989, Winter & Rosenberry 1998), means that groundwater flow systems surrounding prairie potholes can influence the salinity and permanence of water in potholes (Sloan, 1972, Rosenberry & Winter, 1997). Winter (1976) pointed out that the logical first step to defining the interaction of surface water and groundwater is to use numerical simulation to examine the patterns of groundwater flow.

The current investigation improved the ability of Gerla's (1999) numerical model to calculate water table depth and to map the spatial pattern of recharge and discharge for a watershed in the prairie pothole region. The work involved: (1) preparation and development of spatial datasets to define the initial conditions for the numerical model, (2) the integration of a statistical tool into the numerical model to select the configuration of the water table that best matched the observed

water table, and (3) the application of the model to a watershed with heterogeneous physical characteristics (elevation, hydraulic conductivity, and water table depth) and a temporally variable water budget.

Model output provides a numerical representation of hydrodynamics within a watershed. Quantification of the interaction of ground, surface, and atmospheric water has applications in managing water supply and quality. The interaction of wetlands with adjacent groundwater and surface water systems determines its water budget components and its effect on down gradient water quantity and quality.

Hydrologic Framework

Groundwater movement relative to prairie potholes depends on the configuration of the adjacent water table and the hydraulic conductivity of the glacial drift (Sloan, 1972). Hubbert (1940) provided a descriptive model of groundwater flow in which the water table reflects the general pattern of surface topography. Recharge of the groundwater system occurs at topographic highs and discharge occurs at topographic lows. Toth (1962, 1963) used theoretical models to expand this concept indicating that flow systems of different magnitudes could overlie one another. A local flow system is defined as a flow system that recharges at water table highs and discharges to adjacent lowlands. Intermediate and regional systems underlie the local flow system and recharge at major topographic highs and discharge at major topographic lows. Subsequent field

investigation of natural groundwater flow patterns revealed that not all depressions are areas of groundwater discharge. Studies by Meyboom (1966) indicated some prairie potholes contribute to recharge while others receive discharge and contribute to recharge at the same time (Meyboom, 1967). Lissey (1971) proposed a concept of depression focused recharge for prairie potholes in regional and topographic highs. The major portion of all water available for recharge collects in depressions on regional topographic uplands prior to infiltration; the depressions then act as focal points for groundwater recharge. Zebarth et al. (1989) reached similar conclusions in a study of water movement in hummocky terrain in central Saskatchewan. Sloan (1972) and Winter and Carr (1980) reported that seepage from topographically higher wetlands could flow via groundwater to discharge into wetlands at lower elevations. More recent studies by Mills and Zwarich (1986) and Winter and Rosenberry (1995) indicated the process was highly variable temporally and spatially, and the direction of flux changed frequently. Meyboom (1967), Winter and Rosenberry (1995), and Mills and Zwarich (1986) indicated that transpiration can cause water table troughs to form adjacent to some wetlands. Water seeps from the wetland to the groundwater trough during periods of high water and then reverses and flows toward the wetland as evapotranspiration creates a sink for groundwater during the summer.

Groundwater Model

Early studies of theoretical flow fields adjacent to lakes and wetlands were conducted by Winter (1976, 1978), Winter and Pfannkuck (1984), and Pfannkuck and Winter (1984) using numerical simulation. Groundwater flow fields were described by coupling Darcy's Law with an expression for mass conservation (see Freeze & Cherry, 1979, p.64). More recently Stoertz and Bradbury (1989) used numerical methods to calculate the magnitude and direction of groundwater flux for an unconfined aquifer using Darcy's Law and the continuity equation for steady-state flow. The water table in the aquifer was modeled as a fixed specified-head surface. Darcy's Law was used to calculate the flux between adjacent grid cells. The water budget of each cell within the system was calculated using a modified version of MODFLOW (McDonald & Harbaugh, 1984). Conservation of mass was maintained by equating the deficit or surplus in flow balance to discharge or recharge within the cell. Contouring of the flux rates provided the areal distribution of recharge and discharge zones. The investigation concluded that the pattern of flux was more reliable than the magnitude of flux as rates were found to be sensitive to grid scale - the aquifer was discretized at quarter, half, and one mile increments. Zhang and Montgomery (1994) noted a scale effect for topographic and hydrologic parameters calculated for two catchments discretized at 2, 4, 10, 30, and 90 meter scales. Feinstein (1986) indicated that with increasing cell size increasing amounts of "internodal flow" are lost.

Gerla (1999) extended the method of Stoertz and Bradbury (1989) to incorporate digital terrain data in a groundwater model for estimating the spatial distribution of recharge and discharge zones. The estimation technique combined the use of digital elevation models (DEMs) with finite difference code to solve the groundwater equation for transient, unconfined flow (see Wang & Anderson, 1982, p.87). The numerical solution assumes: (1) the water table reflects the general pattern of surface topography, (2) the hydraulic gradient is equal to the slope of the water table, and (3) the gradient within the flow field is gentle and no vertical gradients exist. The first assumption was based on work by Hubbert (1940) and Toth (1962, 1963) and discussed by Fetter (2001, p. 237-243) describing flow in an unconfined aquifer. The other two assumptions are known as the Dupuit approximation and allow a three-dimensional system to be reduced to two dimensions by assuming the vertical component of flow is negligible. Calculations based on the Dupuit assumptions compare favorably with those based on more rigorous methods when the slope of the free surface is small and when the depth of the unconfined flow field is shallow (Freeze & Cherry, 1979).

DEM grid elevations were used as initial heads in the model. The water table was initially assumed to be everywhere coincident with the topographic surface. Stepwise groundwater drainage from the flow domain was simulated until a reasonable match was obtained between the observed and model water table configuration. Gerla (1999) used the model to simulate the water

table at two sites at the United States Geological Survey's (USGS) Shingobee River Headwaters Interdisciplinary Research Initiative site in north central Minnesota. At the Shingobee sites, a reasonable match was obtained between the model and observed water table. Limitations associated with these initial trials included: (1) the modeled area was limited in size, (2) distinct areas were assumed to have homogeneous hydraulic conductivity, (3) a simple qualitative method of comparing the model to the observed water-table was used, and (4) the model was used to describe wetlands and groundwater discharge zones as static, temporally constant features.

The application of the model to limited areas with uniform physical characteristics treats wetlands as isolated homogeneous systems independent of other hydrologic features. As indicated by Labaugh et al. (1987) studies of individual wetlands fail to yield the complete range of groundwater to wetland interactions. The current work applies the model to a watershed containing fifteen hundred documented wetlands representing a continuum of size, permanence, and topographic position. Application of the model to large watersheds renders qualitative assessments of model output impractical and necessitates an automated method of calibration. Integration of statistical methods of calibration into the model code has the benefit of providing a quantitative assessment of model output and an automated method of selecting the iteration that best represents observed conditions.

Site Characterization

The research site is a 96.3 km² watershed along the upper reaches of the North Branch of the Turtle River in northeastern Nelson and northwestern Grand Forks Counties, North Dakota. Boundaries of the watershed fall within the Fordville SE, Fordville SW, Lake Pickard, Lamb Lake, and Michigan East USGS 7.5 minute quadrangles. The watershed is composed of gently rolling low relief topography with poorly integrated drainage. The surface is covered by numerous shallow water-holding depressions of glacial origin termed prairie potholes. Regional climate is continental with evapotranspiration exceeding input from direct precipitation and runoff (Shjeflo, 1968; Eisenlohr, 1972; Woo and Roswell, 1993; and Winter and Rosenberry, 1998). Sediment is predominantly glacial drift deposited beneath active ice or during mudflows that formed on ablation of the glacier. Glacial drift in the watershed is composed primarily of shale, silt, and sand reflecting the lithology of the underlying bedrock (Lemke, 1960). Three well logs available for the site indicate a silty clay till underlies the watershed to a depth of 20-40 ft (wells were installed and logged by the United States Air Force and published in Downey, 1971).

The Pierre Shale underlies glacial drift within the watershed. Sedimentary units formed during transgression and regression of marine waters during the Paleozoic and Mesozoic Eras (Bluemle, 1973). Bedrock dips to the west, but regional groundwater flow is to the east and northeast (Downey, 1973).

CHAPTER II

METHODOLOGY

GIS Environment

Research was initiated by constructing a digital database of spatial information pertaining to the watershed. Watershed data included the following: wetlands from the National Wetlands Inventory (NWI), soils from the National Resource Conservation Service (NRCS), digital elevation models (DEMs), and digital raster graphics (DRGs) from the USGS. Data were downloaded as 1:24,000 scale 7.5 minute quadrangles. Datasets were constructed, adapted, visualized, and analyzed using GIS from Environmental Systems Research Institute (ESRI) (ArcView 3.2) and Golden Software, Inc (Surfer 8.0). The base functionality of ArcView 3.2 was enhanced using extensions available from ESRI.

The watershed was delineated from thirty-meter DEMs (30 meter raster grid cell) using the methodology developed by Jensen and Domingue (1988). The DEMs were preprocessed to remove sinks - cells with undefined flow direction - to create a depressionless DEM. Sinks in coarse DEMs often result from sampling error and only rarely reflect the natural topographic continuum (Mark, 1988). The filled DEMs were used to calculate node-to-node flow direction. A flow accumulation grid was defined by counting the number of cells that flow into each downslope cell. A stream

network was created by applying a threshold value to a subset of cells with a high accumulated flow. A watershed large enough to completely contain the basin and associated till plains of the upper North Branch of the Turtle River was defined by including all cells upslope of the surface water discharge point of the drainage system. The specified watershed served as the fundamental spatial unit for the application of the groundwater model.

Model Input Files

The DEM, soil, and wetland datasets provided the basis for creating the initial head, hydraulic conductivity, and observed water table matrices for the groundwater model. Datasets were generated using GIS and saved as ASCII grids for importation into the model.

Initial Head Grid

The initial head matrix was a numerically filtered DEM of the watershed. Filtering of the DEM was performed with Surfer to smooth the transition between adjacent grid cells. In a grid, the transition between cell values is instantaneous in space and does not reflect the natural topographic continuum. When a grid is filtered, each cell of the grid is calculated as a function of itself and its neighbors resulting in a smoothing of the transition between neighboring cells. Smoothing allows a better approximation of the natural topographic continuum. The type of filter used to smooth the DEM was a linear convolution (computes a weighted average of neighboring cells) low-pass filter (removes

high frequency noise) using distance weighting (weights fall off with increased distance from the origin) (Equation 1 from Golden Software, 2002).

$$W(i, j) = \left(1 - \max \left(\frac{2 \cdot |i|}{S+1}, \frac{2 \cdot |j|}{T+1} \right) \right)^p \quad 1$$

W = distance weighting function
i = integer column number from origin
j = integer row number from origin
S = neighborhood height
T = neighborhood width
p = specified power

The neighborhood was defined to be a 5 x 5 matrix, the specified power for the distance weighting function was 2, and only one pass was performed. The specifications defined iso-weight contour lines that were concentric rectangles about the origin (Figure 1). The effect of filtering can be observed in the smoothing of contour lines (Figures 2 & 3).

	2	1	0	1	2
2	0.111	0.111	0.111	0.111	0.111
1	0.111	0.444	0.444	0.444	0.111
0	0.111	0.444	1.000	0.444	0.111
1	0.111	0.444	0.444	0.444	0.111
2	0.111	0.111	0.111	0.111	0.111

Figure 1. Filter Neighborhood & Weight

A qualitative assessment of the degree of change caused by smoothing the DEM was performed by calculating grid statistics before and after smoothing (Table 1). Computations were performed using the statistical functions available in Surfer.

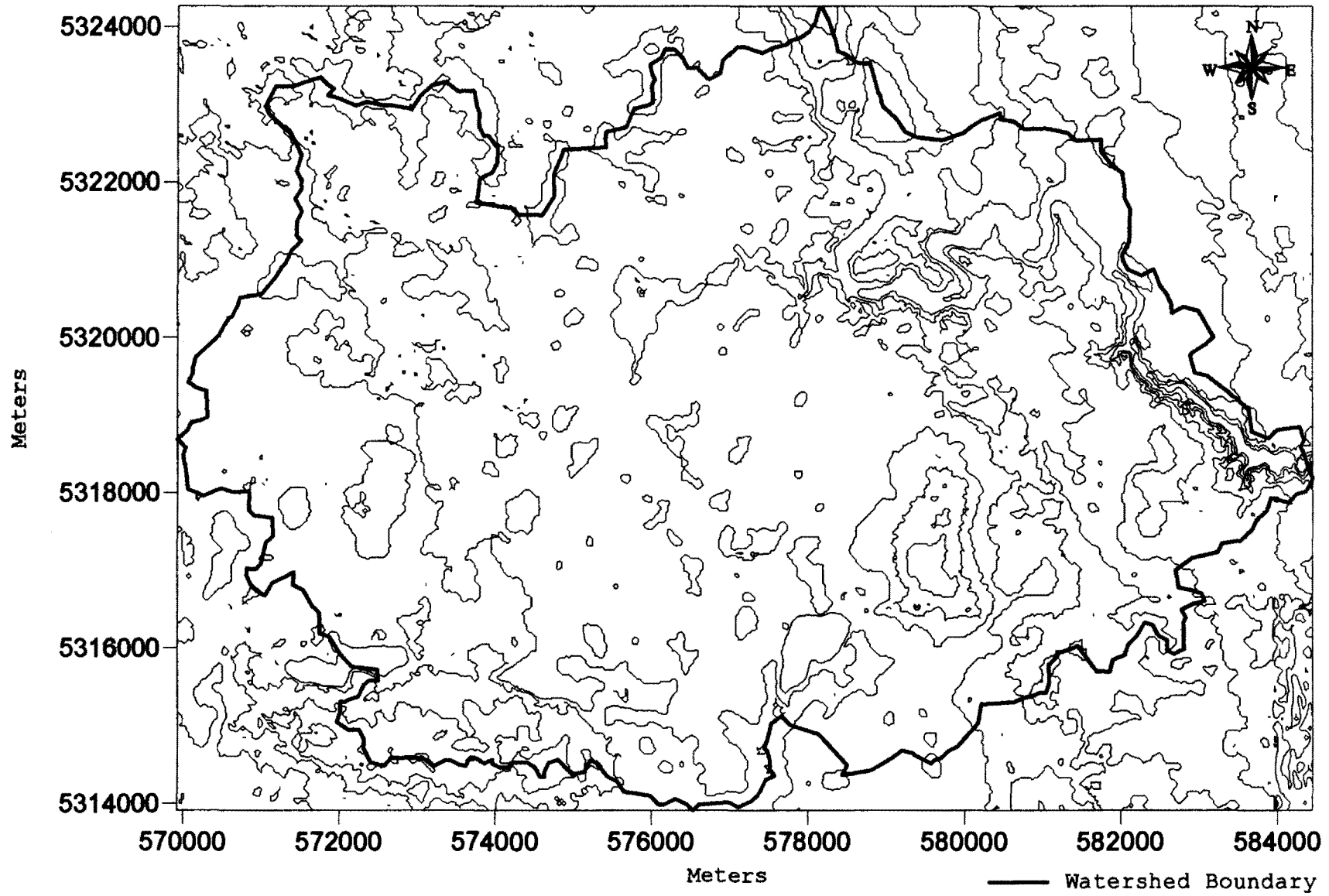


Figure 2. Contoured DEM Before Filtering.

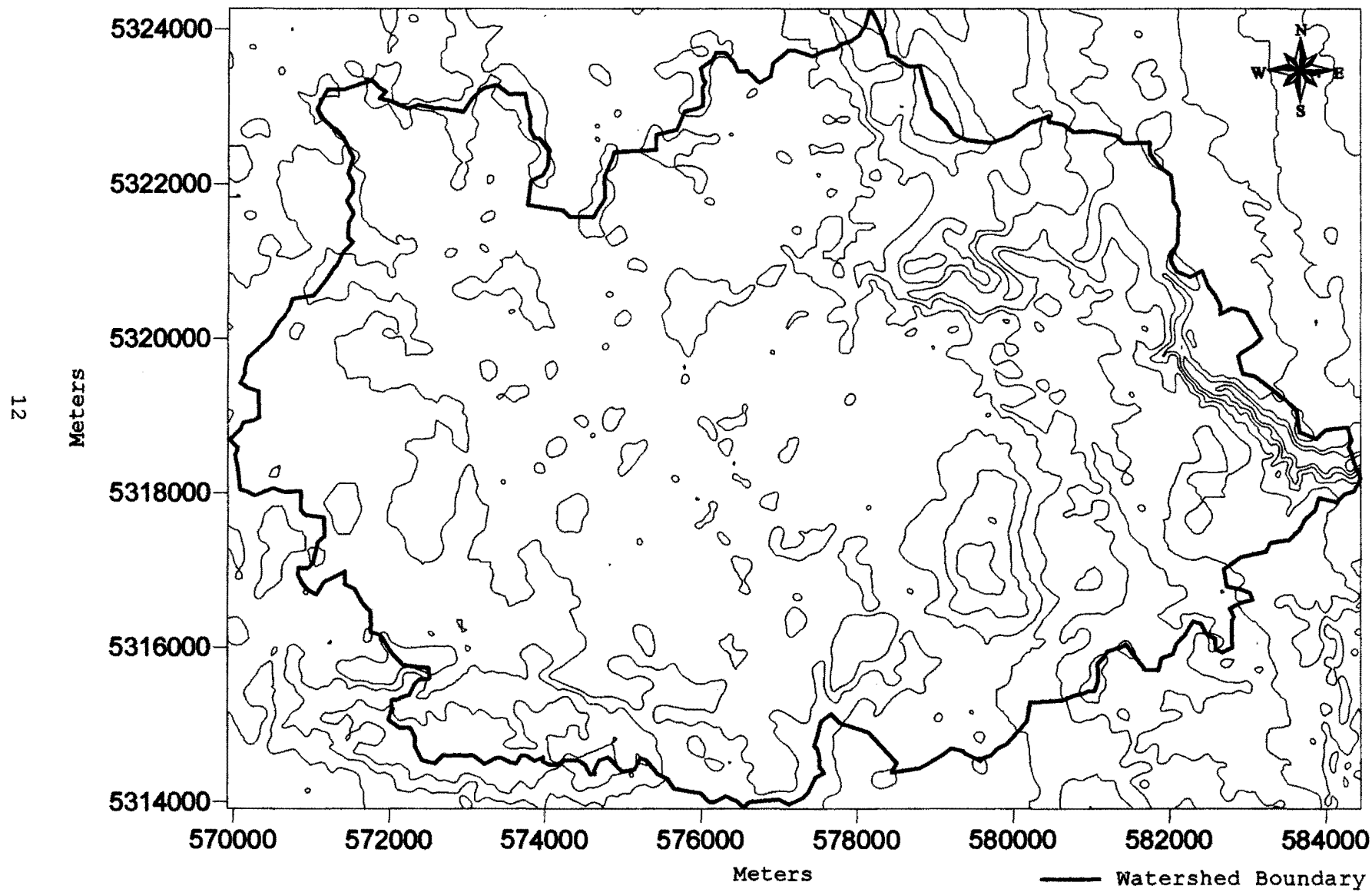


Figure 3. Contoured DEM After Filtering.

Table 1. DEM Elevation Statistics.

Statistics	Original DEM (m)	Smoothed DEM (m)	% Difference
Mean	457.589	457.589	0.000
Variance	134.892	134.176	0.532
Standard Deviation	11.614	11.583	0.267
Root Mean Square	457.736	457.735	0.000

The statistics indicate the smoothing function did little to change the basic characteristics of the grid. Any changes were within the accuracy standards defined by USGS National Mapping Program Standards (1998) for a DEM, the highest standard of which desires a vertical Root Mean Square Error (RMSE) of 7 meters or less, but a maximum of 15 meters is permitted. The smoothed DEM (Figure 4) was prepared for application in the groundwater model by exporting the DEM as an ASCII grid.

Hydraulic Conductivity Grid

The hydraulic conductivity matrix was created from NRCS soil surveys for Grand Forks (Doolittle et al., 1981) and Nelson (Heidt et al., 1989) Counties. Soil maps provided the spatial distribution of soil units while soil descriptions provided the basis for calculating a hydraulic conductivity value. Each soil series was associated with a range of hydraulic conductivity. A limitation of the soil data was hydraulic conductivity values pertained only to the upper 1.5 meters of soil while the numerical model could drain the landscape to depths beyond that. The soil data were viewed as an economical source of data on the general hydraulic regime within the watershed.

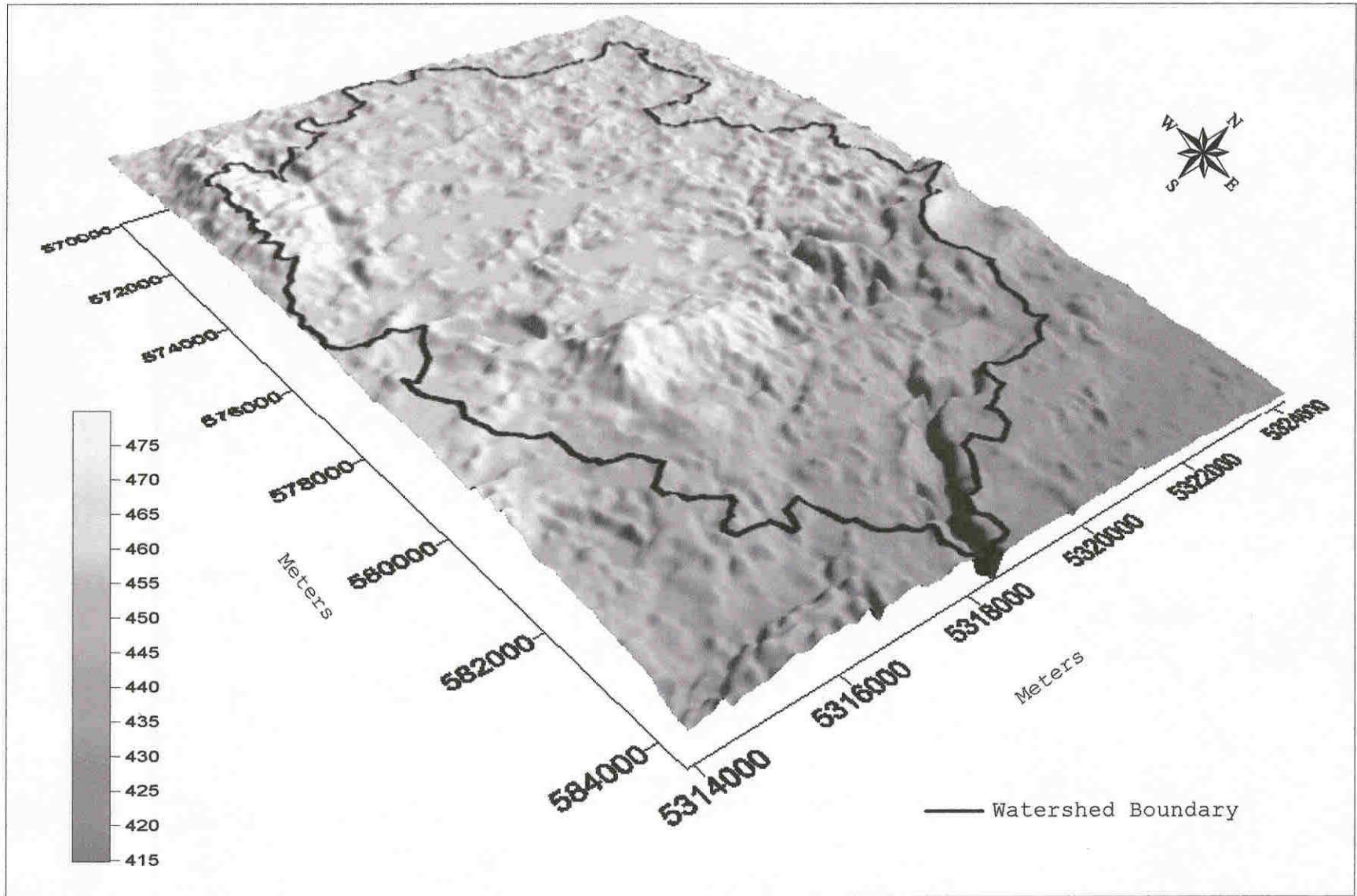


Figure 4. Hillshade of DEM (V.E. 1:24).

The soil surveys for Grand Forks (Doolittle et al., 1981) and Nelson (Heidt et al., 1989) were acquired in hardcopy format. The watershed was found to lie within Nelson County map sheets 16, 17 (Inset), 21, 22, 27, 28, 29, and in Grand Forks County map sheets 26 and 35. The relevant map sheets were scanned, saved, imported into a graphics application, and pasted together to form a composite soils image covering the watershed. The composite soils image was imported into ArcView and georeferenced within the project view using geometric correction - a method of registering one spatial dataset to another.

The soils image was corrected to DRGs containing the watershed. The projection was UTM Zone 14, North American Datum 1927 (NAD 27). Geometric correction of the image was accomplished through selection of ground control points, transformation of points via a first-order polynomial, and the assignment of node values using nearest neighbor resampling. The polynomial established the relationship between points in the reference and distorted image while resampling established the value of the point. The accuracy of the method was assessed by performing a visual inspection of the alignment of features on the soils image with the same features on the DRGs. On average, the error in alignment of transportation networks and political boundaries between the corrected soil image and the DRGs was on the order of 10 meters. As the corrected soils image was a composite of multiple map sheets, some variance existed in the magnitude of

displacement of features. The method and results were considered acceptable in view of model discretization and accuracy.

Once in place, the individual soil polygons were digitized and identified with soil survey mapping units. Soil polygons within the watershed and a 120 meter buffer zone were digitized. The buffer zone was digitized to assure adequate model results at the margins of the watershed. Care was taken in the digitizing process to create an accurate and seamless polygon theme of the original soils image. Each polygon was assigned a symbol (identified from the hard copy maps) as it was created to ensure accurate identification. The Grand Forks and Nelson County soil maps were found to use different symbols to indicate similar soil series. To achieve consistency, all Grand Forks soil symbols were converted to the Nelson County equivalent as the watershed was primarily within Nelson County (Table 2).

Table 2. Soil Symbol Substitutions

Nelson County			Grand Forks County		
Symbol	Name	Slope	Symbol	Name	Slope
10	Svea Loam	1-3	12	Svea Loam	0-3
11B	Svea-Buse Loams	3-6	130B	Svea-Buse Loams	1-6
11C	Svea-Buse Loams	6-9	130C	Buse-Svea Loams	1-9
12B	Barnes-Svea Loams	3-6	13B	Barnes loam	3-6
15	<i>Borup Silt Loam</i>		76	<i>Borup Silt Loam</i>	
20	<i>Hamerly Loam</i>	0-2	19	<i>Hamerly Loam</i>	1-3
21	Vallers and Hamerly loams, saline	0-3	39	Vallers-Manfred Clay Loams, saline	
22	Vallers Loam	0-3	3	Vallers Loam	
23	Cavour-Cresbard Loams	0-3	23	Cresbard-Cavour Loams	0-3
26B	<i>Cresbard-Barnes Loams</i>	3-6	23B	<i>Barnes-Cresbard Loams</i>	1-6
35	LaDelle Silt Loam channeled		46	LaDelle Silt Loam	0-3
38B	<i>Renshaw loam</i>	1-6	89	<i>Renshaw Loam</i>	1-3
70E	Kloten-Buse loams	9-25	98E	Edgeley-Kloten Loams	6-25

-Match based on alignment of soil polygons on soil image.

-Match based on similarity of name (*italicized text above*).

A two-step process was used to create a soils theme with seamless coverage of the watershed. The first step was to enable general snapping during digitizing to ensure the vertices of new polygons aligned with the vertices of adjacent polygons. The second step was to copy the soils theme, combine the polygons in the copy, and correct the intact original. Combining features removed the common boundary between adjacent polygons to create a single continuous polygon. If adjacent polygons overlapped, the area of overlap was removed from the resulting combined polygon, resulting in a hole. Similarly if two selected polygons were separated by a gap, the area of separation resulted in a hole. The end product was a single polygon with holes representing areas where the original had errors, either overlaps or gaps. Errors found in the combined polygon were removed by adjusting the vertices of polygons in the original soils theme. To complete the soils theme, a single polygon with an attribute of no data was described around the watershed to extend the soils theme to the same dimensions as the initial head matrix.

To incorporate hydraulic conductivity data into the soil theme, a table relating soil type to hydraulic conductivity was created and joined to the soil theme. The hydraulic conductivity of soil series was described qualitatively in the NRCS soil descriptions (Heidt et al., 1989, p.75-92). The qualitative description was converted to a single average quantitative value (Table 3) by referencing the definition of each qualitative

description (see Heidt et al., 1989, p.100, definition of permeability).

Table 3. Hydraulic Conductivity Values

Qualitative Description	K Range (in/hr)	K Average (in/hr)	K Average (m/day)
Very Slow	<0.06	0.03	0.02
Slow	0.06 to 0.20	0.13	0.08
Moderately Slow	0.20 to 0.60	0.40	0.24
Moderate	0.60 to 2.00	1.30	0.79
Moderately Rapid	2.00 to 6.00	4.00	2.44
Rapid	6.00 to 20.0	13.0	7.92
Very Rapid	>20	20.0	12.2

The value of hydraulic conductivity assigned to a soil unit was based on a weighted average. Each soil unit was an association of one or more major and minor soil series. The soil series were so intricately intertwined at a local scale that they were described as a unit. Some of the minor constituents had properties that differed substantially from those of the major soil or soils. Such differences could significantly affect soil characteristics (Heidt et al., 1989). The composition of heterogeneous soil units was described by the NRCS in terms of percentages (Heidt et al., 1989, p.17-53). For example, Svea-Buse loams are about 55-70% Svea soil, 20-30% Buse soil, and about 10% Cresbard, Parnell, Tonka, and Vallers soils. To achieve consistency in approach, the following rules were used to calculate average unit composition:

1. If a percentage range was given for the presence of a soil series the value used was the mid-point in the range. For example, 55-70% Svea-Buse soil would provide a value of 62.5%.
2. If a group of soils was assigned a single percentage value, the percentage of each member of the group was equal to the single percentage value divided by the total number of group

members. Continuing the Svea-Buse example, Cresbard, Parnell, Tonka, and Vallers soils compose 10% of the Svea-Buse soil unit so each soil series was assigned a value of $10/4 = 2.5\%$.

3. If after the application of rules one and two the percentages for a soil series did not sum to 100%, the difference between the sum and 100% was divided by the total number of soil series that composed the soil unit. The new number was then added or subtracted from the percentage of each soil series present in the soil unit. The percentage for the Svea-Buse soil summed to 97.5% with a difference from 100% of 2.5%. The difference of 2.5% was divided by six total soils series and added to the value of each soil percentage to achieve 100% (Table 4).

Table 4 Svea-Buse Loam Example

Series	Area	Dscrpt.*	K (m/day)	
			Avg.	Weighted
Buse	0.254	MS	0.24	0.061
Cresbard	0.029	MS	0.24	0.007
Parnell	0.029	S	0.08	0.002
Svea	0.629	MS	0.24	0.151
Tonka	0.029	S	0.08	0.002
Vallers	0.029	MS	0.24	0.007
	1.00			0.230

*Descriptions abbreviated from Table 3.

To provide the best representation of a soil unit all constituents were used to derive an overall average. The value assigned for hydraulic conductivity for a particular soil unit was the average percentage of each major and minor soil series (adjusted to sum to 100%) present in the unit multiplied by the average hydraulic conductivity (Table 3) of each series. The total hydraulic conductivity of the unit was the sum of all the weighted individual conductivities (Table 4). The methodology described was applied to each of the soil units to determine a hydraulic conductivity value (Table 5). In the case of areas without assigned series and areas of permanent water cover, a weighted average of permeability for the entire watershed was

calculated and applied. A hydraulic conductivity value was assigned to cells in areas without an identified soil series to meet model design requirements, but it was of no relevance as areas without soil data were outside the watershed.

Table 5. Watershed Soils Data.

Symbol	Soil Name*	Slope	Watershed Area		K m/day	Hydric Code**
			km ²	%		
2	Parnell Silt	0	1.27	1.32	0.10	H
3	Playmoor Silty Clay	0	1.02	1.06	0.23	H
4	Southam Silty Clay	0	3.36	3.49	0.09	H
5	Hamerly-Tonka Complex	0-3	5.37	5.58	0.09	M
7	Parnell-Vallers Complex	0-3	14.18	14.72	0.14	M
10	Svea	1-3	4.82	5.00	0.24	N
11B	Svea-Buse	3-6	19.97	20.74	0.23	N
11C	Svea-Buse	6-9	7.66	7.96	0.24	N
12B	Barnes-Svea	3-6	7.03	7.30	0.31	N
13D	Buse-Svea	9-15	1.77	1.84	0.40	N
13E	Buse-Svea	15-25	0.00	0.00	0.73	N
14D	Sioux-Barnes	6-15	0.96	1.00	7.40	N
15	Borup Silt	0	0.02	0.02	1.65	H
20	Hamerly	0-2	6.05	6.28	0.09	N
20B	Hamerly	2-5	9.11	9.46	0.09	N
21	Vallers & Hamerly	0-3	3.55	3.69	0.16	M
22	Vallers	0-3	0.20	0.21	0.23	H
23	Cavour-Cresbard	0-3	1.05	1.09	0.15	N
24	Svea-Cresbard	0-3	1.94	2.01	0.24	N
25	Miranda-Cavour	0-3	0.07	0.07	0.08	N
26B	Cresbard-Barnes	3-6	1.04	1.09	0.21	N
35	LaDelle Silt	0	0.03	0.03	1.54	N
36B	Arvilla Sand	0-6	0.01	0.01	7.46	N
38B	Renshaw	1-6	0.19	0.20	2.36	N
39E	Sioux	6-25	0.13	0.13	10.75	N
40	Divide	0-3	0.20	0.20	5.52	N
42B	Brantford	1-6	0.13	0.13	0.74	N
45E	Zell-Maddock Complex	6-25	0.00	0.00	3.79	N
46C	Wamduska-Mauvais Complex	1-9	0.31	0.32	3.83	N
48B	Barnes-Renshaw	1-6	1.91	1.98	1.56	N
70E	Kloten-Buse	9-25	1.42	1.48	0.54	N
73	Lamoure Silty Clay	0	0.98	1.02	0.79	H
	Water	---	0.53	0.55	0.34	H
	No Data	---	0.00	0.00	0.34	N
			96.3	100		

* Soils were all loams

** H = hydric, M = mixed, and N = not hydric

Hydraulic conductivity was calculated from soils data to provide representation of the heterogeneity of permeability rates within the watershed. Stoertz and Bradbury (1989) noted recharge

rates were "extremely" sensitive to hydraulic conductivity. The averaging technique used to calculate hydraulic conductivity was designed to provide the best estimate of conductivity within a soil unit, given the data limitations. The polygon theme containing hydraulic conductivity data (Figure 5) was converted to a grid with the same cell and neighborhood dimensions as the DEM in preparation for import into the model. The hydraulic conductivity grid was exported from ArcView in ASCII format.

Reference Matrix

The groundwater model simulated the water table as a temporally and spatially dynamic feature. To identify the water table configuration that best represented actual water table conditions, observational data on field conditions were input into the model. Sloan (1972) indicated the water table in the Prairie Pothole Region is a shallow surface continuous with the water surface in prairie potholes. Datasets on the spatial distribution of wetlands and hydric soils were used to identify zones where the water table was shallow. The watershed was considered as a dynamic hydrologic feature by using datasets describing the watershed in three separate states: (1) a base state defined by NWI maps, (2) a wet state from Landsat Thematic Mapper images on August 5, 2002, and (3) a dry state from Landsat Thematic Mapper images on July 14, 1991.

The hydrologic state of the watershed was quantified using the Palmer Drought Severity Index (PDSI) (Palmer, 1965) for North Dakota Climate Division 3. PDSI values were obtained from the

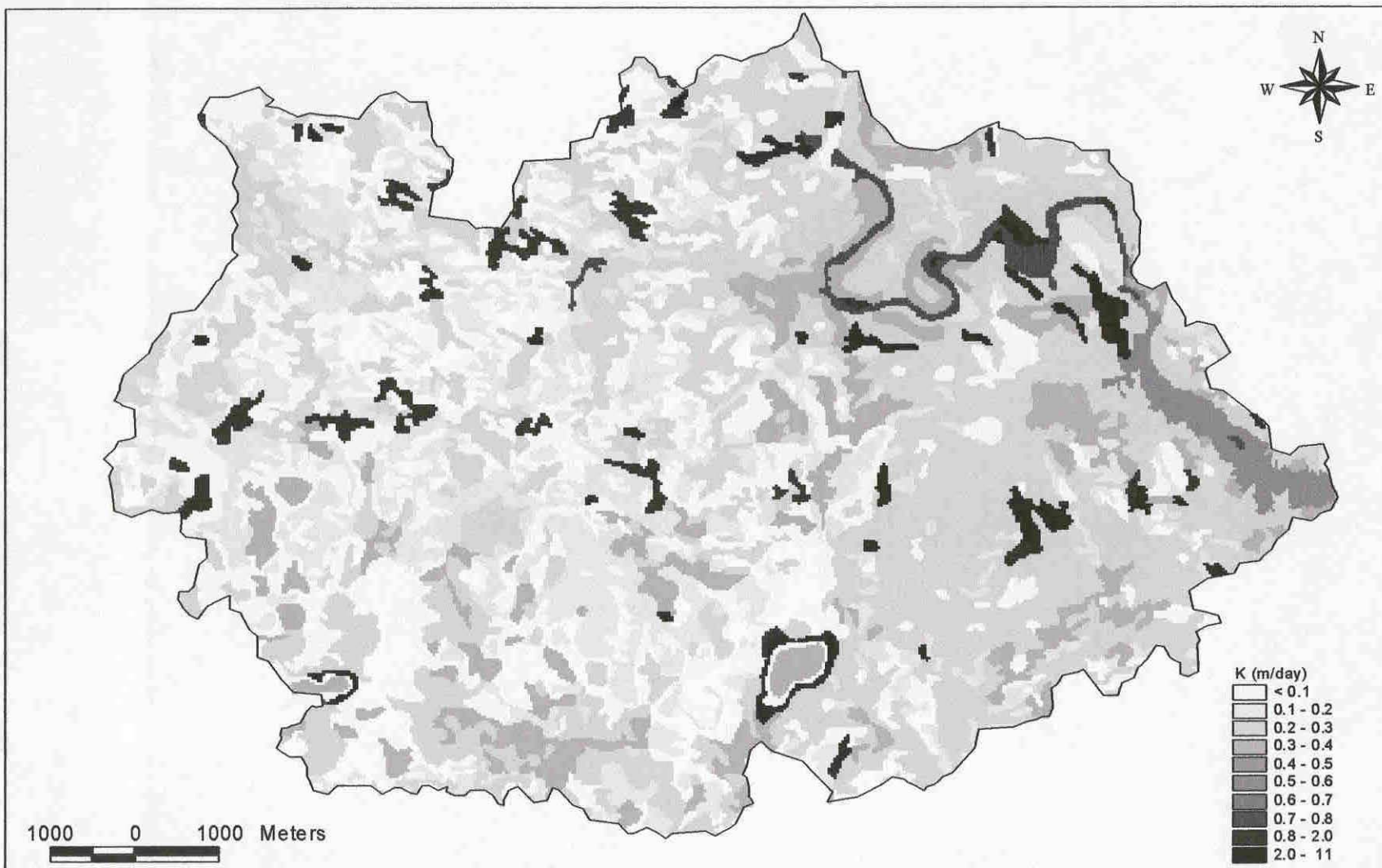


Figure 5. Hydraulic Conductivity Map of the Watershed.

National Climate Data Center (NCDC) drought data file. The PDSI is a drought index, based on precipitation, evapotranspiration, and soil moisture that was found to have a strong relationship to wetland extent (Winter and Rosenberry, 1998; Sorenson et al. 1998). The PDSI assigned a value of zero to neutral conditions, positive to excess moisture, and a negative value to denote drought condition. The magnitude of the number denotes degree of variation from base conditions. The NWI maps described the watershed from aerial photographs taken in June 1979 and April 1981. In June 1979 and April 1981 the watershed was characterized by a PDSI value of 1.89 and 1.85 (mild to moderate wetness), respectively, in August 5, 2002 a value of 3.26 (severe wetness), and in July 1991 a value of 0.85 (near normal). All values fell in the positive moisture range, but were used to define a range from dryer to wetter conditions.

The base distribution of wetlands in the watershed was described from NWI wetlands. The wetland maps were downloaded and reclassified to serve as reference grids for the groundwater model. Reclassification assigned a value of one to grid cells with a shallow water table and zero to areas with deeper water tables. A shallow water table was defined as a water table which intersected the surface and was coincident with the free surface of a wetland. The wetland reference grids were further broken down based on the Cowardin et al. (1979) classification to observe whether the persistence of wetlands on the landscape could be correlated with model output.

The Cowardin et al. (1979) classification takes into account hydrologic setting, which is the interaction of atmospheric, surface, and groundwater with basin topography and hydraulic characteristics (Kantrud et al., 1989). The hydrologic setting of wetlands in the watershed was described following the Cowardin et al. (1979) definitions into one of four categories: A, C, F, or G. Classification A described temporary wetlands as wetlands with surface water present for brief periods and a water table usually "lying well below" the soil surface. Class C described seasonal wetlands as wetlands with surface water present for extended periods and a water table, after drying out, that extended from the surface to "well below" the ground surface. Class F wetlands were semipermanent and had surface water persisting throughout the growing season in most years. When surface water was absent in Class F wetlands, the water table was usually at or "very near" the land's surface. Class G wetlands were defined as intermittently exposed with surface water present throughout the year except in years of extreme drought. Four wetland grids ACFG, CFG, FG, and G, based on increasing permanence, were created and established as reference grids for the model.

A natural corollary of wetland reference grids was the generation of a reference grid from hydric soils data. Hydric soils were defined as soils sufficiently wet in the upper part to develop anaerobic conditions. Hydric soils within the watershed were identified from the NRCS list of hydric soils in North

Dakota. The list of hydric soils was developed based on criteria documented in Soil Taxonomy (Soil Survey Staff, 1999). Soils within the watershed classified as hydric were: poorly drained, had a water table within 0.3 meters of the surface, permeability less than 3.6 meters/day, and/or were ponded for long duration. The reference grid for the model was created by reclassifying grid cell values using 1 for hydric soils and 0 for non-hydric soils.

The dynamic state of the watershed was documented from Landsat images classified according to land cover using Earth Resources Data Analysis System (ERDAS) Imagine 8.5, and an unsupervised ISODATA classification technique (Sethre, 2003). Classification work on the Landsat images was done by the University of North Dakota Geography Department in coordination with this work. A 'clump' function was performed on each layer of Landsat images to identify contiguous pixels of the same class value, an 'eliminate' function was then performed to eliminate all clumps less than one acre in size. The resampling was done to eliminate any solitary pixels and to improve overall appearance by reducing speckling. An accuracy assessment was completed for both land classification datasets. The August 5, 2002 dataset was found to have an overall accuracy of 72.49% while the July 14, 1991 dataset had an overall accuracy of 75.90%. The Landsat images were prepared for the model by converting the images to grid files and assigning a value of 1 to areas covered with water and a value of 0 to the rest of the

watershed. All reference grids were prepared for input into the groundwater model by saving as in ASCII file format.

Model Design & Application

The conceptual approach, design, and procedure of the groundwater model were discussed by Gerla (1999). The initial water table was coincident with the topographic surface represented by the DEM. Water was allowed to flow under the influence of gravity to lower elevations in incremental time steps. The rate of flow was defined by the slope of the water table, computed at each time step, and the magnitude of hydraulic conductivity - applied as a heterogeneous variable in the current model. Each time step served as a possible steady-state water table configuration. Model output at each time step included three grid arrays: water-table elevation, recharge/discharge flux, and an integer array identifying areas of grid with a shallow water table. Calibration of model output was achieved by ensuring groundwater flux did not exceed precipitation and was approximately 35% less (Eisenlohr, 1972, p.A15, Figure 12) due to evapotranspiration. Calibration was completed by selecting the model water table that best matched the observed water table configuration.

Gerla (1999) calibrated the model qualitatively by visually comparing the water table configuration at each time step to observational data. The extent of the current watershed rendered manual methods of calibration impractical. A statistical component was added to the groundwater program to perform an

automated quantitative calibration. The statistical component was fully integrated into the model to offer (1) a correlation coefficient for each time step, (2) water budget parameters based on the watershed domain, and (3) reduction of model output through automated selection of the best fit water table configuration.

Degree of correlation was established through the calculation of a Pearson product moment correlation coefficient as presented in Davis (1986, p.40-45) (Equation 2).

$$R := \frac{\sum_{i=1}^n x \cdot y - \frac{\left(\sum_{i=1}^n x \right) \cdot \left(\sum_{i=1}^n y \right)}{n}}{\sqrt{\left[\sum_{i=1}^n x^2 - \frac{\left(\sum_{i=1}^n x \right)^2}{n} \right] \cdot \left[\sum_{i=1}^n y^2 - \frac{\left(\sum_{i=1}^n y \right)^2}{n} \right]}}$$

2

R = correlation coefficient
n = number of elements
x = primary variable
y = secondary variable

The Pearson correlation coefficient measures the strength of the linear association between two variables (Mann, 1998). The correlation coefficient was calculated between the model output array indicating areas of shallow table and the reclassified reference grids. The data in both arrays were binary, a special subset of nominal, in which the symbolic tags 1 and 0 indicated the presence or absence of a condition. In the model, a value of

1 indicated a shallow water table while a value of 0 indicated a deeper water table - the depth to shallow water table was a user-defined input. The statistical package was designed to exclude grid cells within the model domain but outside the watershed. The correlation coefficient and water budget parameters were calculated based only on the watershed area. Grid cells outside the watershed were necessary to satisfy the boundary conditions for the finite difference computations of groundwater flow.

Validation of the output from the statistical program was achieved by computation of the correlation coefficient using Microsoft Excel™. The validation process was performed on a subset of the watershed to facilitate the importation of grids into Excel. The correlation coefficient was calculated by applying the redesigned model and using the CORREL worksheet function in Excel. The portion of the watershed selected was a localized high relief zone bounding a permanent wetland. The statistics calculated in Excel and those provided by the model were identical, indicating the statistics program was providing valid results (Table 6).

Table 6. Verification of Correlation

Variable	Excel	Model
n =	1221	1221
Σx =	537	537
Σy =	491	491
Σxy =	448	448
Σx^2 =	537	537
Σy^2 =	491	491
R =	0.781	0.781

CHAPTER III

RESULTS

The sensitivity of the redesigned model to input parameters was evaluated. The evaluation process helped identify the value of input variables that maximized the correlation between model output and observational data. Model output was compared to a sequence of reference grids containing information on the observed water table configuration.

Sensitivity Analysis

A sensitivity analysis was performed by varying model input of specific yield, hydraulic conductivity, and water table depth over a reasonable range and observing the relative change in model response. Model response was documented through time by recording changes in the correlation coefficient for each time step. Unless otherwise noted, simulations were run using an initial time step of 1.0 day, a wetland threshold requiring a water table depth of 0.5 m or less, a hydraulic conductivity matrix multiplied by a factor of 0.1, and the hydric soil reference grid.

The sensitivity of the model to specific yield was tested with the values 0.05, 0.15, 0.25, and 0.35. Specific yield is the ratio the volume water a soil will yield by gravity drainage to the volume of the soil. An average specific yield for a clay

matrix is 2% while coarse sand would have a value closer to 27% (Fetter, 2001, p.79). Each of the specific yield values was applied (Figure 6) and relevant grid statistics calculated (Table 7). Specific yield was found to affect only the time to peak correlation and not the magnitude of the peak. The results were consistent with the application of specific yield as a homogeneous parameter across the entirety of the model domain. The correlation coefficient is based on spatial pattern of flux while specific yield is a controlling factor on the rate of flux. A value of 0.15, consistent with a matrix of sandy clay to silt, was selected to represent the glacial sediment in the watershed.

Table 7. Specific Yield Sensitivity Data

Specific Yield	Time (Days)	Correlation (Unitless)	Recharge (m ³ /day)	Discharge (m ³ /day)	Precip* (in/yr)
0.05	343	0.50	-55841	58147	8.3
0.15	1029	0.50	-55862	58168	8.3
0.25	1713	0.50	-55889	58194	8.3
0.35	2397	0.50	-55902	58206	8.3

*Minimum precipitation for simulated recharge.

A hydraulic conductivity matrix was used in the model to provide a more realistic representation of the groundwater flux within the watershed. Stoertz & Bradbury (1989) indicated that flux rates were "extremely" sensitive to hydraulic conductivity. The soils data provided a coarse representation of hydraulic conductivity rates within the watershed but the actual magnitude of hydraulic conductivity values needed to be calibrated from climate data. The groundwater flux could not exceed precipitation. Mean monthly precipitation records for the

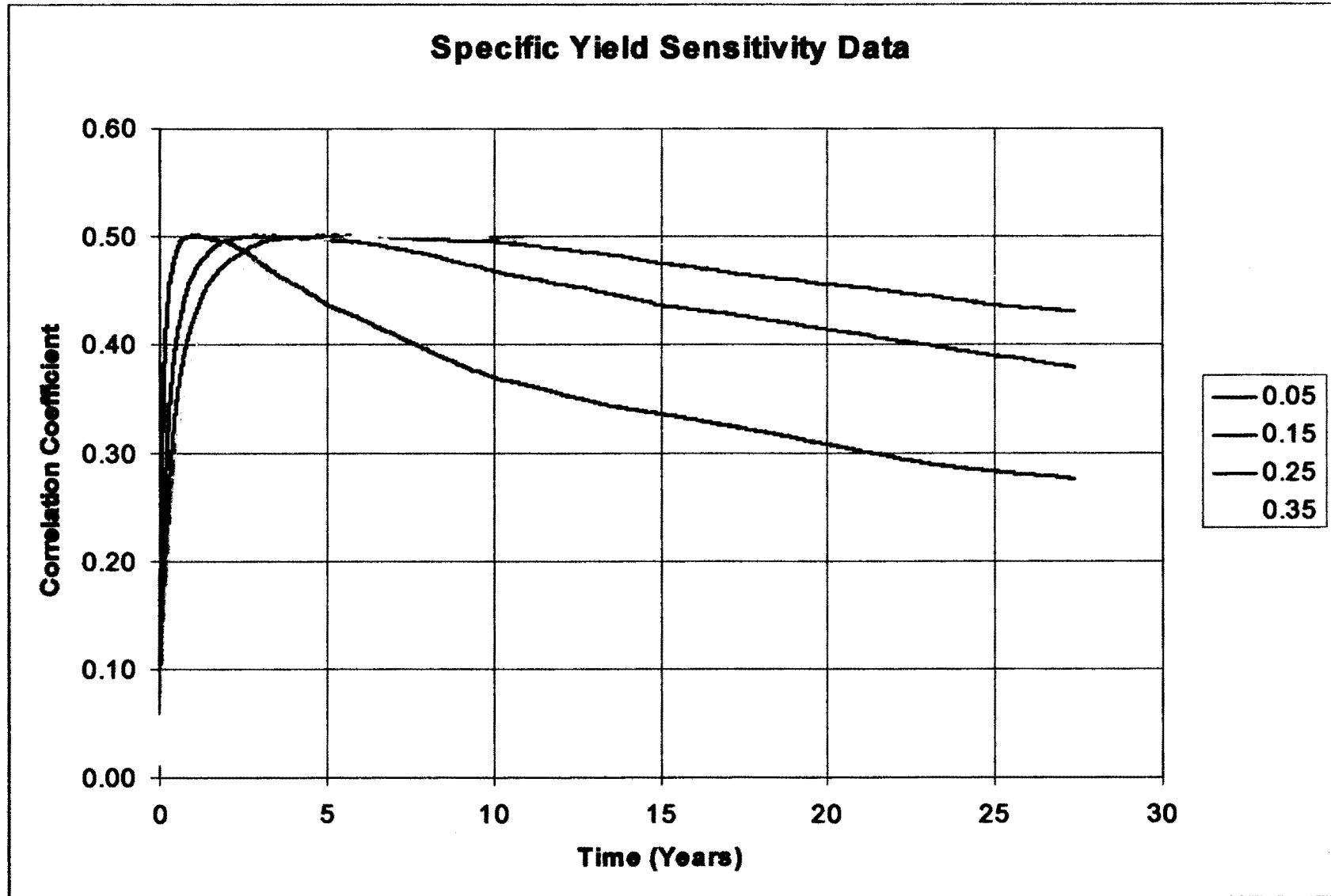


Figure 6. Sensitivity Analysis for Specific Yield.

watershed from 1931-2002 indicate an average value of 46.9 cm/yr (18.5 in/yr). Precipitation data were obtained from the Petersburg 2N National Climatic Data Center (NCDC) weather station located within the watershed.

To bring the groundwater flux rates into agreement with the precipitation data, the hydraulic conductivity matrix was multiplied by coefficients representing orders of magnitude changes in hydraulic conductivity. Multiplying the hydraulic conductivity matrix by a value of 0.1 brought groundwater flux in line with reasonable recharge rates based on precipitation. Orders of magnitude changes in the value of hydraulic conductivity caused time and flux rates to vary by approximately the same magnitude (Table 8 and Figure 7). Slight variations were possibly the result of differences due to temporal discretization.

Table 8. Hydraulic Conductivity Sensitivity Data

K Coefficient	Time (Days)	Correlation (Unitless)	Recharge (m ³ /day)	Discharge (m ³ /day)	Precip* (in/yr)
0.01	9957	0.50	-5661	5890	0.8
0.1	1029	0.50	-55862	58168	8.3
1	109	0.50	-551209	579944	81.9

*Minimum precipitation for simulated recharge.

The definition of shallow water table was varied in half meter increments from 0.0 and 2.0 meters below land surface to identify the depth which provided the maximum correlation coefficient. A water table depth of 0.5 m provided the peak

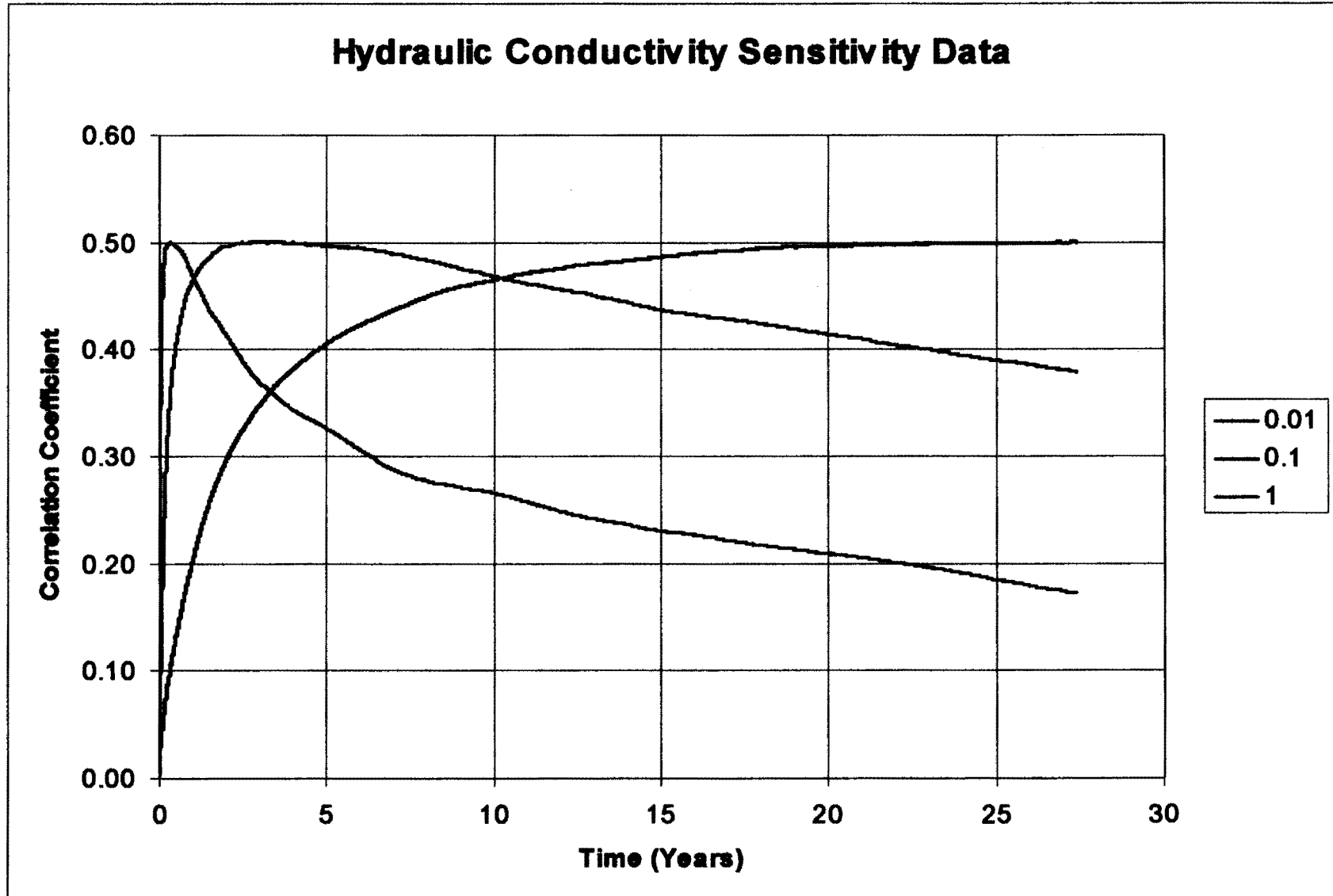


Figure 7. Sensitivity Analysis for Hydraulic Conductivity.

correlation coefficient and an annual precipitation rate most consistent with meteorological records (Table 9 and Figure 8). The peak correlation at a relatively shallow depth reflects the gently sloping nature of the terrain and the relatively slow movement of groundwater.

Table 9. Water Table Sensitivity Data

Depth	Time (Days)	Correlation (Unitless)	Recharge (m ³ /day)	Discharge (m ³ /day)	Precip* (in/yr)
0.0	223	0.34	-102094	102384	15.2
0.5	1029	0.50	-55862	58168	8.3
1.0	3821	0.50	-34726	36766	5.2
2.0	7769	0.46	-28081	29560	4.2

*Minimum precipitation for simulated recharge.

Reference Grids

The sensitivity analysis provided the basis for the selection of parameter values to maximize correlation. Specific yield was taken at 0.15, the hydraulic conductivity matrix was reduced by an order of magnitude, and the threshold "wetland" water table depth was 0.5 meter. The parameters were applied consistently as each of the reference grids were imported into the model. A record of the statistics for each trial was maintained (Table 10) and model output arrays, for the dataset with the highest correlation, were visualized and interpreted in a GIS environment (Figures 9, 10, and 11).

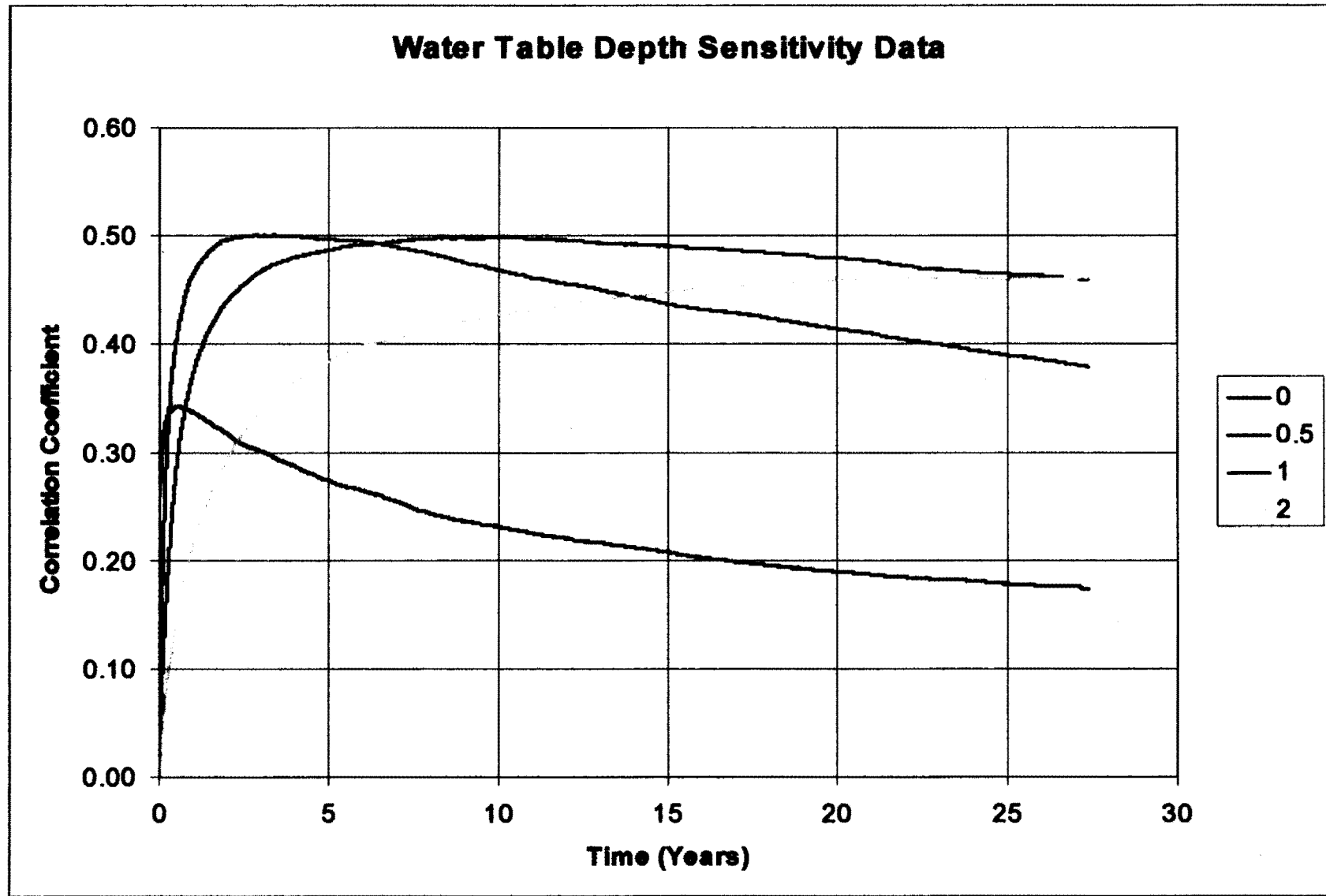


Figure 8. Sensitivity Analysis for Depth to Water Table.

Table 10. Reference Grid Comparison Data.

Base*	STEP	TIME (DAYS)	CORRELATION (UNITLESS)	SHALLOW WT (% AREA)	RECHARGE (M3/DAY)	DISCHARGE (M3/DAY)	% ERROR	PRECIP** (IN/YR)
HYDRIC	517	1029	0.50	40.59	-55862	58168	2.02	8.3
WET	1564	3123	0.45	26.07	-37220	39396	2.84	5.5
ACFG	1531	3057	0.43	26.33	-37495	39683	2.83	5.6
CFG	1642	3279	0.42	25.49	-36600	38749	2.85	5.4
DRY	5417	10829	0.36	12.19	-25648	26821	2.23	3.8
FG	4887	9769	0.35	13.15	-26353	27624	2.35	3.9

*Discussion of each base provided in the "Reference Matrix" section of this paper.

**Minimum precipitation for simulated recharge.

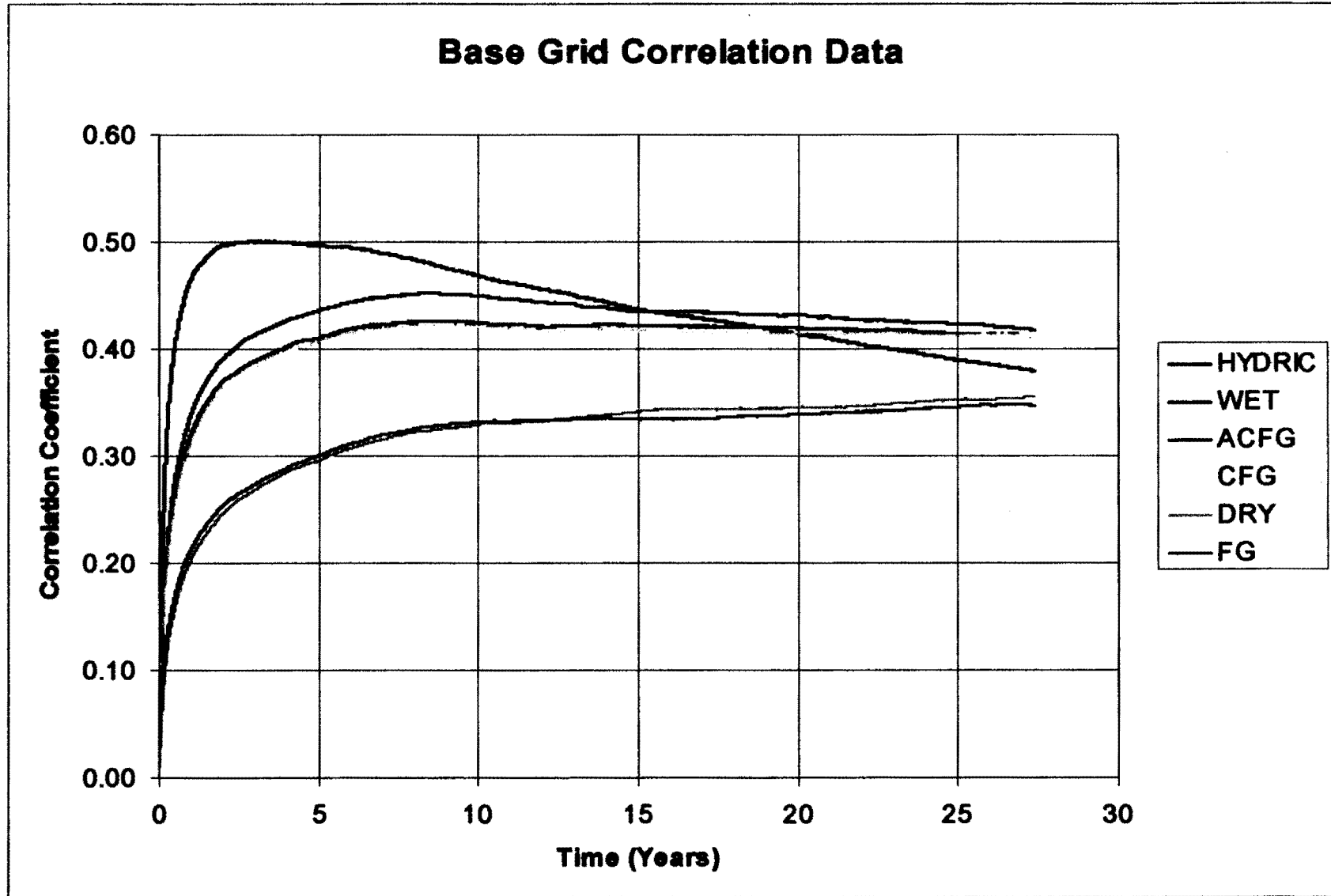


Figure 9. Reference Grid Comparison Data.

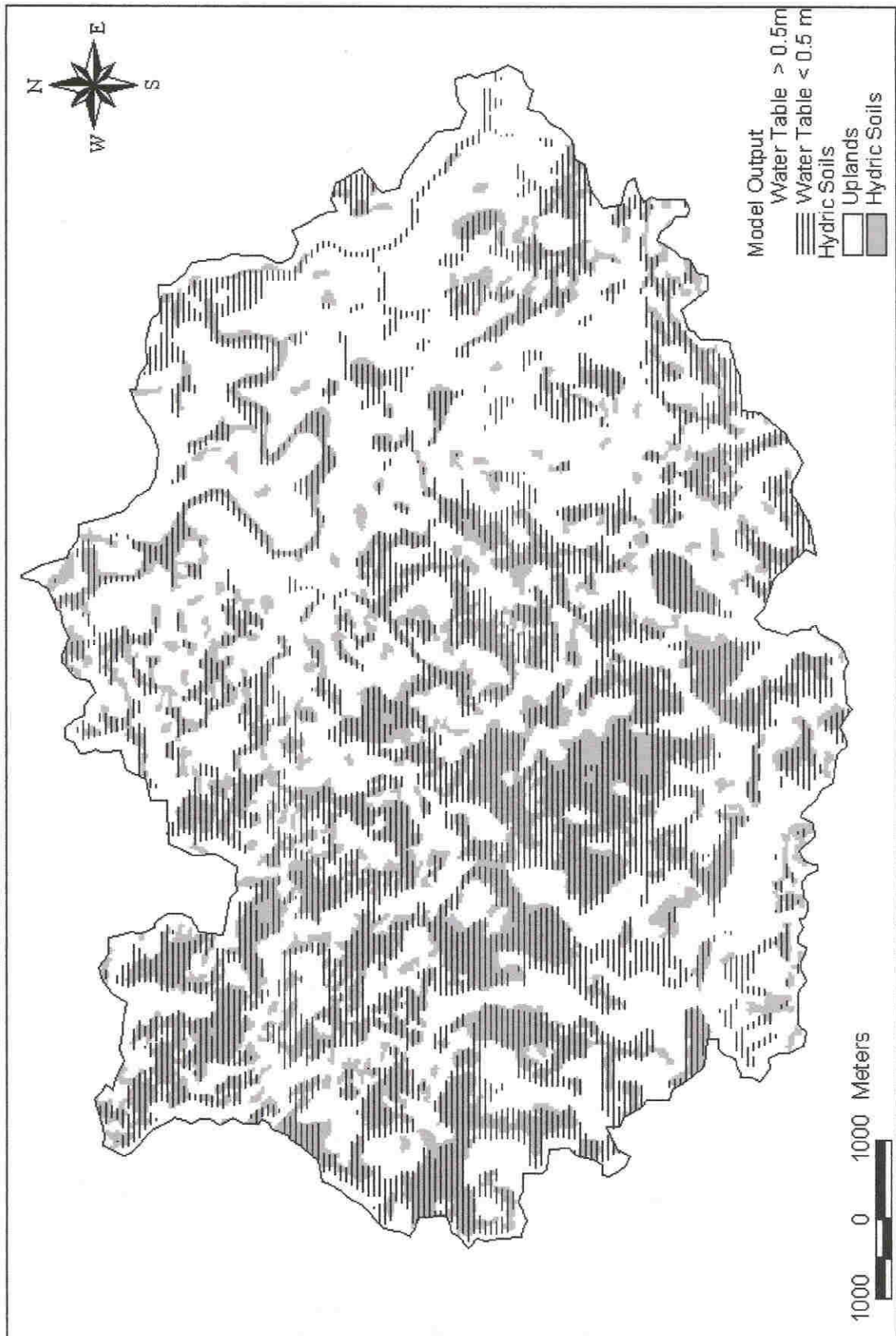


Figure 10. Comparison of Model Output to Hydric Soils Grid.

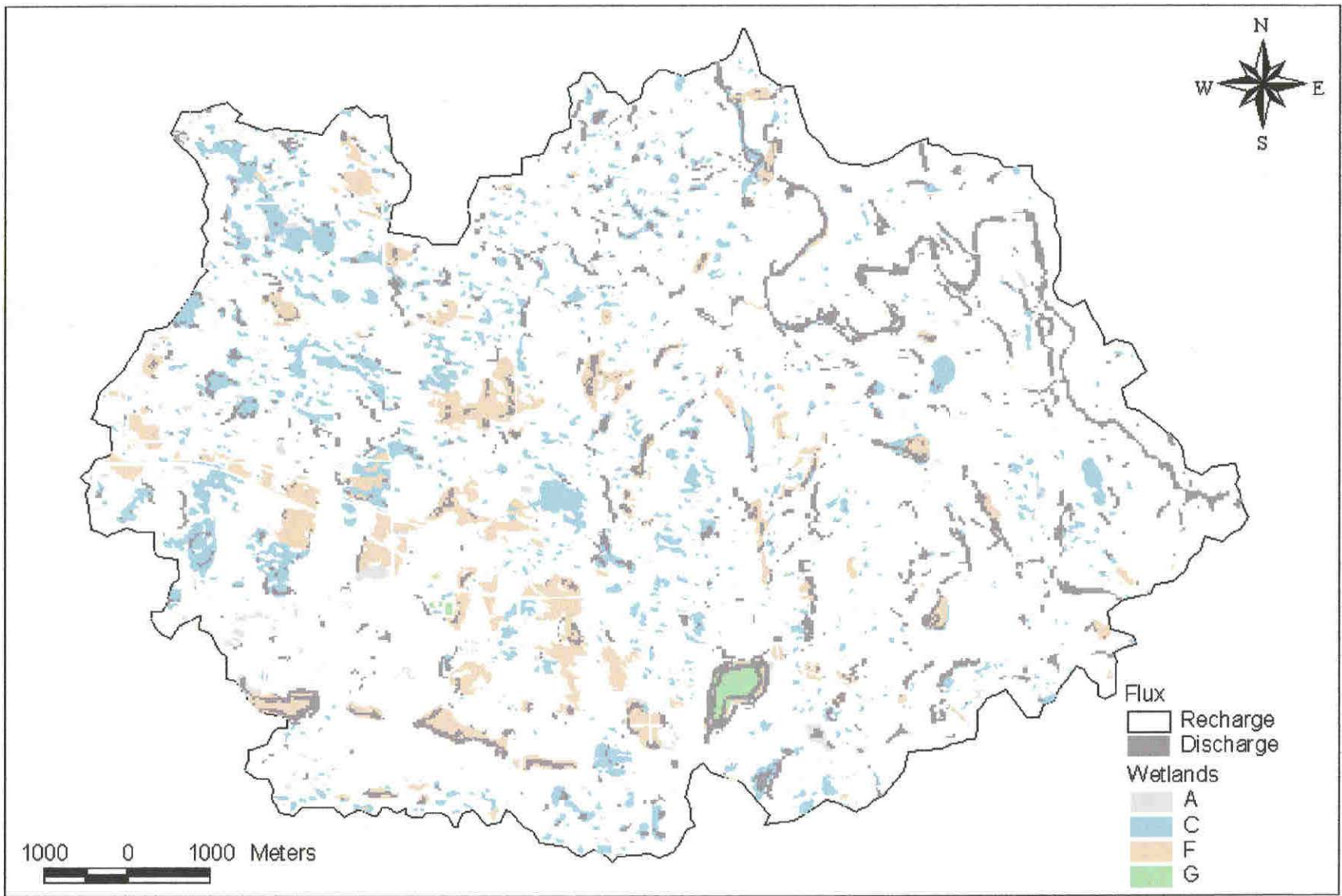


Figure 11. Model Flux With Respect to Wetland Distribution.

CHAPTER IV

DISCUSSION

The verification, sensitivity analysis, and reference grid data indicated model output was controlled by the initial topographic condition. The verification process was conducted on a subset of the watershed with strong topographic control of the hydrologic regime and the correlation between model output and observational data was high at 0.78 indicating a strong positive linear correlation. When the model was applied to the entire watershed, the correlation was at best 0.50 indicating a moderate positive linear correlation. The correlation coefficient increased for the entire watershed as the percent area with shallow water table increased in the reference grids. The model results reflected the fact that topographic position within the landscape was a strong control of hydrologic regime, but is not necessarily the dominant control for wetlands in the gently rolling prairie. Model output may also indicate an inability of the model to simulate local flow systems when the model domain is comparatively large. Local flow systems are progressively lost as the model drains the landscape to increasing depths. A correlation coefficient of 0.50 may reflect the compromise between accounting for small wetlands with local recharge and larger wetlands with a regional component of groundwater input.

The rate of groundwater flux was governed by the magnitude and degree of discretization of input parameters. Calibration of model output with field data allowed the magnitude of input parameters to be constrained. Stoertz and Bradbury (1989) indicated that model output on flux rates is a scale-dependent parameter with flux increasing as cell size decreases. Local flow systems occur at all scales and as cell size decreases more local flow is measured in the model. Although not explicitly tested in this work the scale-dependent nature of flux may account for the necessity of having to reduce the hydraulic conductivity matrix by an order of magnitude to achieve flux rates consistent with annual precipitation. Due to the number of variables influencing flux, rates and water budget values should be used with caution. Stoertz and Bradbury (1989) reached similar conclusions when they indicated the magnitude of calculated rates were less reliable than the spatial patterns of flux. The quality of flux rates produced by the model reflects the challenges of accurately measuring the controlling input parameters and to adequately quantify the effects of grid scale.

CHAPTER V

CONCLUSIONS

Model output on the spatial distribution of recharge and discharge zones was found to be controlled by the initial topographic profile of the watershed. Low points were found to have a water table closer to the surface than high points. The relationship between elevation and water table depth reflects the strong influence topography has on hydraulic head. Model simulations provided a correlation coefficient of 0.50 when model identified points of shallow water table were compared to maps of hydric soils (Figure 10). A correlation coefficient of 0.50 indicates that in the gently rolling prairie factors other than topography may play a role in the development of saturated conditions. The moderate value of correlation could also indicate errors in the delineation of hydric soils. Observation of the relationship between hydric soils and model identified points of shallow water table (Figure 10) shows that where they are not directly correlated there is a close spatial association. The model may be providing insight into water table characteristics that were not readily discernible in the field. The model could have value as a preliminary tool before future field investigations.

Flux rates produced by the model were calibrated with data on annual precipitation rates. Calibration indicated that the hydraulic conductivities values calculated from soils data were too large to sustain observed water table conditions given the restrictions on input imposed by annual precipitation. Work by Stoertz and Bradbury (1989) indicated flux is scale-dependent and raises the question of whether hydraulic conductivities were too large or the grid scale too fine. A fine grid scale captures more local flow than a larger mesh size. In either case, the values of flux calculated by the model should be viewed with more skepticism than the spatial pattern of flux.

The groundwater model developed by Gerla (1999) and advanced in this work has applicability as a preliminary tool for investigating the hydrologic regime of an area. Mapping the spatial pattern of recharge and discharge plays an important role in understanding contaminant transport, water quality, and the spatial and temporal distribution of wetlands. The estimation of model parameters using readily available data offers a practical method for meaningful hydrological analysis. The model and methods applied in this work offer a tool to acquire knowledge of hydrologic systems.

**APPENDIX
MODEL CODE**

(Model code was compiled with a free distribution Fortran compiler called Force, version 2.08, authored by Guilherme Huiz Lepsch Guedes)

```

1: C *****
2: C *
3: C * GERLA, PHIL Date: 09/20/03 *
4: C *
5: C * MODIFIED BY: LAVEAU, CHRIS *
6: C *****
7: C
8: C PROGRAM DESCRIPTION: SIMULATES STEPWISE DRAINAGE OF A SATURATED
9: C LANDSCAPE THROUGH TIME USING DARCY'S LAW AND AN EXPRESSION FOR
10: C CONSERVATION OF MASS.
11: C
12: C INPUT: AN ARRAY REPRESENTING THE INITIAL TOPOGRAPHIC CONDITIONS
13: C (DERIVED FROM A DEM) AND A SECOND ARRAY CONTAINING HYDRAULIC
14: C CONDUCTIVITY.
15: C
16: C DESCRIPTION OF ARRAYS:
17: C HOLD(I,J) = IS THE HEAD SQUARED AT THE CURRENT TIME STEP
18: C HNEW(I,J) = IS THE HEAD SQUARED AT THE NEXT TIME STEP
19: C R(I,J) = RECHARGE RATE (SET EQUAL TO ZERO)
20: C K(I,J) = NODAL AVERAGE HYDRAULIC CONDUCTIVITY
21: C HO(I,J) = INITIAL HYDRAULIC HEAD DERIVED FROM A DEM
22: C KX(I,J) = HARMONIC AVERAGE K AT A NODE IN THE X DIRECTION
23: C KY(I,J) = HARMONIC AVERAGE K AT A NODE IN THE Y DIRECTION
24: C WT(I,J) = COMPUTED WATER TABLE ELEVATIONS AT END OF TIME STEP
25: C FT(I,J) = NODE-TO-NODE FLOW TERMS - SPECIFIC DISCHARGE
26: C RCG(I,J) = NODAL RECHARGE RATE COMPUTED BY DIVIDING THE NET FLOW
27: C INTO OR OUT OF THE NODE BY THE SURFACE X-Y AREA OF
28: C NODAL CELL
29: C ID(I,J) = INDICATOR MATRIX...SHOWS IF THE NODE HAS A SHALLOW (1)
30: C OR DEEP (0) WATER TABLE
31: C
32: C DESCRIPTION OF VARIABLES:
33: C XMIN = MINIMUM X SPATIAL COORDINATE
34: C XMAX = MAXIMUM X SPATIAL COORDINATE
35: C YMIN = MINIMUM Y SPATIAL COORDINATE
36: C YMAX = MAXIMUM Y SPATIAL COORDINATE
37: C ZMIN = MINIMUM Z SPATIAL COORDINATE (ELEVATION)
38: C ZMAX = MAXIMUM Z SPATIAL COORDINATE (ELEVATION)
39: C WTMIN = MINIMUM CALCULATED WATER TABLE ELEVATION AT EACH TIME STEP
40: C WTMAX = MAXIMUM CALCULATED WATER TABLE ELEVATION AT EACH TIME STEP
41: C RCGMIN = MINIMUM RECHARGE RATE AT THE END OF A TIME STEP
42: C RCGMAX = MAXIMUM RECHARGE RATE AT THE END OF A TIME STEP
43: C DWTMAX = THE MAXIMUM DEPTH TO THE WATER TABLE AT EACH TIME STEP
44: C NC = NUMBER OF COLUMNS
45: C NR = NUMBER OF ROWS
46: C DX = CELLSIZE IN THE X DIRECTION
47: C DY = CELLSIZE IN THE Y DIRECTION
48: C DT = TIME STEP
49: C S = SPECIFIC YIELD
50: C ALPHA = IMPLICIT FINITE DIFFERENCE WEIGHTING FACTOR
51: C TOL = ERROR TOLERANCE
52: C TIME = HOLDS THE TOTAL MODEL TIME FOR THE CURRENT TIME STEP IN
53: C THE COMPUTATION
54: C NUMIT = NUMBER OF ITERATIONS IN THE CURRENT TIME STEP
55: C AMAX = USED TO CHECK FOR CONVERGENCE IN A TIME STEP
56: C OLDVAL = TEMPORARY PLACE FOR HEAD VALUE
57: C AVGK =
58: C ERR = USED TO CHECK FOR CONVERGENCE IN A TIME STEP
59: C ISUMSWT = A COUNTER FOR THE NUMBER OF NODES WITH A SHALLOW WT
60: C D = DEPTH TO THE WATER TABLE
61: C SUMPOS = CALCULATED TOTAL DISCHARGE (SUM OF POS FLUX VALUES)
62: C SUMNEG = CALCULATED TOTAL RECHARGE (SUM OF NEG FLUX VALUES)
63: C PCTERR = PERCENT DIFFERENCE BETWEEN RECHARGE AND DISCHARGE

```

```

64: C      AREA = PERCENT AREA WITH SHALLOW WATER TABLE
65: C      NEND = NUMBER OF TIME STEPS THE MODEL WILL RUN
66: C      DEPTH = USER SPECIFIED DEPTH TO SHALLOW WATER TABLE
67: C      RMAX = VARIABLE FOR SUBROUTINE STAT
68: C
69: C      *****
70: C      PROGRAM RELAX
71: C      EXTERNAL STAT
72: C      WT RELAXATION EXAMPLE - UNCONFINED AQUIFER - UNSTEADY CONDITIONS
73: C      DOUBLE PRECISION HNEW(500,500), HOLD(500,500), R(500,500),
74: C      + HO(500,500), KX(500,500), KY(500,500), WT(500,500), FT(500,500),
75: C      + RCG(500,500), K(500,500), ID(500,500), XMIN, XMAX, YMIN, YMAX,
76: C      + ZMIN, ZMAX, WTMIN, WTMAX, RCGMIN, RCGMAX, DWTMAX, S, DT, DX, DY,
77: C      + ALPHA, TOL, TIME, AMAX, OLDVAL, AREA, AVGK, H1, H2, F1, F2, ERR,
78: C      + ISUMSWT, D, SUMPOS, SUMNEG, PCTERR, RMAX, DEPTH, R1, PRECIP
79: C      INTEGER NC, NR, I, J, N, NEND, NUMIT
80: C      CHARACTER*4 DSAA
81: C
82: C      INPUT THE SPECIFIC YIELD, HYDRAULIC CONDUCTIVITY, AND INITIAL
83: C      TIME STEP (NOTE: THESE MUST BE IN CONSISTENT TIME AND SPACE
84: C      UNITS)
85: C
86: C      WRITE(6,*)' Input the estimated average specific yield'
87: C      READ(5,*)S
88: C      WRITE(6,*)' Input the initial time step in days'
89: C      READ(5,*)DT
90: C      WRITE(6,*)' Input depth for a shallow water table in meters'
91: C      READ(5,*)DEPTH
92: C
93: C      *****
94: C      INITIALIZE VALUES FOR SUBROUTINE STAT
95: C      RMAX = 0.0D+00
96: C      CREATE OUTPUT FILE RESULT1 FOR RECORDING GRID STATISTICS AT
97: C      EACH INTERATION
98: C      OPEN(UNIT=12,FILE='C:\STATISTICS\RESULT1.TXT',STATUS='UNKNOWN')
99: C      WRITE(12,160)
100: C      HEADER FOR OUTPUT FILE RESULT1
101: C      160  FORMAT(1X,'STEP',8X,'TIME',10X,'CORRELATION',8X,'SHALLOW WT',
102: C      + 5X,'MAX DEPTH TO WT',7X,'RECHARGE',9X,'DISCHARGE',10X,'ERROR',
103: C      + 10X,'PRECIPITATION')
104: C      WRITE(12,165)
105: C      165  FORMAT(12X,'(DAYS)',9X,'(UNITLESS)',10X,'(% AREA)',11X,'(M)',
106: C      + 14X,'(M3/DAY)',9X,'(M3/DAY)',12X,'(%)',14X,'(IN/YR)')
107: C      *****
108: C
109: C      READ THE HEADER OF AN ASCII FORMAT SURFER GRID FILE FOR K.
110: C      (NOTE: BOTH THE ARRAY FOR K AND FOR ELEVATION MUST BE IDENTICAL
111: C      IN CELL SIZE AND GLOBAL DIMENSIONS)
112: C
113: C      READ(19, '(A4)') DSAA
114: C      WRITE(6,*)DSAA
115: C      READ(19,*)NC, NR
116: C      WRITE(6,*)NC, NR
117: C      READ(19,*)XMIN, XMAX
118: C      WRITE(6,*)XMIN, XMAX
119: C      READ(19,*)YMIN, YMAX
120: C      WRITE(6,*)YMIN, YMAX
121: C      READ(19,*)ZMIN, ZMAX
122: C      WRITE(6,*)ZMIN, ZMAX
123: C
124: C      READ THE K FILE AND THEN AD A LINE AROUND THE OUTSIDE
125: C      (FILE SHOULD HAVE SAME ORIENTATION AS BASE GRID)
126: C

```



```

127:      READ(19,*) ((K(I,J), I=2,NC+1), J=2,NR+1)
128:      DO 51 I=2,NC+1
129:      K(I,1)=K(I,2)
130:      K(I,NR+2)=K(I,NR+1)
131: 51      CONTINUE
132:      DO 52 J=2,NR+1
133:      K(1,J)=K(2,J)
134:      K(NC+2,J)=K(NC+1,J)
135: 52      CONTINUE
136: C
137: C      COMPUTE THE INTERNODAL K VALUES (HARMONIC AVERAGE)
138: C
139:      DO 53 I=2,NC+1
140:      DO 53 J=2,NR+1
141:      KX(I,J)=4/((2/K(I,J))+(1/K(I+1,J))+(1/K(I-1,J)))
142:      KY(I,J)=4/((2/K(I,J))+(1/K(I,J+1))+(1/K(I,J-1)))
143: 53      CONTINUE
144: C
145: C      HO IS THE INITIAL HEAD, READ FROM A SEPARATE FILE
146: C      SET NO-FLOW BOUNDARY AROUND MARGIN
147: C
148: C      READ THE HEADER ON AN ASCII FORMAT SURFER GRID FILE FOR ELEVATION
149: C
150:      READ(18, '(A4)') DSAA
151:      WRITE(6,*)DSAA
152:      READ(18,*)NC, NR
153:      WRITE(6,*)NC, NR
154:      READ(18,*)XMIN, XMAX
155:      WRITE(6,*)XMIN, XMAX
156:      READ(18,*)YMIN, YMAX
157:      WRITE(6,*)YMIN, YMAX
158:      READ(18,*)ZMIN, ZMAX
159:      WRITE(6,*)ZMIN, ZMAX
160:      DX=(XMAX-XMIN)/(NC-1)
161:      DY=(YMAX-YMIN)/(NR-1)
162:      WRITE(6,*)DX, DY
163: C
164: C      HO IS THE INITIAL HEAD, READ FROM A SEPARATE FILE
165: C      SET NO-FLOW BOUNDARY AROUND MARGIN
166: C      (FILE SHOULD HAVE SAME ORIENTATION AS BASE GRID)
167: C
168:      READ(18,*) ((HO(I,J), I=2,NC+1), J=2,NR+1)
169:      DO 75 I=2,NC+1
170:      HO(I,1)=HO(I,3)
171:      HO(I,NR+2)=HO(I,NR)
172: 75      CONTINUE
173:      DO 76 J=2,NR+1
174:      HO(1,J)=HO(3,J)
175:      HO(NC+2,J)=HO(NC,J)
176: 76      CONTINUE
177: C
178: C      USE CRANK-NICHOLSON APPROXIMATION
179: C
180:      ALPHA=0.5D+00
181: C
182: C      SET ERROR TOLERANCE
183: C
184:      TOL=0.01D+00
185: C
186: C      INITIALIZE ARRAYS
187: C      HOLD IS THE HEAD SQUARED AT TIME STEP N
188: C      HNEW IS THE HEAD SQUARED AT TIME STEP N+1
189: C

```

```

190:      DO 4 I=1,NC+2
191:      DO 4 J=1,NR+2
192:      HNEW(I,J)=HO(I,J)**2
193:      HOLD(I,J)=HO(I,J)**2
194:      R(I,J)=0.0D+00
195: 4      CONTINUE
196:      TIME=0.0D+00
197: C
198: C      START TIME STEPS
199: C      AT EACH TIME STEP SOLVE SYSTEM OF EQUATIONS BY ITERATION
200: C
201:      NEND= 20000
202:      DO 5 N=1,NEND
203:      NUMIT=0
204:      TIME=TIME+DT
205: 10     AMAX=0.0D+00
206:      NUMIT=NUMIT+1
207:      DO 15 I=2,NC+1
208:      DO 15 J=2,NR+1
209:      OLDVAL=HNEW(I,J)
210:      AVGK=2/((1/KX(I,J))+(1/KY(I,J)))
211:      H1=(KX(I,J)*(HOLD(I,J+1)+HOLD(I,J-1))+KY(I,J)
212: +      *(HOLD(I+1,J)+HOLD(I-1,J)))/(2*(KX(I,J)+KY(I,J)))
213:      H2=(KX(I,J)*(HNEW(I,J+1)+HNEW(I,J-1))+KY(I,J)
214: +      *(HNEW(I+1,J)+HNEW(I-1,J)))/(2*(KX(I,J)+KY(I,J)))
215:      F1=DX*DY*S/(2.0D+00*AVGK*DT*(HOLD(I,J)**0.5D+00))
216:      F2=1.0D+00/(F1+ALPHA)
217:      HNEW(I,J)=(F1*HOLD(I,J)+(1.0D+00-ALPHA)*(H1-HOLD(I,J))+
218: +      (ALPHA*H2)+(R(I,J)*DX*DY/(KX(I,J)+KY(I,J)))*F2
219:      IF(HNEW(I,J).GT.OLDVAL) HNEW(I,J)=OLDVAL
220:      IF(HNEW(I,J).LT.0.0)WRITE(6,*)I,J,HNEW(I,J),'We have a problem!'
221:      ERR=DABS(HNEW(I,J)-OLDVAL)
222:      IF(ERR.GT.AMAX) AMAX=ERR
223: 15     CONTINUE
224: C
225: C      ADJUST NO-FLOW BOUNDARIES
226: C
227:      DO 16 I=2,NC+1
228:      HNEW(I,1)=HNEW(I,3)
229:      HNEW(I,NR+2)=HNEW(I,NR)
230: 16     CONTINUE
231:      DO 17 J=2,NR+1
232:      HNEW(1,J)=HNEW(3,J)
233:      HNEW(NC+2,J)=HNEW(NC,J)
234: 17     CONTINUE
235:      IF(ALPHA.LT.0.1) GOTO 18
236:      IF(AMAX.GT.TOL) GOTO 10
237: 18     CONTINUE
238: C
239: C      PREPARE FOR THE NEXT TIME STEP
240: C      PUT HNEW VALUES INTO HOLD ARRAY
241: C
242:      DO 20 I=1,NC+2
243:      DO 20 J=1,NR+2
244: 20     HOLD(I,J)=HNEW(I,J)
245: C
246: C
247: C      COMPUTE ELEVATION AND DEPTH TO THE WATER TABLE
248: C      KEEP TRACK OF THE MINIMUM AND MAXIMUM WT ELEVATION
249: C      TALLY CELLS WITH A SHALLOW WT
250: C
251:      DWTMAX=0.0D+00
252:      WTMIN=9.9D+10

```

```

253:          WTMAX=0.0D+00
254:          ISUMSWT=0
255:          DO 25 I=2,NC+1
256:          DO 25 J=2,NR+1
257:          WT(I,J)=HNEW(I,J)**0.5D+00
258:          IF(WT(I,J).LT.WTMIN)WTMIN=WT(I,J)
259:          IF(WT(I,J).GT.WTMAX)WTMAX=WT(I,J)
260:          D=(HO(I,J)-WT(I,J))
261:          IF(D.GT.DWTMAX)DWTMAX=D
262:          IF(D.GT.DEPTH)THEN
263:             ID(I,J)=0
264:          ELSE
265:             ID(I,J)=1
266:             ISUMSWT=ISUMSWT+1
267:          ENDIF
268: 25      CONTINUE
269: C
270: C      COMPUTE THE NODAL FLOW TERMS USING THE DUPUIT APPROXIMATION FOR
271: C      DARCY'S LAW (APPLY TO THE FOUR CORNERS OF THE GRID)
272: C
273:          FT(2,2)=(-0.25D+00*((K(2,2)+K(3,2))/2.0D+00)*DY/DX)*(HNEW(2,2)-
274: + HNEW(3,2))+(-0.25D+00*((K(2,2)+K(2,3))/2.0D+00)*DX/DY)*
275: + (HNEW(2,2)-HNEW(2,3))
276:          RCG(2,2)=FT(2,2)/(DX*DY)
277:          FT(NC+1,2)=(-0.25D+00*((K(NC+1,2)+K(NC,2))/2.0D+00)*DY/DX)*
278: + (HNEW(NC+1,2)-HNEW(NC,2))+(-0.25D+00*((K(NC+1,2)+K(NC+1,3))/
279: + 2.0D+00)*DX/DY)*(HNEW(NC+1,2)-HNEW(NC+1,3))
280:          RCG(NC+1,2)=FT(NC+1,2)/(DX*DY)
281:          FT(2,NR+1)=(-0.25D+00*((K(2,NR+1)+K(3,NR+1))/2.0D+00)*DY/DX)*
282: + (HNEW(2,NR+1)-HNEW(3,NR+1))+(-0.25D+00*((K(2,NR+1)+K(2,NR))/
283: + 2.0D+00)*DX/DY)*(HNEW(2,NR+1)-HNEW(2,NR))
284:          RCG(2,NR+1)=FT(2,NR+1)/(DX*DY)
285:          FT(NC+1,NR+1)=(-0.25D+00*((K(NC+1,NR+1)+K(NC,NR+1))/2.0D+00)*
286: + DY/DX)*(HNEW(NC+1,NR+1)-HNEW(NC,NR+1))+(-0.25D+00*((K(NC+1,NR+1)+
287: + K(NC+1,NR))/2.0D+00)*DX/DY)*(HNEW(NC+1,NR+1)-HNEW(NC+1,NR))
288:          RCG(NC+1,NR+1)=FT(NC+1,NR+1)/(DX*DY)
289: C
290: C      (APPLY TO THE REMAINING EDGES)
291: C
292:          DO 71 I=3,NC
293:          FT(I,2)=(-0.25D+00*((K(I,2)+K(I+1,2))/2.0D+00)*DY/DX)*
294: + (HNEW(I,2)-HNEW(I+1,2))+(-0.25D+00*((K(I,2)+K(I-1,2))/2.0D+00)
295: + *DY/DX)*(HNEW(I,2)-HNEW(I-1,2))+(-0.5D+00*((K(I,2)+K(I,3))/
296: + 2.0D+00)*DX/DY)*(HNEW(I,2)-HNEW(I,3))
297:          RCG(I,2)=FT(I,2)/(DX*DY)
298:          FT(I,NR+1)=(-0.25D+00*((K(I,NR+1)+K(I+1,NR+1))/2.0D+00)*DY/DX)*
299: + (HNEW(I,NR+1)-HNEW(I+1,NR+1))+(-0.25D+00*((K(I,NR+1)+
300: + K(I-1,NR+1))/2.0D+00)*DY/DX)*(HNEW(I,NR+1)-HNEW(I-1,NR+1))
301: + (-0.5D+00*((K(I,NR+1)+K(I,NR))/2.0D+00)*DX/DY)*(HNEW(I,NR+1)
302: + -HNEW(I,NR))
303:          RCG(I,NR+1)=FT(I,NR+1)/(DX*DY)
304: 71      CONTINUE
305:          DO 72 J=3,NR
306:          FT(2,J)=(-0.25D+00*((K(2,J)+K(2,J+1))/2.0D+00)*DX/DY)*(HNEW(2,J)
307: + -HNEW(2,J+1))+(-0.25D+00*((K(2,J)+K(2,J-1))/2.0D+00)*DX/DY)*
308: + (HNEW(2,J)-HNEW(2,J-1))+(-0.5D+00*((K(2,J)+K(3,J))/2.0D+00)*
309: + DY/DX)*(HNEW(2,J)-HNEW(3,J))
310:          RCG(2,J)=FT(2,J)/(DX*DY)
311:          FT(NC+1,J)=(-0.25D+00*((K(NC+1,J)+K(NC+1,J+1))/2.0D+00)*DX/DY)*
312: + (HNEW(NC+1,J)-HNEW(NC+1,J+1))+(-0.25D+00*((K(NC+1,J)+
313: + K(NC+1,J-1))/2.0D+00)*DX/DY)*(HNEW(NC+1,J)-HNEW(NC+1,J-1))
314: + (-0.5D+00*((K(NC+1,J)+K(NC,J))/2.0D+00)*DY/DX)*(HNEW(NC+1,J)-
315: + HNEW(NC,J))

```

```

316:          RCG(NC+1, J) = FT(NC+1, J) / (DX*DY)
317: 72      CONTINUE
318: C
319: C          (COMPUTE NODAL TERMS IN THE INTERIOR)
320: C
321:          DO 73 I=3, NC
322:          DO 73 J=3, NR
323:          FT(I, J) = (-0.5D+00 * ((K(I, J) + K(I+1, J)) / 2.0D+00) * DY/DX) *
324: + (HNEW(I, J) - HNEW(I+1, J)) + (-0.5D+00 * ((K(I, J) + K(I-1, J)) / 2.0D+00)
325: + *DY/DX) * (HNEW(I, J) - HNEW(I-1, J)) + (-0.5D+00 * ((K(I, J) + K(I, J+1)) /
326: + 2.0D+00) * DX/DY) * (HNEW(I, J) - HNEW(I, J+1)) + (-0.5D+00 * ((K(I, J) +
327: + K(I, J+1)) / 2.0D+00) * DX/DY) * (HNEW(I, J) - HNEW(I, J-1))
328:          RCG(I, J) = FT(I, J) / (DX*DY)
329: 73      CONTINUE
330: C
331: C          CHECK THE WATER BUDGET
332: C
333:          SUMPOS = 0.0D+00
334:          SUMNEG = 0.0D+00
335:          DO 74 I=2, NC+1
336:          DO 74 J=2, NR+1
337:          IF (FT(I, J) .GT. 0.0) THEN
338:              SUMPOS = SUMPOS + FT(I, J)
339:          ELSE
340:              SUMNEG = SUMNEG + FT(I, J)
341:          ENDIF
342: 74      CONTINUE
343:          PCTERR = ((SUMPOS - ABS(SUMNEG)) / (SUMPOS + ABS(SUMNEG))) * 100
344:          AREA = (ISUMSWT / (NC * NR)) * 100D+00
345: C
346: C          CALL STATISTICAL SUBROUTINE
347: C
348:          CALL STAT(WT, ID, RCG, NC, NR, DX, RMAX, N, XMIN, YMIN, S, DEPTH, TIME, DT,
349: + NUMIT, SUMPOS, SUMNEG, PCTERR, AREA, DWTMAX, R1, PRECIP)
350: C
351: C          *****
352: C          PRINT TABLE OF MODEL STATISTICS FOR EACH ITERATION TO RESULT1
353: C
354:          WRITE(12, 170) N, TIME, R1, AREA, DWTMAX, SUMNEG, SUMPOS, PCTERR,
355: + PRECIP
356: 170      FORMAT(I5, 1X, E17.10, 1X, E17.10, 1X, E17.10, 1X, E17.10, 1X, E17.10, 1X,
357: + E17.10, 1X, E17.10, 1X, E17.10)
358: C          *****
359: C
360: C          FIND RECHARGE MINIMUM AND MAXIMUM
361: C
362:          RCGMIN = 9.9D+10
363:          RCGMAX = -9.9D+05
364:          DO 78 I=2, NC+1, 1
365:          DO 78 J=2, NR+1, 1
366:          IF (RCG(I, J) .LT. RCGMIN) RCGMIN = RCG(I, J)
367:          IF (RCG(I, J) .GT. RCGMAX) RCGMAX = RCG(I, J)
368: 78      CONTINUE
369: C
370: C          INCREASE THE TIME STEP
371: C
372:          DT = DT * 1.1D+00
373:          IF (DT .GT. 2.0) DT = 2.0D+00
374: 5      CONTINUE
375:          CLOSE(UNIT=12)
376:          PAUSE
377:          END
378: C

```

```

379: C *****
380: C *
381: C * LAVEAU, CHRIS Date: 10/25/03 *
382: C *
383: C *****
384: C
385: C PROGRAM DESCRIPTION: CALCULATES A CORRELATION COEFFICIENT FOR A
386: C SERIES OF ARRAYS IN TWO DISCRETE FILES.
387: C
388: C INPUT: A BASE FILE REPRESENTING THE LOCATION OF SHALLOW WATER
389: C TABLE IN THE FIELD.
390: C
391: C DESCRIPTION OF VARIABLES:
392: C X(I,J) = BASE ARRAY, DEFINED TO CONTAIN X VARIABLES (BASE.TXT)
393: C Y(I,J) = MODEL OUTPUT ARRAY IDENTIFYING AREAS WITH SHALLOW
394: C WATER TABLE. DEFINED TO CONTAIN Y VARIABLES (MODEL.TXT)
395: C FLUX(I,J) = MODEL OUTPUT ARRAY CONTAINING FLUX VALUES IN M/DAY
396: C (FLUX.TXT)
397: C NC = NUMBER OF COLUMNS
398: C NR = NUMBER OF ROWS
399: C NG = NUMBER OF GRIDS BEING COMPARED
400: C DX = CELLSIZE OF GRIDS
401: C N = NUMBER OF ELEMENTS
402: C SUMX = SUM OF X VARIABLES
403: C SUMY = SUM OF Y VARIABLES
404: C SUMXY = SUM OF X VARIABLES MULTIPLIED BY Y VARIABLES
405: C SUMX2 = SUM OF X VARIABLES SQUARED
406: C SUMY2 = SUM OF Y VARIABLES SQUARED
407: C SSX = SUM OF SQUARES FOR X VARIABLE
408: C SSY = SUM OF SQUARES FOR Y VARIABLE
409: C SSXY = SUM OF PRODUCTS XY
410: C R = CORRELATION COEFFICIENT
411: C PERCX = PERCENT AREA WITH SHALLOW WATER TABLE FOR X ARRAY
412: C PERCY = PERCENT AREA WITH SHALLOW WATER TABLE FOR Y ARRAY
413: C DIFF = PERCENT DIFFERENCE BETWEEN PERCX AND PERCY
414: C Q = TOTAL DISCHARGE IN M3/DAY
415: C W = TOTAL RECHARGE IN M3/DAY
416: C PRECIP = AVERAGE RECHARGE FLUX IN INCHES/YR
417: C
418: C ***** Declaration Section *****
419: C
420: C SUBROUTINE STAT(WT,Y,FLUX,NC,NR,DX,RMAX,ITER,XMIN,YMIN,S,DEPTH,
421: C + TIME,DT,NUMIT,SUMPOS,SUMNEG,PCTERR,AREA,DWTMAX,R,PRECIP)
422: C INTEGER I,J,NC,NR
423: C DOUBLE PRECISION X(500,500),Y(500,500),FLUX(500,500),WT(500,500),
424: C + SUMX,SUMX2,SUMY,SUMY2,SUMXY,N,SSX,SSY,SSXY,R,PERCX,PERCY,Q,W,DX,
425: C + DIFF,PRECIP
426: C RELAX VARIABLES
427: C INTEGER ITER, NUMIT
428: C DOUBLE PRECISION RMAX,XMIN,YMIN,DEPTH,SUMNEG,SUMPOS,DT,TIME,
429: C + PCTERR,AREA,DWTMAX,S
430: C
431: C ***** Initialization Section *****
432: C
433: C FILES
434: C OPEN(UNIT=10, FILE='C:\STATISTICS\BASE.TXT', STATUS='OLD')
435: C OPEN(UNIT=13, FILE='C:\STATISTICS\RESULT2.TXT', STATUS='UNKNOWN')
436: C
437: C ***** Input Section *****
438: C
439: C READ GRIDS
440: C DO 5 J=1,NR
441: C READ(10,*) (X(I,J),I=1,NC)

```

```

474:      END IF
475: 20    CONTINUE
476: 25    CONTINUE
477: C    CALCULATE PERCENT DIFFERENCE BETWEEN PERCX AND PERCY
478:      DIFF = ((DABS(PERCX-PERCY))/((1.0D+00/2.0D+00)*(PERCX+PERCY)))
479:      + *100D+00
480: C    CALCULATE AVERAGE RECHARGE FLUX
481:      PRECIP = (DABS(W)*365.0D+00*100.0D+00)/(N*DX*DX*2.54D+00)
482: C    CALCULATE A CORRELATION COEFFICIENT
483:      SSX = SUMX2 - SUMX**2D+00/N
484:      SSY = SUMY2 - SUMY**2D+00/N
485:      SSXY = SUMXY - (SUMX*SUMY)/N
486:      R = SSXY/DSQRT(SSX*SSY)
487:      IF (R.GT.RMAX) THEN
488:          RMAX = R
489:      ELSE
490:          GO TO 145
491:      END IF
492: C
493: C      ***** Output Section *****
494: C
495: C          WRITE STATISTICS FROM SUBROUTINE STAT TO RESULT2
496:      WRITE (13,85)
497: 85    FORMAT(23(' '),2X,'STATISTICS',2X,23(' '))
498:      WRITE (13,90) ITER,N,SUMX,SUMY,SUMXY,SUMX2,SUMY2,SSX,SSY,SSXY,R,
499:      + PERCX,PERCY,DIFF,Q,W,PRECIP
500: 90    FORMAT(
501:      A 13X,'          ITERATION =',I5//,
502:      B 1X,'          N =',1X,E17.10/,
503:      C 1X,'          SUM X =',1X,E17.10/,
504:      D 1X,'          SUM Y =',1X,E17.10/,

```

```

505:      E 1X, '          SUM XY =', 1X, E17.10/,
506:      F 1X, '          SUM X2 =', 1X, E17.10/,
507:      G 1X, '          SUM Y2 =', 1X, E17.10/,
508:      H 1X, '          SSX =', 1X, E17.10/,
509:      I 1X, '          SSY =', 1X, E17.10/,
510:      J 1X, '          SSKY =', 1X, E17.10/,
511:      K 1X, '          R =', 1X, E17.10/,
512:      L 1X, '          PERCX =', 1X, E17.10, 1X, '%', //,
513:      M 1X, '          PERCY =', 1X, E17.10, 1X, '%', //,
514:      N 1X, '          % DIFFERENCE =', 1X, E17.10, 1X, '%', //,
515:      O 1X, '          DISCHARGE =', 1X, E17.10, 1X, 'M3/DAY', //,
516:      P 1X, '          RECHARGE =', 1X, E17.10, 1X, 'M3/DAY', //,
517:      Q 1X, '          PRECIPITATION =', 1X, E17.10, 1X, 'IN/YR', //)
518: C
519: C      WRITE OUTPUT FROM MAIN PROGRAM RELAX
520:      WRITE (13, 95)
521: 95      FORMAT (26 ('*'), 2X, 'RELAX', 2X, 25 ('*'))
522:      WRITE (13, 100)
523: 100     FORMAT ('          DESCRIBE K MATRIX: K*0.1 (M/DAY)')
524:      WRITE (13, 105) S, DEPTH, TIME, DT, NUMIT, SUMPOS, SUMNEG, PCTERR,
525:      + AREA, DWTMAX
526: 105     FORMAT (
527:      A 1X, '          SPECIFIC YIELD =', 1X, E17.10/,
528:      B 1X, '          SHALLOW WT DEPTH =', 1X, E17.10, 1X, 'M', //,
529:      C 1X, '          TIME =', 1X, E17.10, 1X, 'DAYS', //,
530:      D 1X, '          TIME STEP =', 1X, E17.10, 1X, 'DAYS', //,
531:      E 1X, '          NUMIT =', 1X, I17, //,
532:      F 1X, '          TOT DISCHARGE =', 1X, E17.10, 1X, 'M3/DAY', //,
533:      G 1X, '          TOT RECHARGE =', 1X, E17.10, 1X, 'M3/DAY', //,
534:      H 1X, '          % DIFF =', 1X, E17.10, 1X, '%', //,
535:      I 1X, '% AREA W/SHALLOW WT =', 1X, E17.10, 1X, '%', //,
536:      J 1X, '          MAX DEPTH TO WT =', 1X, E17.10, 1X, 'M', //)
537: C
538: C      PRINT SPATIAL ARRAYS IN ARCVIEW FORMAT
539: C      PRINT ARCVIEW HEADER
540: C
541:      WRITE (13, 110) NC, NR, XMIN, YMIN, DX
542: 110     FORMAT (
543:      A 2X, 'ncols      ', 3X, I4, //,
544:      B 2X, 'nrows      ', 3X, I4, //,
545:      C 2X, 'xllcorner', 3X, F12.4, //,
546:      D 2X, 'yllcorner', 4X, F12.4, //,
547:      E 2X, 'cellsize ', 3X, F4.0)
548: C      PRINT INTEGER MAP SHOWING AREAS OF SHALLOW WATER TABLE
549:      WRITE (13, 115) ((Y(I, J), I=2, NC+1), J=2, NR+1)
550: 115     FORMAT (1X, 30F4.1)
551:      WRITE (13, 120)
552:      FORMAT (/)
553: C      PRINT NEW WATER TABLE ELEVATIONS
554:      WRITE (13, 125) ((WT(I, J), I=2, NC+1), J=2, NR+1)
555: 125     FORMAT (1X, 30F7.2)
556:      WRITE (13, 130)
557:      FORMAT (/)
558: C      PRINT SPECIFIC RECHARGE FOR CELLS
559:      WRITE (13, 135) ((FLUX(I, J), I=2, NC+1), J=2, NR+1)
560: 135     FORMAT (1X, 30F12.8)
561:      WRITE (13, 140)
562:      FORMAT (/)
563: C
564: C      ***** Close & End Section *****
565: C
566: 145     CLOSE (UNIT = 10)      568:      RETURN
567:      CLOSE (UNIT = 13)      569:      END

```

- Downey, J.S. 1971. Ground-water basic data Nelson and Walsh Counties, North Dakota. North Dakota Geological Survey, Bulletin 57, Part II, 459p.
- Downey, J.S. 1973. Ground-water resources Nelson and Walsh Counties, North Dakota. North Dakota Geological Survey, Bulletin 57, Part III, 67p.
- Eisenlohr, W.S. 1972. Hydrologic investigations of prairie potholes in North Dakota 1959-1968. United States Geological Survey Professional Paper 585-A, Washington D.C., 102p.
- Feinstein, D.T. 1986. A three-dimensional model of flow to the sandstone aquifer in northeastern Wisconsin with discussion of contamination potential. University of Wisconsin, M.S. Thesis, 240p.
- Fetter, C.W. 2001. Applied Hydrology (Fourth Edition). Prentice Hall. Upper Saddle River, NJ, 598p.
- Freeze, R.A. and J.A. Cherry. 1979. Groundwater. Prentice-Hall Inc. Englewood Cliffs, NJ, 604p.

- Gerla, P.J. 1999. Estimating the groundwater contribution in wetlands using modeling and digital terrain analysis. *Wetlands*, v.19, p.394-402.
- Golden Software. 2002. *User's Guide: Contouring and 3D Surface Mapping for Scientists and Engineers*. Golden Software Inc., Golden, CO, 640p.
- Heidt, C.J. D.E. Moen, and M.W. Morrison. 1989. *Soil Survey of Nelson County North Dakota*. United States Department of Agriculture, Soil Conservation Service, 165p.
- Hubbert, M.K. 1940. The theory of ground-water motion. *Journal of Geology*, v.48:8, p.785-944.
- Jenson, S. K. and J.O. Domingue. 1988. Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric Engineering and Remote Sensing*, v.54:11, p.1593-1600.
- Kantrud, H.A., G.L. Krapu, and G.A. Swanson. 1989. *Prairie basin wetlands of the Dakotas: A community profile*. U.S. Fish and Wildlife Service, Biological Report 85, 111p.
- LaBaugh, J.W., T.C. Winter, V.A. Adomaitis, and G.A. Swanson. 1987. *Hydrology and chemistry of selected prairie wetlands in the Cottonwood Lake area, Stutsman County, North Dakota, 1979-1982*. United States Geological Survey Professional Paper 1431, 26p.
- Lemke, R.W. 1960. *Geology of the Souris River area, North Dakota*. United States Geological Survey Professional Paper 325, 138p.
- Lissey, A. 1971. Depression-focused transient groundwater flow patterns in Manitoba. *The Geological Association of Canada, Special Paper 9*, p.333-341.
- Mann, P.S. 1998. *Introductory Statistics 3rd Edition*. John Wiley & Sons. New York, NY, 789p.
- McDonald, M.G. and A.W. Harbaugh. 1984. *A modular three dimensional finite-difference ground-water flow model*. U.S. Geological Survey Open-File Report 83-875, 528p.
- Mark, D. M. 1988. Network models in geomorphology. In M.G. Anderson (Editor), *Modeling Geomorphological Systems*. John Wiley, New York, 470p.
- Meyboom, P. 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. *Journal of Hydrology*, v.4:1, p.38-62.

Shjeflo, J.B. 1968. Evapotranspiration and the water budget of prairie potholes in North Dakota. United States Geological Survey Professional Paper 585-B, 49p.

Classification for Making and Interpreting Soil Surveys. USDA Natural Resource Conservation Service. Agriculture Handbook 436, U.S. Government Printing Office, Washington, D.C., 869p.

Sorenson, L.G., Goldberg R., Root, T.L., and Anderson, M.G. 1998. Potential effects of global warming on waterfowl populations breeding in the northern Great Plains. Climatic Change, v.40, p.343-369.

Stoertz, M.W. and K.R. Bradbury. 1989. Mapping recharge areas using a groundwater model - a case study. Ground Water, v.27, p.220-228.

Toth, J.A. 1962. A theory of ground-water motion in small drainage basins in central Alberta, Canada. Journal of Geophysical Research, v.67:11, p.4375-4387.

- Toth, J.A. 1963. A theoretical analysis of ground-water flow in small drainage basins. *Journal of Geophysical Research*, v.68:16, p.4795-4811.
- United States Geological Survey National Mapping Program. 1998. Standards for Digital Elevation Models. Department of the Interior, 102p.
- Wang, H.F. and M.P. Anderson. 1982. *Introduction to Groundwater Modeling*. Academic Press. San Diego, CA, 237p.
- Winter, T.C. 1976. Numerical simulation analysis of the interaction of lakes and ground water. Geological Survey Professional Paper 1001, 45p.
- Winter, T.C. 1978. Numerical simulation of steady state three dimensional groundwater flow near lakes. *Water Resources Research*, v.14:2, p.245-254.
- Winter, T.C. 1989. Hydrologic studies of wetlands in the northern Prairie. In A. Van Der Valk (Editor), *Northern Prairie Wetlands*. Iowa State University Press. Ames, IA, p.16-54.
- Winter, T.C., and M.R. Carr. 1980. Hydrologic setting of wetlands in the Cottonwood Lake Area, Stutsman County, North Dakota. *United States Geological Survey Water Resource Investigation 80-89*, 42p.
- Winter, T.C., and H.O. Pfannkuch. 1984. Effect of anisotropy and groundwater system geometry on seepage through lakebeds (2) numerical simulation analysis. *Journal of Hydrology*, v.75, p.239-253.
- Winter, T.C., and D.O. Rosenberry. 1995. The interaction of ground water with prairie pothole wetlands in the Cottonwood Lake area, east-central North Dakota, 1979-1990. *Wetlands*, v.15:3, p.193-211.
- Winter, T.C. and D.O. Rosenberry. 1998. Hydrology of prairie pothole wetlands during drought and deluge: a 17-year study of the Cottonwood Lake wetland complex in North Dakota in the perspective of longer term measured and proxy hydrological records. *Climatic Change*, v.40, p.189-209.
- Woo, M.K. and R.D. Roswell. 1993. Hydrology of a prairie slough. *Journal Hydrology*, v.146, p.175-207.
- Zebarth, B.J., E. deJong, and J.L. Henry. 1989. Water flow in hummocky landscape in central Saskatchewan, Canada, II. Saturated flow and groundwater recharge. *Journal of Hydrology*, v.110, p.181-198.

Zhang, W. and D.R. Montgomery. 1994. Digital elevation model grid size, landscape representation, and hydrological simulations. *Water Resources Research*, v.30, p.1019-1028.