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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

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

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Chris D. Laveau
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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.

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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 km^2 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).

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

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.

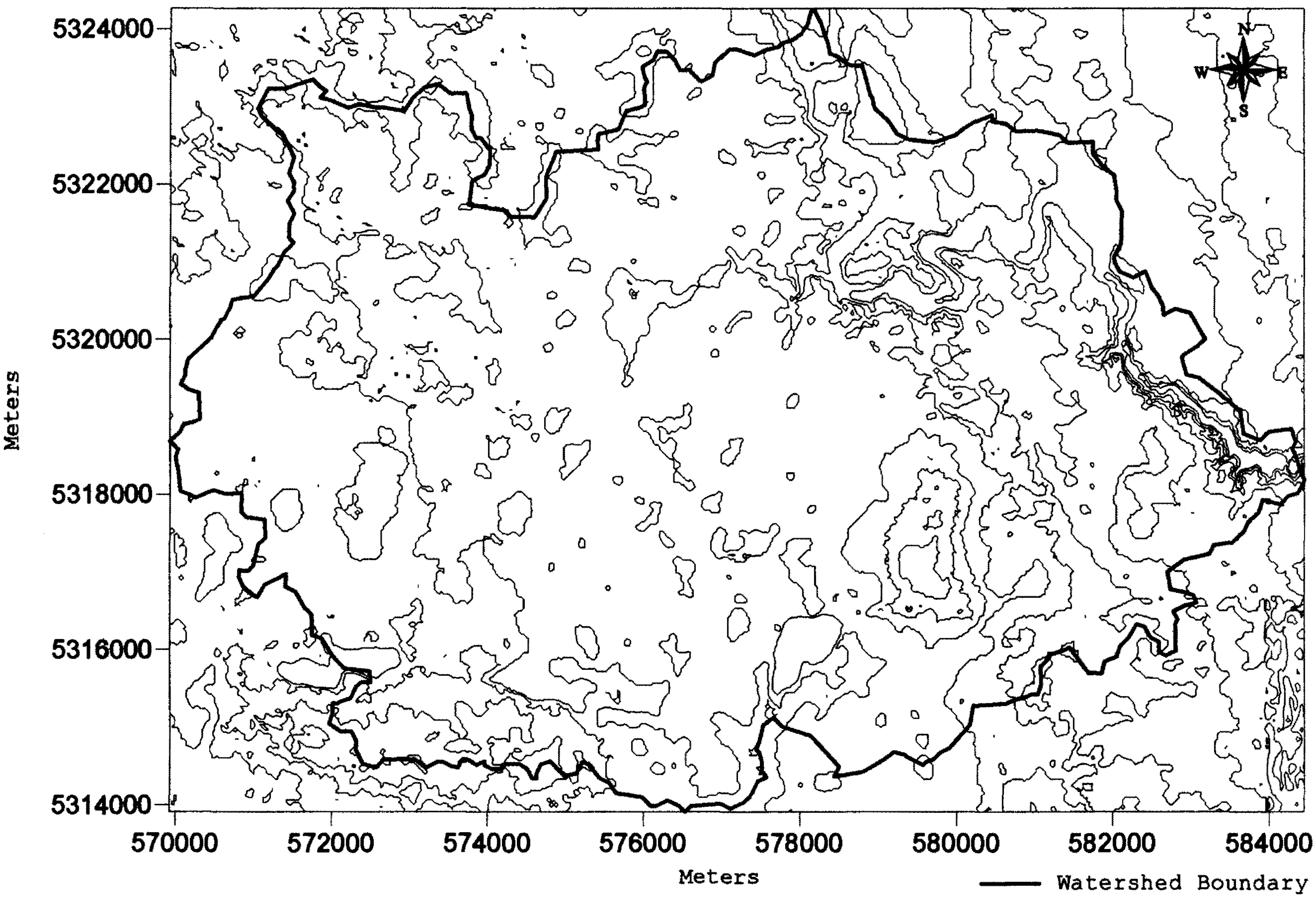

Figure 2. Contoured DEM Before Filtering.

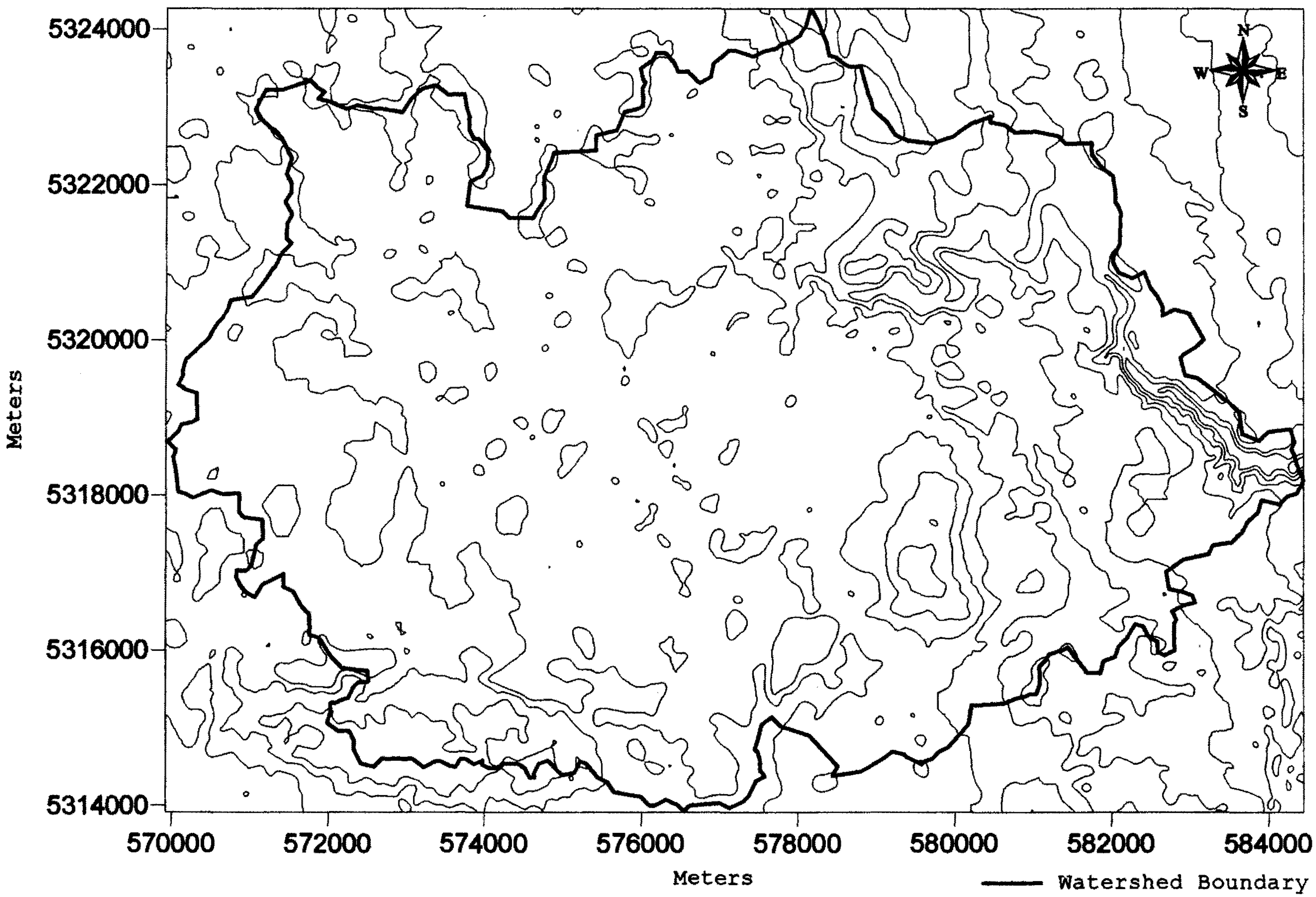

Figure 3. Contoured DEM After Filtering.

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.

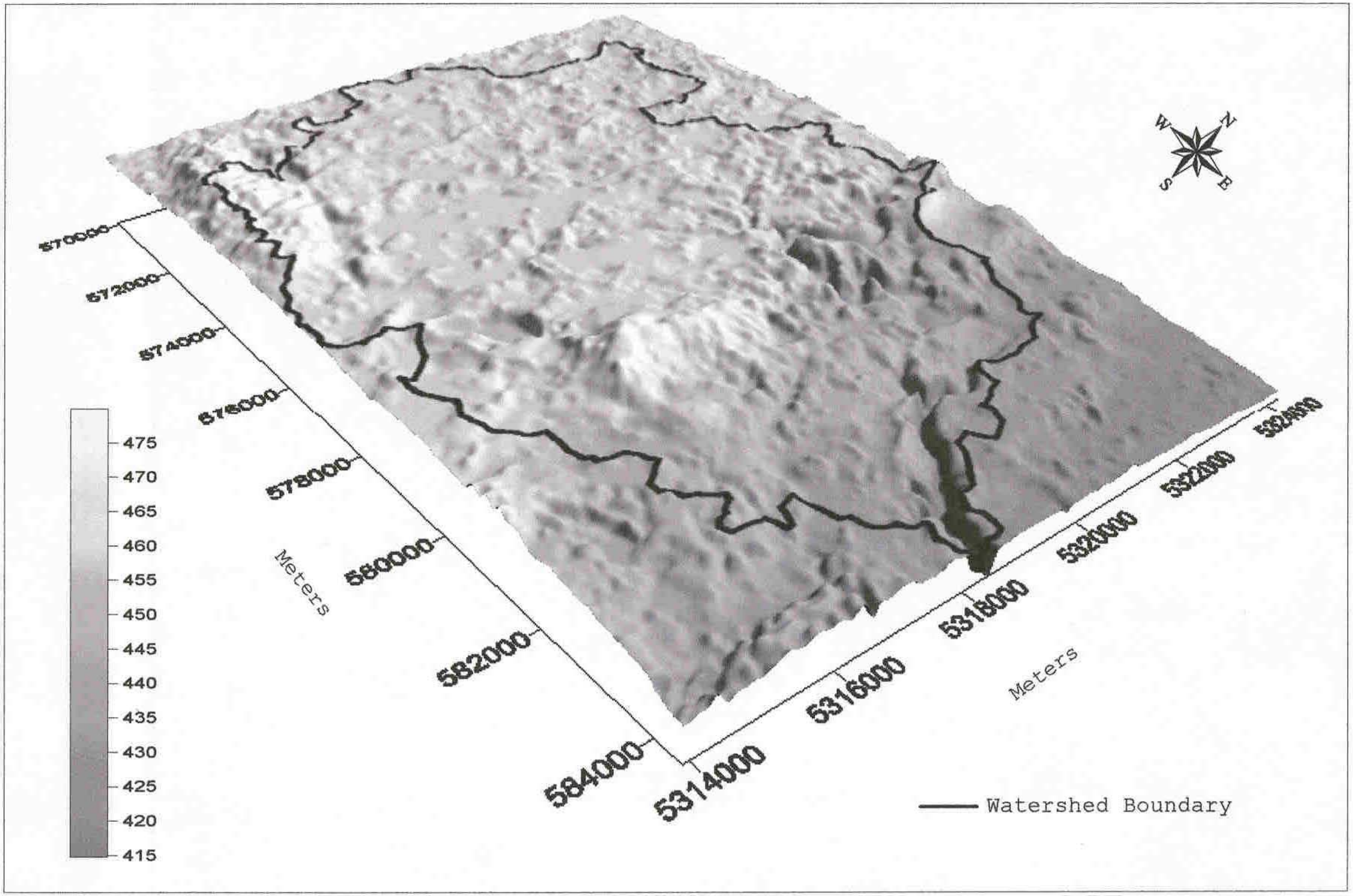

Figure 4. Hillshade of DEM (V.E. 1:24).

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	*Borup Silt Loam*		*76*	*Borup Silt Loam*	
20	*Hamerly Loam*	0-2	*19*	*Hamerly Loam*	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	*Cresbard-Barnes Loams*	3-6	*23B*	*Barnes-Cresbard Loams*	1-6
35	LaDelle Silt Loam channeled		46	LaDelle Silt Loam	0-3
38B	*Renshaw loam*	1-6	*89*	*Renshaw Loam*	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

		K (m/day)		
Series	Area	Dscrpt.*	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	Hydric
			km^2	%	m/day	Code**
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

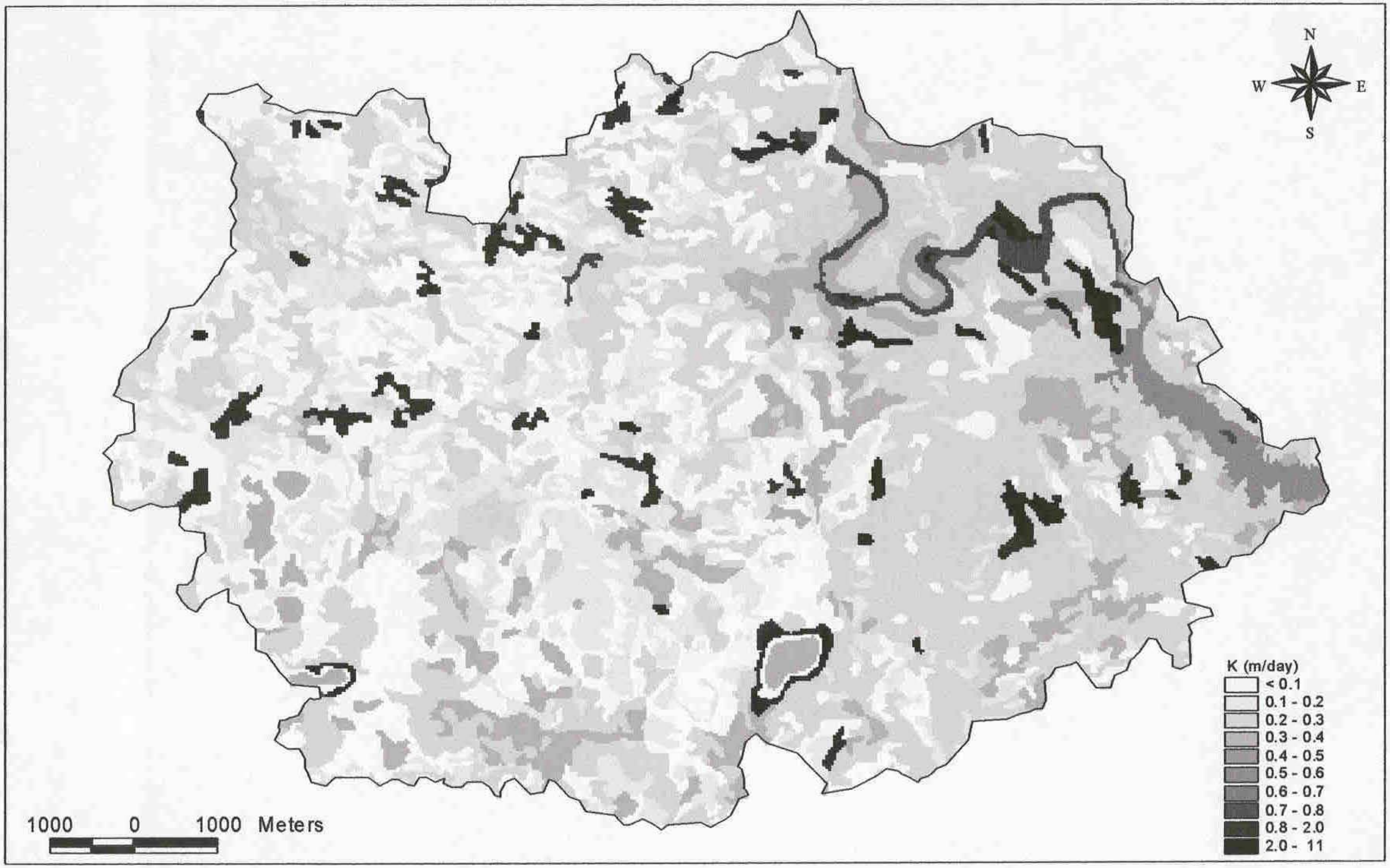

Figure 5. Hydraulic Conductivity Map of the Watershed.

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).

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

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 reclassed 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

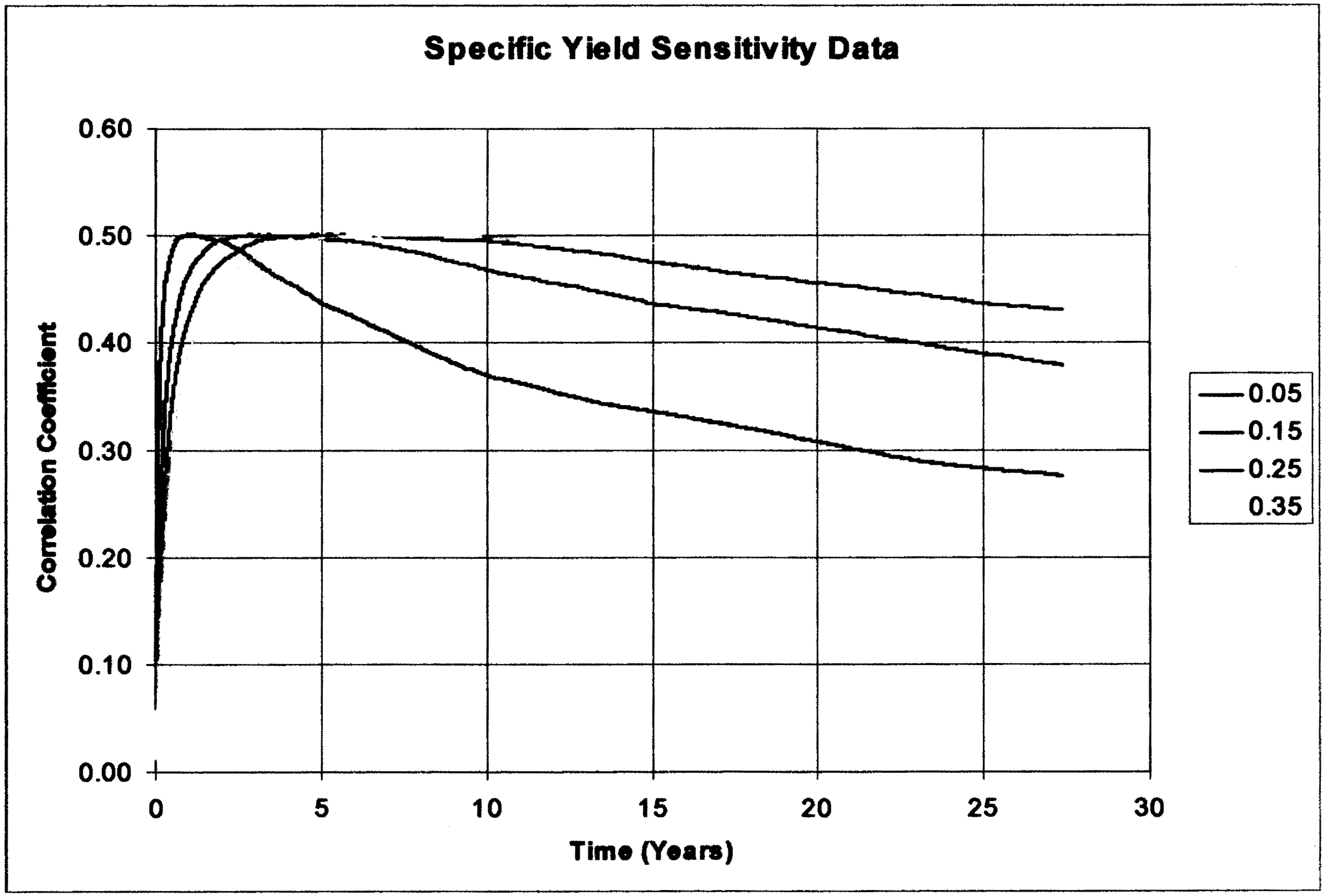

Figure 6. Sensitivity Analysis for Specific Yield.

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

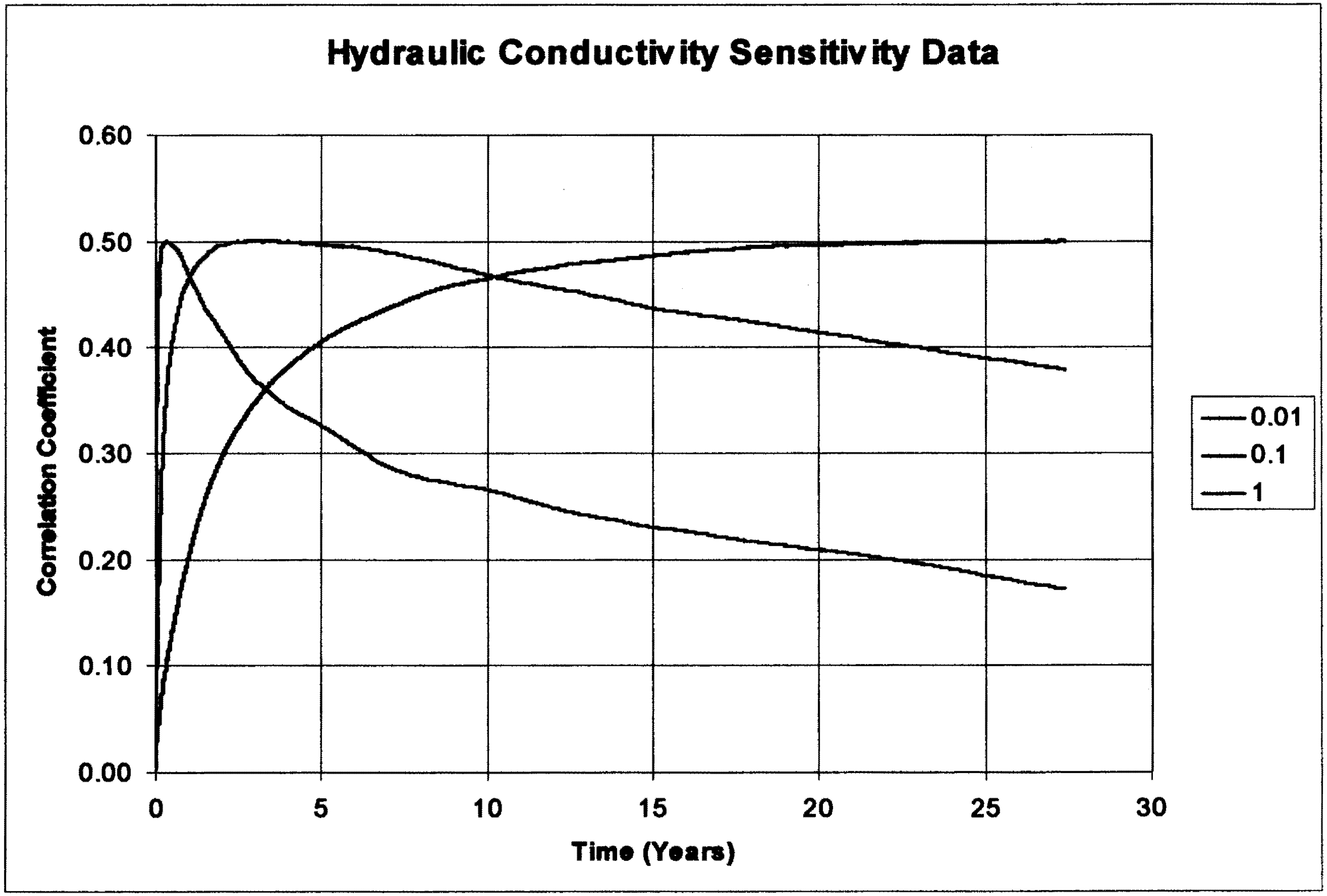

Figure 7. Sensitivity Analysis for Hydraulic Conductivity.

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).

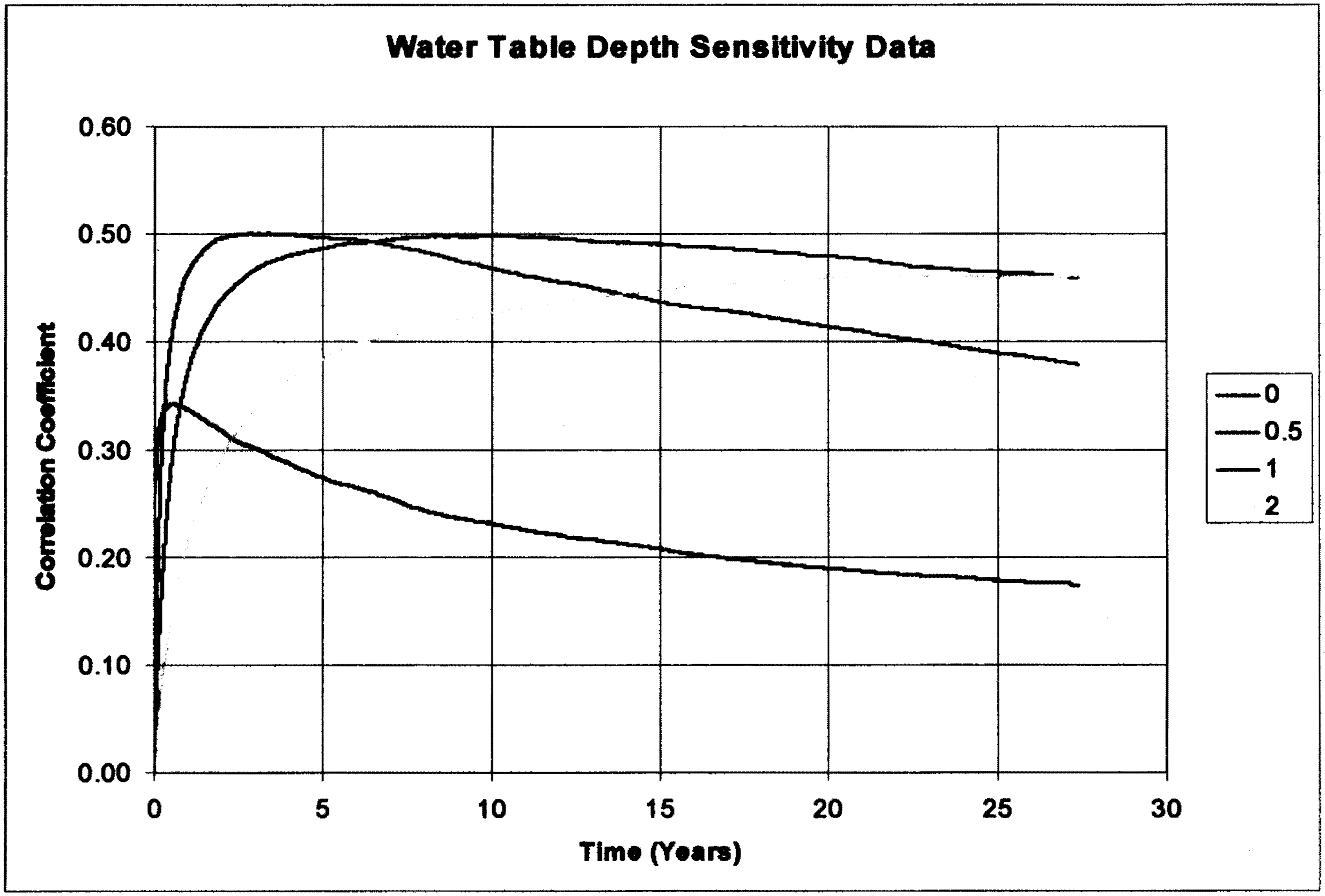

Figure 8. Sensitivity Analysis for Depth to Water Table.

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.

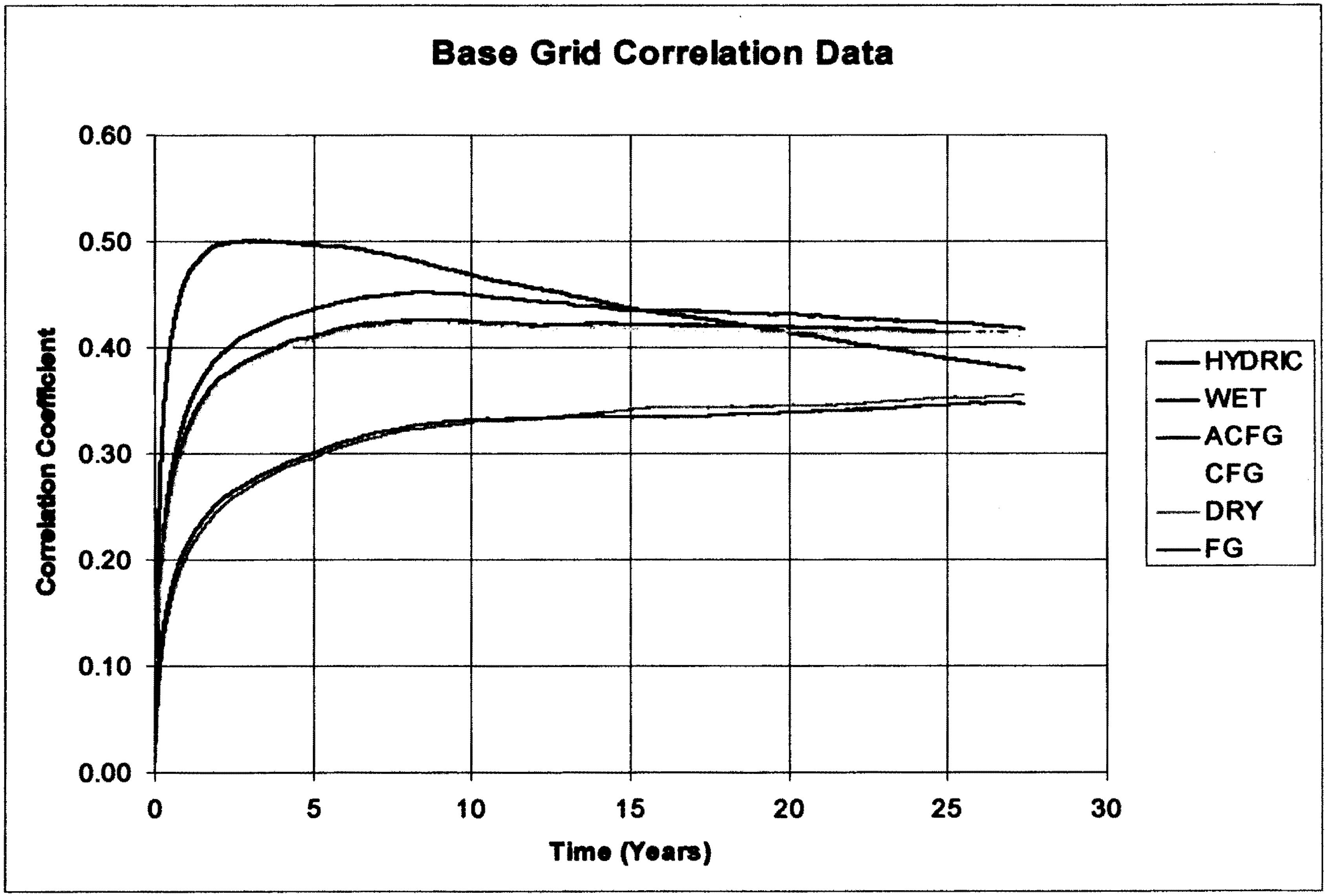

Figure 9. Reference Grid Comparison Data.

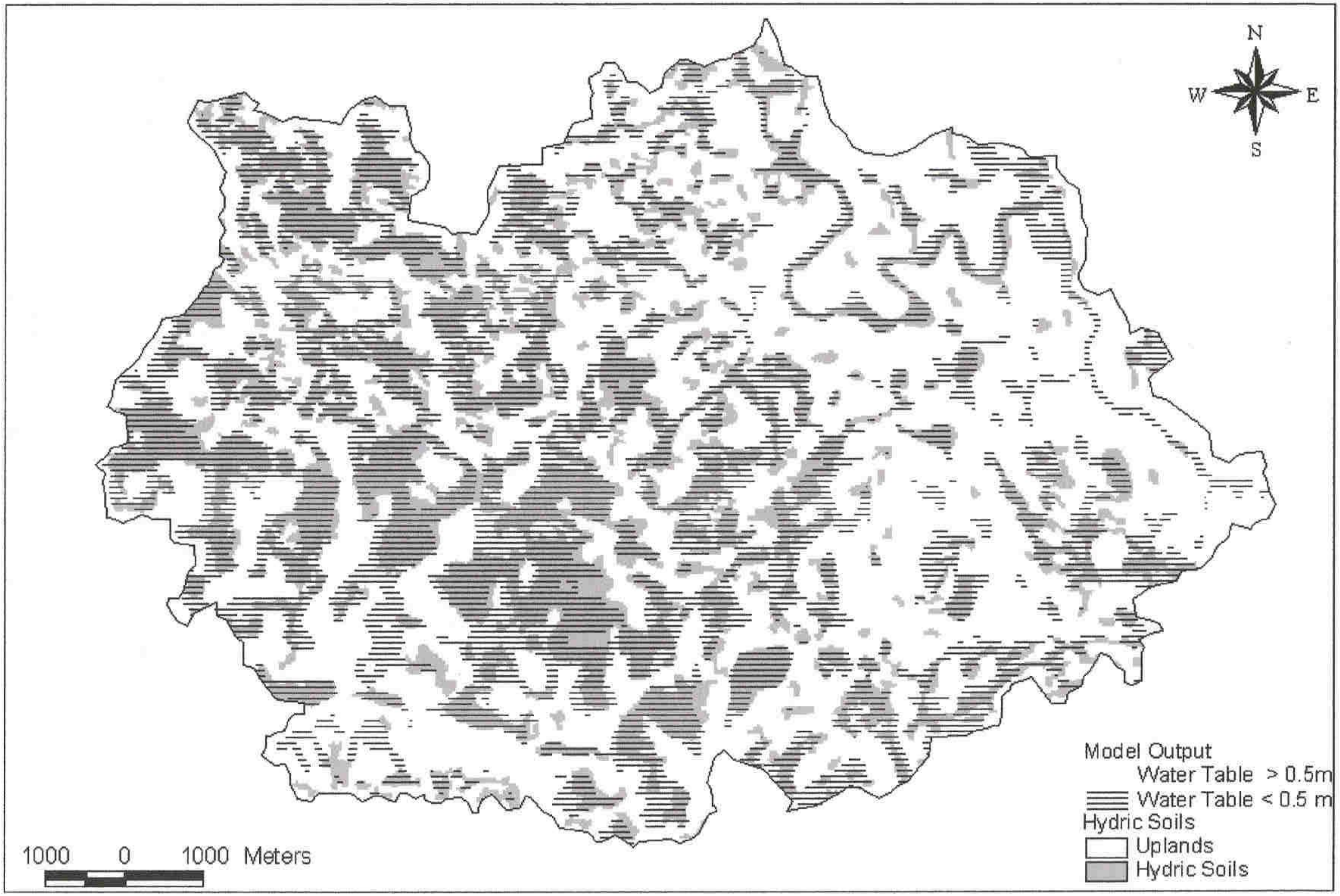

Figure 10. Comparison of Model Output to Hydric Soils Grid.

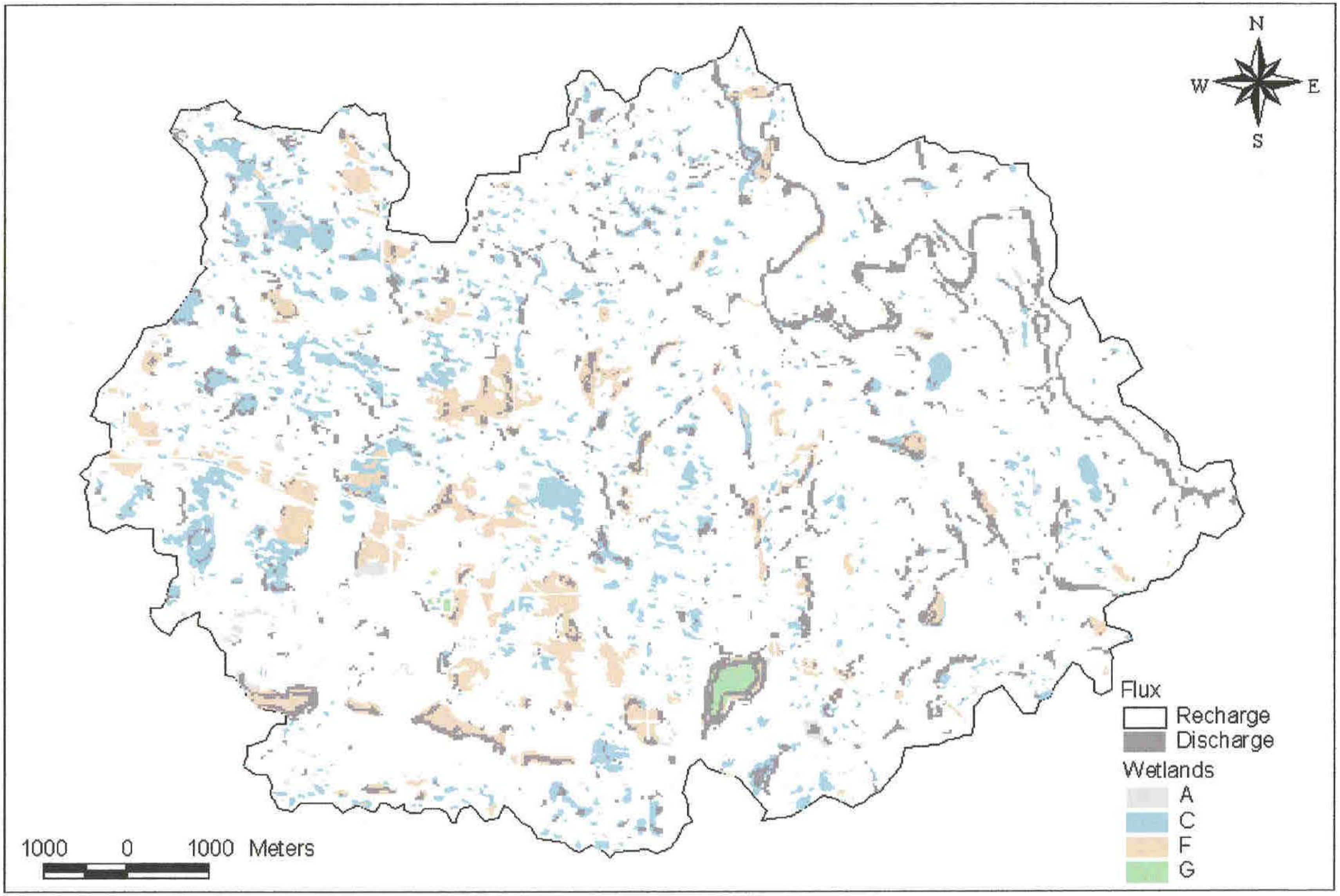

Figure 11. Model Flux With Respect to Wetland Distribution.

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 comprise 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)

```
C     ******************************************************************
C     *                                                                *
C     *    GERLA, PHIL                            Date: 09/20/03       *
C     *                                                                *
C     *    MODIFIED BY: LAVEAU, CHRIS                                  *
C     ******************************************************************
C
C     PROGRAM DESCRIPTION: SIMULATES STEPWISE DRAINAGE OF A SATURATED
C     LANDSCAPE THROUGH TIME USING DARCY'S LAW AND AN EXPRESSION FOR
C     CONSERVATION OF MASS.
C
C     INPUT: AN ARRAY REPRESENTING THE INITIAL TOPOGRAPHIC CONDITIONS
C     (DERIVED FROM A DEM) AND A SECOND ARRAY CONTAINING HYDRAULIC
C     CONDUCTIVITY.
C
C     DESCRIPTION OF ARRAYS:
C      HOLD(I,J) = IS THE HEAD SQUARED AT THE CURRENT TIME STEP
C      HNEW(I,J) = IS THE HEAD SQUARED AT THE NEXT TIME STEP
C         R(I,J) = RECHARGE RATE (SET EQUAL TO ZERO)
C         K(I,J) = NODAL AVERAGE HYDRAULIC CONDUCTIVITY
C        HO(I,J) = INITIAL HYDRAULIC HEAD DERIVED FROM A DEM
C        KX(I,J) = HARMONIC AVERAGE K AT A NODE IN THE X DIRECTION
C        KY(I,J) = HARMONIC AVERAGE K AT A NODE IN THE Y DIRECTION
C        WT(I,J) = COMPUTED WATER TABLE ELEVATIONS AT END OF TIME STEP
C        FT(I,J) = NODE-TO-NODE FLOW TERMS - SPECIFIC DISCHARGE
C       RCG(I,J) = NODAL RECHARGE RATE COMPUTED BY DIVIDING THE NET FLOW
C                  INTO OR OUT OF THE NODE BY THE SURFACE X-Y AREA OF
C                  NODAL CELL
C        ID(I,J) = INDICATOR MATRIX...SHOWS IF THE NODE HAS A SHALLOW (1)
C                  OR DEEP (0) WATER TABLE
C
C     DESCRIPTION OF VARIABLES:
C        XMIN = MINIMUM X SPATIAL COORDINATE
C        XMAX = MAXIMUM X SPATIAL COORDINATE
C        YMIN = MINIMUM Y SPATIAL COORDINATE
C        YMAX = MAXIMUM Y SPATIAL COORDINATE
C        ZMIN = MINIMUM Z SPATIAL COORDINATE (ELEVATION)
C        ZMAX = MAXIMUM Z SPATIAL COORDINATE (ELEVATION)
C       WTMIN = MINIMUM CALCULATED WATER TABLE ELEVATION AT EACH TIME STEP
C       WTMAX = MAXIMUM CALCULATED WATER TABLE ELEVATION AT EACH TIME STEP
C      RCGMIN = MINIMUM RECHARGE RATE AT THE END OF A TIME STEP
C      RCGMAX = MAXIMUM RECHARGE RATE AT THE END OF A TIME STEP
C      DWTMAX = THE MAXIMUM DEPTH TO THE WATER TABLE AT EACH TIME STEP
C          NC = NUMBER OF COLUMNS
C          NR = NUMBER OF ROWS
C          DX = CELLSIZE IN THE X DIRECTION
C          DY = CELLSIZE IN THE Y DIRECTION
C          DT = TIME STEP
C           S = SPECIFIC YIELD
C       ALPHA = IMPLICIT FINITE DIFFERENCE WEIGHTING FACTOR
C         TOL = ERROR TOLERANCE
C        TIME = HOLDS THE TOTAL MODEL TIME FOR THE CURRENT TIME STEP IN
C               THE COMPUTATION
C       NUMIT = NUMBER OF ITERATIONS IN THE CURRENT TIME STEP
C        AMAX = USED TO CHECK FOR CONVERGENCE IN A TIME STEP
C      OLDVAL = TEMPORARY PLACE FOR HEAD VALUE
C        AVGK =
C         ERR = USED TO CHECK FOR CONVERGENCE IN A TIME STEP
C     ISUMSWT = A COUNTER FOR THE NUMBER OF NODES WITH A SHALLOW WT
C           D = DEPTH TO THE WATER TABLE
C      SUMPOS = CALCULATED TOTAL DISCHARGE (SUM OF POS FLUX VALUES)
C      SUMNEG = CALCULATED TOTAL RECHARGE (SUM OF NEG FLUX VALUES)
C      PCTERR = PERCENT DIFFERENCE BETWEEN RECHARGE AND DISCHARGE
```

```
C        AREA = PERCENT AREA WITH SHALLOW WATER TABLE
C        NEND = NUMBER OF TIME STEPS THE MODEL WILL RUN
C       DEPTH = USER SPECIFIED DEPTH TO SHALLOW WATER TABLE
C        RMAX = VARIABLE FOR SUBROUTINE STAT
C
C    *******************************************************************
        PROGRAM RELAX
        EXTERNAL STAT
C       WT RELAXATION EXAMPLE - UNCONFINED AQUIFER - UNSTEADY CONDITIONS
        DOUBLE PRECISION HNEW(500,500), HOLD(500,500), R(500,500),
     +  HO(500,500), KX(500,500), KY(500,500), WT(500,500), FT(500,500),
     +  RCG(500,500), K(500,500), ID(500,500), XMIN, XMAX, YMIN, YMAX,
     +  ZMIN, ZMAX, WTMIN, WTMAX, RCGMIN, RCGMAX, DWTMAX, S, DT, DX, DY,
     +  ALPHA, TOL, TIME, AMAX, OLDVAL, AREA, AVGK, H1, H2, F1, F2, ERR,
     +  ISUMSWT, D, SUMPOS, SUMNEG, PCTERR, RMAX, DEPTH, R1, PRECIP
        INTEGER NC, NR, I, J, N, NEND, NUMIT
        CHARACTER*4 DSAA
C
C       INPUT THE SPECIFIC YIELD, HYDRAULIC CONDUCTIVITY, AND INITIAL
C       TIME STEP (NOTE: THESE MUST BE IN CONSISTENT TIME AND SPACE
C       UNITS)
C
        WRITE(6,*)' Input the estimated average specific yield'
        READ(5,*)S
        WRITE(6,*)' Input the initial time step in days'
        READ(5,*)DT
        WRITE(6,*)' Input depth for a shallow water table in meters'
        READ(5,*)DEPTH
C
C       ****************************************************************
C       INITIALIZE VALUES FOR SUBROUTINE STAT
        RMAX = 0.0D+00
C       CREATE OUTPUT FILE RESULT1 FOR RECORDING GRID STATISTICS AT
C       EACH INTERATION
        OPEN(UNIT=12,FILE='C:\STATISTICS\RESULT1.TXT',STATUS ='UNKNOWN')
        WRITE(12,160)
C       HEADER FOR OUTPUT FILE RESULT1
 160    FORMAT(1X,'STEP',8X,'TIME',10X,'CORRELATION',8X,'SHALLOW WT',
     +  5X,'MAX DEPTH TO WT',7X,'RECHARGE',9X,'DISCHARGE',10X,'ERROR',
     +  10X,'PRECIPITATION')
        WRITE(12,165)
 165    FORMAT(12X,'(DAYS)',9X,'(UNITLESS)',10X,'(% AREA)',11X,'(M)',
     +  14X,'(M3/DAY)',9X,'(M3/DAY)',12X,'(%)',14X,'(IN/YR)')
C       ****************************************************************
C
C       READ THE HEADER OF AN ASCII FORMAT SURFER GRID FILE FOR K.
C       (NOTE: BOTH THE ARRAY FOR K AND FOR ELEVATION MUST BE IDENTICAL
C       IN CELL SIZE AND GLOBAL DIMENSIONS)
C
        READ(19, '(A4)') DSAA
        WRITE(6,*)DSAA
        READ(19,*)NC, NR
        WRITE(6,*)NC, NR
        READ(19,*)XMIN, XMAX
        WRITE(6,*)XMIN, XMAX
        READ(19,*)YMIN, YMAX
        WRITE(6,*)YMIN, YMAX
        READ(19,*)ZMIN, ZMAX
        WRITE(6,*)ZMIN, ZMAX
C
C       READ THE K FILE AND THEN AD A LINE AROUND THE OUTSIDE
C       (FILE SHOULD HAVE SAME ORIENTATION AS BASE GRID)
C
```

```
      READ(19,*)((K(I,J),I=2,NC+1),J=2,NR+1)
      DO 51 I=2,NC+1
      K(I,1)=K(I,2)
      K(I,NR+2)=K(I,NR+1)
51    CONTINUE
      DO 52 J=2,NR+1
      K(1,J)=K(2,J)
      K(NC+2,J)=K(NC+1,J)
52    CONTINUE
C
C     COMPUTE THE INTERNODAL K VALUES (HARMONIC AVERAGE)
C
      DO 53 I=2,NC+1
      DO 53 J=2,NR+1
      KX(I,J)=4/((2/K(I,J))+(1/K(I+1,J))+(1/K(I-1,J)))
      KY(I,J)=4/((2/K(I,J))+(1/K(I,J+1))+(1/K(I,J-1)))
53    CONTINUE
C
C     HO IS THE INITIAL HEAD, READ FROM A SEPARATE FILE
C     SET NO-FLOW BOUNDARY AROUND MARGIN
C
C     READ THE HEADER ON AN ASCII FORMAT SURFER GRID FILE FOR ELEVATION
C
      READ(18, '(A4)') DSAA
      WRITE(6,*)DSAA
      READ(18,*)NC, NR
      WRITE(6,*)NC, NR
      READ(18,*)XMIN, XMAX
      WRITE(6,*)XMIN, XMAX
      READ(18,*)YMIN, YMAX
      WRITE(6,*)YMIN, YMAX
      READ(18,*)ZMIN, ZMAX
      WRITE(6,*)ZMIN, ZMAX
      DX=(XMAX-XMIN)/(NC-1)
      DY=(YMAX-YMIN)/(NR-1)
      WRITE(6,*)DX, DY
C
C     HO IS THE INITIAL HEAD, READ FROM A SEPARATE FILE
C     SET NO-FLOW BOUNDARY AROUND MARGIN
C     (FILE SHOULD HAVE SAME ORIENTATION AS BASE GRID)
C
      READ(18,*)((HO(I,J),I=2,NC+1),J=2,NR+1)
      DO 75 I=2,NC+1
      HO(I,1)=HO(I,3)
      HO(I,NR+2)=HO(I,NR)
75    CONTINUE
      DO 76 J=2,NR+1
      HO(1,J)=HO(3,J)
      HO(NC+2,J)=HO(NC,J)
76    CONTINUE
C
C     USE CRANK-NICHOLSON APPROXIMATION
C
      ALPHA=0.5D+00
C
C     SET ERROR TOLERANCE
C
      TOL=0.01D+00
C
C     INITIALIZE ARRAYS
C     HOLD IS THE HEAD SQUARED AT TIME STEP N
C     HNEW IS THE HEAD SQUARED AT TIME STEP N+1
C
```

```
      DO 4 I=1,NC+2
      DO 4 J=1,NR+2
      HNEW(I,J)=HO(I,J)**2
      HOLD(I,J)=HO(I,J)**2
      R(I,J)=0.0D+00
4     CONTINUE
      TIME=0.0D+00
C
C     START TIME STEPS
C     AT EACH TIME STEP SOLVE SYSTEM OF EQUATIONS BY ITERATION
C
      NEND= 20000
      DO 5 N=1,NEND
      NUMIT=0
      TIME=TIME+DT
10    AMAX=0.0D+00
      NUMIT=NUMIT+1
      DO 15 I=2,NC+1
      DO 15 J=2,NR+1
      OLDVAL=HNEW(I,J)
      AVGK=2/((1/KX(I,J))+(1/KY(I,J)))
      H1=(KX(I,J)*(HOLD(I,J+1)+HOLD(I,J-1))+KY(I,J)
     + *(HOLD(I+1,J)+HOLD(I-1,J)))/(2*(KX(I,J)+KY(I,J)))
      H2=(KX(I,J)*(HNEW(I,J+1)+HNEW(I,J-1))+KY(I,J)
     + *(HNEW(I+1,J)+HNEW(I-1,J)))/(2*(KX(I,J)+KY(I,J)))
      F1=DX*DY*S/(2.0D+00*AVGK*DT*(HOLD(I,J)**0.5D+00))
      F2=1.0D+00/(F1+ALPHA)
      HNEW(I,J)=((F1*HOLD(I,J))+(1.0D+00-ALPHA)*(H1-HOLD(I,J))+
     + (ALPHA*H2)+(R(I,J)*DX*DY/(KX(I,J)+KY(I,J))))*F2
      IF(HNEW(I,J).GT.OLDVAL) HNEW(I,J)=OLDVAL
      IF(HNEW(I,J).LT.0.0)WRITE(6,*)I,J,HNEW(I,J),'We have a problem!'
      ERR=DABS(HNEW(I,J)-OLDVAL)
      IF(ERR.GT.AMAX) AMAX=ERR
15    CONTINUE
C
C     ADJUST NO-FLOW BOUNDARIES
C
      DO 16 I=2,NC+1
      HNEW(I,1)=HNEW(I,3)
      HNEW(I,NR+2)=HNEW(I,NR)
16    CONTINUE
      DO 17 J=2,NR+1
      HNEW(1,J)=HNEW(3,J)
      HNEW(NC+2,J)=HNEW(NC,J)
17    CONTINUE
      IF(ALPHA.LT.0.1) GOTO 18
      IF(AMAX.GT.TOL) GOTO 10
18    CONTINUE
C
C     PREPARE FOR THE NEXT TIME STEP
C     PUT HNEW VALUES INTO HOLD ARRAY
C
      DO 20 I=1,NC+2
      DO 20 J=1,NR+2
20    HOLD(I,J)=HNEW(I,J)

C
C     COMPUTE ELEVATION AND DEPTH TO THE WATER TABLE
C     KEEP TRACK OF THE MINIMUM AND MAXIMUM WT ELEVATION
C     TALLY CELLS WITH A SHALLOW WT
C
      DWTMAX=0.0D+00
      WTMIN=9.9D+10
```

```
      WTMAX=0.0D+00
      ISUMSWT=0
      DO 25 I=2,NC+1
      DO 25 J=2,NR+1
      WT(I,J)=HNEW(I,J)**0.5D+00
      IF(WT(I,J).LT.WTMIN)WTMIN=WT(I,J)
      IF(WT(I,J).GT.WTMAX)WTMAX=WT(I,J)
      D=(HO(I,J)-WT(I,J))
      IF(D.GT.DWTMAX)DWTMAX=D
      IF(D.GT.DEPTH)THEN
      ID(I,J)=0
      ELSE
      ID(I,J)=1
      ISUMSWT=ISUMSWT+1
      ENDIF
25    CONTINUE
C
C     COMPUTE THE NODAL FLOW TERMS USING THE DUPUIT APPROXIMATION FOR
C     DARCY'S LAW (APPLY TO THE FOUR CORNERS OF THE GRID)
C
      FT(2,2)=(-0.25D+00*((K(2,2)+K(3,2))/2.0D+00)*DY/DX)*(HNEW(2,2)-
     + HNEW(3,2))+(-0.25D+00*((K(2,2)+K(2,3))/2.0D+00)*DX/DY)*
     + (HNEW(2,2)-HNEW(2,3))
      RCG(2,2)=FT(2,2)/(DX*DY)
      FT(NC+1,2)=(-0.25D+00*((K(NC+1,2)+K(NC,2))/2.0D+00)*DY/DX)*
     + (HNEW(NC+1,2)-HNEW(NC,2))+(-0.25D+00*((K(NC+1,2)+K(NC+1,3))/
     + 2.0D+00)*DX/DY)*(HNEW(NC+1,2)-HNEW(NC+1,3))
      RCG(NC+1,2)=FT(NC+1,2)/(DX*DY)
      FT(2,NR+1)=(-0.25D+00*((K(2,NR+1)+K(3,NR+1))/2.0D+00)*DY/DX)*
     + (HNEW(2,NR+1)-HNEW(3,NR+1))+(-0.25D+00*((K(2,NR+1)+K(2,NR))/
     + 2.0D+00)*DX/DY)*(HNEW(2,NR+1)-HNEW(2,NR))
      RCG(2,NR+1)=FT(2,NR+1)/(DX*DY)
      FT(NC+1,NR+1)=(-0.25D+00*((K(NC+1,NR+1)+K(NC,NR+1))/2.0D+00)*
     + DY/DX)*(HNEW(NC+1,NR+1)-HNEW(NC,NR+1))+(-0.25D+00*((K(NC+1,NR+1)
     + +K(NC+1,NR))/2.0D+00)*DX/DY)*(HNEW(NC+1,NR+1)-HNEW(NC+1,NR))
      RCG(NC+1,NR+1)=FT(NC+1,NR+1)/(DX*DY)
C
C     (APPLY TO THE REMAINING EDGES)
C
      DO 71 I=3,NC
      FT(I,2)=(-0.25D+00*((K(I,2)+K(I+1,2))/2.0D+00)*DY/DX)*
     + (HNEW(I,2)-HNEW(I+1,2))+(-0.25D+00*((K(I,2)+K(I-1,2))/2.0D+00)
     + *DY/DX)*(HNEW(I,2)-HNEW(I-1,2))+(-0.5D+00*((K(I,2)+K(I,3))/
     + 2.0D+00)*DX/DY)*(HNEW(I,2)-HNEW(I,3))
      RCG(I,2)=FT(I,2)/(DX*DY)
      FT(I,NR+1)=(-0.25D+00*((K(I,NR+1)+K(I+1,NR+1))/2.0D+00)*DY/DX)*
     + (HNEW(I,NR+1)-HNEW(I+1,NR+1))+(-0.25D+00*((K(I,NR+1)+
     + K(I-1,NR+1))/2.0D+00)*DY/DX)*(HNEW(I,NR+1)-HNEW(I-1,NR+1))
     + +(-0.5D+00*((K(I,NR+1)+K(I,NR))/2.0D+00)*DX/DY)*(HNEW(I,NR+1)
     + -HNEW(I,NR))
      RCG(I,NR+1)=FT(I,NR+1)/(DX*DY)
71    CONTINUE
      DO 72 J=3,NR
      FT(2,J)=(-0.25D+00*((K(2,J)+K(2,J+1))/2.0D+00)*DX/DY)*(HNEW(2,J)
     + -HNEW(2,J+1))+(-0.25D+00*((K(2,J)+K(2,J-1))/2.0D+00)*DX/DY)*
     + (HNEW(2,J)-HNEW(2,J-1))+(-0.5D+00*((K(2,J)+K(3,J))/2.0D+00)*
     + DY/DX)*(HNEW(2,J)-HNEW(3,J))
      RCG(2,J)=FT(2,J)/(DX*DY)
      FT(NC+1,J)=(-0.25D+00*((K(NC+1,J)+K(NC+1,J+1))/2.0D+00)*DX/DY)*
     + (HNEW(NC+1,J)-HNEW(NC+1,J+1))+(-0.25D+00*((K(NC+1,J)+
     + K(NC+1,J-1))/2.0D+00)*DX/DY)*(HNEW(NC+1,J)-HNEW(NC+1,J-1))
     + +(-0.5D+00*((K(NC+1,J)+K(NC,J))/2.0D+00)*DY/DX)*(HNEW(NC+1,J)-
     + HNEW(NC,J))
```

```
           RCG(NC+1,J)=FT(NC+1,J)/(DX*DY)
   72      CONTINUE
   C
   C        (COMPUTE NODAL TERMS IN THE INTERIOR)
   C
           DO 73 I=3,NC
           DO 73 J=3,NR
           FT(I,J)=(-0.5D+00*((K(I,J)+K(I+1,J))/2.0D+00)*DY/DX)*
         + (HNEW(I,J)-HNEW(I+1,J))+(-0.5D+00*((K(I,J)+k(I-1,J))/2.0D+00)
         + *DY/DX)*(HNEW(I,J)-HNEW(I-1,J))+(-0.5D+00*((K(I,J)+K(I,J+1))/
         + 2.0D+00)*DX/DY)*(HNEW(I,J)-HNEW(I,J+1))+(-0.5D+00*((K(I,J)+
         + K(I,J+1))/2.0D+00)*DX/DY)*(HNEW(I,J)-HNEW(I,J-1))
           RCG(I,J)=FT(I,J)/(DX*DY)
   73      CONTINUE
   C
   C        CHECK THE WATER BUDGET
   C
           SUMPOS=0.0D+00
           SUMNEG=0.0D+00
           DO 74 I=2,NC+1
           DO 74 J=2,NR+1
           IF(FT(I,J).GT.0.0) THEN
              SUMPOS=SUMPOS+FT(I,J)
           ELSE
              SUMNEG=SUMNEG+FT(I,J)
           ENDIF
   74      CONTINUE
           PCTERR=((SUMPOS-ABS(SUMNEG))/(SUMPOS+ABS(SUMNEG)))*100
           AREA=(ISUMSWT/(NC*NR))*100D+00
   C
   C        CALL STATISTICAL SUBROUTINE
   C
           CALL STAT(WT,ID,RCG,NC,NR,DX,RMAX,N,XMIN,YMIN,S,DEPTH,TIME,DT,
         + NUMIT,SUMPOS,SUMNEG,PCTERR,AREA,DWTMAX,R1,PRECIP)
   C
   C      ******************************************************************
   C        PRINT TABLE OF MODEL STATISTICS FOR EACH ITERATION TO RESULT1
   C
           WRITE(12,170) N, TIME, R1, AREA, DWTMAX, SUMNEG, SUMPOS, PCTERR,
         + PRECIP
   170     FORMAT(I5,1X,E17.10,1X,E17.10,1X,E17.10,1X,E17.10,1X,E17.10,1X,
         + E17.10,1X,E17.10,1X,E17.10)
   C      ******************************************************************
   C
   C        FIND RECHARGE MINIMUM AND MAXIMUM
   C
           RCGMIN=9.9D+10
           RCGMAX=-9.9D+05
           DO 78 I=2,NC+1,1
           DO 78 J=2,NR+1,1
           IF(RCG(I,J).LT.RCGMIN)RCGMIN=RCG(I,J)
           IF(RCG(I,J).GT.RCGMAX)RCGMAX=RCG(I,J)
   78      CONTINUE
   C
   C        INCREASE THE TIME STEP
   C
           DT=DT*1.1D+00
           IF(DT.GT.2.0) DT=2.0D+00
   5       CONTINUE
           CLOSE(UNIT=12)
           PAUSE
           END
   C
```

```
C     ******************************************************************
C     *                                                                *
C     *   LAVEAU, CHRIS                              Date: 10/25/03    *
C     *                                                                *
C     ******************************************************************
C
C     PROGRAM DESCRIPTION: CALCULATES A CORRELATION COEFFICIENT FOR A
C     SERIES OF ARRAYS IN TWO DISCRETE FILES.
C
C     INPUT: A BASE FILE REPRESENTING THE LOCATION OF SHALLOW WATER
C     TABLE IN THE FIELD.
C
C     DESCRIPTION OF VARIABLES:
C        X(I,J) = BASE ARRAY, DEFINED TO CONTAIN X VARIABLES (BASE.TXT)
C        Y(I,J) = MODEL OUTPUT ARRAY IDENTIFYING AREAS WITH SHALLOW
C                 WATER TABLE. DEFINED TO CONTAIN Y VARIABLES (MODEL.TXT)
C     FLUX(I,J) = MODEL OUTPUT ARRAY CONTAINING FLUX VALUES IN M/DAY
C                 (FLUX.TXT)
C            NC = NUMBER OF COLUMNS
C            NR = NUMBER OF ROWS
C            NG = NUMBER OF GRIDS BEING COMPARED
C            DX = CELLSIZE OF GRIDS
C             N = NUMBER OF ELEMENTS
C          SUMX = SUM OF X VARIABLES
C          SUMY = SUM OF Y VARIABLES
C         SUMXY = SUM OF X VARIABLES MULTIPLIED BY Y VARIABLES
C         SUMX2 = SUM OF X VARIABLES SQUARED
C         SUMY2 = SUM OF Y VARIABLES SQUARED
C           SSX = SUM OF SQUARES FOR X VARIABLE
C           SSY = SUM OF SQUARES FOR Y VARIABLE
C          SSXY = SUM OF PRODUCTS XY
C             R = CORRELATION COEFFICIENT
C         PERCX = PERCENT AREA WITH SHALLOW WATER TABLE FOR X ARRAY
C         PERCY = PERCENT AREA WITH SHALLOW WATER TABLE FOR Y ARRAY
C          DIFF = PERCENT DIFFERENCE BETWEEN PERCX AND PERCY
C             Q = TOTAL DISCHARGE IN M3/DAY
C             W = TOTAL RECHARGE IN M3/DAY
C        PRECIP = AVERAGE RECHARGE FLUX IN INCHES/YR
C
C      ********************* Declaration Section *********************
C
       SUBROUTINE STAT(WT,Y,FLUX,NC,NR,DX,RMAX,ITER,XMIN,YMIN,S,DEPTH,
     + TIME,DT,NUMIT,SUMPOS,SUMNEG,PCTERR,AREA,DWTMAX,R,PRECIP)
       INTEGER I,J,NC,NR
       DOUBLE PRECISION X(500,500),Y(500,500),FLUX(500,500),WT(500,500),
     + SUMX,SUMX2,SUMY,SUMY2,SUMXY,N,SSX,SSY,SSXY,R,PERCX,PERCY,Q,W,DX,
     + DIFF,PRECIP
C      RELAX VARIABLES
       INTEGER ITER, NUMIT
       DOUBLE PRECISION RMAX,XMIN,YMIN,DEPTH,SUMNEG,SUMPOS,DT,TIME,
     + PCTERR,AREA,DWTMAX,S
C
C     ********************* Initialization Section ********************
C
C      FILES
       OPEN(UNIT=10, FILE='C:\STATISTICS\BASE.TXT', STATUS='OLD')
       OPEN(UNIT=13, FILE='C:\STATISTICS\RESULT2.TXT',STATUS ='UNKNOWN')
C
C     ************************* Input Section *************************
C
C      READ GRIDS
       DO 5 J=1,NR
       READ(10,*) (X(I,J),I=1,NC)
```

```
      END IF
20    CONTINUE
25    CONTINUE
C     CALCULATE PERCENT DIFFERENCE BETWEEN PERCX AND PERCY
      DIFF = ((DABS(PERCX-PERCY))/((1.0D+00/2.0D+00)*(PERCX+PERCY)))
     + *100D+00
C     CALCULATE AVERAGE RECHARGE FLUX
      PRECIP = (DABS(W)*365.0D+00*100.0D+00)/(N*DX*DX*2.54D+00)
C     CALCULATE A CORRELATION COEFFICIENT
      SSX  = SUMX2 - SUMX**2D+00/N
      SSY  = SUMY2 - SUMY**2D+00/N
      SSXY = SUMXY - (SUMX*SUMY)/N
      R = SSXY/DSQRT(SSX*SSY)
      IF (R.GT.RMAX) THEN
      RMAX = R
      ELSE
      GO TO 145
      END IF
C
C     ************************ Output Section ************************
C
C             WRITE STATISTICS FROM SUBROUTINE STAT TO RESULT2
      WRITE (13,85)
85    FORMAT(23('*'),2X,'STATISTICS',2X,23('*'))
      WRITE (13,90) ITER,N,SUMX,SUMY,SUMXY,SUMX2,SUMY2,SSX,SSY,SSXY,R,
     + PERCX,PERCY,DIFF,Q,W,PRECIP
90    FORMAT(
     A 13X,'         ITERATION =',I5//,
     B 1X,'                   N =',1X,E17.10/,
     C 1X,'               SUM X =',1X,E17.10/,
     D 1X,'               SUM Y =',1X,E17.10/,
```

```
     E 1X,'             SUM XY =',1X,E17.10/,
     F 1X,'             SUM X2 =',1X,E17.10/,
     G 1X,'             SUM Y2 =',1X,E17.10/,
     H 1X,'                SSX =',1X,E17.10/,
     I 1X,'                SSY =',1X,E17.10/,
     J 1X,'               SSXY =',1X,E17.10/,
     K 1X,'                  R =',1X,E17.10/,
     L 1X,'              PERCX =',1X,E17.10,1X,'%'/,
     M 1X,'              PERCY =',1X,E17.10,1X,'%'/,
     N 1X,'       % DIFFERENCE =',1X,E17.10,1X,'%'/,
     O 1X,'          DISCHARGE =',1X,E17.10,1X,'M3/DAY'/,
     P 1X,'           RECHARGE =',1X,E17.10,1X,'M3/DAY'/,
     Q 1X,'      PRECIPITATION =',1X,E17.10,1X,'IN/YR'//)
C
C       WRITE OUTPUT FROM MAIN PROGRAM RELAX
        WRITE(13,95)
 95     FORMAT(26('*'),2X,'RELAX',2X,25('*')/)
        WRITE(13,100)
 100    FORMAT('    DESCRIBE K MATRIX:  K*0.1 (M/DAY)')
        WRITE(13,105)S,DEPTH,TIME,DT,NUMIT,SUMPOS,SUMNEG,PCTERR,
     + AREA,DWTMAX
 105    FORMAT(
     A 1X,'     SPECIFIC YIELD =',1X,E17.10/,
     B 1X,'   SHALLOW WT DEPTH =',1X,E17.10,1X,'M',/
     C 1X,'               TIME =',1X,E17.10,1X,'DAYS'/,
     D 1X,'          TIME STEP =',1X,E17.10,1X,'DAYS'/,
     E 1X,'              NUMIT =',1X,I17/,
     F 1X,'      TOT DISCHARGE =',1X,E17.10,1X,'M3/DAY'/,
     G 1X,'       TOT RECHARGE =',1X,E17.10,1X,'M3/DAY'/,
     H 1X,'             % DIFF =',1X,E17.10,1X,'%'/,
     I 1X,'% AREA W/SHALLOW WT =',1X,E17.10,1X,'%'/,
     J 1X,'    MAX DEPTH TO WT =',1X,E17.10,1X,'M'/)
C
C       PRINT SPATIAL ARRAYS IN ARCVIEW FORMAT
C      PRINT ARCVIEW HEADER
C
        WRITE (13,110) NC,NR,XMIN,YMIN,DX
 110    FORMAT(
     A 2X,'ncols    ',3X,I4/,
     B 2X,'nrows    ',3x,I4/,
     C 2X,'xllcorner',3X,F12.4/,
     D 2X,'yllcorner',4X,F12.4/,
     E 2X,'cellsize ',3X,F4.0)
C       PRINT INTEGER MAP SHOWING AREAS OF SHALLOW WATER TABLE
        WRITE (13,115) ((Y(I,J),I=2,NC+1),J=2,NR+1)
 115    FORMAT(1X,30F4.1)
        WRITE (13,120)
 120    FORMAT(/)
C       PRINT NEW WATER TABLE ELEVATIONS
        WRITE(13,125) ((WT(I,J),I=2,NC+1),J=2,NR+1)
 125    FORMAT(1X,30F7.2)
        WRITE (13,130)
 130    FORMAT(/)
C       PRINT SPECIFIC RECHARGE FOR CELLS
        WRITE(13,135) ((FLUX(I,J),I=2,NC+1),J=2,NR+1)
 135    FORMAT(1X,30F12.8)
        WRITE (13,140)
 140    FORMAT(/)
C
C      *********************** Close & End Section **********************
C
 145    CLOSE(UNIT = 10)
        CLOSE(UNIT = 13)
        RETURN
        END
```

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