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Delineation of a Wellhead Protection Zone and Determination of Flowpaths from Potential Groundwater Contaminant Source Areas at Camp Ripley, Little Falls, Minnesota

Environmental Science Division

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for
Facilities Management Office-Environmental Program,
Department of Military Affairs, Minnesota Army National Guard, Little Falls, MN

by
J.J. Quinn
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DELINEATION OF A WELLHEAD PROTECTION ZONE AND DETERMINATION OF FLOWPATHS FROM POTENTIAL GROUNDWATER CONTAMINANT SOURCE AREAS AT CAMP RIPLEY, LITTLE FALLS, MINNESOTA

by

J.J. Quinn

ABSTRACT

Groundwater at Camp Ripley, Minnesota, is recharged both on post and off site and discharged to rivers, wetlands, and pumping wells. The subsurface geologic materials have a wide range of permeabilities and are arranged in a complex fashion as a result of the region's multiple glacial advances. Correlation of individual glacial geologic units is difficult, even between nearby boreholes, because of the heterogeneities in the subsurface. This report documents the creation of a numerical model of groundwater flow for Camp Ripley and hydrologically related areas to the west and southwest. The model relies on a hydrogeological conceptual model built on the findings of a University of Minnesota-Duluth drilling and sampling program conducted in 2001. Because of the site's stratigraphic complexity, a geostatistical approach was taken to handle the uncertainty of the subsurface correlation. The U.S. Geological Survey's MODFLOW code was used to create the steady-state model, which includes input data from a variety of sources and is calibrated to water levels in monitoring wells across much of the site. This model was used for several applications. Wellhead protection zones were delineated for on-site production wells H, L, and N. The zones were determined on the basis of a probabilistic assessment of the groundwater captured by these wells; the assessment, in turn, had been based on multiple realizations of the study area's stratigraphy and groundwater flowfield. An additional application of the model was for estimating flowpaths and times of travel for groundwater at Camp Ripley's range areas and waste management facilities.

1 INTRODUCTION

Camp Ripley (Figure 1) is located near Little Falls, in the center of the state of Minnesota. Although there are no urgent environmental situations requiring remedial action at the facility, its environmental managers wanted to improve their understanding of the site's hydrogeologic complexity. To meet this goal, Camp Ripley partnered with the University of Minnesota-Duluth (UMD) Department of Geological Sciences. UMD performed a multiyear

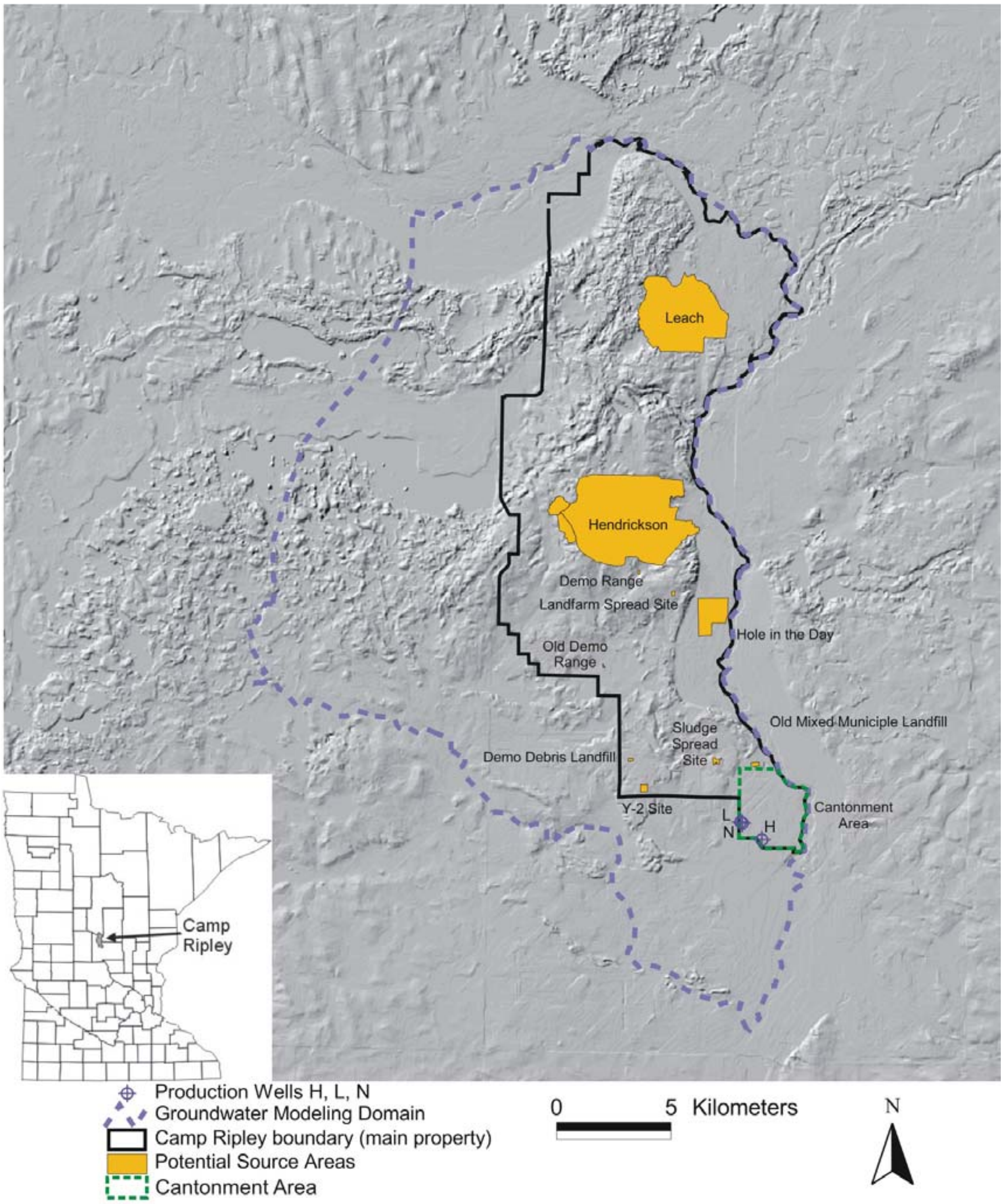

FIGURE 1 Camp Ripley Location, Layout, and Sources of Potential Groundwater Contamination

study that included collecting field data and managing a database pertaining to a wide variety of hydrologic and geologic aspects of the site. Then UMD teamed with Argonne National Laboratory (Argonne) to help create a numerical groundwater flow model of the site.

This report documents the approach, assumptions, results, and conclusions that were involved in constructing a numerical groundwater model to be used to address two site management needs at Camp Ripley. One need was to estimate the routes and flow rates of groundwater beneath the site’s firing ranges and waste management facilities. The second was to delineate a wellhead protection (WHP) zone for the three active Camp Ripley production wells: wells H, L, and N. The WHP zone was determined through a probabilistic approach, built on an updated version of a recent sitewide groundwater model (Quinn 2003). Because of the detailed geologic and hydrologic information included in this model and the probabilistic approach taken to WHP zone delineation, this model is considered to be more accurate than a previous model (Minnesota Army National Guard 2002). The development of specific management strategies and the identification of potential contaminant sources were beyond the scope of the current analysis; however, fairly recent information on these subjects is available in Minnesota Army National Guard (2002).

The model was created by using the U.S. Geological Survey’s MODFLOW code (Harbaugh et al. 2000). The analysis of input and output data was facilitated by using the Groundwater Modeling System (GMS), Version 5.1 (EMRL 2004).

2 GLACIAL GEOLOGIC HISTORY OF CAMP RIPLEY AND VICINITY

2.1 OVERVIEW

In late Wisconsinan time, central Minnesotan was glaciated by the Hewitt phase of the Rainy lobe (Goldstein 1989), which advanced far south and west of the Camp Ripley region and built the Alexandria moraine. Later in the late Wisconsinan stage, glacial lobes advanced into the Camp Ripley vicinity from three directions. These included the Itasca lobe from the north, the Rainy lobe from the northeast, and the Superior lobe from the east.

The Itasca lobe (Mooers and Lehr 1997), Rainy lobe, and Superior lobe have been identified as the key components of the Wisconsinan stage glacial history of central Minnesota (Wright 1972; Schneider 1961). The Itasca lobe emanated from the spreading center in Labrador, Canada, and traveled across the Camp Ripley vicinity from the north (Figure 2). A fan-shaped pattern of drumlins indicates that the flow was radial in central Minnesota (Wright 1972). Its drift is gray if it is unoxidized, yellow-brown if it is oxidized, and calcareous. Its till (unsorted, unstratified material deposited directly by glacial ice) is a sandy loam (Schneider 1961). The character of the drift is the result of its Paleozoic carbonate source area.

The Rainy and Superior lobes originated from the northeast, in the Labradorian spreading center, and both created drumlin fields (Schneider 1961; Wright 1972; Goldstein 1998). The Rainy lobe traveled from the northeast over basalt and other northeastern lithologies, resulting in a drift that is brown and sandy. The Superior lobe flowed out of the Lake Superior basin alongside the Rainy lobe. Like the Rainy drift, the Superior drift is also coarse-grained, but it is red due to a prevalence of rhyolite and red sandstone. The Superior lobe fanned out in central Minnesota, with westward flow to the Camp Ripley vicinity.

Camp Ripley's 214-km^2 area is located primarily on an odd interruption in the otherwise smooth curve of the St. Croix moraine (Figure 2). The St. Croix moraine is generally considered to be built of till and ice-contact deposits of the Superior and Rainy lobes. The moraine does not represent the farthest advance of these lobes, as their deposits are found past the moraine in central Minnesota (Goldstein 1998; Schneider 1961).

2.2 FINDINGS OF ENVIRONMENTAL DRILLING PROGRAM, EnDriP

In late 2002, UMD conducted a drilling and sampling effort called the Environmental Drilling Program (EnDriP). EnDriP relied on rotasonic drilling and sampling techniques to obtain continuous, high-quality, 4-in.-diameter cores of the Camp Ripley glacial sediments. Nine drilling locations (Figure 3) were selected across the Camp Ripley site to provide information on various aspects of the subsurface, such as the depth to bedrock/saprolith, character of various portions of the St. Croix moraine, character of lowland areas, and various information on deep glacial drift units.

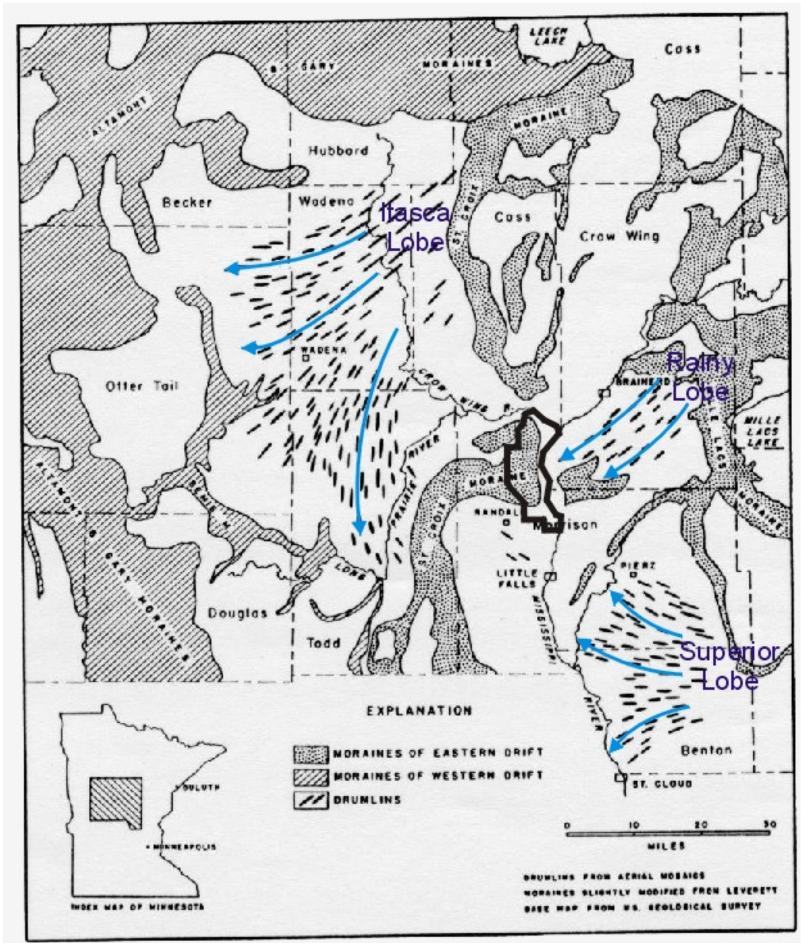

FIGURE 2 Ice Flow Directions, End Moraines, and Drumlin Fields of the Itasca, Rainy, and Superior Lobes in Central Minnesota (Source: Modified from Schneider 1961; used with permission of the Minnesota Geological Survey)

Results of the detailed logging of glacial drift materials during the EnDriP field work are described in UMD (2002). Although not all of the nine borehole locations reach bedrock, in combination they provide a good picture of the site's glacial geologic framework (Figure 4). Eleven materials were noted in the EnDriP investigation: saprolith, coarse sand and gravel, silty fine sand, medium sand, fine sand, lacustrine silt, lacustrine clay, silt loam, red sandy till, red/brown sandy loam till, and dense clay loam till. Key attributes include red and brown drift in the south, grey drift above bedrock, interbedded drift examples, and an overall dominance by brown drift. The character of the uppermost sediment varies with location; examples include brown sand, brown till, and red sand.

Well logs for numerous wells drilled on and off site were inspected for stratigraphic data. Drilling data from on-site wells were provided by Camp Ripley, while data for off-site wells were obtained from the online county well index (Minnesota Department of Health 2006). Drillers' descriptions were interpreted on the basis of direct observations of EnDriP-derived

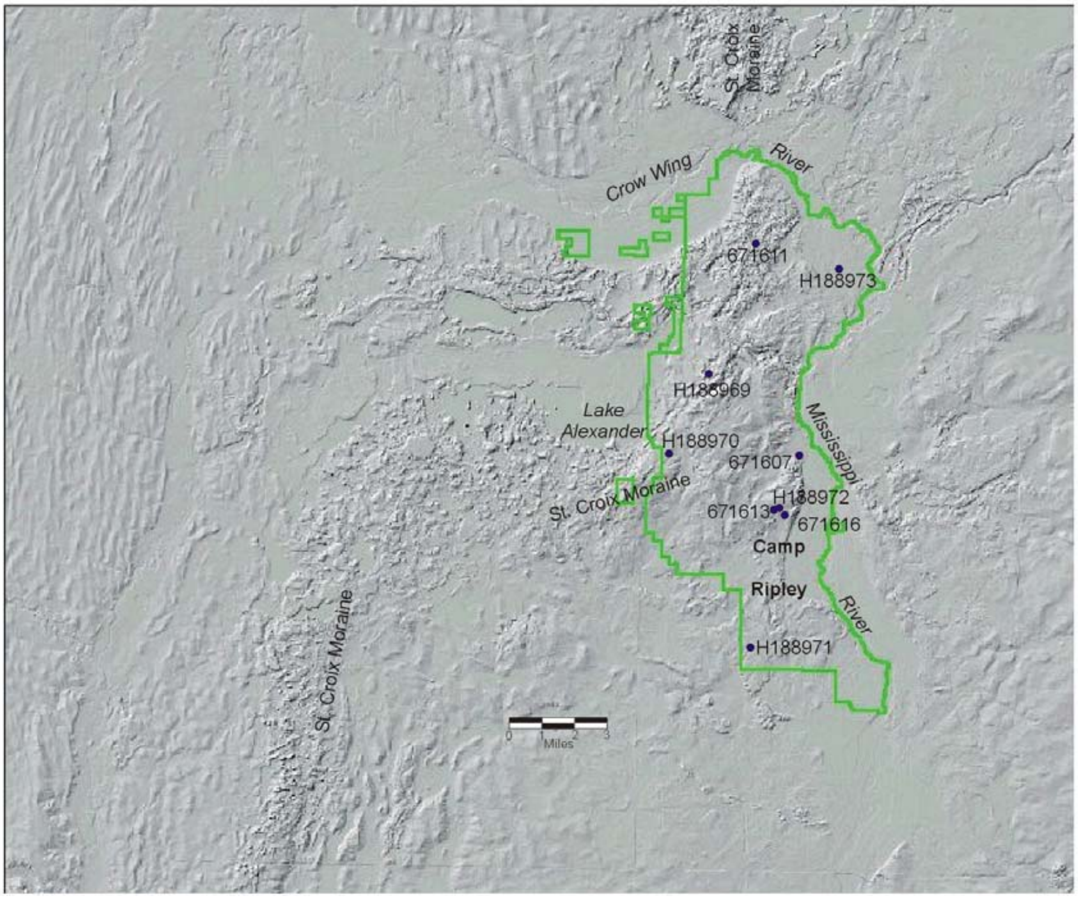

FIGURE 3 Camp Ripley and Vicinity, with the EnDriP Drilling Locations

materials. These additional well logs improved the stratigraphic data coverage over the study area.

To understand the complex arrangement of the glacial drift units at and near Camp Ripley, Animation 1 on the attached CD should be viewed. The animation is a visualization of the 11 lithologic units from the EnDriP boreholes and a subset of the regional drilling data.

The EnDriP data suggest that the bulk of the St. Croix moraine at Camp Ripley is sand rather than till. Most of these sands are interpreted to be lacustrine in origin, rather than glaciofluvial (outwash), on the basis of their grain size and sorting. The sands are mainly well-sorted medium sands, fine sands, and silty sands. The medium sands are locally interbedded with silts and clays. The drilling data also indicate a previously unrecognized possibility for this portion of the St. Croix moraine: that it is primarily glaciolacustrine in origin. In order to create a large, thick lacustrine deposit, an ice-bounded basin must have been present. This basin would probably have had the Rainy lobe as its eastern boundary, and the Rainy lobe would have contributed most of the sediment load (on the basis of the sand color). The Superior lobe would have been present on the southern end of the basin. The Itasca lobe would have advanced to the current St. Croix moraine location in the Camp Ripley vicinity, forming the western boundary of

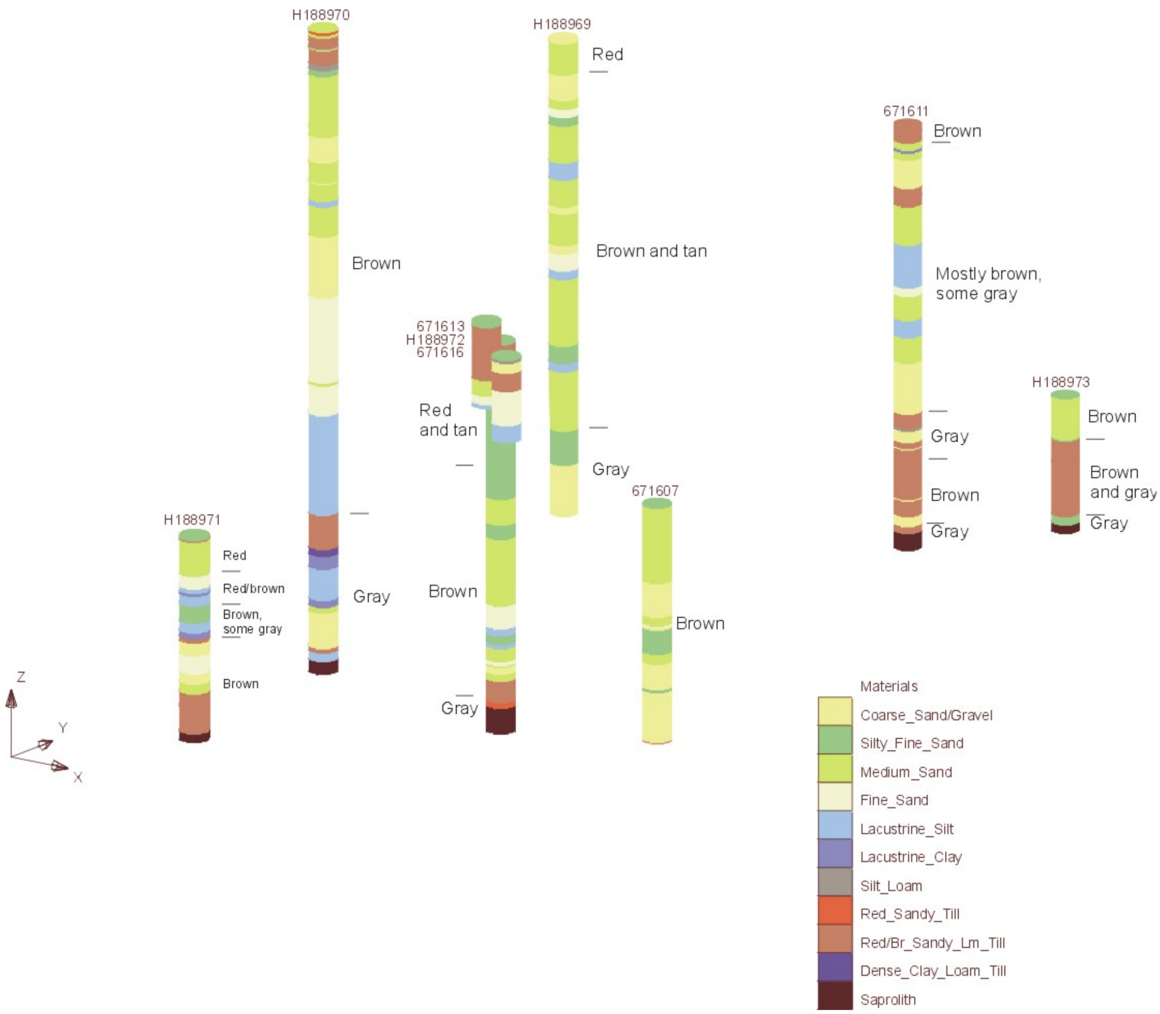

FIGURE 4 Oblique View of EnDriP Borehole Stratigraphy and Approximate Color Contacts within the Drift (Y direction is due north; X direction is due east)

the basin. This idea is supported in part by interbedded gray and brown drift as described by UMD (2002) and Schneider (1961). The basin could have collected sediment for a time sufficient to create a thickness of roughly 60 m. Afterward, melting of all bounding ice would have created the current inverted topography composed of lacustrine deposits that is now much of Camp Ripley.

Several past investigations (e.g., Goldstein 1998; Carney and Mooers 1998; Schneider 1961) have identified the Itasca, Rainy, and Superior lobes as contemporary at around 15,000 before present (B.P.). Until now, however, the location of the Itasca lobe was thought to have been further north than the Camp Ripley area at the time when the Rainy and Superior lobes were present there.

On the basis of the available data, the boundaries of the paleo lake basin are not fully defined; the masked glaciolacustrine deposits could be present north of the Pillager Gap, where the Crow Wing River now flows through the moraine. The St. Croix moraine extends to the north from the Camp Ripley and Pillager Gap vicinity as a product of the Rainy lobe. South and east of Camp Ripley are morainal deposits of the Superior lobe, including the arcuate section connected to the south end of Camp Ripley and the continuation of the moraine to the south (Figure 3). Both the Rainy and Superior lobe portions of the adjacent portions of the St. Croix moraine are likely conventional till moraines, although exceptions may occur locally.

2.3 GLACIAL GEOLOGY SUMMARY

The geology and topography of the Camp Ripley property and its vicinity are the result of a complex glacial depositional history involving three ice lobes that deposited drifts of various characters and colors. These lobes were thought to have been concurrently active in central Minnesota; however, a detailed geologic characterization of the site by UMD (2002) suggests new, previously unrecognized possibilities for the juxtapositioning of the ice lobes and for the nature of the St. Croix moraine at Camp Ripley. The lobes appear to have been present in the Camp Ripley vicinity concurrently, depositing well-sorted sands into an ice-bounded lacustrine basin. Occasional ice advances deposited discontinuous till units in the basin at various elevations.

3 GEOLOGIC AND HYDROLOGIC SITE CHARACTERIZATION

3.1 CLIMATE AND TOPOGRAPHY

Camp Ripley is located in the center of Minnesota, a region with a continental climate. Annual precipitation is 66 cm (USDA 1994). The site has a large amount of topographic relief associated with the St. Croix moraine. The lowest point, along the Mississippi River, is about 341 m MSL (above mean sea level); the highest point is 453 m MSL.

3.2 SURFACE WATER

The site is bounded on the east by the Mississippi River and on the north by the Crow Wing River (Figure 5). The Crow Wing has two dams: the Sylvan dam along the northeastern site boundary and the Pillager dam approximately 12 km upstream of the Sylvan dam. The Little Elk River is located southwest of the site and is a tributary to the Mississippi. Within and outside the site boundaries are numerous lakes, and west of the site is a large lake, Lake Alexander. The site has many large wetlands in low areas near the rivers and elsewhere. Drainages from the site are minimal; only a few small creeks leave the site and are tributaries to the Mississippi, Crow Wing, or Little Elk Rivers.

The water levels of several lakes close to the Camp Ripley site boundary are monitored frequently by the Minnesota Department of Natural Resources (MDNR 2006). Long-term data from six of these lakes suggest that water levels generally fluctuate by much less than 1 m (Figure 6).

3.3 AQUIFER RECHARGE

Recharge to an aquifer can be a difficult parameter to measure and is often estimated regionally by relying on numerical model calibration. One researcher (St. George 1994) used a detailed groundwater model to study an area that includes the Itasca moraine. Because the climate of that study area is similar to the climate of Camp Ripley and because that area has similar glacial geologic materials, St. George’s estimates of recharge were applied in the Camp Ripley model. St. George delineated recharge zones on the basis of geomorphological map units. Mooers (1996) provides mapping of the geomorphological units in the Camp Ripley region (Figure 7). These units were grouped into six categories (Table 1), which were then compared to relevant units in St. George’s study (Table 2). For two of the categories, an adequate match in St. George’s units was not available, so estimates were made for the recharge values. The calibrated estimates of St. George, along with the two rough estimates, were used as recharge inputs in the flow model.

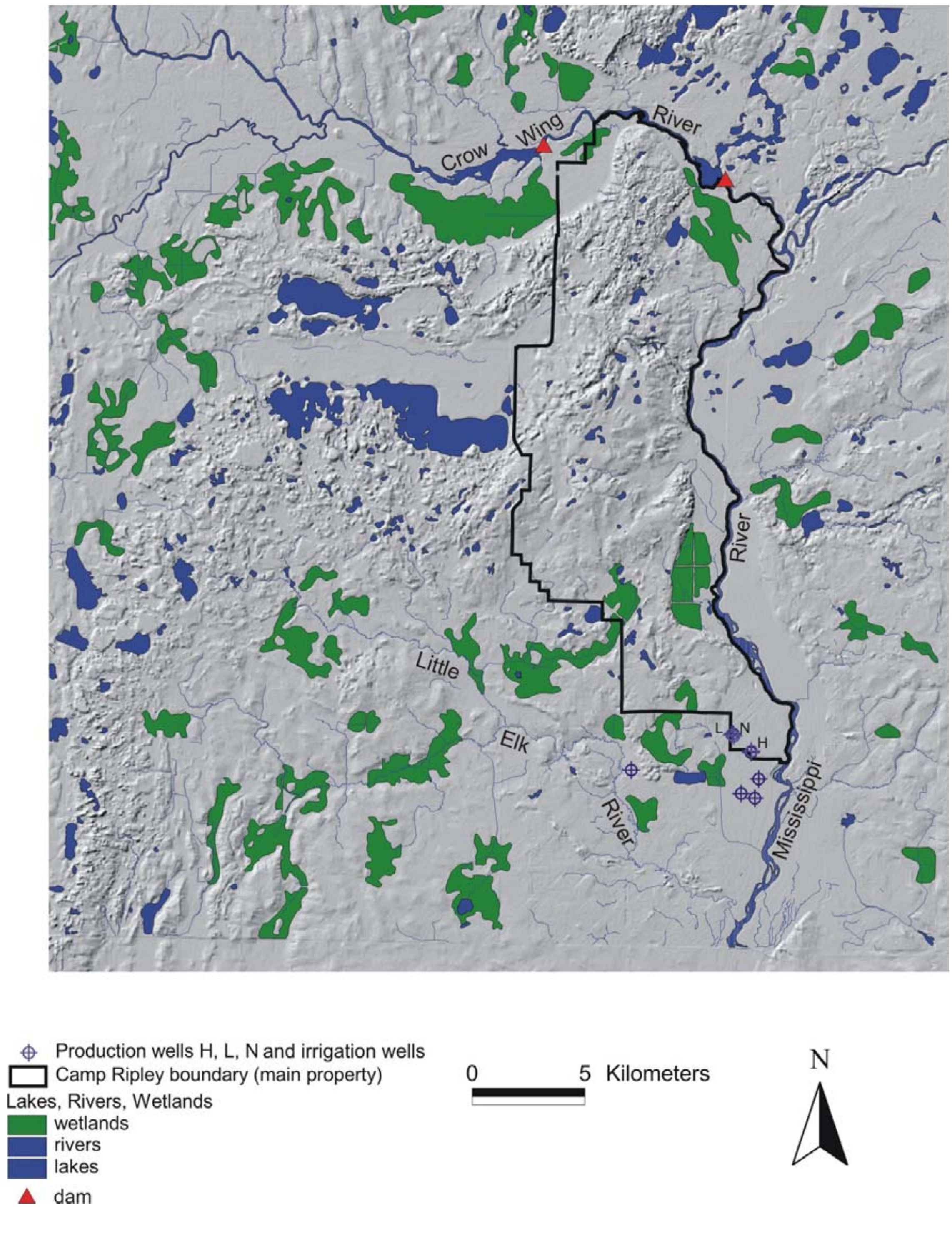

FIGURE 5 Surface Water Features in the Vicinity of Camp Ripley

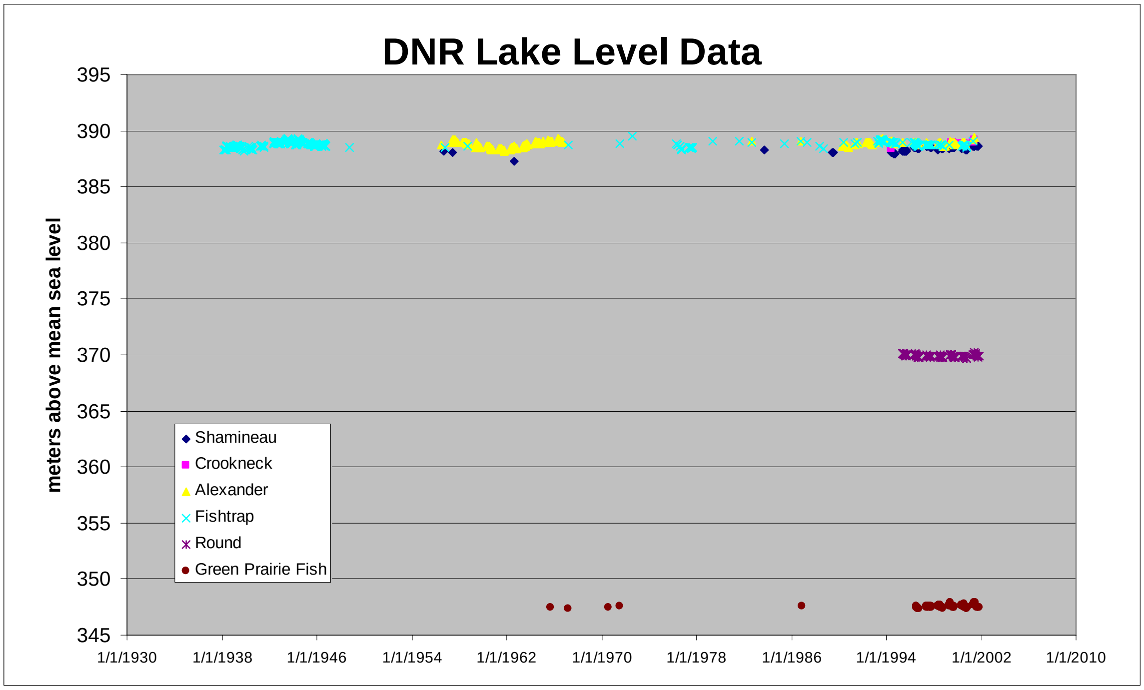

FIGURE 6 Water Levels at Six Lakes near Camp Ripley That Are Monitored by the Minnesota Department of Natural Resources

At least in the case of the sandy outwash plain, the estimate in Table 2 is similar to the value in a similar setting in Minnesota found by using a hydrographic method (Helgesen and Lindholm 1977).

3.4 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity (K) is a measure of the permeability of a material with respect to the seepage of water. Hydraulic conductivity can be measured or estimated in a variety of ways. One method is to use grain size analyses, in which geologic samples are separated according to the amounts retained or the amounts that pass through various sized standard screen openings. Then information from plots of the grain size distribution is used with empirical formulas to estimate K. UMD staff performed grain size analyses for a variety of geologic samples obtained during the EnDriP project. These samples provide information for essentially all major materials present in the Camp Ripley subsurface. Results are shown in Table 3. The results are similar to expected values in standard texts (e.g., Freeze and Cherry 1979) and compare well to similar units determined by St. George (1994) through model calibration in a similar study area.

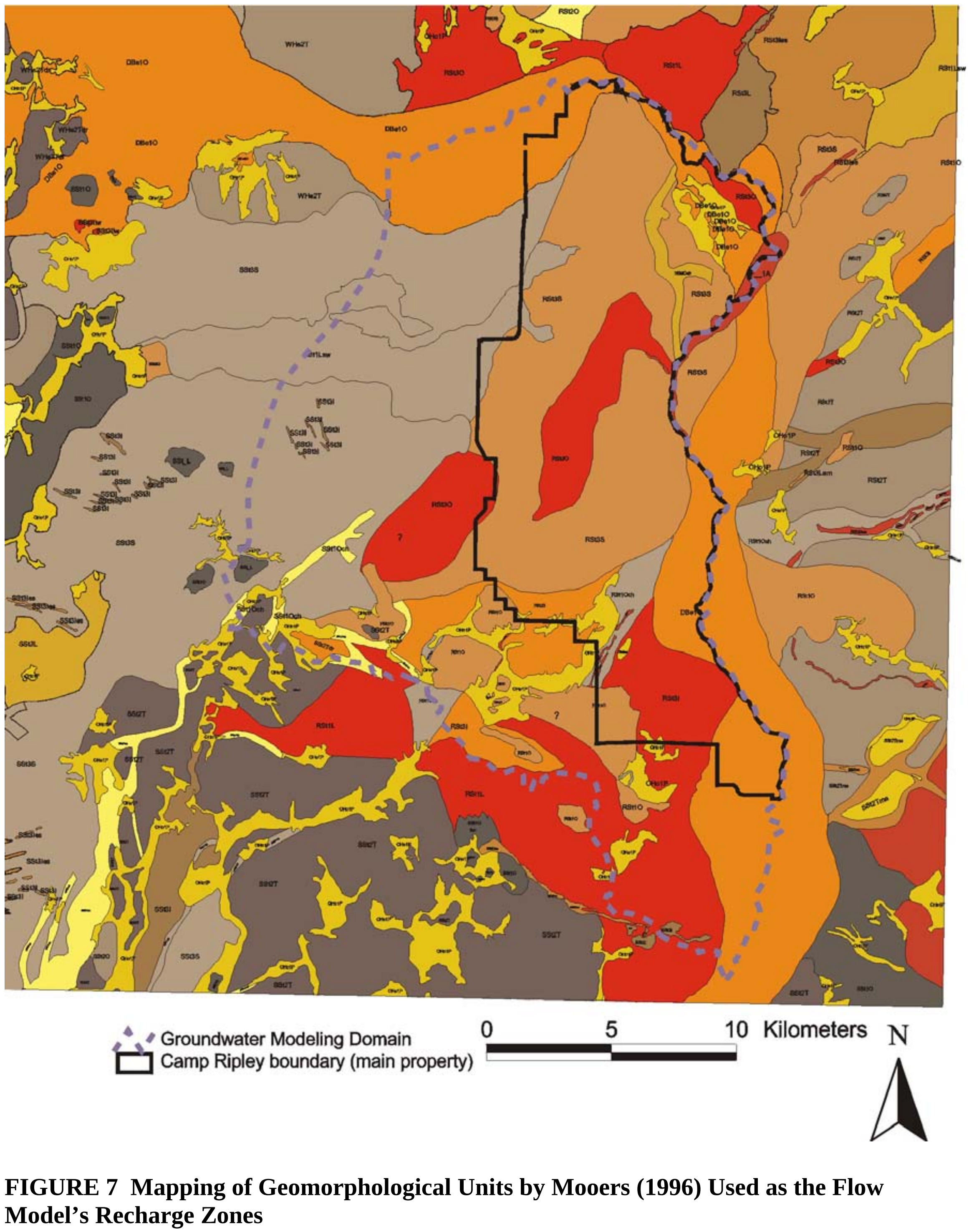

FIGURE 7 Mapping of Geomorphological Units by Mooers (1996) Used as the Flow Model's Recharge Zones

TABLE 1 Mooers (1996) Mapping Units in the Camp Ripley Study Area

Grouping in GMS	Code	Geomorphic Association	Glacial Phase	Topographic Expression	Sedimentary Association	Qualifier
A	RSt3S	Rainy lobe	St. Croix	Hummocky	Supraglacial drift complex	
B	RSt3O	Rainy lobe	St. Croix	Hummocky	Outwash	
C	RSt1O	Rainy lobe	St. Croix	Level	Outwash	
C	RSt1Och	Rainy lobe	St. Croix	Level	Outwash	Outwash channel
B	RSt3I	Rainy lobe	St. Croix	Hummocky	Ice contact	
D	RSt1L	Rainy lobe	St. Croix	Level	Lacustrine	
A	SSt3S	Superior lobe	St. Croix	Hummocky	Supraglacial drift complex	
E	SSt1Lsw	Superior lobe	St. Croix	Level	Lacustrine	Shallow water lake sands
F	OHo1P	Organic deposits	Holocene	Level	Peat	
C	DBe1O	Des Moines lobe	Bemis	Level	Outwash	
G	WHe2T	Wadena lobe	Hewitt	Rolling to undulating	Till plain	
C	RSt3Och	Rainy lobe	St. Croix	Hummocky	Outwash	Outwash channel
G	SSt2T	Superior lobe	St. Croix	Rolling to undulating	Till plain	
C	F_1A	Fluvial		Level	Alluvium	

TABLE 2 St. George (1994) Calibrated Recharge Values for Units Relevant to Camp Ripley and Estimated Recharge Values

St. George's (1994) Landforms	Sediment Classification	Calibrated Recharge (cm/yr)	Calibrated Recharge (m/d)	Low End of Range Determined by Sensitivity Analysis (m/d)	High End of Range Determined by Sensitivity Analysis (m/d)	Grouping in GMS
Collapsed outwash	Loamy sand	7.6	2.08E-04	1.26E-04	2.49E-04	B
Till plain (Wadena)	Sandy loam	0.15	4.11E-06	–4.11E-06	8.22E-06	G
Outwash fan	Sand	15.2	4.16E-04	2.49E-04	5.84E-04	C
Outwash plain	Sand	21.3	5.84E-04	3.34E-04	7.51E-04	A
Estimated material values:			Estimated Recharge (m/d)			
Fine lacustrine			1.00E-04			D, E
Peat			1.00E-04			F

TABLE 3 Geometric Mean Hydraulic Conductivities from UMD Grain Size Analyses

Unit	Geometric Mean K (m/d)				Geometric Mean (All Methods) (m/d)
	Hazen	Krumbein and Monk	Puckett	Harleman	
Dense clay loam till	1.06E-03	7.34E-01	8.63E-03	1.13E-01	2.96E-02
Lacustrine clay	1.13E-03	1.60E-01	1.35E-01	1.20E-01	4.13E-02
Red sandy till	8.14E-03	3.97E+01	8.25E-01	8.69E-01	6.94E-01
Lacustrine silt	1.69E-02	8.19E-01	1.13E+00	1.80E+00	4.09E-01
Red/brown sandy loam till	2.40E-02	2.78E+01	1.12E+00	2.38E+00	1.16E+00
Silty fine sand	3.26E-02	6.17E+00	1.11E+00	3.15E+00	9.16E-01
Saprolith	6.06E-02	1.44E+01	2.60E+00	6.47E+00	1.96E+00
Fine sand	3.60E-01	9.32E+00	2.40E+00	2.80E+01	3.87E+00
Medium sand	3.72E+00	4.77E+01	2.55E+00	3.08E+02	1.93E+01
Coarse sand/gravel	5.15E+01	2.50E+02	2.76E+00	3.02E+03	1.02E+02

Source: UMD data.

3.5 PUMPING WELLS

Pumping stresses in the modeling domain include the active wells H, L, and N, which are located in the Cantonment Area of Camp Ripley (Figure 1). These wells are the focus of the WHP project, although the model includes several irrigation wells and private wells (Figure 8).

The MDNR requires water appropriation permits for groundwater or surface water withdrawals of more than 10,000 gal/d or 1 million gal/yr. Throughout the permitting process, long-term pumping rate information is available for the on-site production wells and the wells that they have replaced (1988–2002 from MDNR appropriation permits and 2001–2004 from Klinker [2005]). These values are summarized in Table 4. Irrigation wells (unique numbers 214597, 214434, 214433, and 121834), which are located south and west of the Cantonment Area, are also included in the model, with pumping rates based on average withdrawal rates over 1988–2002. This information is also included in Table 4. On the basis of the MDNR appropriation database, no other large groundwater users are in the modeling domain.

Most private wells in the modeling domain are assumed to have little impact on the groundwater flowfield in the study area. Therefore, most of them were not included in the model. However, several private wells were included in the model because of their proximity to the Cantonment Area. These wells were located by using the county well index (MDOH 2006) and are within about 2 km of the Cantonment Area. The private wells include four households along the west edge of the Cantonment Area (unique numbers 451315, 592566, 543433, and 571415), two wells further west of those (224540, 136967), and one well (495271) near the Camp Ripley main gates. The estimated groundwater pumping rate of 350 gal/d per household (AWWA 2006) was used as model input at each private well location.

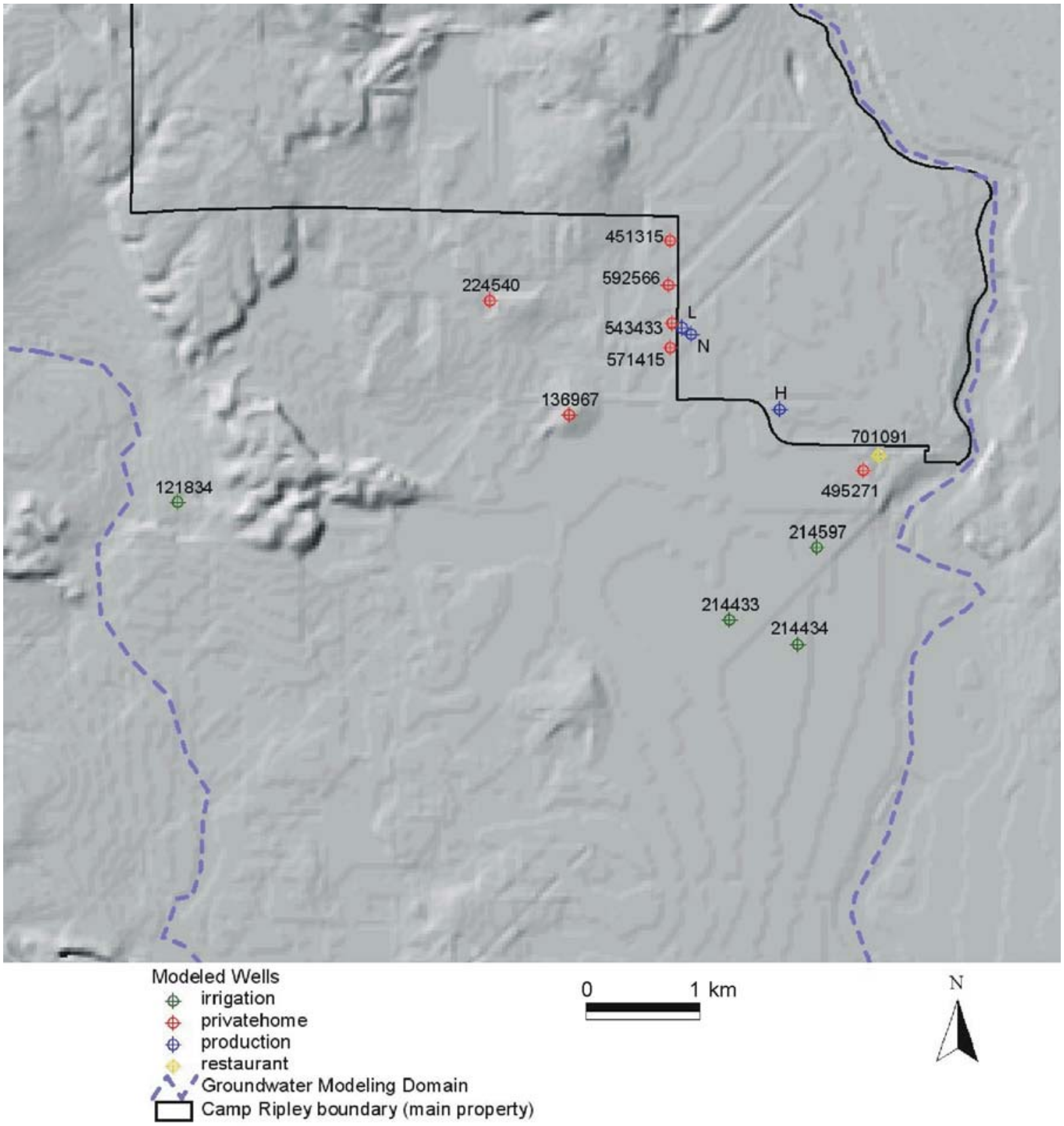

FIGURE 8 Modeled Pumping Wells

Also near the main gates is a commercial establishment (unique number 701091) for which no pumping rate information was available. An assumption was therefore made that the water usage here is 20 times the average daily household rate.

3.6 GROUNDWATER LEVELS

UMD staff collected hand measurements of water levels at numerous wells, and they collected continuous (at 30-min intervals) automated measurements of groundwater levels at four

TABLE 4 Pumping in the Study Area

Unique Number or Name	User	Ground Elevation (m)	Well Depth (m)	Historical Average Pumping Rate (10^6 gal/yr)	Peak-Year Pumping Rate (10^6 gal/yr)	Historical Average Pumping Rate (m^3/d)	Peak-Year Pumping Rate (m^3/d)
H	Production	348.54	18.6	27.6	42.9	285.9	444.4
L	Production	348.54	29.9	20.9	34.9	216.5	361.6
N	Production	348.54	31.1	24.3	30.0	251.7	310.8
121834	Irrigation	350.5	19.5	16.7	16.7	173.0	173.0
214597	Irrigation	344.4	21.6	37.7	77.4	390.6	801.9
214433	Irrigation	344.4	18.0	57.8	44.1	598.8	456.9
214434	Irrigation	344.4	16.5	37.8	27.2	391.6	281.8
451315	Private home	350.82	15.2	0.128	0.128	1.326	1.326
592566	Private home	347.78	16.5	0.128	0.128	1.326	1.326
543433	Private home	348.69	17.1	0.128	0.128	1.326	1.326
571415	Private home	348.69	17.1	0.128	0.128	1.326	1.326
701091	Restaurant	346.86	17.1	2.560	2.560	26.522	26.522
495271	Private home	341.99	16.8	0.128	0.128	1.326	1.326
136967	Private home	355.09	27.1	0.128	0.128	1.326	1.326
224540	Private home	352.04	22.9	0.128	0.128	1.326	1.326

wells. The hand measurements, combined with static water levels noted on drillers' logs for selected regional wells, are presented in Quinn (2003), as are the continuous water level measurements obtained at four on-site monitoring wells. The data show that long-term fluctuations at the wells are generally within a range of only 0.3 m. This suggests that water level measurements across the site and region are useful in calibrating a regional-scale model. Average continuous data values were therefore combined with average monitoring well hand measurements and static water level information to create a set of target water levels for calibration of the model (Table 5). The wells listed in Table 5 are those that represent the regional flow system, as indicated by inspections of data on well screen location and water levels. Wells determined to be finished in perched zones were not included as calibration points.

TABLE 5 Calibration Targets and Statistics for Relevant Monitoring Wells

Well	Observed Head (m MSL)	Computed Head (m)	Residual (m)	Absolute Value of Residual (m)	Squared Residual (m^2)
534079	345.16	344.29	-0.87	0.87	0.75
534077	342.17	344.36	2.19	2.19	4.78
530010	345.95	344.40	-1.55	1.55	2.40
523496	342.90	343.92	1.02	1.02	1.05
523495	342.90	343.95	1.05	1.05	1.09
523494	341.83	343.90	2.06	2.06	4.26
523493	341.77	343.97	2.20	2.20	4.84
523492	343.33	343.85	0.52	0.52	0.27
523491	341.38	343.95	2.58	2.58	6.65
495630	383.13	372.41	-10.73	10.73	115.06
470668	342.47	347.18	4.70	4.70	22.11
470506	367.89	359.52	-8.37	8.37	70.14
466293	344.88	347.55	2.66	2.66	7.10
466292	344.36	347.60	3.23	3.23	10.46
466291	343.97	347.56	3.59	3.59	12.90
466290	344.52	347.50	2.98	2.98	8.90
466289	364.69	365.82	1.13	1.13	1.27
466288	369.51	365.87	-3.64	3.64	13.24
466286	367.13	366.02	-1.11	1.11	1.24
451233	367.28	359.33	-7.95	7.95	63.22
451232	351.74	351.36	-0.38	0.38	0.14
451231	345.95	348.45	2.50	2.50	6.25
451230	356.62	352.57	-4.04	4.04	16.34
451229	373.08	370.06	-3.02	3.02	9.11
224577	343.81	345.31	1.50	1.50	2.24
214597	340.77	343.93	3.16	3.16	9.98
150536	345.34	345.21	-0.13	0.13	0.02
150535	343.20	345.62	2.41	2.41	5.81
671608	349.07	351.57	2.50	2.50	6.23
578602	387.53	380.04	-7.49	7.49	56.09
530012	345.84	344.30	-1.54	1.54	2.37
451238	355.09	355.55	0.45	0.45	0.21
130267	349.61	349.73	0.13	0.13	0.02
			-0.25	2.83	3.76
			ME (m)	MAE (m)	RMSE (m)

4 GROUNDWATER FLOW MODEL

4.1 CONCEPTUAL GROUNDWATER MODEL

Before a numerical groundwater flow model is constructed, it is important to describe a conceptual model of the site's groundwater flow system. For Camp Ripley and nearby areas to the west and southwest, precipitation (as rainfall or snowmelt) infiltrates and becomes aquifer recharge. It is assumed that only a small amount of water runs off, on the basis of the fact that there are only a few very minor creeks in the entire study area. This internal drainage is also demonstrated by closed topographic depressions that are dry in the bottom (e.g., along Easy Street), and it is consistent with what an abundance of sandy soil and subsoil is understood to mean.

Lakes are assumed to be either flow-through lakes, representing the groundwater flow system, or perched features. Although perched groundwater may be present locally as the result of a low-permeability lacustrine clay or fine-grained till, most groundwater is assumed to be part of the regional flow system, discharging to the main nearby rivers (Mississippi, Crow Wing, Little Elk), to wetlands, or to pumping wells.

Flow in the subsurface is complicated by countless irregular contacts between different types of glacial depositional units with widely different permeability. The uncertainty in subsurface correlation is apparent even at the Landfarm Spread Site, an area of relatively dense data. Here, boreholes 50 to 100 m apart show little apparent correlation in their stratigraphic contacts because the subsurface changes occur at a scale finer than the borehole spacing (see Animation 2 on the attached CD).

4.2 MODEL PURPOSE

This numerical model provides a quantitative tool for analyzing groundwater flow at Camp Ripley and hydraulically related areas to the west and southwest. This model is steady state, relying on time-averaged values for factors such as recharge or water level measurements at various observation wells. It is regional in scale but can be modified to address future local issues, provided sufficient local-scale data are available. Key applications, such as WHP zone delineation and forward particle tracking from potential source areas, are discussed at the end of this report.

4.3 MODEL SELECTION

Because the site is a porous-media setting, the U.S. Geological Survey's MODFLOW 2000 code (Harbaugh et al. 2000) was selected to model it. MODFLOW is the world's standard for modeling groundwater flow through porous media, in part because of its documentation, ability to be verified, and adaptability. MODFLOW can handle a variety of hydrologic and geologic inputs. It is a finite-difference model, relying on a three-dimensional (3D) grid for the solution space. MODFLOW 2000 includes parameter estimation capabilities (Hill et al. 2000), which provide a means of optimal estimation of model inputs based on nonlinear regression techniques. A companion code, MODPATH (Pollock 1994), produces particle tracking results on the basis of the results from MODFLOW. The particle tracking results illustrate the calculated groundwater movement under advective flow (i.e., in the absence of any retardation processes).

The Groundwater Modeling System (GMS) (EMRL 2004) is a preprocessor and postprocessor for MODFLOW and other codes, and it includes related tools for subsurface analysis. GMS allows the modeler to work from map information to design a grid that matches the study area's 3D hydraulic boundaries. Many forms of model input may be imported in spreadsheet form, facilitating accurate model setup. GMS also has the option of using Transition Probability Geostatistics (TPROGS) to populate the subsurface permeability framework of its MODFLOW models. TPROGS is discussed in some detail below.

4.4 GRID DESIGN AND BOUNDARY CONDITIONS

The extent of a modeling domain is determined by evaluating a study area's hydrologic and geologic factors for their potential as natural boundaries to groundwater flow. Examples are specified head boundaries, such as those along rivers in direct connection with the groundwater flow system, or no-flow boundaries, such as known or assumed divides in the groundwater flow system.

Much of Camp Ripley is bounded by the Mississippi and Crow Wing Rivers (Figure 9). By inspecting water level data for wells across the region to the west and south of Camp Ripley, the location of a north-northeast to south-southwest trending flow divide was estimated. This no-flow divide extends from the Crow Wing River on the north to the Little Elk River to the south. The no-flow boundary is between Lake Alexander and a large lake to the west, Fishtrap Lake. Fishtrap Lake is connected to Lake Alexander. The channel, however, rarely has much flow because the water elevations of the two lakes are nearly equal (Minnesota Pollution Control Agency 1999). Because of the low surface water gradient between these lakes and the regional groundwater flowfield, the no-flow boundary condition is supported for the western edge of the modeling domain.

The bottom of the modeling domain is the saprolith (weathered bedrock) surface (Figure 10). The upper boundary of the model is the ground surface. The model grid was constructed with uniform 200-m cells. Digital Elevation Model (DEM) data at 60-m spacing were obtained for the region. This data set provides strong control of the upper surface of the glacial drift sequence (Figure 11). Although the locations of the DEM grid nodes do not exactly match the locations of model cell centers, the DEM data were interpolated to the cells by GMS, and they provide a highly accurate upper surface elevation for the geologic package. An inspection of cell elevations along the major rivers showed that the river stage was accurately incorporated into the model by relying on the DEM data at 60-m spacing. These cells along the Mississippi, Crow Wing, and Little Elk Rivers were each fixed as specified heads.

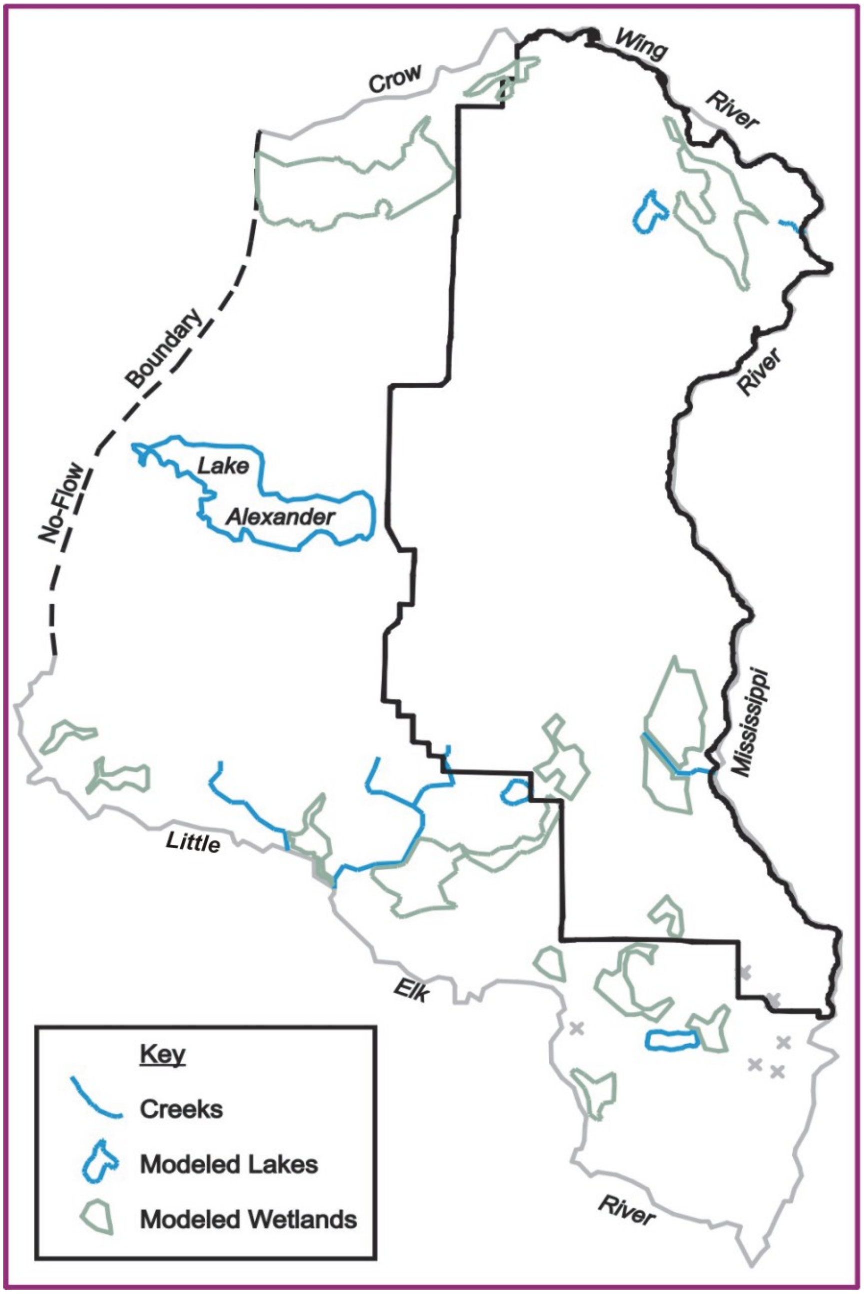

FIGURE 9 External and Internal Boundary Conditions

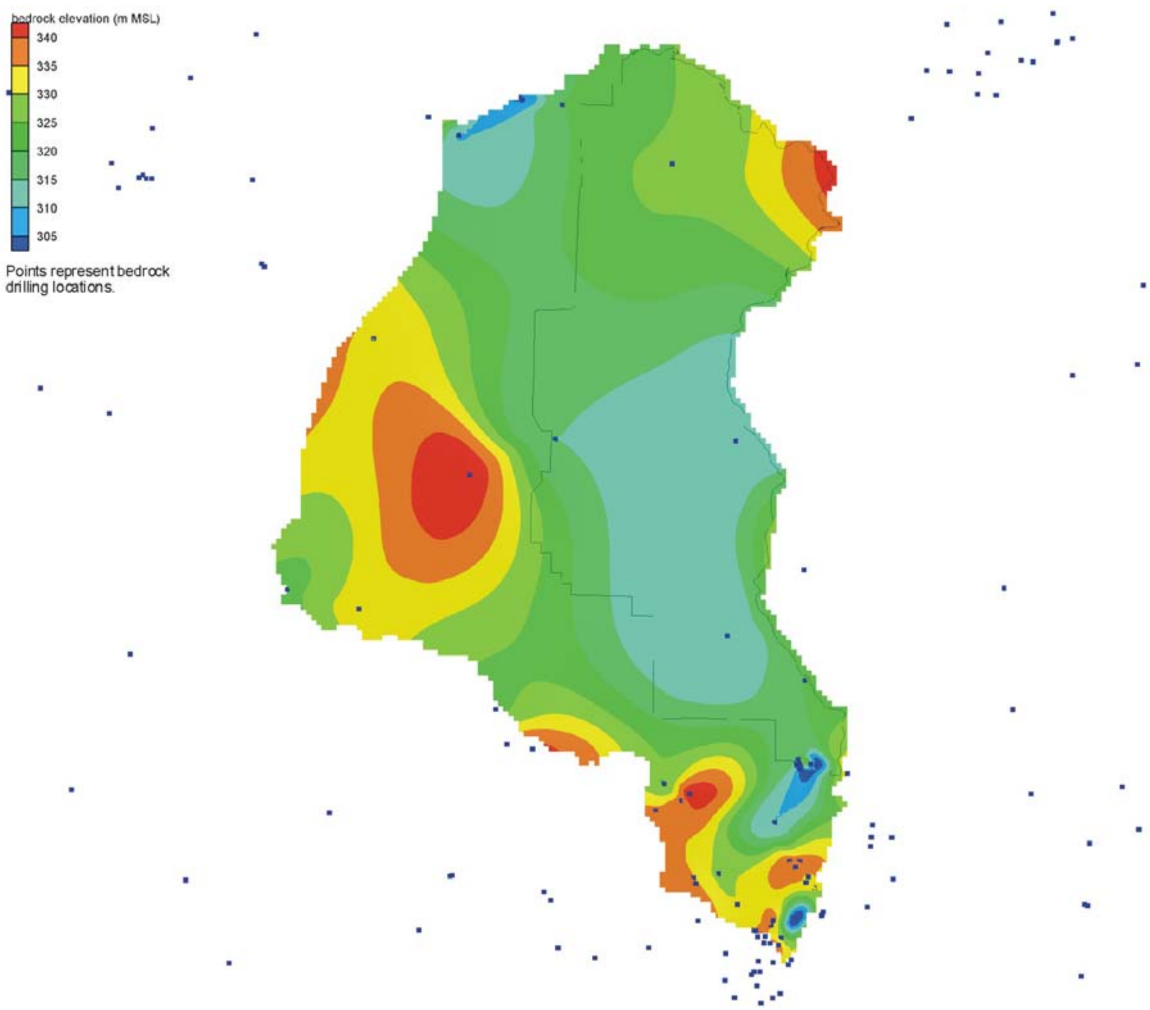

FIGURE 10 Bedrock Surface Elevation in Model Domain

Ten layers were modeled by dividing the glacial drift thickness evenly throughout the modeling domain. As a result, some locations, such as those along major rivers, have 10 thin, saturated model cells, whereas other locations, such as those along the St. Croix moraine, have 10 thick cells, and one or more cells below the ground surface may be unsaturated. Animation 3 is a 3D illustration of the model's grid design and boundary conditions.

4.5 GEOSTATISTICAL MODELING OF THE SUBSURFACE

The geological structure of the subsurface of Camp Ripley and its vicinity poses a challenge in flow model construction because of the products of the glacial depositional events. The distances between boreholes are such that the correlation of units throughout the site is quite uncertain, because average lens lengths are less than the average borehole spacing. An understanding of the distribution of materials is important to the model because the hydraulic conductivities of the units vary so widely.

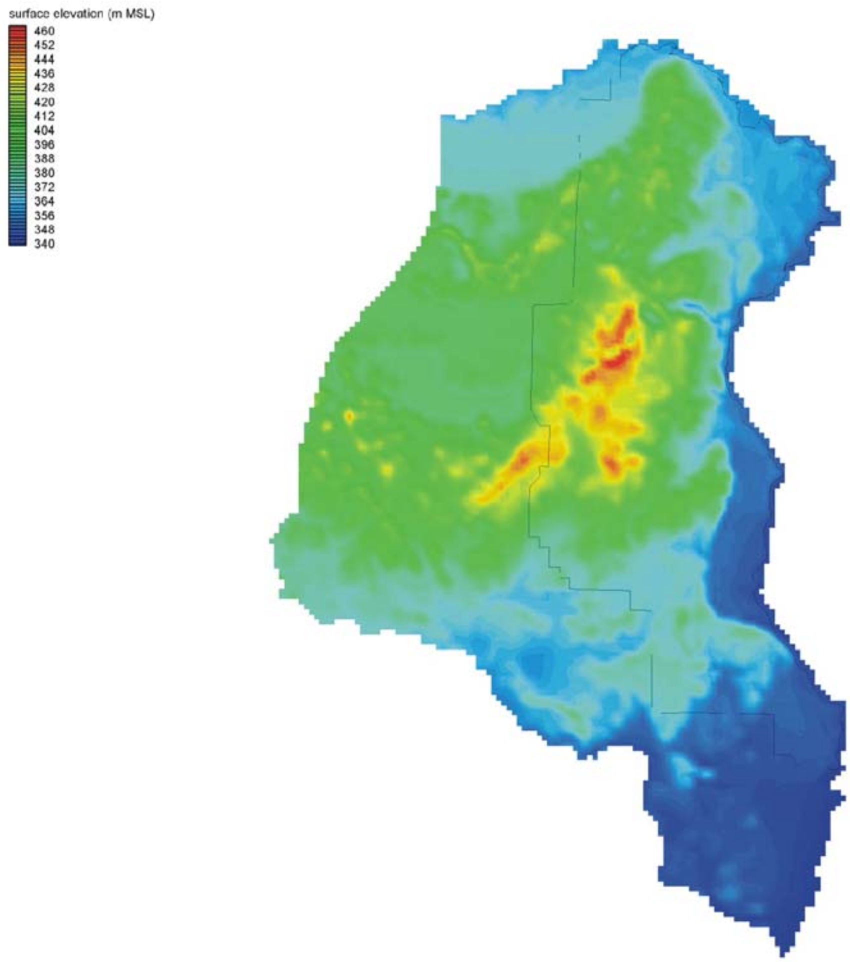

FIGURE 11 Ground Surface Elevation in Model Domain

For this reason, modeling of the geologic framework was performed by using the transition probability geostatistics (TPROGS) approach. TPROGS (Carle 1999) determines the volumetric proportions, mean thicknesses, mean lens lengths, and juxtapositional tendencies of a site's hydrogeologic units. It may then be used in conditional simulation — stochastic model runs of multiple, equally probable spatial distributions of the hydrogeologic units — while the hard data are honored. TPROGS analyses may be performed within GMS, and results may be imported by GMS into a MODFLOW flow model.

To implement TPROGS, a site's hydrogeology must be simplified into a maximum of five units. For Camp Ripley, the 10 glacial hydrogeological materials identified by EnDriP were converted to five units on the basis of the similarities in both depositional setting and hydraulic conductivity values (Table 6). Of these five units, lacustrine sand dominates, at a proportion of 70% (Table 7). While Animation 1 illustrates the complexity of the glacial drift with 10 different units, Animation 4 displays the results with the simplified groupings of 5 units. The hydrogeologic framework of the site remains complicated even after it has been reduced to five materials.

TABLE 6 TPROGS Categories Based on EnDriP Interpretations

EnDriP Material Name	TPROGS Unit Grouping	Initial Modeled Hydraulic Conductivity (m/d)
Lacustrine clay	Lacustrine clay	0.01
Dense clay loam till	Tills	0.1
Red/brown sandy loam till	Tills	0.1
Red sandy till	Tills	0.1
Silt loam	Lacustrine silt	0.1
Lacustrine silt	Lacustrine silt	0.1
Silty fine sand	Lacustrine silt	0.1
Fine sand	Lacustrine sand	5
Medium sand	Lacustrine sand	5
Coarse sand/gravel	Outwash	75

TABLE 7 Proportions of TPROGS Categories in Camp Ripley Study Area

Material	Percentage	Assumed Effective Porosity
Outwash	9.4	0.3
Lacustrine sand	70.2	0.3
Lacustrine silt	2.8	0.2
Lacustrine clay	6.1	0.1
Till units	11.5	0.1

The TPROGS analysis determines the interrelationships of the modeled units through Markov chains (Carle 1999), which are best in vertical directions because of abundant data relationships. They are inferred for horizontal directions, where data relationships are sparser, according to Walter’s law: Any juxtapositional tendencies observed in the vertical direction will also hold true in the horizontal directions.

The TPROGS analysis resulted in geostatistically determined lateral correlation lengths for each material type. These lengths translate to average lens lengths. For the five units, the average lens length for the unit with the greatest correlation, lacustrine clay, was about 100 m. This analysis supports the notion of short correlation of units, as demonstrated in Animation 2.

In the Camp Ripley analysis, different realizations are generated by TPROGS. Each realization is a statistically valid and equally probable model that honors the hard data. However, the hard data are far apart relative to both the geostatistical ranges (correlations) of the units and the grid spacing. The results of different realizations, therefore, are all quite similar, with lacustrine sand dominating, and the amounts of till units, lacustrine clay, outwash, and lacustrine silt being less. An example result for model layer 1 is shown in Figure 12. Units have a random distribution across each model layer, except at locations near boreholes where results are consistent with the hard data. An animation illustrating the TPROGS results for model layers 1 through 10 is shown in Animation 5.

4.6 INPUT PARAMETERS

In addition to requiring the distribution of initial recharge values (Table 2 and Figure 7), the estimated hydraulic conductivity values (Table 5), and the steady-state pumping rates (Table 4), the model also requires information on its interior creeks, lakes, and wetlands (Figures 5 and 9). These were determined to represent an expression of the water table in many instances. In MODFLOW, these types of features can be accommodated in several ways.

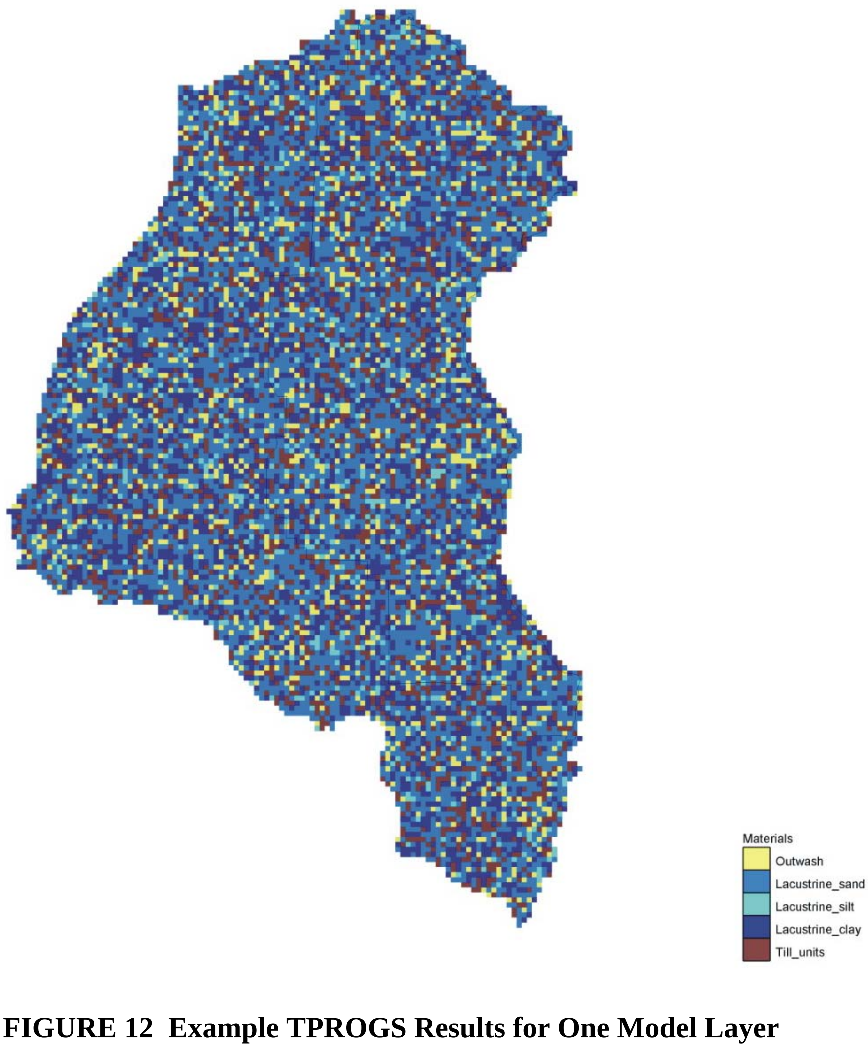

FIGURE 12 Example TPROGS Results for One Model Layer

The creeks were modeled by using the Drain Package of MODFLOW. A tool in GMS allows the tracing of linear features such as creeks, and cells along the traces are automatically assigned as drain cells. Drain cells require two input parameters: elevation and conductance. Elevations were assigned to cells on the basis of the creek stage. Conductance per unit length was assigned on the basis of estimated values of a creek sediment's thickness, width, and vertical permeability.

Wetlands were also modeled by using the Drain Package, through the use of another mapping tool in GMS. Wetlands were delineated, and these polygons were each assigned an elevation (wetland elevation) and a conductance per unit area (on the basis of estimated values of wetland sediment thickness and vertical permeability).

Large lakes (Alexander, Round, Green Prairie Fish, and Mud) were modeled by using MODFLOW's general head boundary package. In this manner, the lakes' levels remain steady, allowing the lakes to be a continuous source or sink for groundwater. In the case of a flow-through lake, the lake would be a source at one end and a sink at the other. A value for conductance per unit area was assigned to the lake sediments on the basis of estimated values of sediment thickness and vertical permeability.

Pumping stresses in the study area were modeled by calculating or estimating average groundwater withdrawals, as described above. These pumping rates were incorporated in the 3D model by assigning the withdrawal across each individual well's screened interval. In a case where a well screen's top and bottom elevations straddle two or more model layers, GMS (EMRL 2004) automatically divides the pumping rate across the model layers on the basis of the proportion of well screen present in each.

4.7 CALIBRATION

PES, the calibration tool contained in MODFLOW 2000 (Hill et al. 2000), was used to estimate parameters of the model's hydraulic conductivity. Initial values used to begin the parameter estimation process are shown in Table 5. These values were bounded by appropriate minimum and maximum values, allowing PES to have a wide range of values to explore.

The regression techniques of the PES process resulted in an outwash K of 77 m/d, a lacustrine sand K of 21 m/d, a lacustrine silt K of 1 m/d, a lacustrine clay K of 0.81 m/d, and a till K of 50 m/d. These final values differ by varying degrees from their initial values (Table 6). Lacustrine sand, which dominates the modeled volume of glacial drift, increased somewhat; this alone likely improved the overall model calibration because of this unit's prevalence. The glacial till units' K underwent the greatest change. Its relatively high permeability from the PES analysis may be a result of the generally sandy till materials in the study area.

The match between simulated head values and measured heads at target wells provides an indication of the model's calibration. Three equations for addressing the bulk accuracy of the model are the mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE) equations (Anderson and Woessner 1992). The ME is calculated simply as the mean

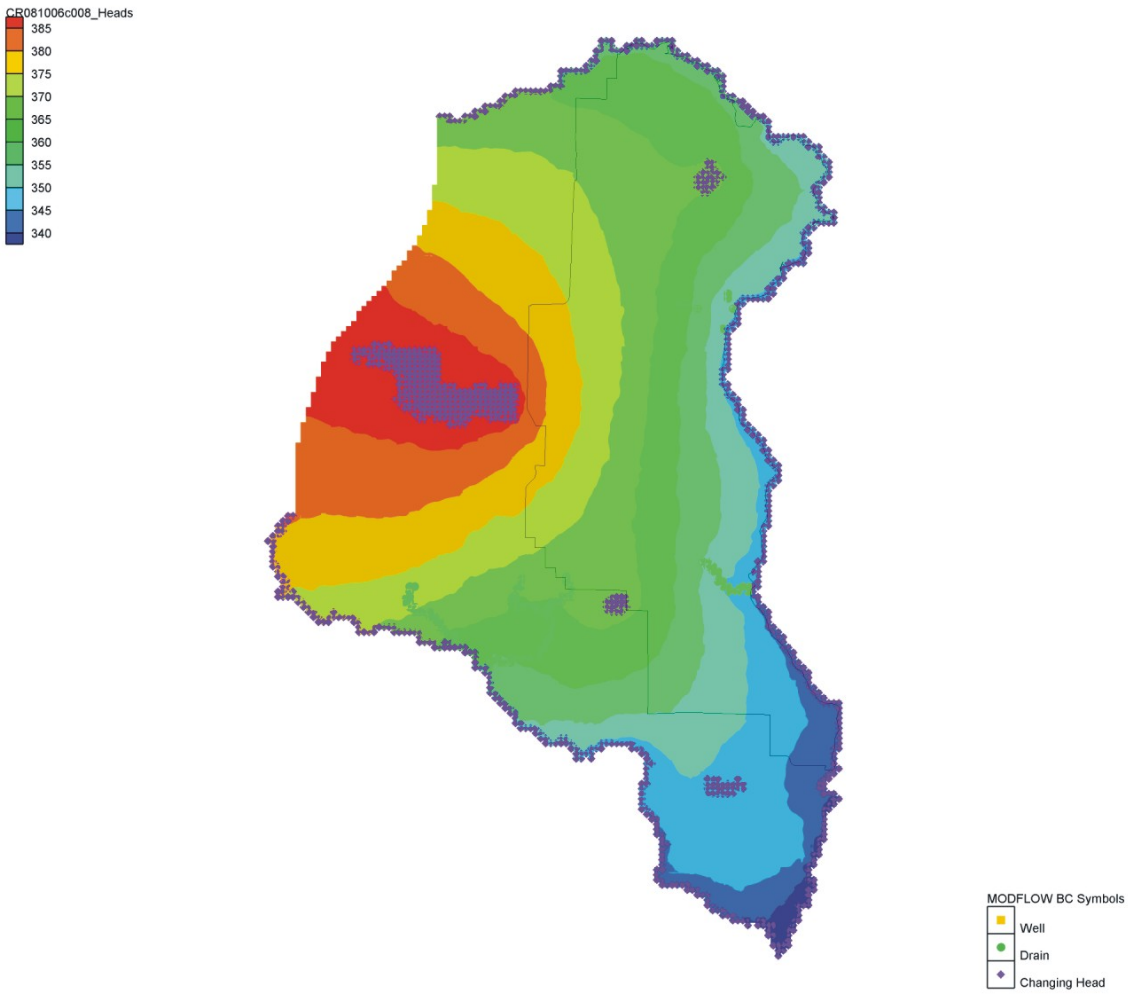

FIGURE 13 Example of Calibrated Potentiometric Surface from One Model Realization

difference between simulated and measured heads. The MAE is the mean absolute value of the difference between simulated and measured heads. The RMSE, which is generally the best measure of error, is the square root of the average squared difference between simulated and measured heads.

Table 5 presents calibration statistics for the model's target monitoring wells from one realization. Other realizations would have different statistics, but they would have a similar overall quality. Figure 13 illustrates the calibrated heads across the modeling domain. A model that is regional in scale may have difficulty in matching many of the target values. However, this model provides a reasonably good match to the distribution of target heads.

4.8 MODELED FLOWFIELD

Animation 6 on the attached CD demonstrates the simulated heads from model layer 1 through model layer 10 for one of the multiple stratigraphic realizations. Other model runs based on other stratigraphic models show similar results. In the animation, the upper layers show many dry zones (areas with a gray background) within the glacial drift that result from high topography above the regional water table.

The results suggest that the pumping wells in the southern part of the study area obtain their water from upgradient areas rather than from infiltration of Mississippi River water or from a mixture of infiltrated surface water and groundwater. Water levels in the study area are highest in the Lake Alexander vicinity, consistent with the location of this area relative to model boundaries and with the modeling approach for the lake.

The potentiometric surface in the vicinity of smaller lakes was inspected relative to the lake levels and depths. Most of those lakes for which bathymetric data were available (Ferrell, Alott, Long, Cockburn, Fosdick, and Rapoon Lakes) were determined to be perched relative to the calibrated model's regional potentiometric surface. These lakes likely exist because of a low-permeability material below the lake bottom and/or low-permeability lake sediments. Modeled flow near Round Lake, located along the southwest edge of the facility boundary, suggest that it is a flow-through lake.

One concern of the Camp Ripley site managers is the groundwater flow direction at the Demo Debris Landfill. On the basis of the model, groundwater flow is to the southeast at an elevation of about 357 m MSL. On the basis of synoptic hand measurements at wells 250122, 539404, 539405 (data from 1996 to 2002) and 671612 (data from 2001 and 2002), the flow direction at this facility ranges from southwest to southeast. The water levels at these wells, however, are at about 368 m MSL. Drilling data indicate that these wells penetrate and are completed in permeable materials. A borehole (H188971) that was drilled at the site as part of the EnDriP study is much deeper and indicates a low-permeability zone beneath the level of the well screens. These wells are therefore interpreted to be completed in a perched zone, above the modeled regional flow system. No other local boreholes or wells are deep enough to provide information on the extent of the low-permeability zone. It appears that the perched groundwater flow direction at the Demo Debris Landfill is sensitive to small changes in the flow system, and groundwater flow is not in a uniform direction. Careful assessment of water levels at the site, in the form of additional synoptic measurements and/or continuously logging water level probes, would provide a better understanding of the local perched flow direction. Additional drilling data would be required to assess the thickness and extent of the low-permeability unit and the hydraulic connectivity of the perched zone to the regional aquifer.

5 WELLHEAD PROTECTION ZONE DELINEATION

5.1 WHP ZONE MODELING APPROACH AND RESULTS

The probabilistic method for delineating a WHP zone for production wells H, L, and N relies on a numerical modeling and geostatistical approach. Multiple, equally probable realizations of the glacial drift stratigraphy were used to produce multiple numerical groundwater flow models, as described above. This approach is referred to as a stochastic approach. Forward particle tracking from every cell throughout the 3D model is performed by GMS for each of the flow model solutions. For each cell, GMS then calculates the percentage of its particles ultimately captured by wells. The contoured results indicate the probability of each grid cell being in the zone of contribution to each well. The rate of travel of the particles is determined by the modeled flowfield and the effective porosities of the hydrogeological materials (Table 6).

The probabilistic assessment for the average annual pumping rates (Table 4) of wells H, L, and N indicates that high probabilities are present off post immediately west of the Cantonment Area (Figure 14). Lower probabilities are present further upgradient on post. The furthest upgradient portion of the capture zone is in an off-post area; its probability of contributing to the combined well capture zone is less than 30%. Results illustrating the 10-year and 1-year times of travel to the wells are provided in Figures 15 and 16, respectively. In the 10-year case, most of the WHP zone for well H is located on post, but the WHP zone for wells L and N extends off post. For the 1-year time-of-travel scenario, the capture zone for well H is essentially all on post, and the capture zone for wells L and N extends about 200 m west of the site boundary.

The modeling was also performed for the case in which the maximum annual pumping rates of Table 4 were used. Compared with the results for the average pumping scenario, the results for maximum pumping (Figure 17) show probabilities of capture that are slightly higher and broader. The 10-year and 1-year times of travel (Figures 18 and 19, respectively) are also similar to those generated by using average pumping rates.

5.2 PRIOR WHP ZONE DELINEATION

A WHP program was initiated for Camp Ripley's production wells several years ago (Minnesota Army National Guard 2002). This plan included management strategies and identified potential contaminant sources, and it focused on wells H, J, L, and N. Well N is a replacement of former wells K and M, and well J has since become inactive.

The model, however, was a very simplified version of the facility's hydrogeologic framework. Rather than accounting for any spatial variability in the geology, the analysis assumed an unconfined aquifer with uniform properties (hydraulic conductivity, porosity) throughout its thickness and areal extent, uniform recharge (6.65 in./yr, equivalent to one-fourth of the average annual precipitation), and a flat base. The aquifer thickness was set high enough to maintain unconfined conditions. Hydraulic conductivity was assigned on the basis of a

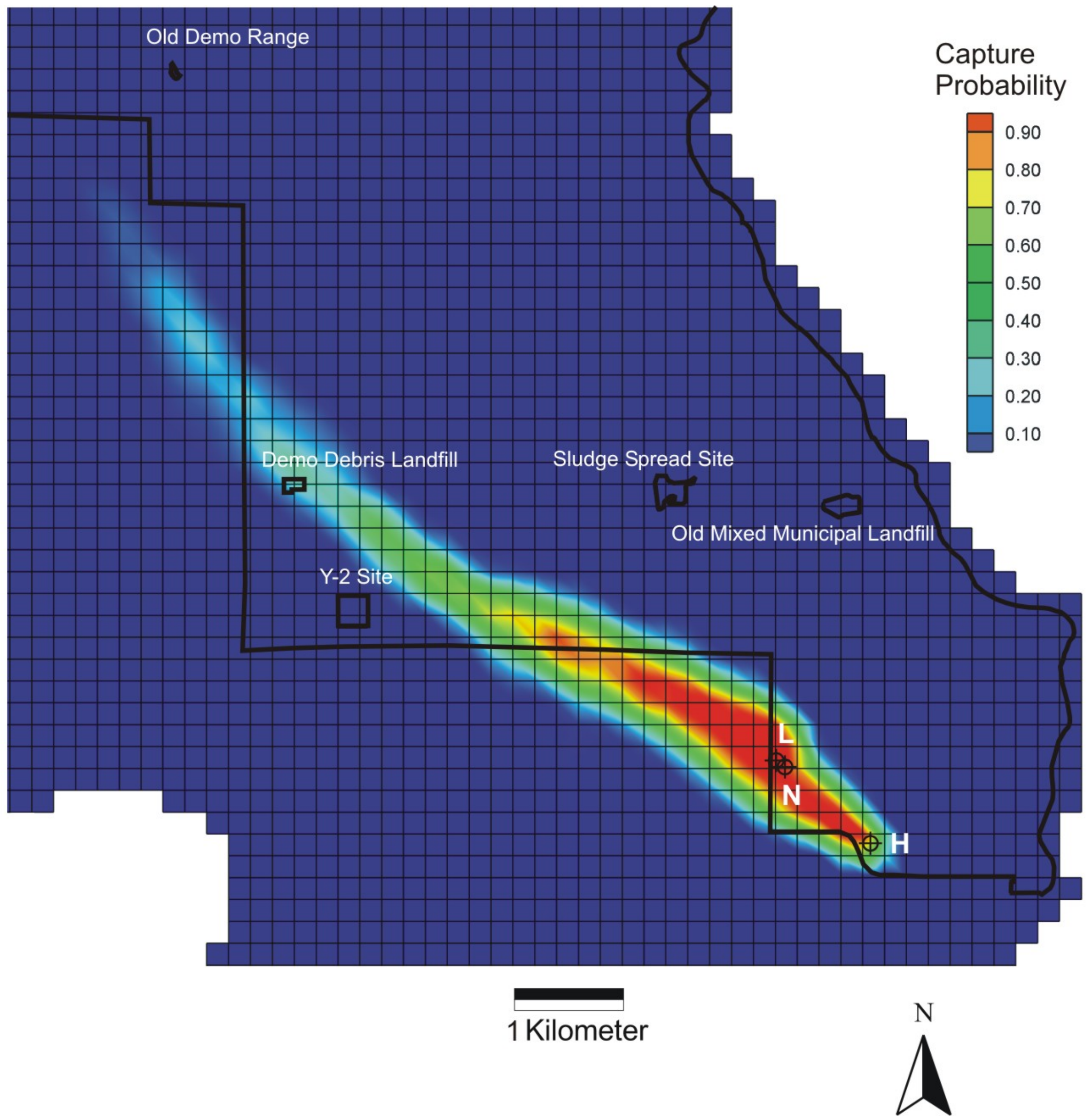

FIGURE 14 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Average Annual Pumping Rates

value that resulted from a pumping test at well L (Driscoll 1990). The porosity value selected was the mid-range value of “glacial till” porosities (17.5%) as listed in Driscoll (1986), despite the fact that the subsurface was dominated by other materials. The modeling technique was the analytic element method. The resulting deterministic model shows a WHP zone extending approximately 9 km through on-site and off-site areas (Figure 20). The analytic element method requires a reference point, which is a head value at a certain location — namely, a monitoring well. Model accuracy was addressed by comparing model-predicted heads to measured heads at four monitoring wells. Model runs relying on different reference points demonstrated that the model was sensitive to the reference point selected.

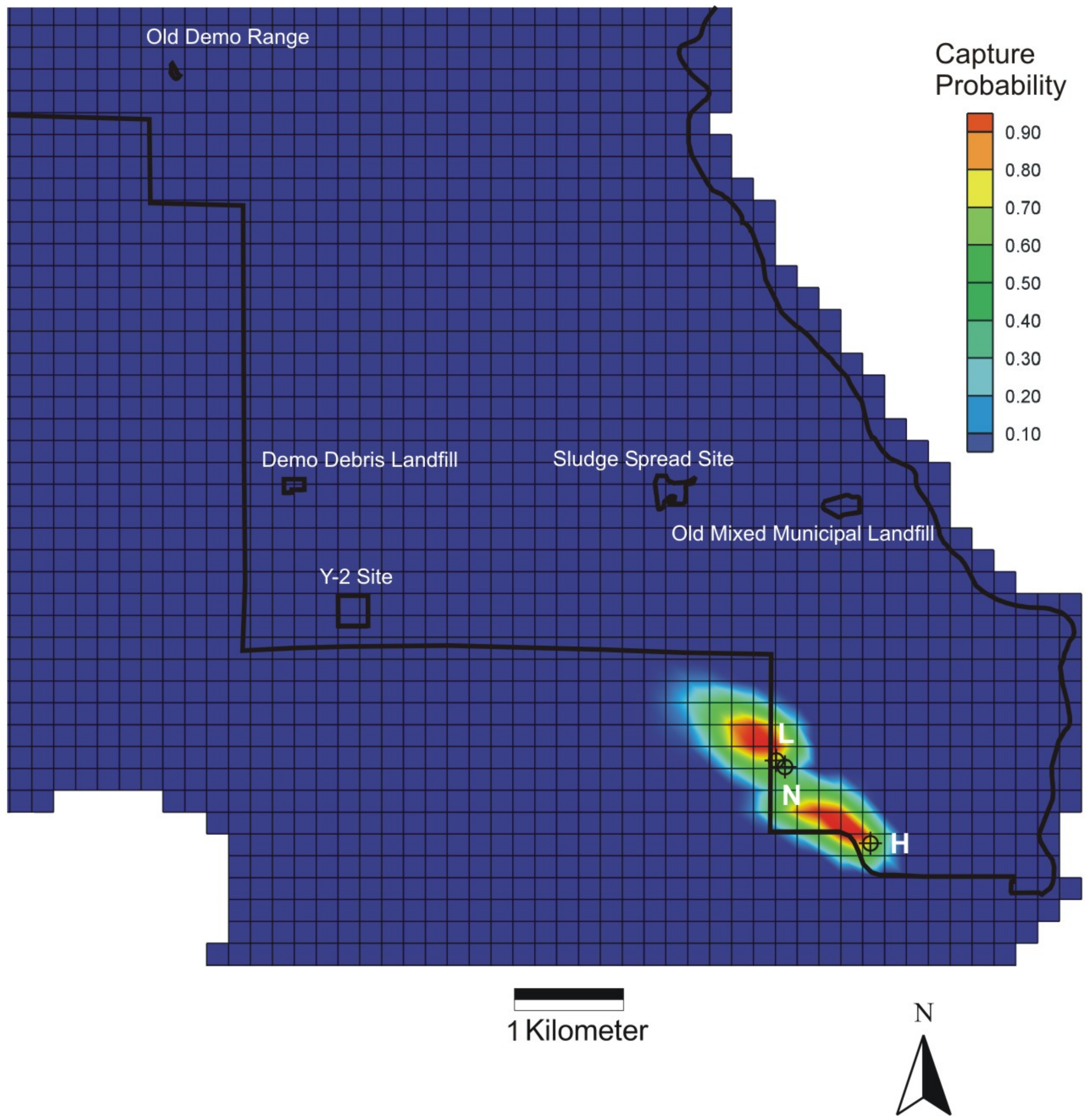

FIGURE 15 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Average Annual Pumping Rates and 10-Year Time of Travel

5.3 COMPARISON OF CURRENT AND PRIOR WHP MODEL RESULTS

In terms of overall flow direction in the production well vicinity, the prior model and the current model are similar. However, the prior model was a deterministic model, relying on a single, simplified hydrogeologic model to determine the groundwater flowfield. The current model is supported by an abundant amount of drilling data, which, in turn, supports multiple geostatistical realizations of the subsurface. The multiple numerical groundwater modeling results and the probabilistic particle capture method provide a means of addressing uncertainty in the model's subsurface framework and in the subsequent flow modeling and capture zone results.

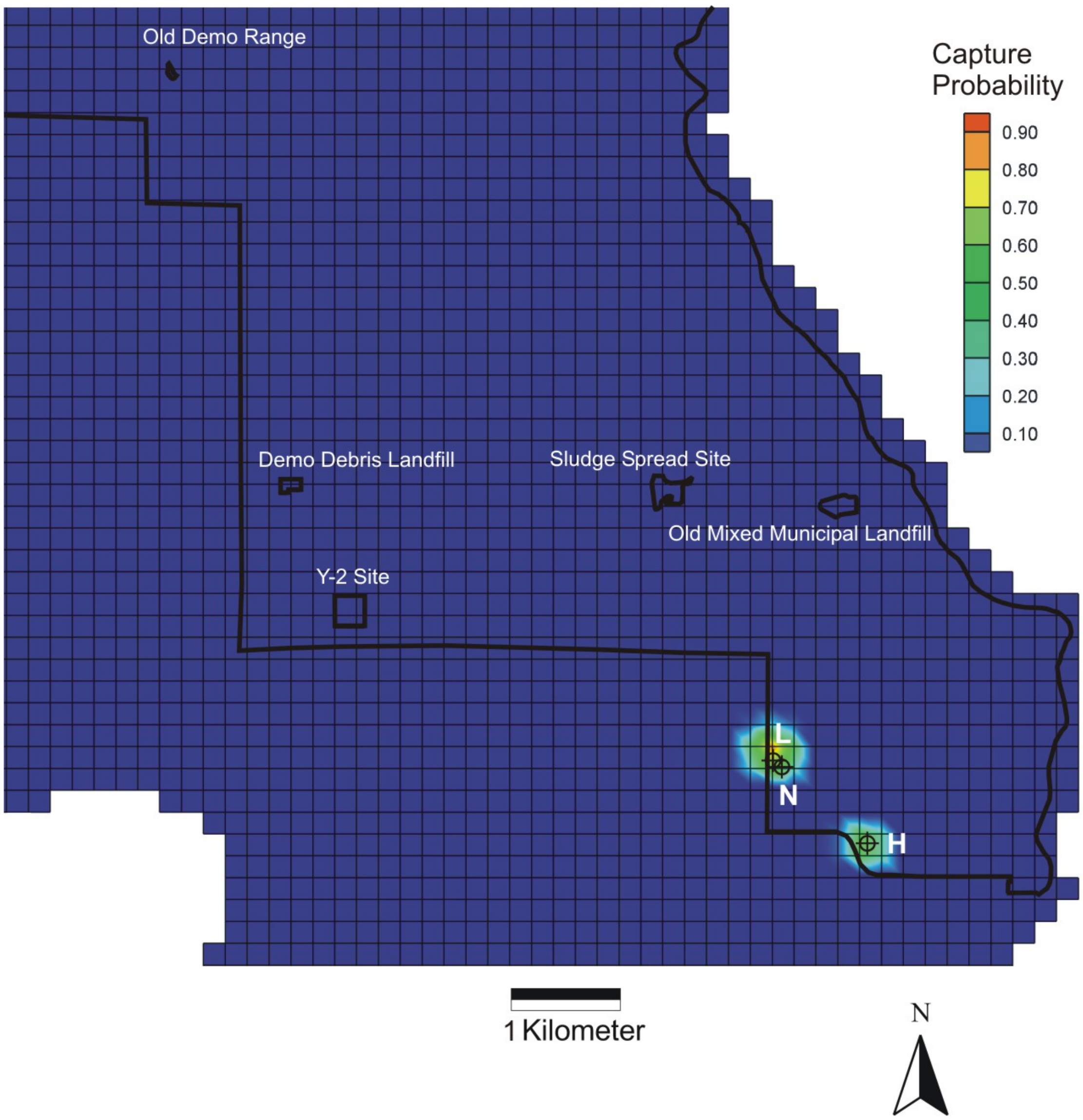

FIGURE 16 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Average Annual Pumping Rates and 1-Year Time of Travel

When the combined capture zone of wells H, L, and N in Figure 14 is compared with that of the prior model (Figure 20), they are similar in orientation. In terms of the breadth of the capture zone, the current model's width at a 50% probability of capture is similar to the capture zone of the prior model. However, the current model results may be used in a conservative fashion to delineate the WHP zone. Relying on a 10% probability level, for example, produces a WHP zone nearly twice as wide as that of the prior model. This is mainly because of the multiple realizations of the geostatistically characterized subsurface, which tend to spread out the particle traces in a manner more consistent with natural flow processes. In contrast, the prior model's deterministic approach provided only a single result of a narrowing capture zone. For facility

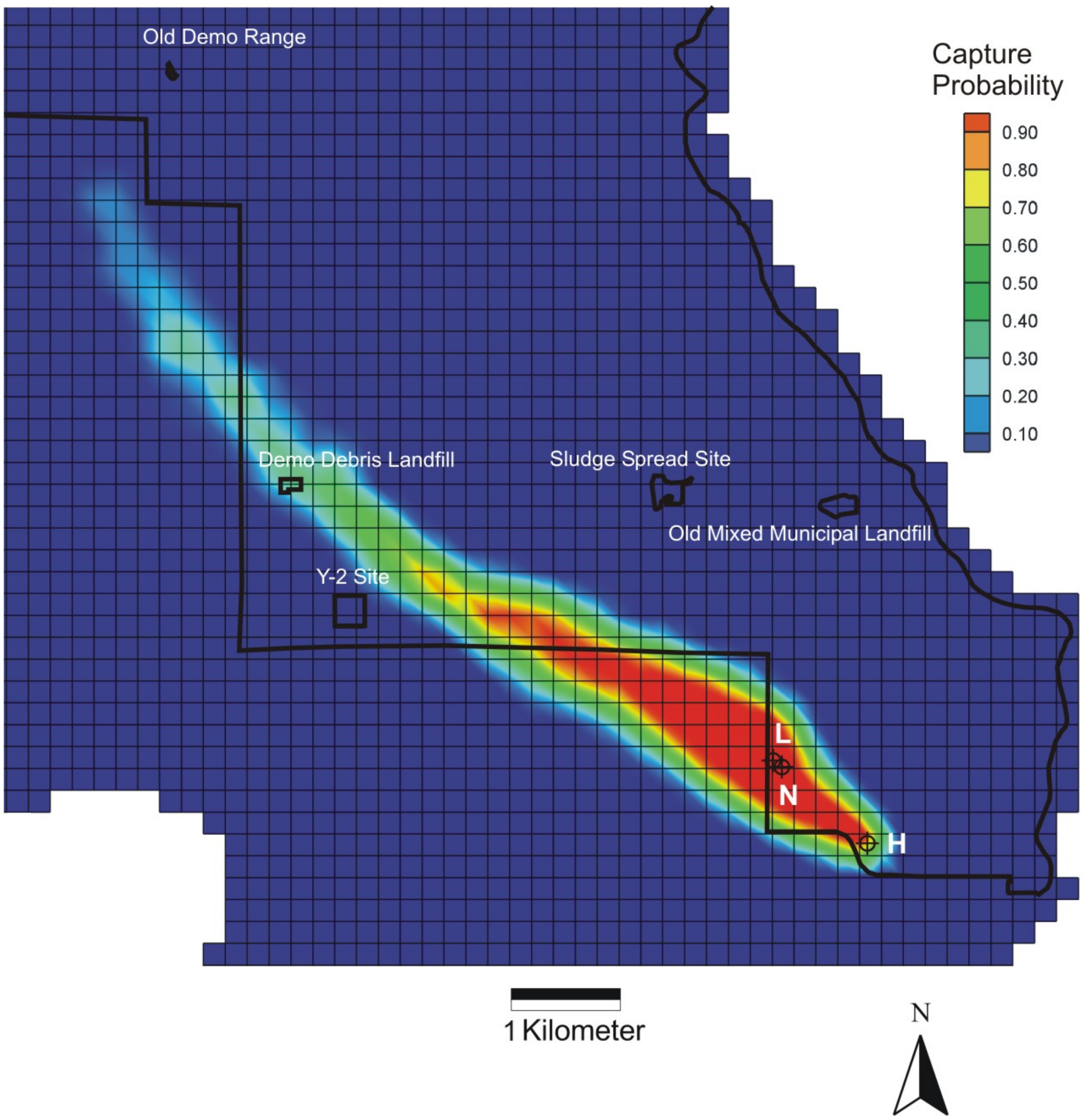

FIGURE 17 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Maximum Annual Pumping Rates

managers, selecting a capture zone probability level is analogous to choosing the degree of certainty associated with a WHP zone.

The prior model's report contains a figure of the 1-year time-of-travel capture zone for emergency response (Figure 3-4A of Minnesota Army National Guard [2002]). In the figure, the upgradient end of the capture zone is bounded by a somewhat arbitrary-appearing straight line. More importantly, the 1-year capture zone of the prior model is longer than that of the current model. One reason is that the prior model relied on a uniform porosity of 0.175, which is smaller than that assigned to the bulk of the current model's materials. A lower porosity value results in faster flow rates.

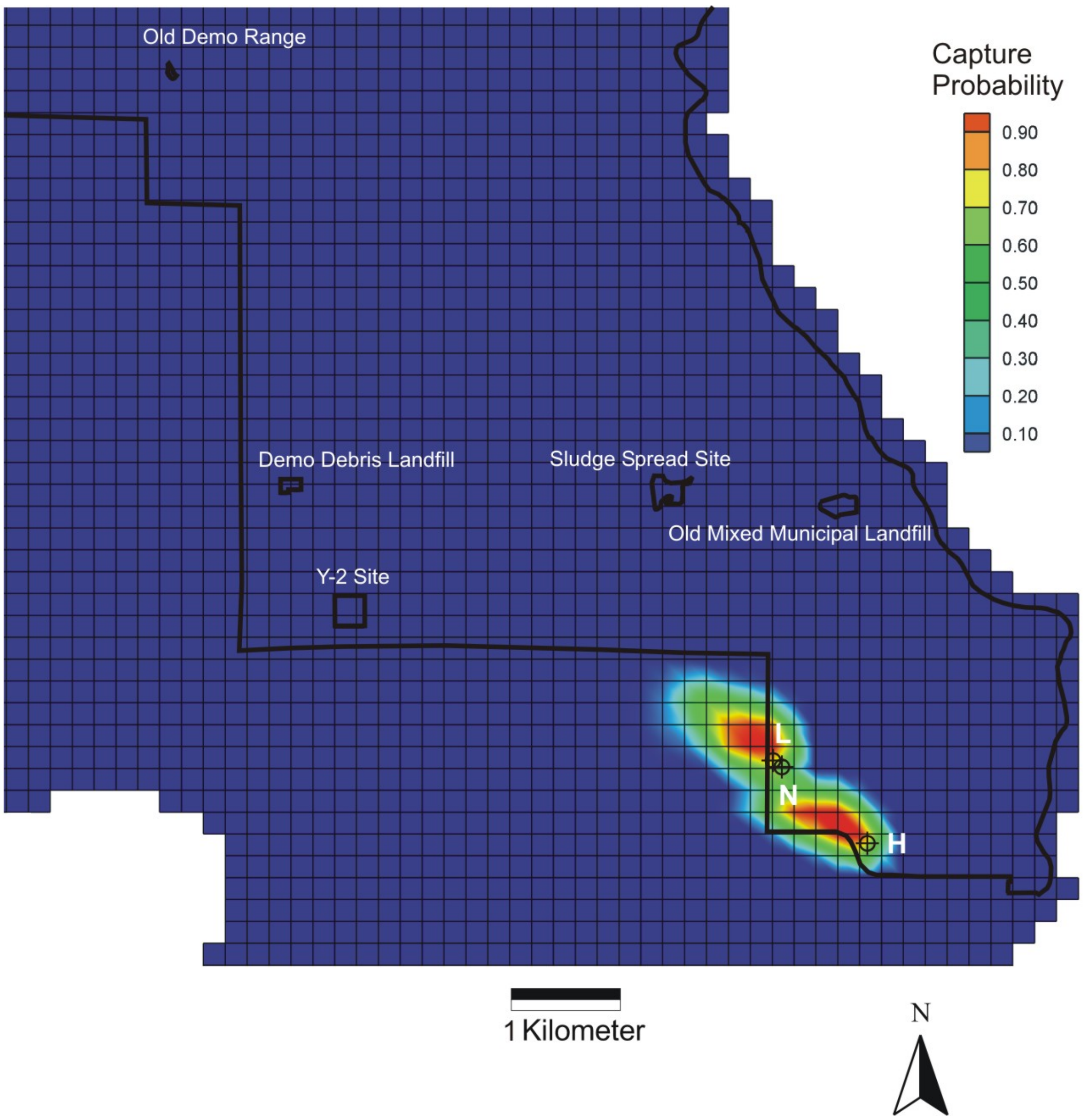

FIGURE 18 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Maximum Annual Pumping Rates and 10-Year Time of Travel

Guidance on WHP delineation may call for variation of a capture zone orientation by ±10% in order to resolve some of the uncertainty in the model. In the case of the geostatistical current model, this uncertainty is already addressed.

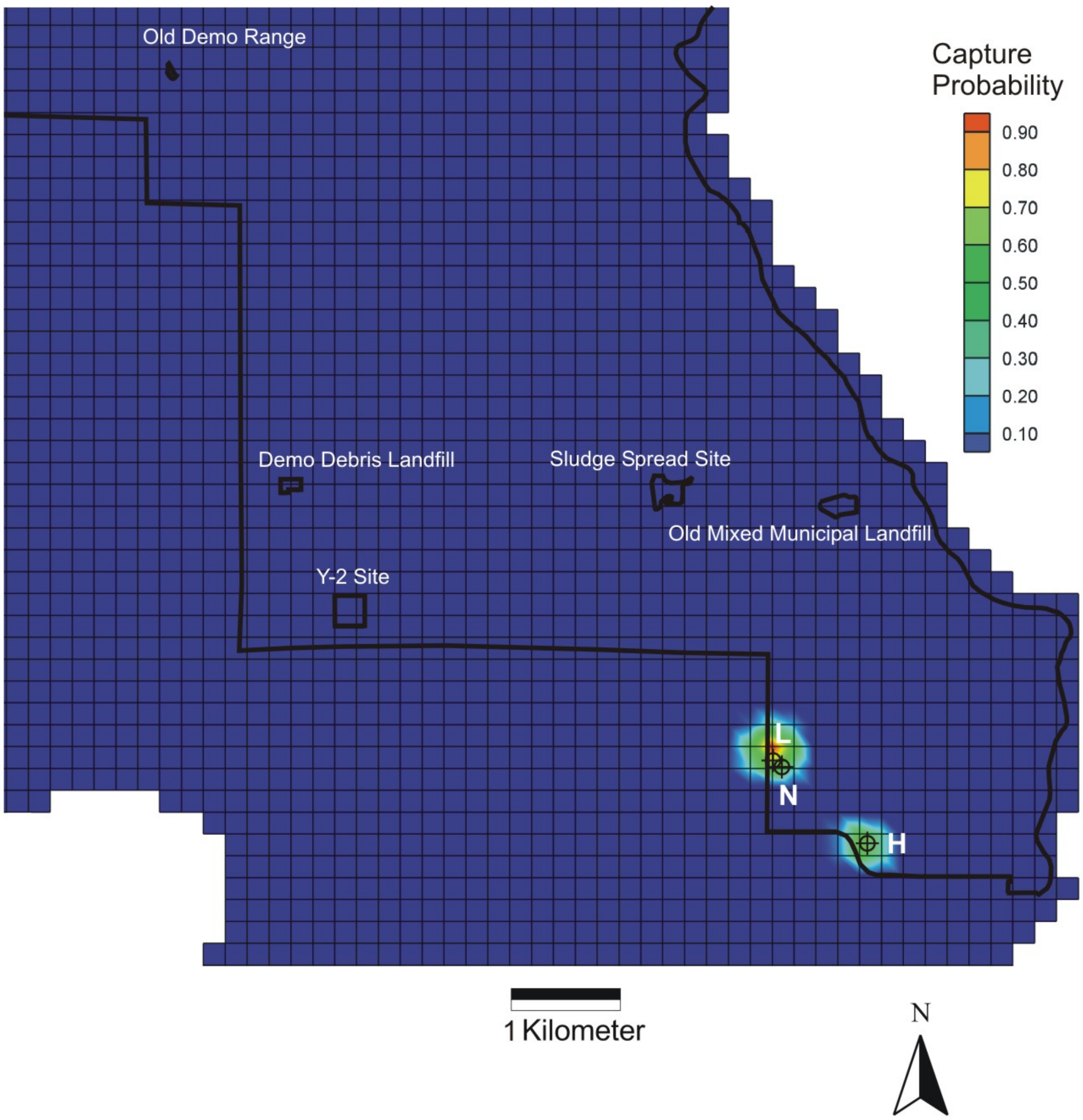

FIGURE 19 Probabilistic Wellhead Protection Zone for Production Wells H, L, and N Combined at Maximum Annual Pumping Rates and 1-Year Time of Travel

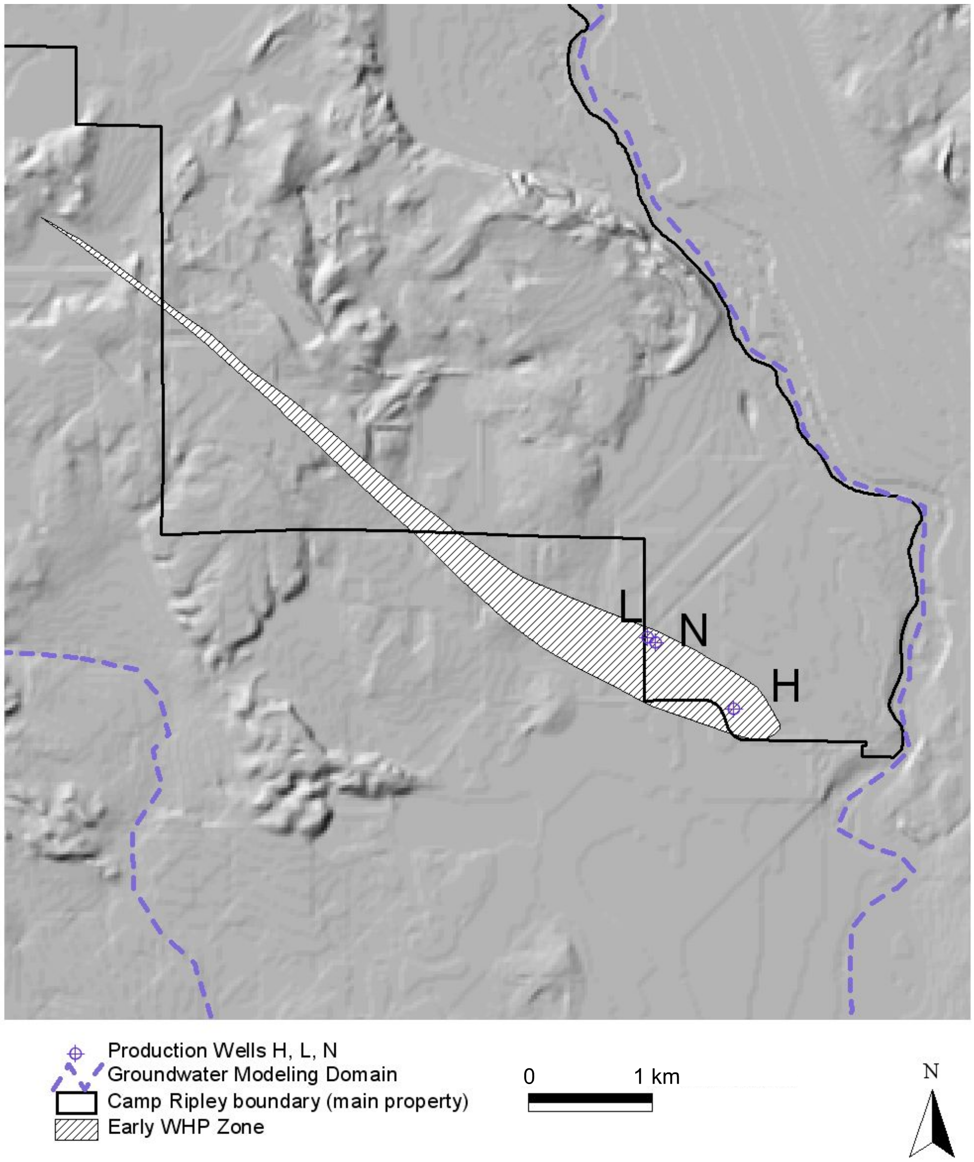

FIGURE 20 Prior WHP Zone (Source: Modified from Minnesota Army National Guard 2002)

6 FLOWPATHS FROM POTENTIAL GROUNDWATER CONTAMINANT SOURCE AREAS

On the basis of discussions with Camp Ripley staff, several areas at the facility were selected for analysis of groundwater flowpaths. This analysis was performed by conducting forward particle tracking from the potential source areas by using any of the calculated numerical model flowfields. Particles were started in cells of the uppermost active (saturated) model layer beneath the selected site and were tracked to their discharge locations (i.e., surface water or wetland). In this manner, the modeling approach assumes that any contaminants have already traveled through the unsaturated zone. The flowpaths are 3D, and when viewed interactively in 3D, they illustrate a somewhat tortuous flowpath because of preferential flow through higher-permeability model cells and around lower-permeability model cells.

The analysis focused on three impact areas (Leach, Hendrickson, and Hole-in-the-Day), several waste management facilities (Demo Debris Landfill, Sludge Spread Site, Old Mixed Municipal Landfill, and Landfarm Spread Site), two ranges (Demo Range and Old Demo Range), and a proposed training facility (the Y-2 site).

Two-dimensional (2D) projections of results appear in Figures 21–23, with 10-year time-of-travel markers along each flowpath. Large areas are represented by scattered, representative particle starting locations. The particle tracking method assumes advective flow, so that particles move with the bulk groundwater and are not affected by contaminant transport processes such as sorption, dilution, or biological or chemical decay. The results are therefore conservative, in the sense that most contaminants would travel slower than the overall groundwater flow rate.

These results may be used by site managers to understand groundwater flow directions in order to monitor well placement. A 3D inspection of the flowpaths would guide decisions regarding well screen depth. The time-of-travel information on the particle traces provides an initial, conservative estimate of the rate of transport of any groundwater contaminants from these potential source areas.

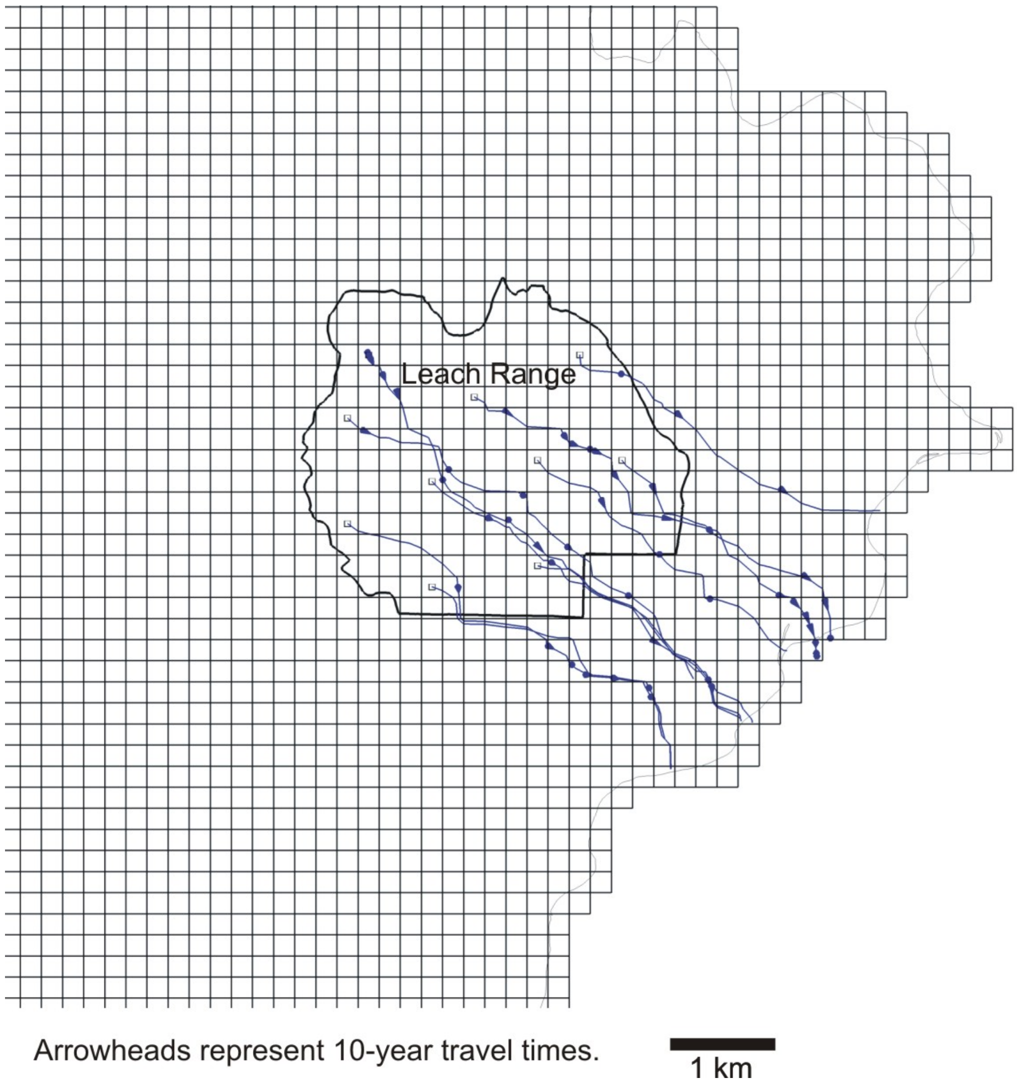

FIGURE 21 Particle Tracking from the Leach Range to Discharge Areas

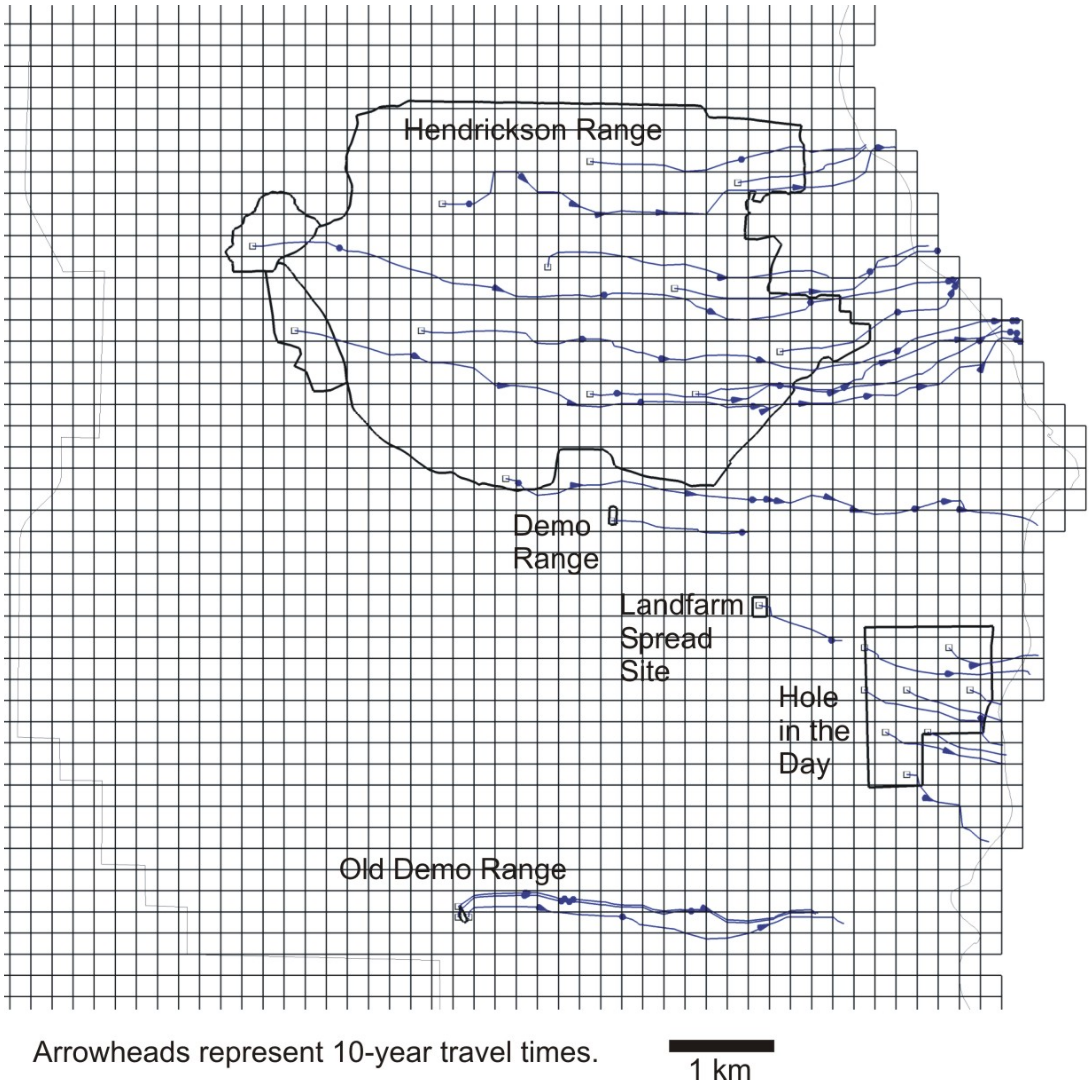

FIGURE 22 Particle Tracking from the Hendrickson Range, Demo Range, Old Demo Range, Landfarm Spread Site, and Hole in the Day Range to Discharge Areas

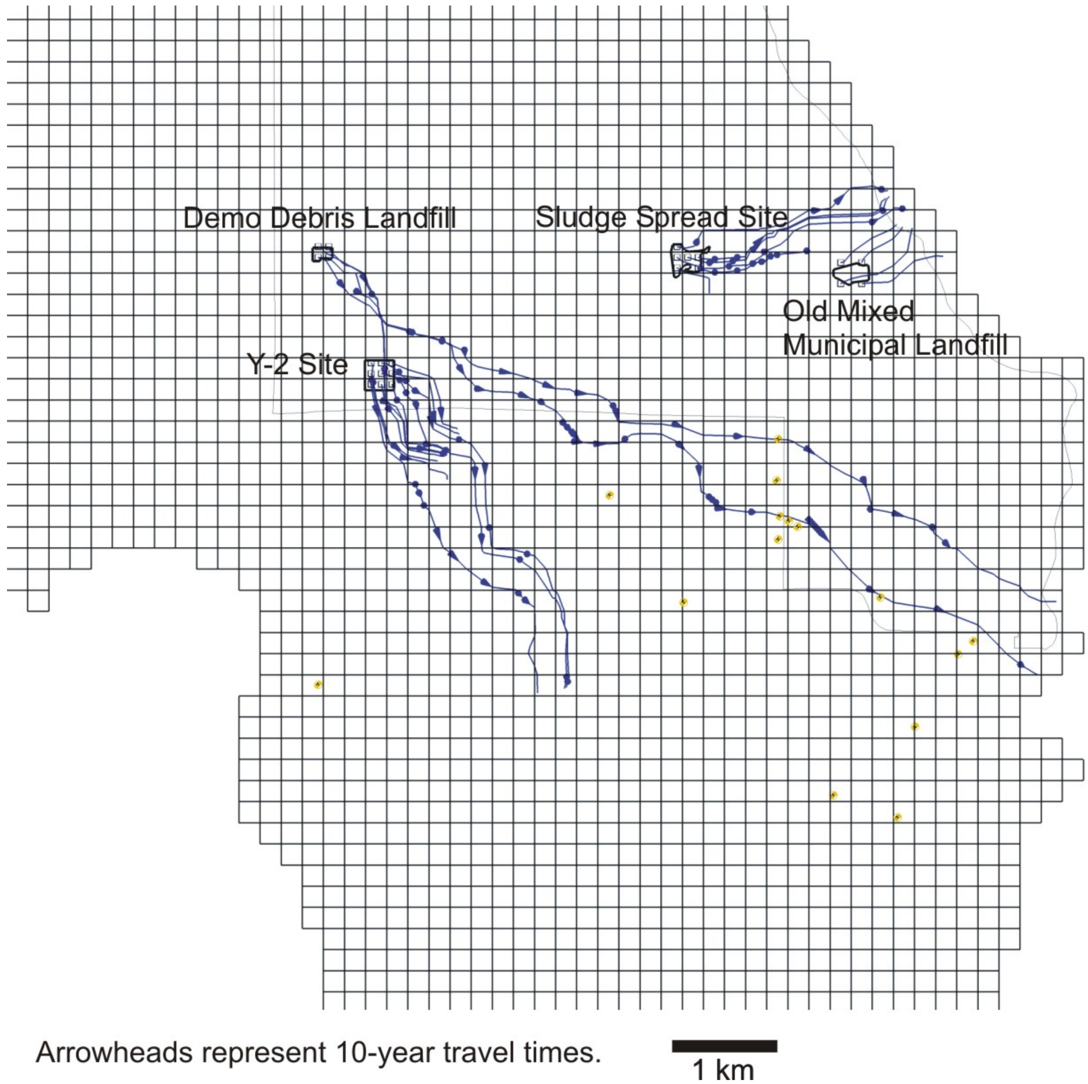

FIGURE 23 Particle Tracking from the Demo Debris Landfill, Sludge Spread Site, Old Mixed Municipal Landfill, and Y-2 Site to Discharge Areas

7 SUMMARY AND RECOMMENDATIONS

The model documented in this report relies on a variety of geologic and hydrologic input sources. These data were used to construct and calibrate the model. Because of the site's underlying stratigraphic complexity, fixed hydrogeologic contacts in a subsurface model would be difficult to defend. Therefore, because a geostatistical approach is used instead of assumed contacts, the variability and uncertainty of the subsurface are addressed explicitly by the model.

A numerical groundwater model may be a dynamic tool that is updated with additional data or modified to address a local groundwater concern. Applications for the model include geologic characterization of sites (through the 3D inspection of borehole data); identification of geologic and hydrologic data gaps; determination of flowpaths, especially for Wellhead Protection studies; remedial design; water resources planning; and permitting. Depending on a model's purpose and scale issues, calculated water levels from the model in this report could be used as boundary conditions for a model focused on a smaller area and designed to address a specific problem.

As described above, the current model, with its geostatistical approach to handling hydrogeological uncertainty, supports a WHP zone for wells H, L, and N. The WHP zone modeling for average historical pumping rates is slightly smaller than that determined for maximum historical pumping rates for the three time-of-travel scenarios (1-year, 10-year, and unlimited). The WHP zone is similar in orientation and dimension to a prior model; however, the 1-year time-of-travel zone of the current model is significantly smaller than that of the prior model.

The probabilistic approach of the current model provides decision makers with a means of delineating the WHP zone on the basis of the relative risk. While the 50% probability of capture contour provides the best estimate of the WHP zone, the probabilistic results allow facility managers to understand the uncertainty in the WHP zone delineation and select a WHP zone on the basis of the probability of capture.

The Minnesota WHP Program states that owners of private property within the WHP zone need to be notified at least once per year. The communication is to include information on the facility's WHP manager, guidance about aquifer protection and conservation, and contacts for Morrison County, DNR, and MDOH regarding septic system compliance and maintenance, agricultural best management practices, water well testing, etc. Signs are to be installed in the WHP zone. On the basis of the current modeling results, site managers should feel confident in maintaining WHP management strategies over property areas that are consistent with those of the prior evaluation.

As described above, the groundwater flow direction of the regional aquifer beneath the Demo Debris Landfill is to the southeast. Site-specific monitoring well data, however, indicate that a perched flow system is present with variable flow directions. Additional synoptic measurements and/or continuous recorders would provide data for understanding the dynamic nature of the shallow groundwater flow at this facility, and a drilling program would give insight on the relationship between the shallow and regional flow systems. The 10-year time of travel of regional flow beneath the facility extends to a distance of about 400–600 m. Although the landfill is in the modeled WHP zone that is indicated in Figures 14 and 17, the time of travel for regional groundwater to reach the production zones much longer than 10 years (Figures 15 and 18), and the overall probability of groundwater from this location reaching the production wells is <30%.

Regional groundwater flow at the Y-2 site, which may require permitting for gray water discharge from a newly proposed facility, is to the southeast.

8 REFERENCES

AWWA (American Water Works Association), 2006, *Stats on Tap*, http://www.awwa.org/Advocacy/pressroom/statswp5.cfm, accessed Aug. 4, 2006.

Anderson, M.P., and W.W. Woessner, 1992, *Applied Groundwater Modeling: Simulation of Flow and Advective Transport*, Academic Press, Inc., San Diego, CA.

Carle, S.F., 1999, *T-PROGS: Transition Probability Geostatistical Software, Version 2.1*, University of California, Davis, CA.

Carney, L.M., and H.D. Mooers, 1998, "Landform Assemblages and Glacial History of a Portion of the Itasca Moraine, North-Central Minnesota," in C.J. Patterson and H.E. Wright, Jr., eds., *Contributions to the Quaternary of Minnesota*, Minnesota Geological Survey Report of Investigations 49, St. Paul, MN.

Driscoll, F.G., 1986, *Groundwater and Wells*, Johnson Controls, St. Paul, MN.

Driscoll, F.G., 1990, "Pump Test Results for Well L," in *Hydrogeologic Report for New Water Well*, prepared by Fletcher G. Driscoll and Associates, Feb. 22.

EMRL (Environmental Modeling Research Laboratory), 2004, *Groundwater Modeling System (GMS), Version 5.1*, Brigham Young University, Provo, UT.

Freeze, R.A., and J.A. Cherry, 1979, *Groundwater*, Prentice-Hall, Inc., Englewood Cliffs, NJ.

Goldstein, B.S., 1998, "Quaternary Stratigraphy and History of the Wadena Drumlin Region, Central Minnesota," in C.J. Patterson and H.E. Wright, Jr., eds., *Contributions to the Quaternary of Minnesota*, Minnesota Geological Survey Report of Investigations 49, St. Paul, MN.

Goldstein, B.S., 1989, "Lithology, Sedimentology, and Genesis of the Wadena Drumlin Field, Minnesota, U.S.A.," *Sedimentary Geology* 62:241–277.

Harbaugh, A.W., et al., 2000, *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model — User Guide to Modularization Concepts and the Ground-Water Flow Process*, Open-File Report 00-92, U.S. Geological Survey, Reston, VA.

Helgesen, J.O., and G.F. Lindholm, 1977, *Geology and Water-Supply Potential of the Anoka Sand-Plain Aquifer*, Technical Paper No. 6, Minnesota Department of Natural Resources, Division of Waters, St. Paul, MN.

Hill, M.C., et al., 2000, *MODFLOW-2000, The U.S. Geological Survey Modular Ground-Water Model — User Guide to the Observation, Sensitivity, and Parameter-Estimation Processes and Three Post-Processing Programs*, Open-File Report 00-184, U.S. Geological Survey, Reston, VA.

Klinker, R., 2005, e-mail correspondence from Klinker (Camp Ripley, Little Falls, MN), to J. Quinn (Argonne National Laboratory, Argonne, IL), June 15.

MDNR (Minnesota Department of Natural Resources), 2006, *Lake Finder*, http://www.dnr.state.mn.us/lakefind/index.html, accessed April 3, 2006.

MDOH (Minnesota Department of Health), 2006, *County Well Index*, http://www.health.state.mn.us/divs/eh/cwi/, accessed April 3, 2006.

Minnesota Army National Guard, 2002, *Wellhead Protection Program for Camp Ripley Water Supply Wells*, Little Falls, MN.

Minnesota Pollution Control Agency, 1999, *Lake Assessment Program 1997, Fishtrap Lake (ID #49-0137), Morrison County, Minnesota*, St. Paul, MN, Aug.

Mooers, H.D., 1996, *Geomorphology of the Brainerd 1:100,000 Quadrangle and the Development of the Land Type Association Layer of the Ecological Classification System*, Minnesota Department of Natural Resources, Division of Forestry, St. Paul, MN.

Mooers, H.D., and J.D. Lehr, 1997, "Terrestrial Record of Laurentide Ice Sheet Reorganization during Heinrich events," *Geology* 25(11):987–990.

Pollock, D.W., 1994, *User's Guide for MODPATH/MODPATH-PLOT, Version 3: A Particle Tracking Post-Processing Package for MODFLOW, The U. S. Geological Survey Finite-Difference Ground-Water Flow Model*, Open-File Report 94-464, U.S. Geological Survey, Reston, VA.

Quinn, J.J., 2003, *Numerical Groundwater Flow Model of Camp Ripley, Minnesota*, prepared by Argonne National Laboratory, Argonne, IL, for Camp Ripley Environmental Program, Department of Military Affairs, Aug.

St. George, L.M., 1994, *A Landform-Based Approach to the Estimation of Groundwater Recharge in Complex Glacial Topography*, M.S. thesis, University of Minnesota, Duluth, MN.

Schneider, A.F., 1961, *Pleistocene Geology of the Randall Region, Central Minnesota*, Bulletin 40, Minnesota Geological Survey, Minneapolis, MN.

USDA (U.S. Department of Agriculture), 1994, *Soil Survey of Morrison County, Minnesota*, Soil Conservation Service.

UMD (University of Minnesota-Duluth), 2002, *Environmental Drilling Field Report*, Department of Geological Sciences.

Wright, H.E., Jr., 1972, "Quaternary History of Minnesota," pp. 515–547 in P.K. Sims and G.B. Morey, eds., *Geology of Minnesota: A Centennial Volume*, Minnesota Geological Survey, Minneapolis, MN.

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