DOI: 10.1007/s00267-003-0018-1

A GIS Model of Subsurface Water Potential for Aquatic Resource Inventory, Assessment, and Environmental Management

MATTHEW E. BAKER*
School of Natural Resources and Environment
University of Michigan
430 East University
Ann Arbor, MI 48109-1115, USA
and Smithsonian Environmental Research Center
647 Contees Wharf Road
Edgewater, MD 21037-0028, USA

MICHAEL J. WILEY
MARTHA L. CARLSON
School of Natural Resources and Environment
University of Michigan
430 East University
Ann Arbor, MI 48109-1115, USA

PAUL W. SEELBACH
Institute for Fisheries Research
Michigan Department of Natural Resources
212 Museums Annex
1109 North University
Ann Arbor, MI 48109, USA

ABSTRACT / Biological, chemical, and physical attributes of aquatic ecosystems are often strongly influenced by groundwater sources. Nonetheless, widespread access to predictions of subsurface contributions to rivers, lakes, and wetlands at a scale useful to environmental managers is generally lacking. In this paper, we describe a "neighborhood analysis" approach for estimating topographic constraints on spatial patterns of recharge and discharge and discuss how this index has proven useful in research, management, and conservation contexts. The Michigan Rivers Inventory subsurface flux model (MRI-DARCY) used digital elevation and hydraulic conductivity inferred from mapped surficial geology to estimate spatial patterns of hydraulic potential. Model predictions were calculated in units of specific discharge (meters per day) for a 30-m-cell raster map and interpreted as an index of potential subsurface water flux (shallow groundwater and event through-flow). The model was evaluated by comparison with measurements of groundwater-related attributes at watershed, stream segment, and local spatial scales throughout Lower Michigan (USA). Map-based predictions using MRI-DARCY accounted for 85% of the observed variation in base flow from 128 USGS gauges, 69% of the observed variation in discharge accrual from 48 river segments, and 29% of the residual variation in local groundwater flux from 33 locations as measured by hyporheic temperature profiles after factoring out the effects of climate. Although it does not incorporate any information about the actual water table surface, by quantifying spatial variation of key constraints on groundwater-related attributes, the model provides strata for more intensive study, as well as a useful spatial tool for regional and local conservation planning, fisheries management, wetland characterization, and stream assessment.

River, lake, and wetland ecosystems are strongly influenced by routing of source waters because relative contributions of precipitation, runoff, through-flow, and groundwater shape seasonal hydrography, chemical properties, thermal characteristics, and ultimately, the character of aquatic biota (Dunne and Leopold 1978, Wiley and others 1997, Winter 2001). Subsurface water inputs in particular can have strong influences on local biology due to their relatively cold summer temperatures, high dissolved mineral content, and stabilizing influence on water levels during periods of reduced precipitation (Hendrickson and Doonan 1972a, Brunke and Gonser 1997, Wiley and others 1997, Winter 2001). Thus, accounting for spatial variation in subsurface water sources is a fundamental requisite for science-based resource management of aquatic ecosystems.

Although groundwater modeling has been an exceptionally active field of study since the US Federal Clean Water Act of 1972, the ability to predict groundwater contributions to local surface water ecosystems at the multiple scales useful for ecological study and routine resource assessment has lagged behind. One reason is that results based on local or point-scale implementations of fully dynamic groundwater flux models are

KEY WORDS: Groundwater hydrology; GIS; Modeling; Stream ecology; Wetlands

Published online November 20, 2003.

*Author to whom correspondence should be addressed, *email:* bakerm@si.edu

often difficult to generalize to broader landscapes. Most methods for estimating or predicting groundwater flow are based in whole or in part on the principles of Darcy's Law. Darcy's Law states that flow through a porous medium is proportional to the difference in hydraulic head over some flow path length (hydraulic slope), the area of flow, and the hydraulic conductivity of the medium (Darcy 1856, Freeze and Cherry 1979). In common practice, the conservation of energy described by Darcy's Law is combined with the principle of continuity, or conservation of mass, in order to reduce the characterization of groundwater flow to a partial differential equation. Finite-element or finite-difference models (e.g., MODFLOW) predict distributed groundwater flow patterns from a series of known conductivity or head data points within a specific, bounded area (e.g., McDonald and Harbaugh 1988, Molson and Frind 1995, Harbaugh and McDonald 1996a,b). Models of this type require calibration in order to generate accurate predictions through time as well as space, and thus are typically restricted to local geographic areas due to computational constraints during validation (e.g., Christensen and others 1998, Martin and Frind 1998, Anderton and others 2002, Molenat and Gascuel-Odoux 2002, Beven 2002).

Environmental researchers, managers, and policymakers increasingly require location-specific information over broad geographic areas (e.g., whole river basins, states, ecoregions). Various important ecological phenomena occur at the scale of specific stream segments, lake subbasins, or wetland vegetative units, yet resource management decisions are often made with little hydrologic context. Therefore, there exists a very practical need for explicit, yet extensive, predictions of spatial variation in subsurface water sources across broad regions. It is not clear that such predictions must be absolute, but some relative characterization of flux is needed at multiple scales. Numerical groundwater flux models can be implemented across broad spatial scales, but because existing head and/or conductivity information tends to be sparse, and because acquiring such information at sufficient density can be cost-prohibitive, cell-to-cell error propagation and assumptions of isotropy across broad areas can add uncertainty to numerical groundwater solutions. As a result, regional predictions tend to be fairly coarse and are frequently underutilized in local or site-level environmental management. Moreover, estimates at broad spatial scales tend to focus on the dynamics of deep aquifers and regional flow rather than more local patterns of shallow subsurface flux (e.g., Mandle and Westjohn 1989, Holtchlag and others 1996, Hoaglund and others 2002).

Our approach was to explore whether a simple, yet specific, interpretation of Darcy's Law could be effectively applied using a geographic information system (GIS) to predict spatial variation in potential subsurface water flux at scales useful for resource inventory and assessment. As ecologists, we are interested in a subset of the dynamics typically addressed by groundwater hydrologists, and we see a distinction between predicting dynamics of the water table surface (that may lead to discharge or recharge) and characterizing potential flux from one surface locality to another. Using a GIS integration and spatial averaging of a digital elevation model (DEM) to estimate hydraulic head and a surficial geology map to estimate hydraulic conductivity, we developed a model (MRI-DARCY) and produced a map of local potential subsurface water flux to surface locations throughout the Lower Peninsula of Michigan. In this paper, we describe our relatively simple "neighborhood analysis" approach for estimating constraints on spatial patterns of subsurface flow and discuss how this index has proven useful in several research, management, and conservation planning contexts.

Study Area

The Lower Peninsula of Michigan, USA, has a very diverse surficial geology composed of glacial and periglacial deposits (Farrand and Bell 1982, Dorr and Eschmann 1990). Approximately 20 major river basins as well as many lakes and wetlands, display nearly the full spectrum of possible groundwater deliveries as a result of this heterogeneous landscape. For example, base flows in these rivers range from 5% to 95% of annual flow (Hendrickson and Doonan 1972a) and make Lower Michigan an ideal natural laboratory for the study of spatial variation in subsurface water movement. In addition, the Michigan Department of Natural Resources and the University of Michigan's School of Natural Resources and Environment cooperatively maintain extensive data records for aquatic resources (river flow, water temperatures, stream chemistry, channel surveys, riparian communities, macroinvertebrates, fish) in an existing digital database as part of the Michigan Rivers Inventory (MRI; Seelbach and Wiley 1997, Wiley and Seelbach 1997). The spatial extent of this data record was important for iterative model development and evaluation.

MRI-DARCY Model Description

Assumptions and Approach

MRI-DARCY is a topographically based model (e.g., TOPMODEL; Beven and Kirkby 1979) that estimates whether a particular DEM raster cell is likely to be

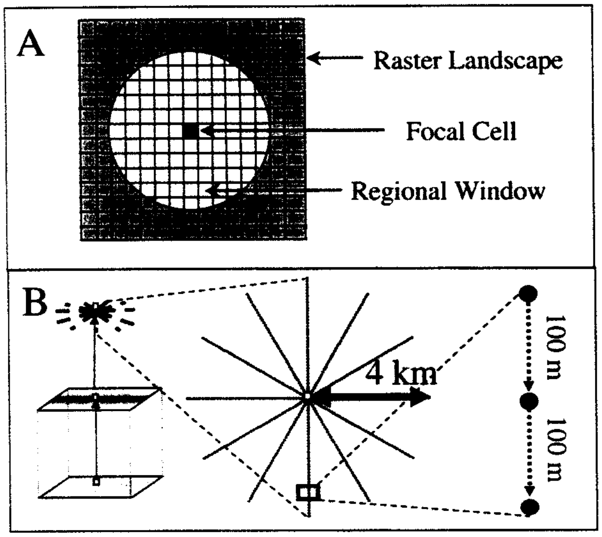

Figure 1. Diagram of (A) neighborhood analysis using a "regional" window and (B) a transect template for integrating digital elevation model (two-tone) and hydraulic conductivity (gray) cell values at 100-m intervals along 12 radial 4-km transects.

either a discharge point for subsurface flows (shallow groundwater or event through-flow) or a recharge point for subsurface flows likely to provide a hydrologic source for nearby surfaces. It is a spatial model of topographically constrained (hydraulic) energy gradients relevant to the hydrology of surface water systems. Thus, unlike fully dynamic groundwater flux models, MRI-DARCY does not require information about continuity constraints or boundary conditions.

Our approach assumes that local subsurface flow vectors can be inferred from the topographic position of a focal DEM raster cell within a regional landscape context. We estimate the conductivity and hydraulic slopes through a "neighborhood" surrounding the focal cell rather than relying upon topographic slopes calculated to and from adjacent raster cells, and this process is repeated for every cell in the landscape extent of interest. This "moving window" analysis uses a unique regional landscape to determine the local values computed for each focal cell (Figure 1A).

A key feature of the MRI-DARCY approach is the areal neighborhood (region) used to predict local conditions. We utilized a 4-km, radial sample of the surrounding landscape to generate distinct flux values for every focal cell in a raster grid (Figure 1B). Four-kilometer neighborhoods were a relatively arbitrary, effective regional scale that we believe may require further exploration in Michigan and which we expect to vary in other regions with climate, landscape physiography, or stratigraphy.

Table 1. Inferred hydraulic conductivity (*K*) values used in the MRI-DARCY model

Deposit	*K* (m/day)
Lacustrine clay	0.001
Fine textured till	0.005
Medium textured till	0.500
Organic deposits	1.000
Thin till over bedrock	1.000
Lacustrine sand	10.000
Dunes	20.000
Glacial outwash	20.000
Coarse textured till	30.000
Ice-contact terrain	100.000

Within each regional neighborhood, our approach relies upon a topographic approximation of potential energy gradients from a smoothed DEM surface. These gradients are not measured across the surface, but through the landscape between a pair of surface localities. At this scale of landscape interpretation, we were primarily concerned with subsurface flow occurring as a direct result of elevation head rather than pressure head. Similarly, instead of using in situ conductivity measurements, we estimated hydraulic conductivity from a surficial geology map. While this was perhaps a gross oversimplification of conductivity at local scales, it provides a generalized estimate of shallow subsurface water conduction related to soil or geologic formations across broad landscapes.

The MRI-DARCY Algorithm

We employed a 30-m raster DEM from the 1:24,000 National Elevation Dataset (NED) (USGS 1997) to describe landscape topography. The hydraulic conductivity grid was derived from a map of surficial geology (1:250,000) (Farrand and Bell 1982) and published conductivity values for glacial drift (Davis and DeWiest 1966, Todd 1976, Freeze and Cherry 1979, Bedient and Huber 1989, Dorr and Eschmann 1990). Maximum hydraulic conductivity was assigned based on the texture inferred from the composition of each geologic formation (Table 1). Rare areas of relatively shallow drift (< 5 m) or exposed bedrock were assigned average conductivity values based on the particular bedrock at or near the surface. The following algorithm was implemented as an executable for use either within or independent of commonly available GIS software.

Within a regional neighborhood, we utilized a "transect template" to sample the surrounding landscape. The template consisted of 12 transects oriented 30 degrees apart (like the hours on a clock) for 4 km away from the centroid of a given focal grid cell (Figure

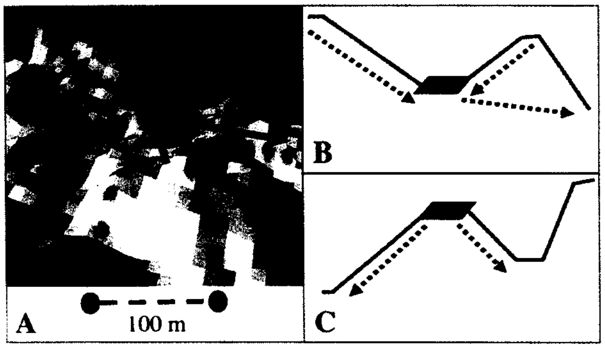

Figure 2. (A) The transect template and sample locations (black dots) over a grid of land surface slope and aspect combined topographic and geologic information. Arrows indicate the direction and magnitude of transect contributions relative to the central, focal grid cell. (B) Transect profiles assumed to contribute to the focal cell and (C) transect profiles assumed to withdraw from the focal cell.

1B). Along each transect, elevation and hydraulic conductivity values were sampled at 100-m intervals. At each interval, slope to the focal cell was calculated (positive or negative), mean conductivity of the flow path was estimated, and the two were multiplied by each other to derive a potential flux estimate. Transect profiles that increased in elevation relative to the focal cell were assumed to have the potential to contribute water to the focal cell (Figure 2A, B). Transect profiles that dropped below the elevation of the focal cell were assumed to have the potential to draw water away from the focal cell (Figure 2A, C). If a particular transect profile first rose above, then dropped below the elevation of the focal cell, we assumed the potential for both contributions and withdrawals (Figure 2B). If a particular transect profile first dropped below, then rose above the elevation of a focal cell, we assumed the resulting depression was a sink with the potential to withdraw from, but not to contribute to, the focal cell (Figure 2C). The overall value of a particular transect, positive or negative, was determined by averaging all of the relevant interval flux values. Unlike distributed hydrologic models that generate flow estimates to and from proximal cells, each of the 12 transects represented *multiple potential routes* of contribution and/or withdrawal between the focal cell and the surrounding landscape. Individual transect values were further averaged across the entire template to determine the overall value of the focal cell.

Analytical Methods

In the absence of an area term, the values produced by the model, while dimensionally correct (velocity = length/time), are meant to represent *Darcian velocities* to a surface location. Velocity in this sense is not meant to describe the true velocity of flow; rather it is analogous to *specific discharge* or average velocity along a flow path (Freeze and Cherry 1979). Since the model is "topographic" (see Beven and Kirkby 1979) and contains no information about the actual distribution or transport of water, values should be treated principally as an index of potential subsurface water flux. Because these potential Darcian velocities are not directly measurable in the field, validation was necessarily indirect. To the extent that the model successfully identifies locations where subsurface water flux to surface systems can occur, it is possible to use groundwater-related attributes of surface water systems to test model predictions. Likewise, we expected that model predictions should correspond to general trends in spatial (rather than temporal) patterns of instantaneous groundwater discharge rates.

Quantitative evaluation of model predictions was performed at three spatial scales. Therefore, mapped raster cell values were summarized three ways for comparison with field measurements. At broad spatial scales, we assessed the model's ability to predict stream base flow from 128 USGS stream gauges. Mapped watershed boundaries were used to identify the surface landscape draining to gauge locations, and model values from this areal landscape were summed and regressed against average annual base flow, defined here as the 90% exceedance flow. Because all watershed sums were negative, they required a sign change prior to transformation using the natural logarithm. At intermediate spatial scales, we compared sums of positive mapped values (discharge locations) within 100 m of the river channel with local discharge accrual estimates from 48 river reaches in a second evaluation effort. Stream discharge accrual (downstream flow increases in the absence of tributary streams) in this context was interpreted as a relatively direct measure of instantaneous groundwater delivery rates to the channel. Upstream–downstream discharge measurements were obtained through various descriptive publications of Michigan's river resources (Tody and others 1954, Wicklund and Dean 1957, 1958, Spaulding and others 1961, Knutilla 1970, Hendrickson and Doonan 1971a, b, 1972b, Nowlin 1973, Coopes 1974, Knutilla and Allen 1975, Larson and others 1975).

At local scales, we compared the mean of mapped values within 100 m of point-based measures of hyporheic temperature profiles. We used temperature profiles below stream channels as a general estimate of local groundwater flux (see Stallman 1963, Lapham 1989, Taniguchi 1993, Hunt and others 1996, Bartolino and Niswonger 1999, Constantz and others 2002). Stream temperatures and hyporheic temperature profiles were measured over 10-cm depth intervals up to 80 cm at 33 locations across a gradient of model predictions in July, August, and September of 2001. Profile measurements were made at 5–12 points within 15-m stream reaches (depending upon the ability of the temperature probe to penetrate the sediment), and all measurements were made in the afternoon to maximize the solar heating temperature differential between air and groundwater. We averaged these point measures and estimated groundwater temperatures at 500 cm using published local average air temperatures (Heath and Trainer 1968) to derive a single groundwater-to-stream temperature profile for each site. Then we employed these profiles in simplified models of one-dimensional heat and fluid flux using exponential decay functions as well as a published heat flux equation.

In the exponential decay approach, an expected profile was estimated using stream temperatures and groundwater temperatures as boundary conditions. The equation is as follows:

$$t_x = t_0 e^{-bx} \quad (1)$$

where t_x is the temperature at depth x (degrees centigrade), t_0 is the temperature at the surface (degrees centigrade), b is the dimensionless exponential decay constant, and x is the depth (centimeters). The exponential decay constant, b, was calculated for each profile by inputting a depth of 500 cm for x, groundwater temperature for t_x, and surface water temperature for t_0. The expected temperature profile was then generated using corresponding temperatures and depths in the measured profile (Figure 3). At each depth, the deviation from expected temperature value was calculated. Two types of flux estimates issued from this approach: finite depth estimates and estimates from the average of all deviations.

A second type of analysis made use of an equation developed by Bredehoeft and Papadopulos (1965) for calculating velocity from measured temperature profiles in semi-confined aquifers:

$$V_z = k\beta / c_0 \rho_0 L \quad (2)$$

where V_z is fluid velocity in the vertical (z) direction (meters per second), k is the thermal conductivity of the sediment and pore water (calories per second per meter per degree centigrade), β is a dimensionless parameter dependent on temperature, c_0 is the specific heat of water (calories per gram per degree centigrade), ρ_0 is the density of water (grams per cubic centimeter), and L is the length in the z direction over the extent of temperature measurements (meters). Following their conceptual approach, we determined β and calculated velocity values for each site with and without unique values of thermal conductivity (k) (Carlson 2002). In estimates where thermal conductivity was held constant, its value was set to 0.004 cal/s/m/°C. In estimates where we employed unique values of thermal conductivity, values were inferred for the substrate at each site from Birch (1942) and Clark (1966).

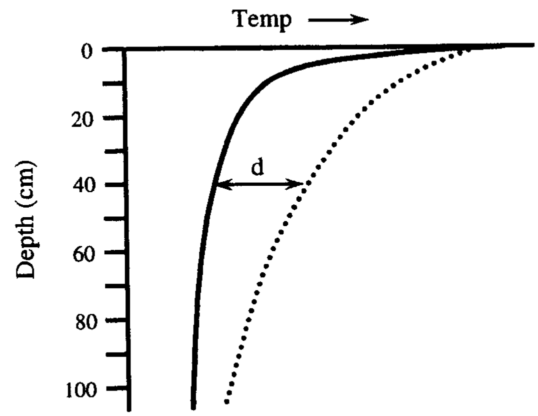

Figure 3. Schematic diagram of an expected hyporheic temperature profile generated from an exponential decay function (dashed line) and an observed profile (solid line). The deviation value (d, shown here at 40-cm depth) was calculated by subtracting the observed profile value from the expected profile value at each depth increment.

Because it was unclear which heat/fluid flux prediction method (finite depth, average deviation, or flux with or without unique k values) resulted in the most accurate groundwater delivery estimate, we combined the estimates into a single groundwater flux index by taking the first axis from a principal components analysis (PCA). Values from the first PCA axis were regressed against the mean of MRI-DARCY cell values within 100 m of the measurement location, as well as against other independent variables, to control for among-site and among-measurement differences in time of day, time of year, and a north–south climatic gradient. Temporal and climatic variables were employed in one regression to account for variation in the groundwater flux index, and in another regression to account for variation in model predictions. The residual variation from each of these analyses (i.e., the portion of among-site variation not associated with climate) was used to assess the ability of the model to account explicitly for spatial patterns in local groundwater flux.

Results of Model Evaluation

The product of the MRI-DARCY modeling approach consists of a raster map of potential subsurface flux

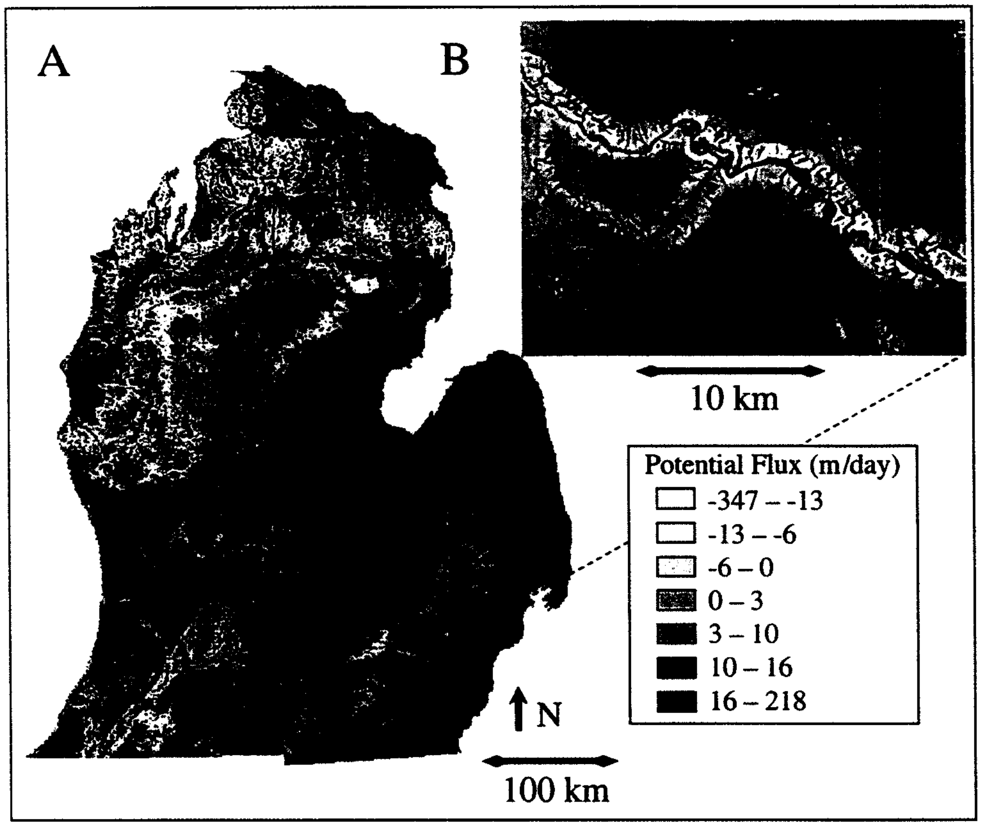

Figure 4. MRI-DARCY map of subsurface hydraulic potential for (A) the Lower Peninsula of Michigan and (B) a local landscape along the Huron River valley near Ann Arbor, Michigan, USA.

values (Figure 4). In practice, we have found it helpful to view the map values standardized relative to a net flux of zero for qualitative visual comparisons. Initially, MRI-DARCY was used as a watershed-scale qualitative indicator of catchment hydrology, distinguishing surface-water dominated from groundwater-dominated streams as strata for statistical classification and prediction of flow exceedance throughout Lower Michigan (see Seelbach and others 1997, Wiley and others 1997, Baker and others 2003). It was in this context that base flow data from USGS stream gauges were employed to assess model predictions. In regressions with a single independent predictor, watershed size accounted for 62% of the total variation of stream base flow, whereas MRI-DARCY values increased this value to 85% (Figure 5). Thus, model predictions improved upon our ability to account for spatial variation in stream base flow by more than 23%. Moreover, when standardized for watershed size, model predictions accounted for over 68% of the variability in base-flow yield. Inspection of the scatter plot in Figure 5 revealed greater deviations from the predictions at lower values of base flow, indicating

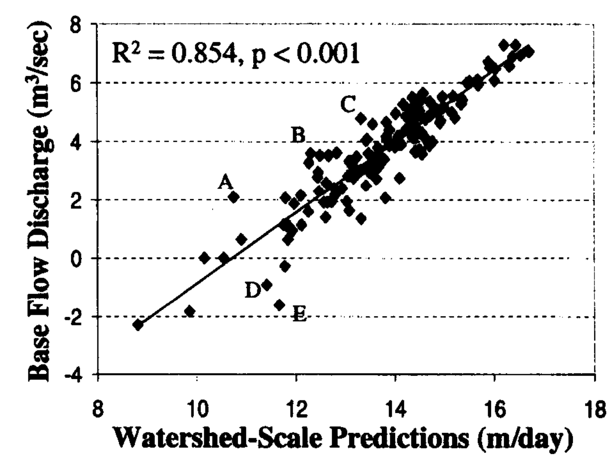

Figure 5. Scatter plot of watershed-scale sums of MRI-DARCY model predictions and base flow discharge from 128 USGS stream gauges in Lower Michigan, USA. Model sums were multiplied by −1, and both axes were transformed using the natural logarithm. Letters indicate outliers mentioned in text.

the model was far better at predicting base flow when subsurface water sources were important.

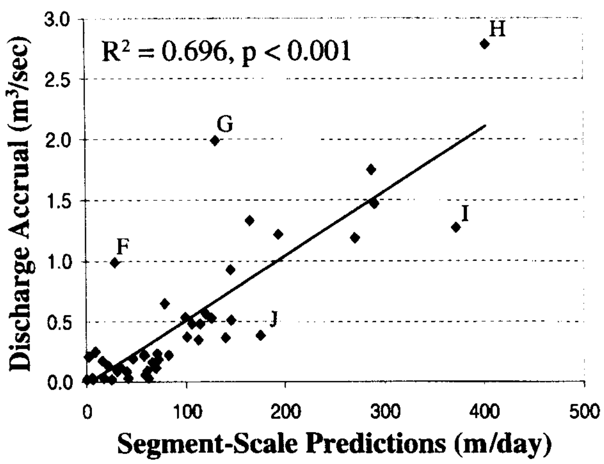

Figure 6. Scatter plot of segment-scale sums of MRI-DARCY model discharge predictions (positive values) and stream discharge accrual from 48 river reaches across Lower Michigan, USA. Letters indicate outliers mentioned in text.

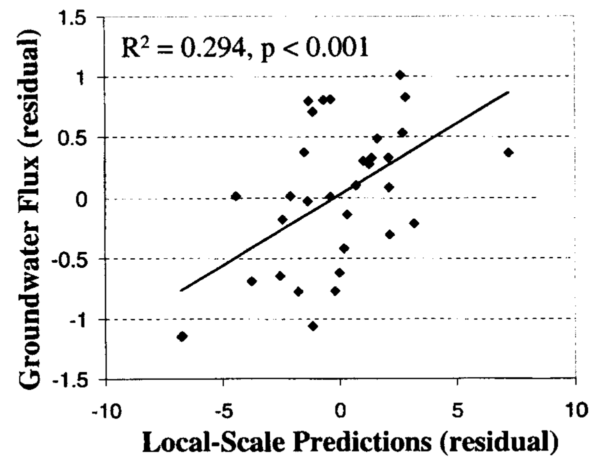

Figure 7. Partial plot of local-scale MRI-DARCY model predictions and hyporheic groundwater flux from 33 sites across western Lower Michigan, USA after accounting for the effects of climatic variation on hyporheic temperature differentials. The overall multiple regression also included time of day, Julian day, latitude, and explained 74% of the observed variation in estimated groundwater flux. Residuals were computed by employing these variables in regressions with groundwater flux as well as model values.

At segment scales, we compared MRI-DARCY predictions within 100 m of the river channel with local discharge accrual measurements from 48 river reaches as an additional evaluation. The reaches ranged from 1.5 to 30 km in length. In regressions using a single independent predictor, reach length accounted for 17% of the total variation of discharge accrual, whereas MRI-DARCY increased this value to 69% (Figure 6). Thus, model predictions improved upon our ability to account for spatial variation in stream discharge accrual by approximately 52%. Moreover, when standardized for reach length, model predictions accounted for 57% of the variability in discharge increases per unit length. Inspection of the outliers in Figure 6 revealed that the model appeared to under-predict discharge accrual more often and to a greater degree than it over-predicted accrual.

At local or point scales, we used hyporheic temperature differentials at 33 sites to estimate variation in groundwater flux at a scale of 15–100 m. The sites were highly variable spatially, ranging from small, headwater streams to large, main channels. One-dimensional models of heat and fluid flux were all significantly correlated; loadings on the first PCA axis ranged from 0.96 to 0.64, and the first two PCA axes explained 71% and 95% of the cumulative variance, respectively. Estimates of groundwater flux were significantly correlated with MRI-DARCY model predictions (Pearson R = 0.527, $P < 0.01$). A regression using time of day, Julian day, latitude, and MRI-DARCY predictions within 100-m of the measuring point accounted for 74% of the variation in groundwater flux. After statistically removing the effects of climatic variables, MRI-DARCY model predictions accounted for nearly 30% of the local variation in groundwater flux estimates (Figure 7).

Discussion

Model Evaluation

Base flow data from USGS stream gauges were employed in early indirect validation efforts because we expected the model to correspond to hydrologic variation among watersheds, despite the fact that MRI-DARCY was not specifically designed for stream discharge prediction per se. Larger inputs of subsurface water generally result in greater, more stable stream base flows in Michigan, although stable base flows do not always result from subsurface water sources. One might expect the predictive ability of the model to be confounded by effects that likely increase with watershed size such as the evapotranspirative drag of lakes and wetlands, network channel storage, or reservoirs. Thus, a key component of our evaluation analysis was to compare the model while both implicitly including and explicitly excluding the effects of watershed size. By employing model cell values summed across watersheds, we were implicitly including a measure of watershed size in our predictions of base flow. Although analogous to adding an areal term to our Darcian predictions so as to facilitate comparison with a familiar response variable (i.e., base flow rather than base-flow yield), it had the effect of inflating our correlation coefficient. However, the additional explanatory power of the model over watershed size alone and the ability of the model to account for base-flow yield (when size effects were removed) are clear evidence for the effectiveness of MRI-DARCY predictions at the watershed scale.

One clear pattern that emerged from our exploration of base flow data was that the model resulted in greater error in low base-flow watersheds. This was not surprising since other confounding factors are likely to have a greater impact on base flow as subsurface water sources become less important. For example, two of the outliers in Figure 5 (watersheds A and D) drain agricultural watersheds of relatively impermeable lacustrine deposits. Whereas watershed A in the Erie Lakeplain contains channelized streams that may tap the water table or receive regional groundwater discharge (Hoaglund and others 2002), watershed D in the Saginaw Lakeplain simply has an extremely low base flow (0.2 m^3/sec from 277 km^2). Watershed B in the headwaters of the Rifle River and C on the Platte River drain more coarse-textured glacial outwash, yet the Rifle "steals" regional groundwater from a neighboring watershed (MRI, unpublished data; see Hoaglund and others 2002) and the Platte contains a number of in-line lakes. As another example, watershed E drains a mixture of till and glacial outwash near Detroit. However, as much as 45% of this watershed is developed, so human-driven alterations such as impervious surfaces and storm sewers may have influenced our results. Thus, the model is an excellent predictor of groundwater-driven patterns of high base flow across Lower Michigan. In low base-flow streams, the model also appears to be an excellent predictor of constraints on local patterns of subsurface flux, yet in these streams the influence of other factors on base flow can lead to greater predictive error.

Our initial coarse-scale predictions worked well because rivers are perhaps the ultimate landscape integrators due to their linear configuration and high rates of advective transport, and because rivers are relatively large physical systems. As we explored more fine-scale uses of MRI-DARCY (e.g., understanding subsurface water contributions to stream reaches, lakes, or wetlands), we found that such assessments were subject to inherent error in the resolution of the DEM, mapped features (i.e., streams and geologic boundaries), as well as their alignment. Moreover, the nature of the topographic and conductive generalizations inherent in the model makes it unlikely that specific cell values will correspond exactly to local flux measures. Therefore, we deemed it entirely appropriate to average our predictions across a local landscape in fine-scale assessments.

Measures of stream discharge accrual in the absence of tributary streams are a more direct estimate of groundwater flux than base flow data. Yet because of time-scale differences between model predictions, groundwater flow, and observed data, we might expect our analyses to be confounded by temporal variation in local water tables, especially over larger reaches. In fact, predicting accrual with reach length resulted in increasing error with longer reaches. Yet despite such potential effects, we observed no such trend in the strong relationship between model predictions and discharge accrual (Figure 6). In cases where the model was less than accurate at segment scales, deviations highlight some important shortcomings of our approach. For segments F near Lake Michigan and H in the Manistee River headwaters, regional flow patterns (Hoaglund and others 2002) suggest high segment accrual results from upwelling due to proximity to the lake in the case of segment F and from "stealing" groundwater from underneath neighboring watersheds in the case of segment H. Segment G lies in a valley bordered on one side by a large conductive hill and on the other by a flat sand plain. When we summarized model discharge predictions within 100 m of the channel, half the values were quite large and the others quite low, and the computed prediction for the segment was apparently half that of actual accrual. This was initially surprising because we expected overestimates to be more common due to the topographic origin of our head parameter. Segments I and J both lie in valleys bordered by large ice-contact hills, although head estimates are much greater for segment I and valley-bottom wetlands may compete for water in segment J. In these cases, overpredictions may also result from overestimating the relative conduction of ice-contact terrain (Table 1). Thus, regional groundwater flow patterns, strong contrasts in bank delivery rates or volumes, wetlands, and inadequate conductivity specification can all lead to error in segment-scale model predictions.

Our point-based temperature profile approach was conceived as a relatively efficient method for capturing local spatial patterns of groundwater delivery along local sections of stream channel. A more detailed exploration of this method is described by Carlson (2002). We located sites along gradients of model predictions to capture patterns of groundwater flux across a range of local values, yet we treated each site measurement as an independent test of the model. Because MRI-DARCY predictions are meant to highlight general spatial patterns across a landscape, they are insensitive to the temporal variation that inherently constitutes a large portion of the variance in instantaneous groundwater measurements. Therefore, we expected that model predictions at this local scale were likely influenced by climatic variation at the time of measurement, day of measurement, and along the strong north–south climatic gradient in Lower Michigan (see Albert and others 1986). Moreover, north–south climatic differences during the period of measurement may have confounded greater MRI-DARCY predictions (due to coarse glacial deposits) in northern Lower Michigan. Despite our preconceptions, the model was significantly correlated with flux rates and a significant predictor of the residual spatial variation in groundwater flux once we removed the effects of temporal and spatial patterns of climate. While we suspect it is unlikely that such point-scale predictions will compare accurately across large regions without proxy variables for subregional climatic variation (gradients), our results suggest the model is useful at capturing the relative magnitude of spatial variation at local scales both among and within stream reaches.

Model Limitations

Following Beven (2002), we consider MRI-DARCY to be "physically based" because it relies upon a fundamental physical principle (the conservation of energy) and it represents known physical relationships (e.g., that the topographic surface is a constraint on shallow subsurface water flow). More importantly, its predictions are consistent with observed spatial patterns (to the extent that potential subsurface water flux is observable). Although the model clearly estimates the relative magnitude of local potential subsurface flow paths, it does not account for actual water movement, nor, in fact, does it account for deeper, regional groundwater flows or the magnitude of down-valley hyporheic transport. A key assumption of our approach is that surface topography, as represented by a DEM, may be used to estimate the likelihood and direction of subsurface water flux. Unlike distributed groundwater models and other topographic indices like TOPMODEL, which compute slope from proximal raster cells (e.g., Quinn and others 1991), MRI-DARCY incorporates a *topographic smoothing algorithm* to compute a spatially averaged estimate of slope from a broad characterization of the surrounding landscape. It is the topographic position of focal cells relative to a large averaged landscape that produces variation in "local" model predictions, rather than reliance on local, or proximal, information alone. In Michigan, surface topography is the most important factor driving patterns of regional groundwater flow (Hoaglund and others 2002). Elsewhere, research suggests that surface topography can be an important predictor of groundwater flux (Gerhart 1984, Hinton and others 1993, Dawes and Short 1994, Gerla 1999). Thus, this assumption is not at all uncommon in conceptualizations of water table dynamics, although it is clear that it does not hold equally well in all climates or in all stratigraphies (Heath 1987, Winter and others 1998, Winter 2001).

As a model of flux potential, MRI-DARCY does not incorporate any information about actual hydraulic slopes, and therefore it is likely to predict high flux potential in places where actual water delivery is infrequent or unlikely. This limitation could be evaluated and accounted for in certain areas using interpolations from direct observations of the water table surface. However, water table interpolation at broad spatial scales has more intensive data requirements and its own set of potential errors. We believe that the regions where an assumed relationship between the land surface and the water table tends to hold are also regions where subsurface water sources can make important contributions to the condition of surface water systems (e.g., in the United States: northern glaciated regions, the Pacific Northwest, Florida, portions of the Atlantic Slope). In many of these areas, assuming some relationship between the surface topography and the water table is reasonable, physically sound, and a practical necessity for managers and researchers alike. Although Lower Michigan is likely an ideal conductive landscape for the development of our simple spatial approach, we believe that the empirical relationships it describes can and should be applied and evaluated in other regions.

Another attribute of MRI-DARCY related to topography is the implicit assumption that a 4-km radius adequately describes the most effective scale for linking regional landscapes to patterns of subsurface water flux. "Regional" in this context is simply a concept; we do not know what the effective regional scale is except that it is also likely to vary with climate, physiography, and stratigraphy. We consider the matter of appropriate scale for interpreting the landscape in this manner to be an open research question; thus we designed MRI-DARCY to allow rapid adjustment of its scaling parameters to better address this issue.

In addition to general interpretations of topography, the model takes only inferred conductivity derived from relatively coarse-resolution (1:250,000) surficial geology and very limited stratigraphy into account. In glaciated landscapes, complexities in drift deposition can lead to exponential variation of in situ conductivity within a single geologic formation (Holtschlag 1996). This is particularly problematic in landscapes with layered stratigraphy because estimates of recharge and subsurface flow paths may be still further influenced by variation in belowground conductivity (Engelen and Jones 1986, Dunne 1990, Toth 1995). Thus, flux underestimates can occur as the result of local meltwater splays, buried outwash deposits, and/or relict channel systems. Despite this fact, the apparent success of our analyses suggests that the potential for error from highly variable, layered permeability is probably less important across entire catchments than at very local scales. Future models might incorporate more specific modifications to adjust for known variation in conductivity or restrict flow path estimates to minimum conductance values rather than the average. In any case, we believe such limitations underscore the need for development of more high-resolution maps of shallow subsurface stratigraphy and its conductive properties.

MRI-DARCY map values should be interpreted as an index of long-term averages in hydrologic conditions, such as those considered in environmental planning and management. In addition, we have frequently used areal summaries of model predictions rather than individual pixel values to describe local landscapes. In the context of this further smoothing and areal averaging, the magnitude of specific point-scale prediction errors was less of a concern than the correct identification of a more general spatial pattern. Because the model is an index in units of specific discharge, predictive error may also result from different volumes of flow with similar Darcian velocities. Thus the model should be considered a powerful but imperfect predictive tool. There is still considerable room for refinement and improvement of the model algorithm and its application in different landscapes.

Regional Applications

In the upper Midwest, spatial variation in both flow and thermal regime is maintained primarily by differences in river size, regional climate, and groundwater accrual among catchments and stream segments (Meisner and others 1988, Wehrly and others 2002). Heuristic understanding of local and upstream physiographic controls on groundwater can provide insight into both local and landscape level controls of the spatial and temporal variability of environmental conditions and aquatic communities (Wiley and others 1997). For example, summer stream temperature is a well-established correlate of groundwater input in Michigan streams (Hendrickson and Doonan 1972a, Wiley and others 1997). Larger inputs of groundwater typically result in cooler summer stream temperatures, all else being equal. Not surprisingly, Wehrly and others (1998) found that the MRI-DARCY model was a significant predictor of spatial patterns in stream temperature. Their regressions accounted for 60% of observed summer temperature variation at 171 stream locations (70% when outliers were removed). Evaluation of standardized regression coefficients revealed that only volumetric surrogates such as channel cross-sectional area and stream width eclipsed the total predictive power of the MRI-DARCY model (Wehrly and others 1998).

Spatial indices such as MRI-DARCY were instrumental in the development of a stream classification system for Lower Michigan (Seelbach and others 1997), and this approach became the basis for conservation planning across the Great Lakes Basin (Higgins and others 1998, Seelbach and others 2001). Quantifying the spatial variation of key habitat features such as flow and temperature is critical to understanding mechanisms regulating species assemblage structure and to evaluating the potential impacts of environmental perturbations (Poff and Ward 1990, Schlosser 1990). Insight from MRI-DARCY has informed predictions of fish community structure in Michigan (Zorn and others 2002), as well as in South Dakota, where the model was a key predictor of potential habitat for the endangered Topeka shiner (*Notropis topeka*) (Wall and others 2001). Wiley and others (2001) used model predictions to standardize comparisons of fish index of biotic integrity (IBI) reference communities throughout Lower Michigan, whereas Baker and others (2002) used model predictions across the entire Northern Lakes and Forest Ecoregion (northern portions of Michigan, Wisconsin, and Minnesota) to adjust reference conditions in a regional aquatic assessment. Furthermore, the model has been employed by the Michigan Department of Natural Resources to define ecological strata for design of a statewide, long-term fish monitoring program, and to guide release locations for hatchery trout.

Local Applications

As a key component of local habitat predictions, the spatially explicit estimates of MRI-DARCY were useful in a variety of more localized and application-specific studies. For example, Horne (2001) used the model to predict thermal regime changes habitat availability and to evaluate salmonid population responses resulting from projected dam removals along the Manistee River in northwestern Lower Michigan. Beside rivers, the hydrology of wetlands and riparian areas is considered an essential attribute of their ecological function in a landscape context. Baker and others (2001) used model predictions to classify the riparian hydrology of upstream river networks for 290 locations throughout Lower Michigan in a nutrient export study. By adding estimates of riparian hydrology to those of agricultural land use and drainage area, they improved their predictions of nutrient export by up to 20%. Moreover, map-based predictions of wetlands further informed aerial photo-based wetland estimates by distinguishing between saturated and seasonally inundated wetland types. Merkey (2002) used the model to develop a map-based hydrogeomorphic classification of 59 wetlands in southeastern Lower Michigan. The classification successfully identified subsurface water-dominated depressional wetlands with significantly higher average water levels ($P < 0.001$) and significantly lower water level fluctuation ($P < 0.001$) than wetlands fed by surface-water sources.

MRI-DARCY has also informed conservation planning, threat assessment, and strategy development where groundwater plays a key role in maintaining the unique biological character of focus areas. The Grand Traverse Regional Land Conservancy (GTRLC) used the model to evaluate the relative conservation value of land parcels and to prioritize protection efforts in the Upper Manistee watershed (Kazmierski and others 2002). The Nature Conservancy (TNC) has also used the model to delineate boundaries for conservation planning, so as to include important local recharge areas for fens within focal landscapes of concern (P. Marangelo, TNC Michigan Chapter Planning Ecologist, personal communication). Because MRI-DARCY maps provide a qualitative visualization of places in the landscape likely to receive shallow subsurface water as well as those locations likely to deliver pollutants rapidly to surface ecosystems, the maps are able to identify spatial variation in sensitive recharge areas along river valleys and lake margins. In contrast to fixed-width environmental buffers, which prescribe a standard zone of protection around rivers and streams regardless of local conditions, the model offers a landscape-specific estimate of the relative risk associated with different site locations.

A Hydrologic Context for Different Management Questions

We have described a number of scales and applications for the MRI-DARCY approach. While not a replacement for numerical groundwater models, the utility of MRI-DARCY lies in its ability to identify places where subsurface connectivity is likely to exist and where researchers, managers, and planners might be interested in obtaining more explicit estimates of groundwater flux. For many management problems, precise, localized estimates from numerical models with high data requirements and temporal detail may provide the "right" answer to the "wrong," or at least different, question (see Holling 1998). An ecologist or manager working along a single river reach may be concerned with detailed groundwater dynamics such as those resulting from pressure head and complex stratigraphy, but those working across broader spatial scales do not require the same kind of information and may not be concerned with local water table dynamics. In such cases, even relative predictions of spatial patterning of subsurface water sources can prove useful. As an extreme example, a map of soil texture implies a model with relevance to the hydrologic character of watersheds.

The MRI-DARCY map clearly highlights variation in a landscape—it creates detailed pictures of subsurface energy potential across broad areas that have heretofore been largely unavailable to many environmental managers Although many aquatic ecologists acknowledge that hydrologic setting is an important determinant of aquatic ecosystem function, there is still an urgent need to accumulate, synthesize, and communicate the extent and implications of hydrologic variation to researchers, environmental managers, conservation planners, and the general public. Across broad regions, GIS-based modeling approaches such as described here can be a cost-effective and eminently practical alternative for understanding complex spatial phenomena (Levine and Jones 1990, O'Neill and others 1997). As a visual tool, MRI-DARCY maps emphasize variation in subsurface water potential throughout the landscape—a simple, yet powerful illustration of what is typically obscure or abstract information in environmental planning. As a quantitative tool, the model provides estimates of the relative potential for discharge from or recharge to a surrounding surface landscape realized at a focal surface location. We believe the model represents an important addition to any environmental manager's spatial toolbox. In the absence of such hydrologic context, the importance of variation in subsurface water sources to streams, lakes, and wetlands is easily overlooked by decision-makers.

Acknowledgments

We would like to thank B. Horne, K. Wehrly, and D. Merkey for providing preliminary evaluation data; P. Richards and S. Brunzell for computer programming assistance; as well as K. Wehrly, P. Richards, J. Higgins, N. Granneman, S. Aichele, K. Titlow, R. King, and G. Poole for helpful theoretical and pragmatic feedback. We are especially grateful for the constructive criticism of several anonymous reviewers whose suggestions improved this manuscript considerably. This work was supported through a multidivisional grant from the Michigan Department of Natural Resources Virtual Geographic Information Laboratory (ViGIL).

References

Albert, D. A., S. R. Denton, and B. V. Barnes. 1986. Regional landscape ecosystems of Michigan. School of Natural Resources, University of Michigan, Ann Arbor.

Anderton, S., J. Latron, and F. Gallart. 2002. Sensitivity analysis and multi-response, multi-criteria evaluation of a physically based distributed model. *Hydrological Processes* 16:333–353.

Baker, E. A., K. E. Wehrly, P. W. Seelbach, M. J. Wiley, L. Wang, and T. P. Simon. 2002. Use of explicit statistical modeling to assess ecological stream condition in the northern lakes and forests ecoregion. US Environmental Protection Agency R-EMAP, Final report for grant R-82620701-2, Duluth, Minnesota.

Baker, M. E., M. J. Wiley, and P. W. Seelbach. 2001. GIS-based hydrologic modeling of riparian areas: implications for stream water quality. *Journal of the American Water Resources Association* 37:1615–1628.

Baker, M. E., M. J. Wiley, and P. W. Seelbach. 2003. GIS-based models of groundwater loading in glaciated landscapes: considerations and development in Lower Michigan. Fisheries Research Report 2064, Michigan Department of Natural Resources, Ann Arbor.

Bartolino, I.R., and R. Niswonger. 1999. Numerical simulation of vertical ground-water flux of the Rio Grande from ground-water temperature profiles, Central New Mexico. US Geological Survey Water-Resources Investigations Report 99–4212.

Bedient, P. B., and W. C. Huber. 1989. Hydrology and floodplain analysis. Addison-Wesley Publishing. Reading, Massachusetts.

Beven, K. 2002. Towards an alternative blueprint for a physically based digitally simulated hydrologic response modeling system. *Hydrological Processes* 16:189–206.

Beven, K., and J. Feyen. 2002. The future of distributed modeling special issue. *Hydrologic Processes* 16:169–172.

Beven, K. J., and M. J. Kirkby. 1979. A physically based variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin* 24:43–69.

Birch, A. F. 1942. Thermal conductivity and diffusivity, *in* A. F. Birch, J. F. Schairer, and H. C. Spicer (eds.), Handbook of physical constants. Special Paper, no. 36. Geological Society of America.

Bredchoeft, J. D., and I. S. Papadopulos. 1965. Rates of vertical groundwater movement estimated from the Earth's thermal profile,. *Water Resources Research* 1(2):325–328.

Brunke, M., and T. Gonser. 1997. The ecological significance of exchange processes between rivers and groundwater. *Freshwater Biology* 37:1–33.

Carlson, M. L. 2002. Groundwater discharge to stream channels: a test of a topographic groundwater model. MS thesis. University of Michigan, Ann Arbor.

Christensen, S., K. R. Rasmussen, and K. Moller. 1998. Prediction of regional groundwater flow to streams. *Groundwater* 36:351–360.

Clark S. P. 1966. Handbook of physical constants—revised edition. Memoir 97. Geological Society of America, 587 pp.

Coopes, G. F. 1974. Au Sable River Watershed Project, Biological Report (1971–1973). An investigation into the effects of human use and development on the biology of a coldwater river system. Fisheries Management Report No. 7. Michigan Department of Natural Resources, Fisheries Division, Lansing.

Constantz, J., A. E. Stewart, R. Niswonger, and L. Sarma. 2002. Analysis of temperature profiles for investigating stream losses beneath ephemeral channels,. *Water Resources Research* 38(12):1316.

Darcy, H. 1856. Les fontaines publique de la ville de Dijon. Victor Dalmont, Paris.

Davis, S. N., and R. J. DeWiest. 1966. Hydrogeology. John Wiley & Sons, New York.

Dawes, W. R., and D. Short. 1994. The significance of topology for modelling the surface hydrology of fluvial landscapes. *Water Resources Journal* 182:31–43.

Dorr Jr, J. A., and D. F. Eschman. 1990. The geology of Michigan. University of Michigan, Ann Arbor.

Dunne, T. 1990. Hydrology, mechanics, and geomorphic implications of erosion by subsurface flow. Pages 1–28 *in* C. G. Higgins, and D. R. Coates. eds, Groundwater geomorphology: the roles of subsurface water in earth-surface processes and landforms. The Special Paper 252. Geological Society of America, Boulder, Colorado.

Dunne, T., and L. B. Leopold. 1978. Water in environmental planning. W. H. Freeman and Co., New York.

Engelen, G. B., and G. P. Jones. 1986. Development in the analysis of groundwater flow systems. Publication No. 163. *IAHS*, Amsterdam, The Netherlands.

Farrand, W. R., and D. Bell. 1982. Quaternary geology of Michigan. Michigan Department of Natural Resources, Geological Survey, Lansing, color map.

Freeze, R. A., and J. A. Cherry. 1979. Groundwater. Prentice-Hall, Englewood Cliffs, New Jersey.

Gerhart, J. M. 1984. A model of regional groundwater flow in secondary permeability terrain. *Groundwater* 22:168–175.

Gerla, P. J. 1999. Estimating the ground-water contribution in wetlands using modeling and digital terrain analysis. *Wetlands* 19:394–402.

Harbaugh, A. W., and M. G. McDonald. 1996a. Programmer's documentation for MODFLOW-96, an update to the US Geological Survey modular finite-difference ground-water flow model. US Geological Survey Open-File Report 96–486

Harbaugh, A. W., and M. G. McDonald. 1996b. User's documentation for MODFLOW-96, an update to the US Geological Survey modular finite-difference ground-water flow model. US Geological Survey Open-File Report 96–485.

Heath, R. C. 1987. Basic ground-water hydrology. US Geological Survey Water Supply Paper 2220.

Heath, R. C., and F. W. Trainer. 1968. Introduction to groundwater hydrology. John Wiley & Sons, New York.

Hendrickson, G. E., and C. J. Doonan. 1971a. Reconnaissance of the Black River, a cold water river in the north central part of Michigan's southern peninsula. Hydrologic Investigations Atlas HA-354. US Geological Survey, Lansing.

Hendrickson, G. E., and C. J. Doonan. 1971b. Reconnaissance of the Pere Marquette River, a cold water river in the central part of Michigan's southern peninsula. Hydrologic Investigations Atlas HA-384. US Geological Survey, Lansing.

Hendrickson, G. E., and C. J. Doonan. 1972a. Hydrology and recreation on the cold-water resources of Michigan's Southern Peninsula. Water Information Series Report 3. US Geological Survey, in cooperation with the Michigan Geological Survey, Lansing.

Hendrickson, G. E., and C. J. Doonan. 1972b. Reconnaissance of the Manistee River, a cold water river in the northwestern part of Michigan's southern peninsula. Hydrologic Investigations Atlas HA-436. US Geological Survey, Lansing.

Higgins, J. V., M. Lammert, M. T. Bryer, M. M. DePhilip, and D. H. Grossman. 1998. Freshwater conservation in the Great Lakes basin: development and application of an aquatic community classification framework. Great Lakes Program, The Nature Conservancy, Chicago.

Hinton, M. J., S. L. Schiff, and M. C. English. 1993. Physical properties governing groundwater flow in a glacial till catchment. *Journal of Hydrology* 142:229–249.

Hoaglund, J. R., G. C. Huffman, and N. G. Grannemann. 2002. Michigan basin regional ground water flow discharge to three Great Lakes. *Groundwater* 40:390–406.

Holling, C. S. 1998. Two cultures of ecology. *Conservation Ecology* 2:4.

Holtschlag, D. J. 1996. A generalized estimate of ground-water recharge rates in the Lower Peninsula of Michigan. Open-file Report 96–593. US Geological Survey, Lansing.

Holtschlag, D. J., C. L. Luukkonen, and J. R. Nicholas. 1996. Simulation of ground-water flow in the Saginaw Aquifer, Clinton, Eaton, and Ingham counties, Michigan. Open-file Report 96–174. US Geological Survey, Lansing.

Horne, B. 2001. Prediction of temperature regime, steelhead production, and recreational angler benefit following hypothetical removal or selective withdrawal retrofit of Tippy and Hodenpyl dams on the Manistee River, Michigan. MS thesis. University of Michigan, Ann Arbor.

Hunt, R. J., D. P. Krabbenhoft, and M. P. Anderson. 1996. Groundwater inflow measurements in wetland systems. *Water Resources Research* 32(3):495–507.

Kazmierski, J. M. Kram, E. Mills, D. Phemister, N. Reo, C. Riggs, R., and Tefertiller, O. 2002. Upper Manistee River watershed conservation plan. MS project report to the Grand Traverse Land Conservancy, University of Michigan, Ann Arbor.

Knutilla, R. L. 1970. Water resources of the Black River basin, southeastern Michigan. Hydrologic Investigations Atlas HA-338. US Geological Survey, Lansing.

Knutilla, R. L., and W. B. Allen. 1975. Water resources of the River Raisin Basin, southeastern Michigan. Hydrologic Investigations Atlas HA-520. US Geological Survey, Lansing.

Lapham, W. W. 1989. Use of temperature profiles beneath streams to determine rates of vertical groundwater flow and vertical hydraulic conductivity. US Geological Survey Water Supply Paper 2337.

Larson, R. W., W. B. Allen, and S. D. Hanson. 1975. Water resources of the Huron River basin, southeastern Michigan. Hydrologic Investigations Atlas HA-514. US Geological Survey, Lansing.

Levine, D. A., and W. W. Jones. 1990. Modeling phosphorous loading to three Indiana reservoirs: a geographic information system approach. *Lake and Reservoir Management* 6:81–91.

Mandle, R. J., and D. B. Westjohn. 1989. Geohydrologic framework and ground-water flow in the Michigan basin. Pages 83–110, *in:* L. A. Swain and A. I. Johnson (eds.), Regional aquifer systems of the United States—aquifers of the Midwestern area. Monograph series 13. American Water Resources Association

Martin, P. J., and E. O. Frind. 1998. Modeling a complex multi aquifer system: the Waterloo moraine. *Groundwater* 36:679–690.

McDonald, M. G., and A. W. Harbaugh. 1988. A modular three- dimensional finite-difference ground-water flow model. Techniques of Water-Resources Investigations, Book 6, chap. A1. US Geological Survey.

Meisner, J. D., J. S. Rosenfeld, and H. A. Regier. 1988. The role of groundwater in the impact of climate warming on stream salmonids. *Fisheries* 13:2–8.

Merkey, D. H. 2002. Development of a landscape-level wetland assessment method for depressional wetlands in the southern Lower Peninsula of Michigan. Final Report for Grant CD005663-01–0. US Environmental Protection Agency Region 5, Chicago.

Molenat, J., and C. Gascuel-Odoux. 2002. Modelling flow and nitrate transport in groundwater for the prediction of water travel times and consequences of land use evolution on water quality. *Hydrological Processes* 16:479–492.

Molson, J. W., and E. O. Frind. 1995. WATFLOW/3D: A 3D groundwater flow model, version 1.0. Waterloo Centre for Groundwater Research

Nowlin, J. O. 1973. Water resources of the Clinton River Basin, southeastern Michigan. Hydrologic Investigations Atlas HA-469. US Geological Survey, Lansing.

O'Neill, R. V., C. T. Hunsaker, K. B. Jones, K. H. Riitters, J. D. Wickham, P. M. Schwartz, I. A. Goodman, B. L. Jackson, and W. S. Baillargeon. 1997. Monitoring environmental quality at the landscape scale. *Bioscience* 47:513–519.

Poff, N. L., and J. V. Ward. 1990. Physical habitat template of lotic systems: recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental Management* 14:629–645.

Quinn, P. F., K. Beven, P. Chevallier, and O. Planchon. 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes* 5:59–79.

Schlosser, I. J. 1990. Environmental variation, life history attributes, and community structure in stream fishes: implications for environmental management and assessment. *Environmental Management* 14:621–628.

Seelbach, P. W. and M. J. Wiley. 1997. Overview of the Michigan Rivers Inventory (MRI) Project. Fisheries Technical Report 97–3. Michigan Department of Natural Resources, Ann Arbor.

Seelbach, P. W., M. J. Wiley, J. C. Kotanchik, and M. E. Baker.

1997. A landscape-based ecological classification system for river valley segments in Lower Michigan (MI-VSEC 1.0). Fisheries Research Report 2036. Michigan Department of Natural Resources, Ann Arbor.

Seelbach, P. W., M. J. Wiley, P. A. Soranno, and M. T. Bremigan. 2001. Aquatic conservation planning: using landscape maps to predict ecological reference conditions for specific waters. Pages 454–478 *in* K. Gutzwiller eds, Concepts and applications of landscape ecology in biological conservation. Springer-Verlag, New York.

Spaulding, W. M., B. C. Dean, and R. G. Wicklund. 1961. Tobacco River watershed. Survey and plans report. Michigan Department of Conservation, Fish Division, Lansing.

Stallman, R. W. 1963. Computation of groundwater velocity from temperature data. Pages 26–46, *in* R. Bentall (ed.), Methods of collecting and interpreting groundwater data. Water Supply Paper 1544-H. US Geological Survey, Lansing.

Taniguchi, M. 1993. Evaluation of vertical groundwater fluxes and thermal properties of aquifers based on transient temperature-depth profiles. *Water Resources Research* 29(7):2021–2026.

Todd, D. K. 1976. Groundwater hydrology. John Wiley and Sons, New York.

Tody, W. H., R. G. Wickund, and B. C. Dean. 1954. Cedar River watershed. Surveys and plans report No. 1. Michigan Department of Conservation, Fish Division. Lake and Stream Improvement Section, Lansing.

Toth, J. 1995. Hydraulic continuity in large sedimentary basins. *Hydrogeology Journal* 3:4–16.

USGS. 1997. U.S. Geological Survey digitized data for vector and raster layers: documentation and metadata. Downloaded from US Geological Survey website: http://mapping.usgs.gov/

Wall, S. S., C. M. Blausey, J. A. Jenks, and C. R. Berry Jr. 2001. Topeka shiner (*Notropis topeka*) population status and habitat conditions in South Dakota streams. South Dakota State University, Bookings.

Wehrly, K. E., M. J. Wiley, and P. W. Seelbach. 1998. Landscape-based models that predict July thermal characteristics of Lower Michigan rivers. Fisheries Research Report 2037. Michigan Department of Natural Resources, Ann Arbor.

Wehrly, K. E., M. J. Wiley, and P. W. Seelbach. 2002. Classifying regional variation in thermal regime using stream fish community patterns. *Transactions of the American Fisheries Society* 132:18–38.

Wicklund, R. G., and B. C. Dean. 1957. Little Manistee River Watershed: Survey and plans report. Dingell-Johnson Project F4R7. Michigan Department of Conservation, Fish Division. Lansing.

Wicklund, R. G., and N. C. Dean. 1958. Betsie River Watershed. Survey and plans report. Dingell-Johnson Project F4R6. Michigan Department of Conservation, Fish Division, Lansing.

Wiley, M. J., Kohler, S. L., and Seelbach., P. W. 1997. Reconciling landscape and local views of aquatic communities: lessons from Michigan's trout streams. *Freshwater Biology* 37:133–148.

Wiley, M. J., and Seelbach, P. W. (1997) An introduction to rivers: the conceptual basis for the Michigan Rivers Inventory (MRI) Project. Fisheries Special Report No. 20. Michigan Department of Natural Resources, Ann Arbor.

Wiley, M. J., P. W. Seelbach, K. E. Wehrly, and J. Martin. 2001. Regional ecological normalization using linear models: a meta-method for scaling stream assessment indicators. Chapter 22. *in* T. P. Simon Eds, Biological response signatures: multimetric index patterns for assessment of freshwater aquatic assemblages. CRC Press, Boca Raton, Florida.

Winter, T. C. 2001. The concept of hydrological landscapes. *Journal of the American Water Resources Association* 37:335–349.

Winter, T. C., J. W. Harvey, O. L. Franke, W. M. Alley. 1998. Ground water and surface water: a single resource. Circular 1139. US Geological Survey, Lansing.

Zorn, T. G., P. W. Seelbach, and M. J. Wiley. 2002. Distributions of stream fishes and their relationship to stream size and hydrology in Michigan's Lower Peninsula. *Transactions of the American Fisheries Society* 131:70–85.