Dressing the Emperor: The Role of Three-Dimensional Information Visualization Software (3DIVS) in the Development of Three-Dimensional Hydrogeologic Models

Cristian R. Medina (*crmedina@indiana.edu*), Department of Geological Sciences, Center for Geospatial Data Analysis, Indiana University, Bloomington, Indiana.
Greg A. Olyphant (*olyphant@indiana.edu*), Department of Geological Sciences, Center for Geospatial Data Analysis, Indiana University, Bloomington, Indiana.
Sally L. Letsinger (*sletsing@indiana.edu*), Center for Geospatial Data Analysis, Indiana Geological Survey, Indiana University, Bloomington, Indiana.

Center for Geospatial Data Analysis

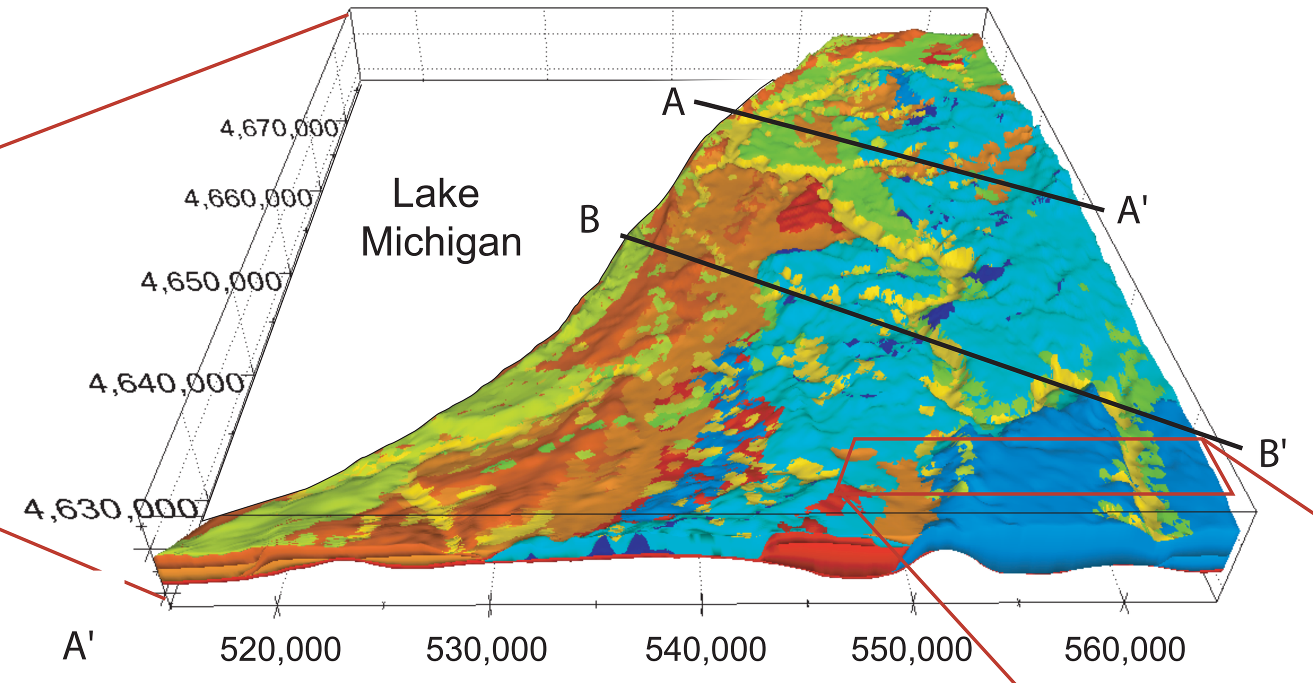
Abstract No. 114864

The goal of this research is to develop a model that describes the saturated and unsaturated groundwater flow in Berrien County, Michigan (1,350 km^2), an area containing a complex sequence of glacio-lacustrine deposits. Stone and others (2001) mapped the morphosequences in Berrien County at a scale 1:24,000, which includes georeferenced structure contours for 20 individual units. We have developed a methodology to translate this detailed morphostratigraphy into a solid three-dimensional geologic model, and then into a three-dimensional block of data that can be used input to a finite-difference groundwater-flow model. Letsinger and others (2006) describe the process of using geographic information system software to convert the structure contours into georeferenced raster layers that describe each unit. At this stage of the reconstruction, only the bounding surfaces between the units are defined. In order to stack the units in vertical space, using customized code, a "virtual well field" (regularized two-dimensional array of points) samples each x-y location in each of the 20 rasterized data layers. Units that are intersected from the top bounding surface (surface topography) to the bottom bounding surface (bedrock surface) are then identified. The result of this step is a vector (one-dimensional array) at each virtual well location that describes the elevation of each morphostratigraphic unit boundary intersected at that location. However, at this stage, the model is essentially a regularized three-dimensional point cloud, and three-dimensional information visualization software (3DIVS) is then utilized to generate a solid geologic model by interpolating the vertical geologic "samples" throughout the model domain.

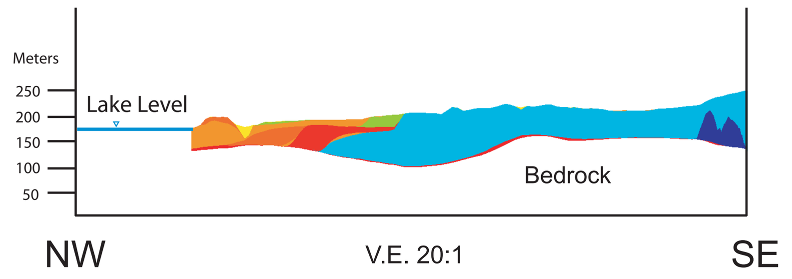
3-D GEOLOGIC MODEL WITH REPRESENTATIVE CROSS SECTIONS

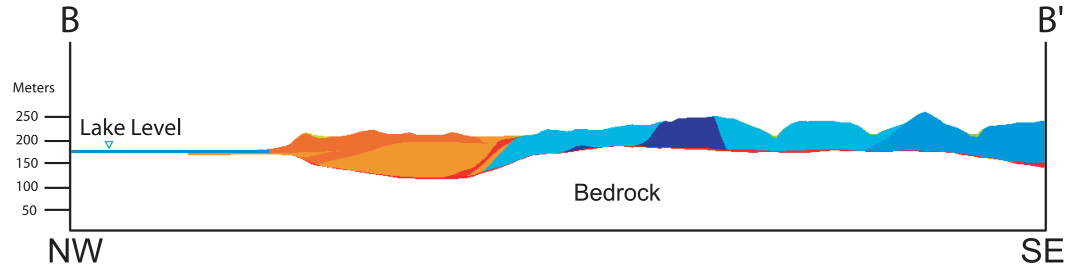
The solid model developed from the "Virtual Well Field" generated using GIS (ArcMap) and custom computer code (FORTRAN) can be visualized using a 3DIVS.

3-D perspective view of Berrien County surficial geology
(Meaning of colors is provided in the table below)



The 3DIVS Software (EVS) allows cross sections to be extracted from the solid model.





Legend	Hydraulic Conductivity (cm/s)	K_h/K_v	van Genuchten Functions
Recent Alluvium	$5 * 10^{-3}$	3:1	Sand/Gravel
Diamicts (basal till, moraine)	$1 * 10^{-6}$	1:1	Clay
Lake-bottom deposits	$4 * 10^{-3}$	100:1	Intermediate
Littoral Sand, Older Alluvium Dune Sand	$5 * 10^{-2}$ $1 * 10^{-2}$	3:1 1:1	Sand/Gravel Intermediate
Undifferentiated Deltaic	$5.2 * 10^{-2}$	10:1	Sand/Gravel
Coarse Grained Deltaic	$9.8 * 10^{-2}$	3:1	Sand/Gravel

GROUNDWATER MODEL AND FINITE-DIFFERENCE GRID

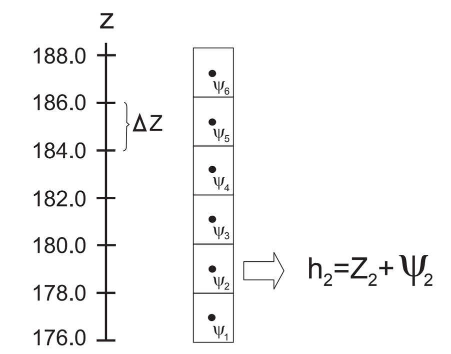
It is necessary to have a numerical model capable of handling variably-saturated flow subject to a heterogeneous distribution of hydraulic properties and non-uniform topography.

GOVERNING EQUATION OF FLOW (FREEZE, 1971):

$$\frac{\partial}{\partial x}\left[K_x(\Psi)\frac{\partial \Psi}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_y(\Psi)\frac{\partial \Psi}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_z(\Psi)\left(\frac{\partial \Psi}{\partial z}+1\right)\right]=C(\Psi)\frac{\partial \Psi}{\partial t}$$

Where:
$K(\Psi)$: hydraulic conductivity, pressure dependent in the unsaturated zone.
$C(\Psi)=d\theta/d\Psi$: specific moisture capacity, pressure dependent in the unsaturated zone.
Ψ: pressure head, negative in the unsaturated zone.

Solving for the pressure head (Ψ) allows to calculate the hydraulic head (h):



$h_2 = Z_2 + \Psi_2$

van Genuchten Characteristic Equations:

$$Se=\frac{\theta(\psi)-\theta_r}{\theta_s-\theta_r}=\left[1+(\alpha|\psi|)^n\right]^{-m}$$

$$K(\psi)=K(Se)=K_s Se^{1/2}\left[1-\left(1-Se^{1/m}\right)^m\right]^2$$

$$C(\Psi)=\alpha(\theta_s-\theta_r)(n-1)(\alpha|\psi|)^{n-1}\left[1+(\alpha|\psi|)^n\right]^{\frac{1}{n}-2}$$

$C(\psi)$ = 0 in the saturated zone

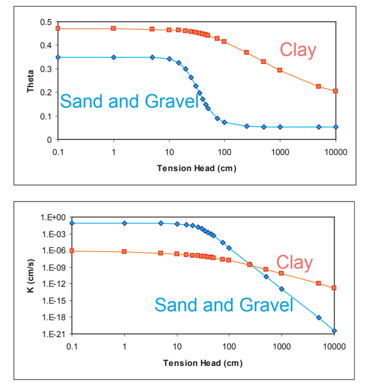
θ_s = 0.35, 0.39, 0.47

θ_r = 0.053, 0.065, 0.10

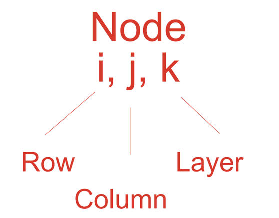
α = 0.035, 0.026, 0.011 cm-1

n = 3.18, 1.67, 1.27

Ks = 8x10-2, 4x10-3, 10-6 cm/s



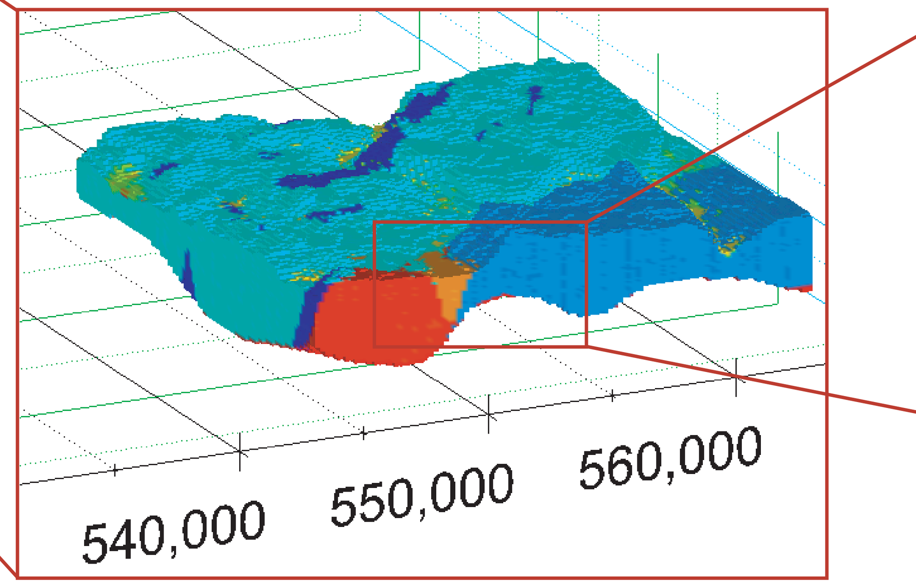
We created 3-D arrays, where each grid cell node is characterized by: i (row), j (column), k (layer), an ID for van Genuchten characteristic equation parameters as well as saturated hydraulic conductivity and Kh/Kv ratio



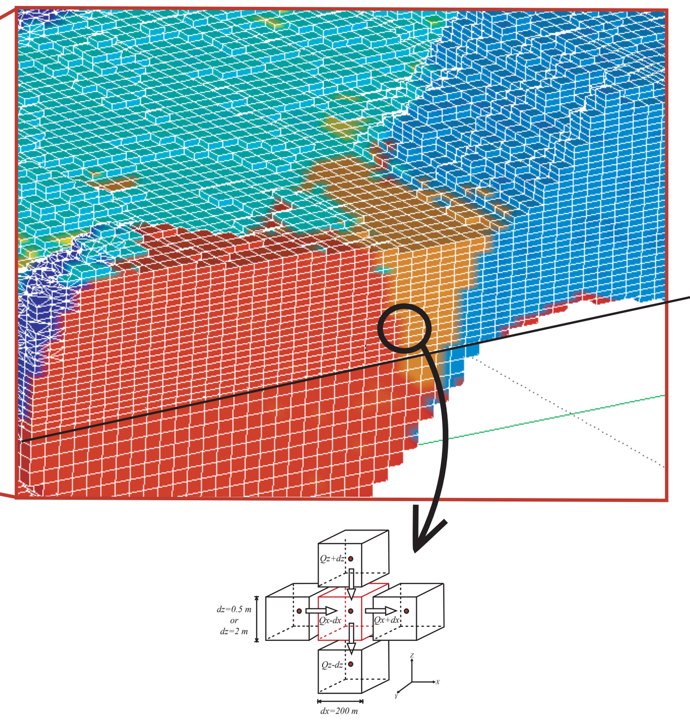
Grid Details:
269 Grid cells in the Y direction (Rows)
248 Grid cells in the X direction (Columns)
250 Grid cells in the Z direction (Layers)

16x10^6 Potential Grid Cells
~5x10^6 Calculation Grid Cells

The colors in the figures below represent the 3-D finite-difference grid ("brickpile") at its current resolution. The brickpile was generated from the virtual wells using a custom computer program and is visualized here using 3DIVS.

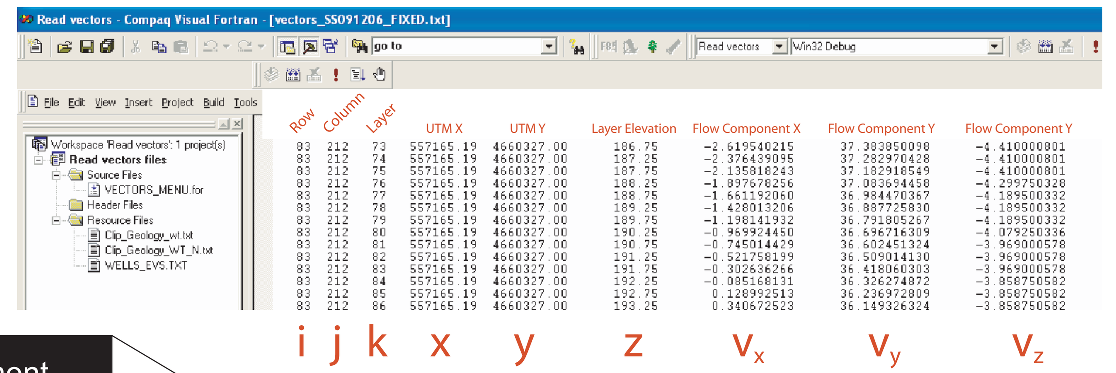


dx=dy=200 m

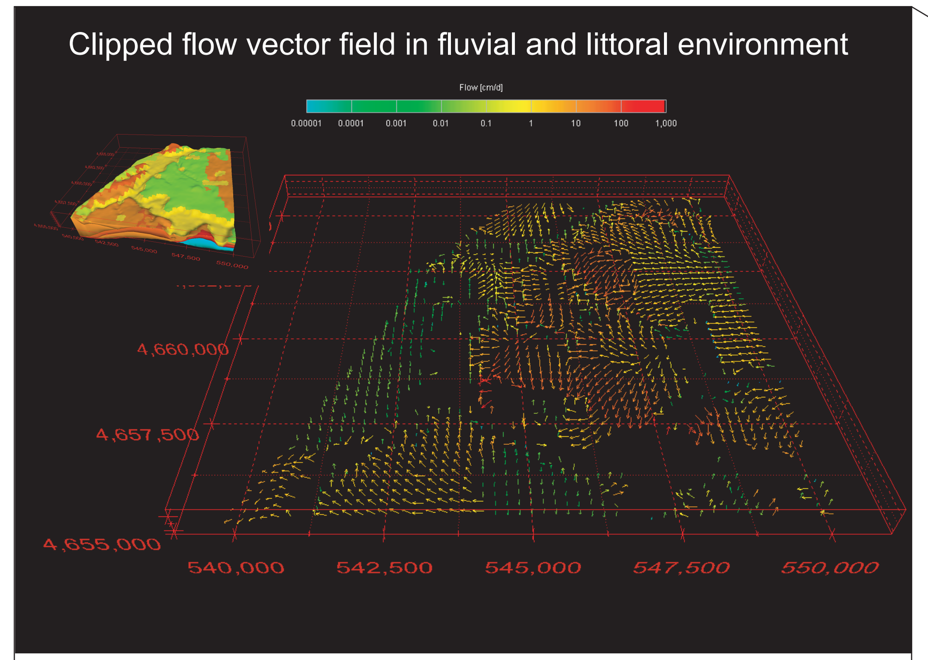


PROCESSING MODEL OUTPUT AND VISUALIZING RESULTS

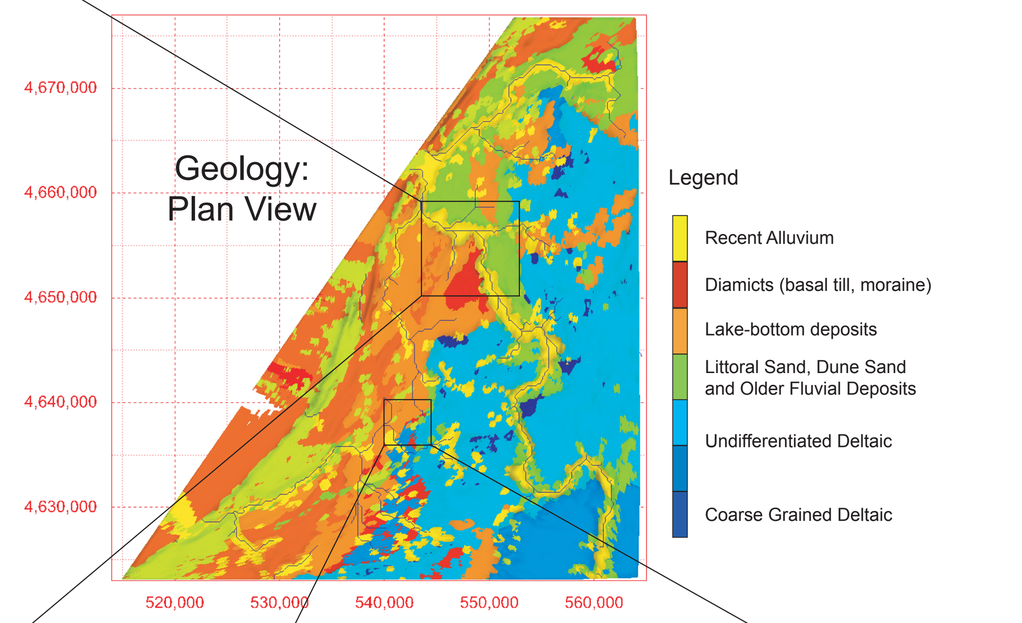
The ASCII output table from the Groundwater flow model (right) is processed using custom computer code to facilitate input to a 3DIVS (EVS) for visualization of resultant vectors and associated geology at any location



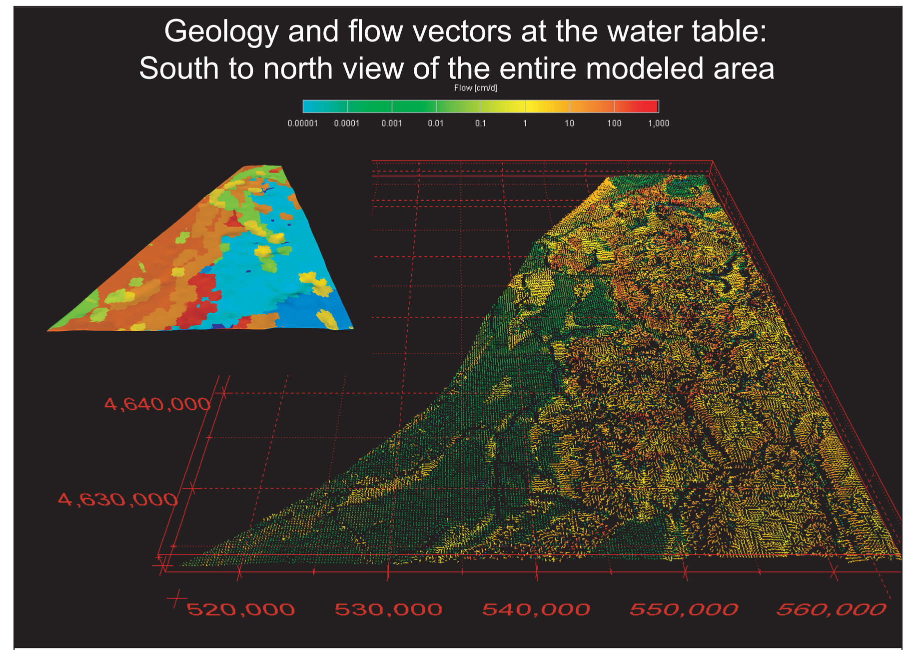
Clipped flow vector field in fluvial and littoral environment



This closeup shows strong organization of the flow field near the outlet of St. Joseph River. Flow directions are dictated by topography but flow magnitudes are conditioned by material types.

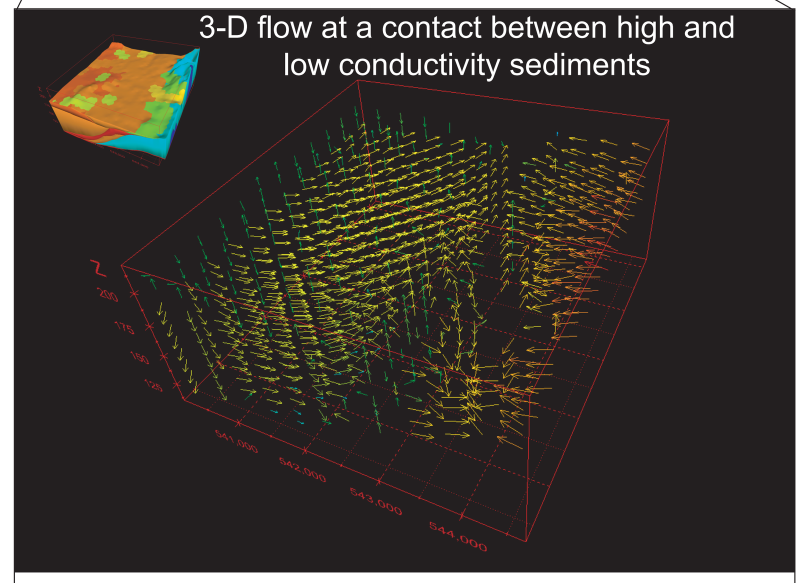


Geology and flow vectors at the water table:
South to north view of the entire modeled area



Vector colors indicate the strong correspondance between flow rates and the types of materials occurring at the water table.

3-D flow at a contact between high and low conductivity sediments



Note the strong turning of flow at the contact between deltaic and lacustrine sediments.

References:
Freeze, R. A. 1971. Three-dimensional, transient, saturated-unsaturated flow in a groundwater basin. Water Resources Res., 7, pp. 347-366.
Stone, B.D., K.A. Kincare and D.W. O'Leary. 2002. Glacial geology mapping in Berrien County, Michigan: Resolving the third dimension for increasing the accuracy of resource assessment. Geological Models for Groundwater Flow Modeling, Denver, Colorado.
Stone, B.D., J.R. Stone, J.P. Masterson, and D.W. O'Leary, 2004. Integrating 3-D Facies Analysis of Glacial Aquifer Systems with Ground-water Flow Models: Examples from New England and the Great Lakes Region, USA, in Berg, Richard C., Russell, Hazen and Thorleifson, L. Harvey, (eds): Three-Dimensional Geological Mapping For Groundwater Applications: 49th annual Meeting Geological Association of Canada, Mineralogical Association of Canada, St. Catherines Ontario, Canada, Workshop Extended Abstracts. Illinois State Geological Survey, Open File Series 2004-8, 100p.
Schaap, M. G., Feike, J. L., and van Genuchten, M. Th. (2000). Estimation of the Soil Hydraulic Properties. in *Vadose Zone Science and Technology Solutions, Vol. 1,* edited by B. B. Looney and R. W. Falta, pp. 501-509, Battelle Press, Columbus, OH.

This research is part of a multi-institutional effort by the Central Great Lakes Geologic Mapping Coalition.

Funded By: