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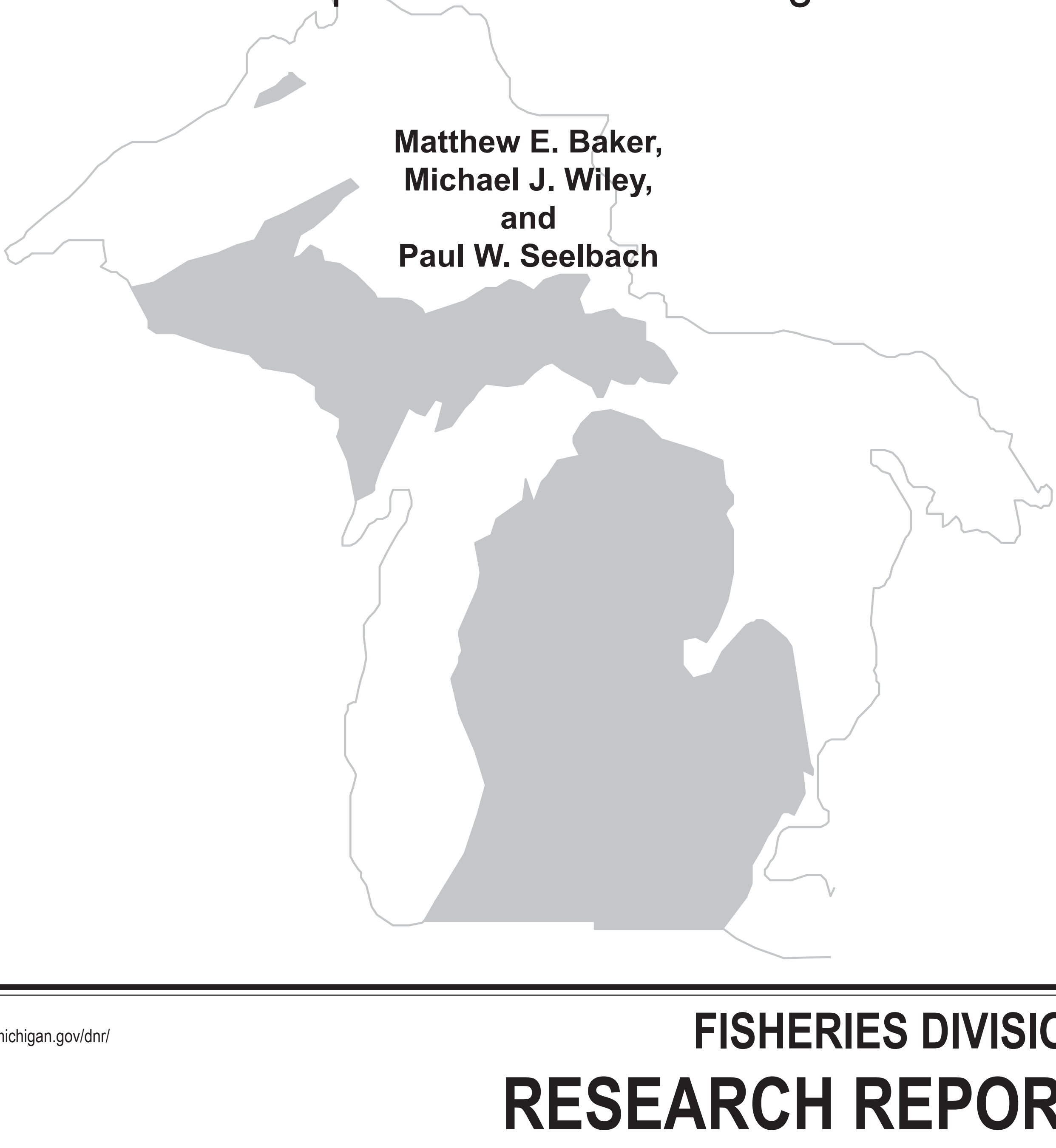

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GIS-based models of potential groundwater loading in glaciated landscapes: considerations and development in Lower Michigan

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Abstract.–Biological, chemical, and physical attributes of aquatic ecosystems are often strongly influenced by groundwater delivery. Nonetheless, access to predictions of groundwater contributions to rivers, lakes, and wetlands at a scale useful to resource managers is generally lacking due to the data requirements of current groundwater models. In this paper, we implement and validate a simple, terrain-based approach for predicting groundwater delivery to streams and other surface water systems using mapped data within a GIS environment. Model output was calculated in units of m day^{-1} for every 30 m^2 grid cell across Lower Michigan. Validation of the models was performed by accounting for variance in observed low flow yields (48-54%), summer stream temperatures (23-40%), and rates of channel discharge accrual (59-65%). This modeling approach has been useful in describing spatial variation in groundwater contributions to general patterns of stream flow, thermal characteristics, and biotic communities at hundreds of specific sites across Lower Michigan. Such terrain-based ground water modeling can provide the regional "big picture" perspective many resource managers, planners, and policy makers require.

Introduction

The ecology of river, lake, and wetland ecosystems is strongly influenced by the routing of the source water they receive. Relative contributions of direct precipitation, land surface runoff, and groundwater help shape seasonal hydrography, chemical properties, thermal characteristics, and ultimately the character of aquatic biota (Dunne and Leopold 1972; Brinson 1993a,b; Wiley et al. 1997; Winter et al. 1998). Groundwater inputs in particular can have strong influences on local biology due to their cold summer temperatures, relatively high dissolved content, and stabilizing influence during droughts and seasons of reduced precipitation (Hendrickson and Doonan 1972b; Brunke and Gosner 1997; Wiley et al. 1997; Winter et al. 1998). While there is a long history of incorporating physiographic characteristics of contributing catchments into predictive models of runoff and stream flow (e.g., Snyder 1938;

SCS 1957; Gray 1962; Beven and Kirkby 1979; Holtschlag and Crosky 1984; Bedient and Huber 1989), the ability to predict groundwater contributions to local surface water ecosystems, at a scale useful in ecological study and routine resource assessment, has lagged behind.

Groundwater modeling has been an exceptionally active field of study in the years since the Clean Water Act of 1972. Nevertheless, most groundwater modeling studies have been concerned with water balance dynamics of specific supply aquifers, individual wetland units and lakes, or the tracking of localized contaminant plumes. Accounting for groundwater contributions to stream discharge has also been the focus of previous work (e.g., Freeze 1969; Freeze and Cherry 1979). However, relatively little attention has been paid to modeling regional spatial variation of groundwater delivery to surface water systems. Likewise, few of the many techniques and models developed by hydrologists to study groundwater movement have found routine application in fisheries or other areas of aquatic ecology.

Methods for estimating or predicting local groundwater flow are based in whole or in part on the principles of Darcy's Law (Freeze and Cherry 1979; Mandle and Westjohn 1989; Martin and Frind 1998). Darcy's Law states that the velocity of flow through a porous medium is proportional to the difference in hydraulic head over some flow path length (hydraulic slope), and the hydraulic conductivity of the medium. In general, hydraulic head estimates are determined from well drilling logs or direct measurement in wells, and hydraulic conductivity can be derived from well pumping tests or estimated from geologic stratigraphy. Finite-difference or finite-element models (e.g., MODFLOW; McDonald and Harbaugh 1988; Harbaugh and McDonald 1996a,b) are widely used to predict groundwater flow patterns. Employing some proxy for groundwater flow such as stream baseflow; these methods back-calculate various parameters of Darcy's Law from a series of known conductivity or head data points within a specific, bounded area (e.g., McDonald and Harbaugh 1988; Hill 1992; Molson et al. 1992; Harbaugh and McDonald 1996a,b). Models of this type require intensive calibration, and remain dependent upon the availability of extensive stratigraphy and/or well level data. As a result, the modeled landscape is usually restricted to relatively small geographic areas (Harbaugh and McDonald 1996a,b; Christensen et al. 1998; Martin and Frind 1998). Such model predictions are primarily used for tracking of infiltration, contaminants, or short-term temporal variation in the delivery of water to subsurface aquifers or surface waters at local scales (Uhlman and Portman 1991). Consequently, results based on local implementations of these models are difficult to generalize to broader landscapes.

Increasingly, both researchers and natural resource managers require site-specific information over broader geographic areas (e.g., whole river basins, states, eco-regions). Groundwater flux and recharge rates can be modeled at these coarser scales using existing techniques, but because data density tends to be low, the resulting information is frequently too coarse for use in local or site-level environmental management. Moreover, most estimates at broad spatial scales tend to focus on regional subsurface flow patterns of deep aquifers rather than more local patterns of shallow subsurface flux (e.g., Mandle and Westjohn 1989; Holtshlag et al. 1996). It is at the scale of specific stream segments, lake sub-basins, and wetland vegetative units that most resource management decisions are made and various important ecological phenomena occur. Therefore, it is at these scales (typically 1-10 km) that there remains a very practical need for explicit models of the spatial variation in groundwater delivery.

Our interest in modeling groundwater flow evolved from a desire to better understand the landscape "drivers" of spatial variation in river flows and thermal regimes as they influence aquatic biota (*sensu* Seelbach and Wiley 1997; Wiley et al. 1997). Our approach was to explore whether simple interpretations of Darcy's Law could be effectively applied using a Geographic Information System (GIS) to predict spatial variation in potential groundwater delivery at a scale useful for stream inventory and resource assessment. Using a GIS-integration of a digital elevation model (DEM) indexing hydraulic head and a surficial geology map indexing hydraulic conductivity, we produced several models and maps of potential groundwater delivery to surface water systems for the entire Lower Peninsula of Michigan. In this paper, we (1) describe two relatively simple “neighbor analysis” algorithms that demonstrate potential for using spatial data sets and maps to estimate groundwater delivery to streams, (2) report the results of several validation studies, and (3) discuss the utility of terrain-based approaches to the study of groundwater hydrology and aquatic ecology.

Models and Methods

Study Area

The Lower Peninsula of Michigan has a diverse surficial geology composed of glacial and pro-glacial deposits (Farrand and Bell 1982; Dorr and Eschman 1990). It contains approximately 20 major river basins, as well as many lakes and wetlands (Figure 1). Because these systems display nearly the full spectrum of possible groundwater deliveries, they make Lower Michigan an ideal natural laboratory for the study of shallow groundwater movement as it relates to variation in aquatic ecosystems. In addition to the suitability of the landscape, the Michigan Department of Natural Resources (MDNR) and the University of Michigan’s School of Natural Resources and Environment (UM-SNRE) cooperatively maintain an extensive record of fish community inventories (Zorn et al. 1997), stream temperatures (Wehrly et al. 1997), and an existing digital database across Michigan’s Lower Peninsula as part of the Michigan Rivers Inventory (MRI; Seelbach and Wiley 1997). The spatial extent of this data record was important for iterative model development, initial validation, and evaluation relative to aquatic conditions. For finer-scale evaluations, we focused on 48 river reaches distributed across a wide range of catchment and local landscape conditions in Lower Michigan (Figure 1).

MRI-DARCY v.1 & v.2 (the buffer algorithm)

The first version of the model was developed in 1993 using a 1-km raster (1:250,000) version of a 3 arc-second Digital Elevation Model (DEM; USGS 1997) in an ERDAS GIS environment on a PC platform. A subsequent iteration (*version 2*) used a 1-ha, higher resolution (1:100,000) DEM and was developed in an ARC/INFO environment on a UNIX platform (*see* Wiley et al. 1997 for a conceptual overview and preliminary validation). The hydraulic conductivity grid was derived using a map of surficial geology (1:250,000) (Farrand and Bell 1982) and published maximum conductivity values for glacial drift (Davis and DeWiest 1966; Dunn and Leopold 1972; Todd 1976; Freeze and Cherry 1979; Bedient and Huber 1989; Dorr and Eschman 1990). 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.

Both of these models employed a simple neighborhood filter, which we will refer to throughout the rest of this paper as the "buffer algorithm." We estimated hydraulic slope by calculating the difference between each target DEM cell elevation and the maximum DEM elevation in a circular “buffer” with a 4-km radius (Figure 2a). These elevation differentials were divided by the buffer radius for head estimates and multiplied by the conductivity value of each cell. The resulting target pixel value was taken to represent an estimate of potential groundwater velocity for fluxes from adjacent uplands to the surface of that target cell. Four-kilometer neighborhoods were used because they represented the greatest distance in a series of observed associations between known major seepage areas and adjacent topographic relief. This model did not incorporate actual water table elevations. Instead, it used the DEM neighborhood information as a surrogate for maximum proximate water table elevation relative to the focal surface elevation. The rationale for this assumption was that surface topography averaged over broad landscapes provided a constraint on maximum potential flow. Output resulting from MRI-DARCY v.2 is illustrated in Figure 3A and Figure 4A.

MRI-DARCY v.3 (the transect algorithm)

Several specific weaknesses of earlier efforts were addressed MRI-DARCY v.3. First, location-specific estimates of relative groundwater potential were highly dependent upon the resolution of the DEM and the cell size of the conductivity grid. We used both the original "low" resolution data and a 7.5 minute (1:24,000) 30 m DEM with ~1 m vertical resolution (USGS 1997) in this new model. We also re-sampled the geology map using the corresponding grid cells to obtain conductivity estimates at a similar "high" level of resolution. Second, slope calculations in the original models relied solely on the difference in elevation between the target cell and the maximum elevation of the entire buffer neighborhood (Figure 2A). Slope was estimated in this manner irrespective of how far from the focal cell the maximum elevation value occurred within the neighborhood. Another potential error in the slope estimation of the buffer models was that only the end-points of the path were used to estimate hydraulic slope. If a deep valley occurred between the end-points, the original model assumed that groundwater flow might yet continue from one side of the valley to the other. Finally, the original model used conductivity values from the buffered cell but made no attempt to account for conductivity values along the flow path. The original model therefore assumed the flow path had the same conductivity as each buffered cell.

In MRI-DARCY v.3 we used a "transect template" created in Visual Basic to address many of the weaknesses of earlier versions. The transect template consisted of 12 transects, 4 km in length, with headings spaced 30 degrees apart like the hours of a clock (Figure 2B). Every 100 meters along each transect, corresponding cells from the DEM and conductivity grids were sampled to generate elevation and conductivity information about the potential flow path. To generate the template, a Visual Basic program loads binary DEM and conductivity files into memory as two-dimensional matrices, then creates the transect template by calculating the change in x and y values necessary to acquire pixel samples at every interval along each of the 12 transects. The program determines the matrix row and column locations relative to a given cell, stores these values in memory, and then works its way through every 30 x 30 m cell in the grid extent. For each cell in both the DEM and the conductivity matrices, the program samples the cell value, applies the transect template, and computes one or many output matrices. The program writes each output matrix to an ASCII data file formatted for conversion by ARC/INFO or ArcView. Grid errors and 'No Data' values found in either of the two input grids are assigned a 'No Data' value. Transect intervals outside the grid extents are set to the edge values.

The use of the transect template allowed much greater accuracy and flexibility in estimating flow path slope and conductivity than the buffer models, but because the orientation of the transects was fixed it also limited the ability of the model to sample the landscape in between transects. We assumed transect profiles had the potential to contribute water to the focal cell if they increased in elevation relative to the focal grid cell without falling below the original focal elevation. Thus for each transect sample point, hydraulic slope was computed by subtracting the focal elevation from each sampling point elevation, then dividing by the linear distance between them. We chose to use a simple average of potential elevation head across all point along a transect for reasons of simplicity, although many other algorithms might be used. Mean conductivity estimates were computed by averaging the conductivity values (K) along the flow path from the focal cell to the sampling point. For each sampling point along a transect, mean conductivity was multiplied by estimated slope. This process was repeated for the number of contributing sample points along each transect up to a maximum of 40, and then across all of the 12 radial transects. Model output was computed as a velocity value (m day^{-1}) for each 30 m^2 grid cell across Lower Michigan.

The "delivery" version of the model (MRI-DARCY v.3) limited the estimation of contributing flow paths to those that did not fall below the elevation of the receiving cell. Although flow paths are known to run for short distances up-slope depending on hydraulic heads and local conditions, we decided to ignore the potential for these paths in the new model for several reasons. At the scale of our interpretation of the landscape, we were primarily concerned with subsurface flow occurring as a direct result of elevation head rather than pressure head. Often such uphill flows occur due to a confining layer that we were unable to account for due to a lack of regional scale information about subsurface stratigraphy. Furthermore, water tables in Lower Michigan often occur quite close to the landscape surface so that the flow-path sinks we describe often contain a river, lake, or wetland, which can compete for subsurface flow. Output from models using both low- and high-resolution versions of the transect method are shown in examples B and C of Figures 3 and 4.

Multiple transects also allowed the simultaneous estimation of both influent and effluent flow paths. In one variation of the transect model (MRI-DARCYIO), transect profiles that drop below the elevation of the focal cell were also allowed to draw water away from the focal cell. Withdrawals were estimated using the hydraulic slope and mean conductivity resulting in the maximum effluent flow path from the focal cell to an interval along each transect. 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, and computed a net transect value. If a particular transect profile first dropped below, then rose above the elevation of the focal cell, we assumed the resulting depression was a sink with the potential to withdraw from, but not to contribute to, the focal cell. Output from these versions is shown in Figures 3D and 4D. Unlike distributed hydrologic models that generate estimates via cell-to-cell flow, any of the 12 transects could contribute to or withdraw from a given focal cell from any distance along their length. Thus, the MRI-DARCY v3 and IO models used a “moving landscape window”, incorporating a 4 km radial “snapshot” of the surrounding landscape relative to the focal cell in the generation of their delivery estimates.

Model Validation

The grid values produced by the MRI-DARCY models, while dimensionally correct (velocity = length*time^{-1}), represent only potential velocities to a surface location. Since the models are "topographic" (*sensu* Bevin and Kirkby 1979) and contain no information about the actual distribution or transport of water, values should be treated principally as an index of *potential* groundwater delivery. For visualization purposes, we found that model output values could be usefully scaled in standard deviations from their mean value across Lower Michigan. Because these potential velocities were not directly measurable in the field, validation was necessarily indirect. To the extent that these models successfully identified locations where groundwater loading to surface systems could occur, groundwater related attributes of the surface water systems could be used to test model predictions of spatial patterning. Likewise, we expected that model predictions should correspond to spatial patterns in statistical summaries of instantaneous groundwater delivery rates.

The earliest validation tests of the MRI-DARCY models were qualitative in nature. MRI-DARCY v.2 was routinely used as a predictor of base flow yield and cold-water fish communities in a stream classification developed in the mid 1990's for Lower Michigan (Seelbach et al. 1997). Hydrologic characteristics inferred from MRI-DARCY v.2 maps were subsequently and systematically checked against both field data and interviews with MDNR field biologists. The general experience during that process was that the spatial model resulting from the "buffer algorithm" was accurate enough to be very helpful in remotely classifying unsampled stream reaches. Successful multiple linear regression (MLR) modeling of coldwater fish distributions from landscape data provided early quantitative validation of the v.2 model at a regional level (Wiley et al. 1997).

Recently, we have performed more rigorous validation tests of MRI-DARCY v.2 and v.3 catchment-scale predictions by examining correlations between model output summaries for sample site catchments and 90% exceedance yield (low flow yield; LFY) values from summaries of USGS gauge site records (N=52). We also examined correlations between catchment and channel-buffer summaries of model output and observed July monthly mean stream water temperatures (JulMM, N=171) from a recent stream temperature study across

Lower Michigan (Wehrly et al. 1997, 1998). Both LFY and summer stream temperatures are well-established correlates of groundwater input to Michigan streams (Hendrickson and Doonan 1972b; Wiley et al. 1997). Larger inputs of groundwater result in larger stream baseflows and colder summer stream temperatures in Michigan. It is worth noting that a complex suite of factors influences both of these variables. Therefore, our expectation was not to account for all of the observed variance, but to test for significant correlation and to use the amount of variance explained to evaluate the relative ability of different versions of the models. Regressions of MRI-DARCY output with LFY and JulMM were also used to evaluate the relative performance of buffer versus transect algorithms, as well as estimates of hydraulic conductivity and hydraulic slope.

Across the 52 gauged sampling sites in the MRI, catchment-wide averages of both the buffer and the transect method using the lower resolution DEM accounted for nearly half of the total variance in LFY (Table 2). Moving the transect method to high-resolution data increased the explained variance by approximately four percent. All of the groundwater models outperformed hydraulic conductivity alone, but all of the models were outperformed by buffer method estimates of hydraulic slope, which accounted for almost 60 percent of the variance in LFY (Table 2).

Using observed JulMM stream temperatures from 171 sites, both old and new algorithms resulted in substantial increases in the adjusted R-square over conductivity alone (Table 2). A change from lower to higher data resolution resulted in an increase of the adjusted R-square of just over seven percent, whereas the change from old to new model algorithm increased the adjusted R-square just under ten percent. Once again, however, buffer method estimates of hydraulic slope outperformed both models (Table 2). In a related study, Wehrly et al. (1997) found using MLR and structural equation (SEM) models that July monthly maximum stream temperature was highly correlated with both basin average and local predicted potential groundwater values (MRI-DARCY v.2). Their highly significant models accounted for 59-60% of observed temperature variation (71-80% when outliers were removed) and standardized regression coefficients showed that the total effect of groundwater potential was superseded only by estimates of stream size (Wehrly et al. 1997).

River discharge accrual, in the absence of tributary streams, is a relatively accurate measure of groundwater delivery at a spatial scale closer to the resolution of model predictions themselves. Local evaluations of discharge accrual from 48 river segments (Figure 1) were standardized by segment length and regressed with summaries of the Darcy model predictions within a 100-m buffer of the river channel by Horne (2001). Discharge measurements were obtained through various descriptive publications of Michigan's river resources (Tody et al. 1954; Wicklund and Dean 1957, 1958; Spaulding et al. 1961; Knutilla 1970; Hendrickson and Doonan 1971a,b, 1972a; Nowlin 1973; Coopes 1974; Knutilla and Allen 1975; Larson et al. 1975). Initial model estimates accounted for 20-27 percent of observed variance in discharge accrual. When a single outlier with massive accrual indicative of piping flows and/or artesian loading was removed, this value increased to almost 60 percent for the low-resolution buffer model (Table 2). Changing the algorithm from the buffer method to the transect method increased the explained variation by 3 percent, and changing the data resolution an additional 2 percent (Table 2). An examination of the 3 versions of MRI-DARCY shows that the predominant error in model predictions is an under-estimate of groundwater delivery in the low-velocity part of the data set (Figure 5).

Discussion

Many researchers have previously advocated using topography as a basis for hydrologic models because surface slopes can influence patterns of both surface runoff and groundwater recharge (e.g., Beven and Kirkby 1979; O'Loughlin 1981; Wolock 1993; Dawes and Short 1994). All versions of the MRI-Darcy model demonstrated that simple interpretations of landscape geology and topography could provide important insight into spatial patterns of groundwater delivery to stream channels and related ecological attributes. As we explored the data sets, we found that the models were useful in describing landscape contributions to general patterns of stream flow, thermal characteristics, chemical conditions, and biotic communities at hundreds of specific sites across Lower Michigan's rivers. In this manner, the models illustrated that relatively simple interpretations of the landscape might explain complex spatial patterns of natural variation in river conditions through the application of existing spatial data sets and a GIS (Seelbach et al. 1997). The initial models 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 site-specific uses of the original models (e.g., understanding local contributions to stream reaches, lakes, or wetlands), we found that the model output was generally good but occasionally too coarse for accurate local predictions. More recent versions of the model (MRI-DARCY v.3) provided increased predictive resolution, a more intelligent filter, and a basic template that can easily be adapted for landscape- or question-specific modeling efforts.

Validation of the MRI-DARCY models was performed by relating model output to LFY and summer stream temperatures at coarse spatial scales, and to river accrual at local scales. Low-flow (or baseflow) and water temperature estimates are commonly used by hydrologists to evaluate the performance of groundwater models (Freeze and Cherry 1979). Because of the time-scale differences between the model output and the validation data, one might expect the predictive ability of the models to be confounded by effects of additional factors such as the evapotranspirative drag of lakes and wetlands, stream size, or dams. Despite such potential effects, the simple predictions were significantly correlated with LFY, JulMM, and segment-scale accrual. In each case, models with higher spatial resolution outperformed lower resolution models, transect models outperformed buffer models, and all Darcy models outperformed hydraulic conductivity alone. These results underscore the importance of topographic position in groundwater flux and suggest that coarse-scale groundwater recharge estimates in Lower Michigan (e.g., Holtshlag 1996) might be significantly improved with the addition of topographic information.

Because of its improved spatial resolution, the new model (v.3) provided much more specific predictions of groundwater movement and lent itself to more intensive field evaluation. In addition, increasing the DEM resolution altered absolute and relative model values and improved their predictive power somewhat (Figure 4, Table 2). Map scale, resolution, or other limitations of the DEM frequently influence the predictions of topographically based hydrologic models (Quinn et al. 1991; Chairat and Delleur 1993; Zhang and Montgomery 1994; Wolock and Price 1994). For example, Zhang and Montgomery (1994) used various DEM grid sizes to model the hydrograph of two basins in the northwestern U.S. The authors found using grid sizes coarser than 10 m led to less accurate predictions in the steeply sloping terrain of their study, but that smaller grid sizes led to insignificant gains. In general, they recommend that landscape features of interest guide the choice of resolution of DEMs used to calculate topographic indices for hydrological models.

Our analyses suggest that the model algorithm had a significant effect on the spatial pattern and relative values of the model output (Figure 4), as well as influencing its overall predictive power (Table 2). Although it utilizes an areal expanse of the DEM, the buffer approach essentially reduces the area to a single linear estimate. The multi-directional transect approach represents a compromise between simple linear and more complex areal interpretations of subsurface flow. Multiple flow path estimation provides greater detail about landscape structure, relative proximity, and improved model performance compared to the single flow path buffer estimates. Examinations of other topographic models have also found this to be the case (Quinn et al. 1991).

One additional flexibility inherent in the transect method is that the transect length, interval step, and computational algorithm can be modified. We generally encourage experimentation with the computational algorithm. However, it is not clear at all that changing the spatial resolution of the model itself (by changing the transect interval or transect length) will improve the predictive power of the output. Improving DEM data resolution provides the model with a more accurate picture of the landscape for model input, whereas changing the transect interval alters the implied estimate of how the actual water table surface mimics surface topography. However, rather than ignoring the transect interval, we concur with Zhang and Montgomery (1994) in suggesting that modelers find the interval step that optimizes model performance in their region.

Perhaps the most surprising validation result was that low-resolution buffer estimates of hydraulic slope outperformed other more sophisticated algorithms. Because of the tremendous variety of hydraulic conductivity in Lower Michigan, we felt that slope was by itself unlikely to produce the observed variation in groundwater delivery. Therefore, we explored these relationships further using a path analysis and summer stream temperatures. Path analysis allows for the decomposition of the correlations among multiple variables in a model (Wright 1934; Bollen 1989). Utilizing both the covariance structure of the data and a given model structure, path analysis allows the estimation of implied causal effects, both direct and indirect, as well as non-causal or spurious effects, though it does not prove causality. The path analysis (Figure 6) included both components of the low-resolution buffer model (MRI-DARCY v.2), as well as the model output itself. In addition, because stream temperature is a known correlate of stream size (Wehrly et al. 1997, 1998), the natural logarithm of the drainage area was also included. The path coefficients demonstrated that in addition to being a strong direct predictor of the groundwater model, slope is also correlated with both hydraulic conductivity and drainage area across Lower Michigan (Figure 6).

Due to the covariance among exogenous variables, a large proportion of the observed correlation between hydraulic slope and stream temperature can be considered non-causal or spurious (Table 3). In Lower Michigan, large hydraulic slopes tend to occur along smaller streams in high, coarse-textured, inter lobate glacial drift near the center of the peninsula (Figure 1). As rivers become larger and approach the Great Lakes, they typically flow into flat, low-lying lacustrine plains. Thus, the largest hydraulic conductivity values and the greatest likelihood for temperature effects from groundwater delivery occur in landscapes with the highest slopes. This analysis suggests that although hydraulic slope estimates work well in Lower Michigan, in other landscapes where such correlations are not as strong or do not exist, models will likely require both parameters of Darcy’s Law in order to perform optimally. A final point is that the models presented here may be considered powerful but imperfect predictive tools. There is still considerable room for refinement and improvement of the model algorithms and their application in different landscapes.

Limitations and Weaknesses

There are several limitations and weaknesses inherent in the present MRI-DARCY models, some of which we hope to address in the near future. First, it is important to remember that these models are only meant to predict the *relative potential* velocity of shallow subsurface flows. There has been no direct parameterization of the models in terms of direct measurement of groundwater movement, though several studies are currently underway. Because it is these flows that appear to be most important to stream flow and temperatures in Lower Michigan, we view parameterization as a critical developmental step.

At present the two-dimensional, topographically based models do not incorporate any information about actual hydraulic slopes and therefore are liable to predict high groundwater potential in places where actual water delivery is infrequent or unlikely. In the MRI-DARCY models, surface topography is used to constrain the maximum potential gravitational heads contributing to subsurface delivery. This limitation could be evaluated and accounted for in certain areas by using local interpolated estimates or observations of the water table surface. However, water table interpolation at coarse spatial scales has much more extensive data requirements and its own set of potential errors. As a result, hydrologists often use topography as a surrogate for the water table surface in hydrologic models (Beven and Kirkby 1979; O'Loughlin 1981; Wolock 1993; Dawes and Short 1994). Troch et al. (1990) showed that the assumption of a linear relationship between the depth to water table and the topographic index was reasonable in Pennsylvania watersheds, but others have found conflicting results (Quinn et al. 1991; Hinton et al. 1993).

In addition, the current models take only inferred conductivity derived from a relatively coarse-resolution (1:250,000) surficial geology and very limited stratigraphy into account. In glaciated landscapes like Lower Michigan, complexities in drift deposition can lead to exponential variation of actual conductivity within a single geologic formation. 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). Despite this fact, our analyses suggest the potential for error from highly variable, layered permeability is probably less important across entire catchments. Future versions of the model might incorporate site-specific modifications (data permitting) to adjust for known variation in conductivity, or more specific conductivity estimates using soil-profile data.

Finally, despite a slight but frequent tendency to over-estimate segment accrual in the regressions, the greatest error occurred when the models seemed to under predict actual groundwater delivery (Figure 5). Because topography provides a constraint on head estimates, we expected to the model to over-predict actual flow. Underestimates of segment accrual were likely the result of coarse-scale maps of surficial geology missing very local meltwater or buried outwash deposits, and/or relict channel systems. In a limited number of cases where large sandy hills on one side of a river channel lead to high rates of unidirectional groundwater delivery, our use of channel buffers to summarize the MRI-DARCY v3 output may have contributed to underestimates. In other cases, larger volumes of flow might offset low delivery rates. Some of this error may be eliminated in the mass-balance (IO) version of the new model because it predicts net groundwater accumulation, but this version was not included in the present validation study. Another interpretation is that groundwater delivery in the flatter, less conductive parts of Lower Michigan is neither local in origin nor driven by local topography. In fact, regional groundwater delivery is known to occur in the lacustrine plain rivers of coastal Michigan (Mandle and Westjohn 1989).

Future Development

As a further exploration of the utility of coarse-scale, high-resolution, remote modeling of groundwater delivery, versions of the MRI-DARCY models are being field tested in and adapted for other landscapes. Efforts just underway include the Upper Peninsula of Michigan, Wisconsin, Ohio, Illinois, Iowa, South Dakota, and Ontario. Another arena of potential investigation is the relative importance of different scales of local and regional water delivery across various landscapes. This issue has long been a subject of considerable debate among hydrologists (Freeze 1969; Toth 1995).

The alternate version of the new model, MRI-DARCYIO, incorporates a two-dimensional mass-balance calculation (Figures 3D and 4D), and represents the potential for net groundwater accumulation or loss in a particular grid cell based on the difference between transects contributing water (influent) and transects to which the cell is expected to contribute (effluent). Whereas models of potential velocity are useful predictors of rate-dependent variables such as stream flow or temperature, the mass-balance version is expected to be better at predicting areas influenced by the mere presence of groundwater such as wetland soils, plant communities, and certain lakes. MRI-DARCYIO may also have permitting and zoning applications because it indicates flow direction and identifies areas likely to contribute to surface water, as well as those areas where groundwater may tend to accumulate. Finally, inherent in MRI-DARCYIO is a model of subsurface source areas. Input-Output algorithms might be used to describe groundwater recharge areas as well as vectors for relatively rapid subsurface transport of water, dissolved substances, and pollutants to surface waters (Baker et al. 2001). Thus, the models presented here may be refined for use in riparian buffer delineation, zoning decisions, and environmental quality regulation.

The potential for inexpensive, widespread, and flexible application adds to the utility of such GIS-based models. Such extensive, spatially explicit estimates of groundwater delivery provide a stark contrast to more intensive hydrologic methods. Hydrologists often concentrate on developing empirical mechanistic models to predict groundwater flow because, due to their extensive parameterization, they are more accurate through time as well as space. However, from a resource management standpoint, this may be a case of the right answer to the wrong question. In the absence of a general hydrologic framework, the importance of variation in groundwater delivery to streams, lakes, and wetlands is easily overlooked. At a regional scale, GIS-based modeling approaches can provide an index of the "bigger picture" that resource managers, planners, and policy makers require.

Although Lower Michigan is likely an ideal conductive landscape for the development of our simple spatial models, we believe that the relationships they describe can be applied in many other landscapes. For example, such models will likely be useful throughout the glaciated areas of the Great Lakes Region and in conductive landscapes of the southeastern coastal plain. In landscapes where river valley colluvium can play an important role in conducting groundwater such as in the Pacific Northwest and Rocky Mountain regions, we believe similar GIS-based models can be adapted to predict physical constraints on subsurface flows at relatively fine scales of resolution. Previous hydrologic research in areas of high secondary permeability suggests that surface topography can be an important predictor of groundwater flow (Gerhart 1984). Recent application of the models in unglaciated, southwestern Wisconsin seems to support this finding (J. Lyons, Wisconsin Dept. of Natural Resources, personal communication). Because shallow subsurface contribution plays a significant role in the hydrograph of many river systems, as well as lakes and wetlands, similar models may well be helpful to aquatic ecologists and resource managers throughout the U.S.

Implications

The MRI-DARCY model output can be viewed as a new "groundwater movement landscape" that is a powerful quantitative and heuristic tool for evaluating spatial patterns of groundwater influence across any landscape of interest. If an appropriate goal for aquatic ecologists is to minimize unexplained variance in groundwater delivery, topographically derived predictions of spatial variation in local subsurface flow can help identify the mechanisms for ecologically important patterns of accrual. In Michigan, where groundwater accrual plays a large role in structuring river ecosystems, versions of these models have been extremely useful in the development of stream-flow and stream-temperature predictions (Seelbach and Wiley 1997; Wehrly et al. 1997, 1998; Zorn et al. 1997). Such relationships continue to provide insight into both local and landscape-level controls of the spatial and temporal variability of fish communities (Wiley et al. 1997; Zorn et al. 1997). Furthermore, developing an understanding of the relationships between local and upstream landscape physiography and river conditions has led to the development of both river and riparian classification systems (Seelbach et al. 1997; Baker et al. 2001; Baker 2002). In addition, these models of groundwater potential provide invaluable decision-support information for site-specific permitting issues, evaluating restoration/remediation potentials, water quality protection, trout stocking, and fishing regulations in Michigan. Currently, similar models are being developed for evaluation in other areas of the Great Lakes Basin to provide a common, regional tool for promoting widespread understanding of aquatic ecosystems.

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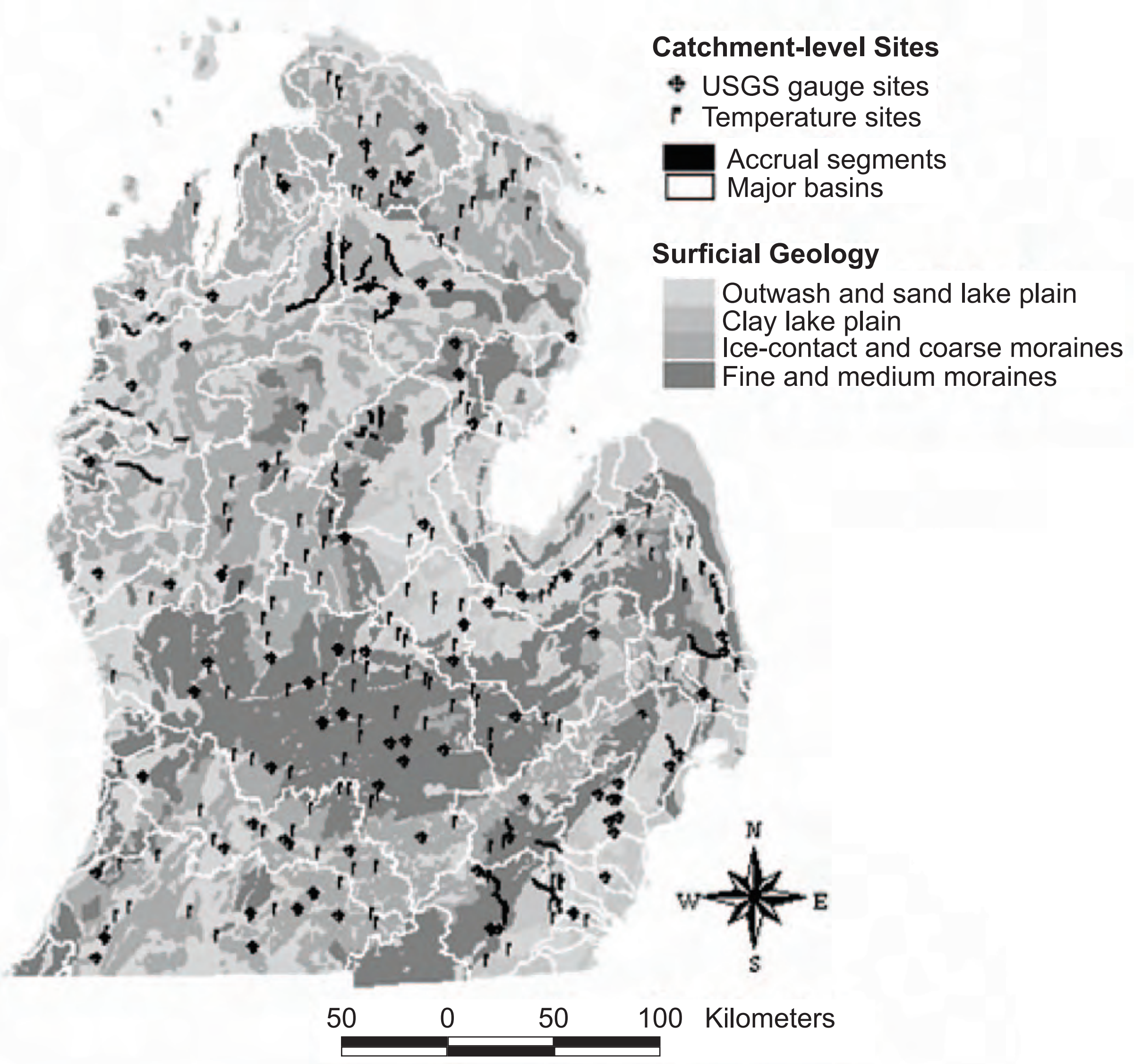

Figure 1.–Map of surficial geology of Lower Michigan (after Farrand and Bell 1982) showing major river basins, study sites, and study segments.

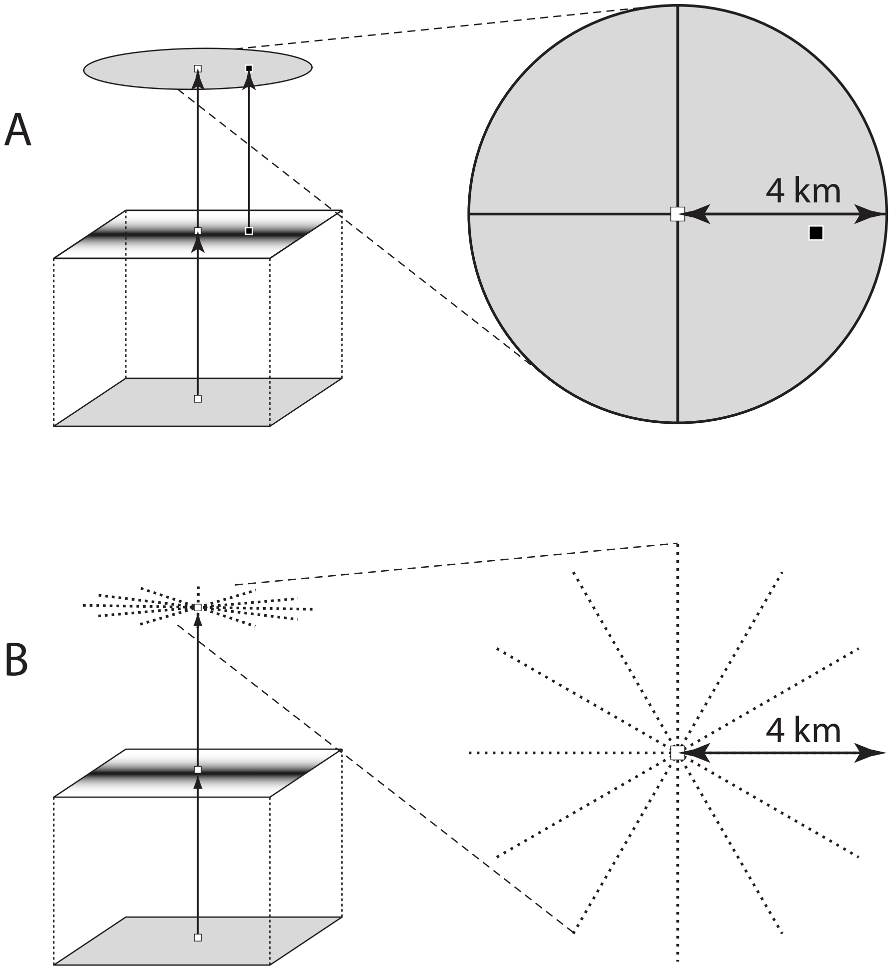

Figure 2.–Diagram of (A) buffer method and (B) transect method for integrating digital elevation model (two-tone) and hydrologic conductivity (gray) grids. The buffer method uses maximum elevation in a 4-km neighborhood to estimate hydraulic slope, and the conductivity value of the buffered cell (light squares). The transect method uses elevation and conductivity cell values at 100 m intervals along 12 radial 4 km-long transects.

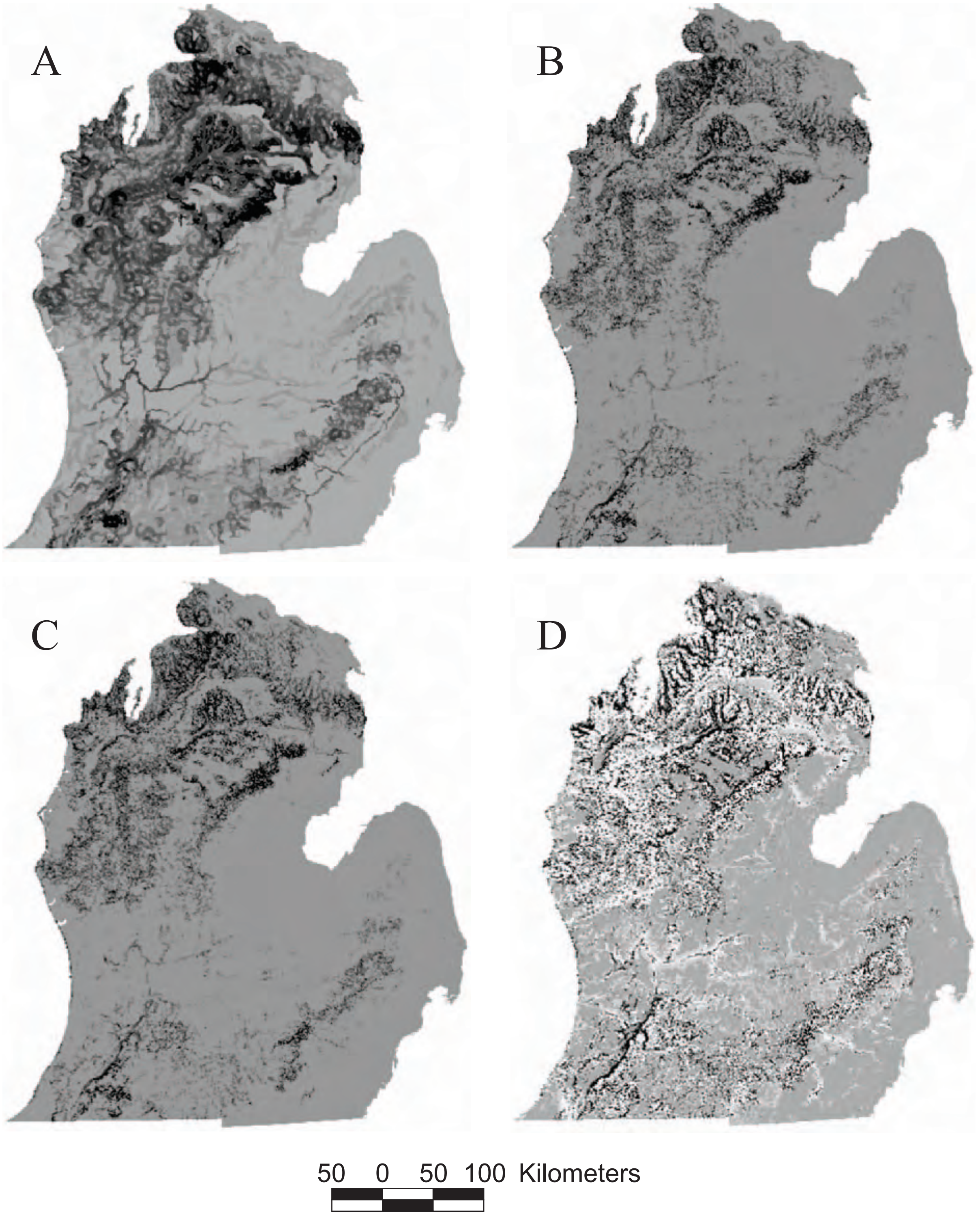

Figure 3.–Comparison of (A) low resolution, buffer model (MRI-DARCY v.2) output with (B) low resolution, transect model output; (C) high resolution, transect model (MRI-DARCY v.3) output; and (D) the mass-balance version of the high resolution transect model (MRI-DARCY IO). In A-C shades correspond to ½ standard deviations above model means for Lower Michigan. In D, shades darker than the neutral gray represent potential net accumulation, lighter shades correspond to potential net withdrawal.

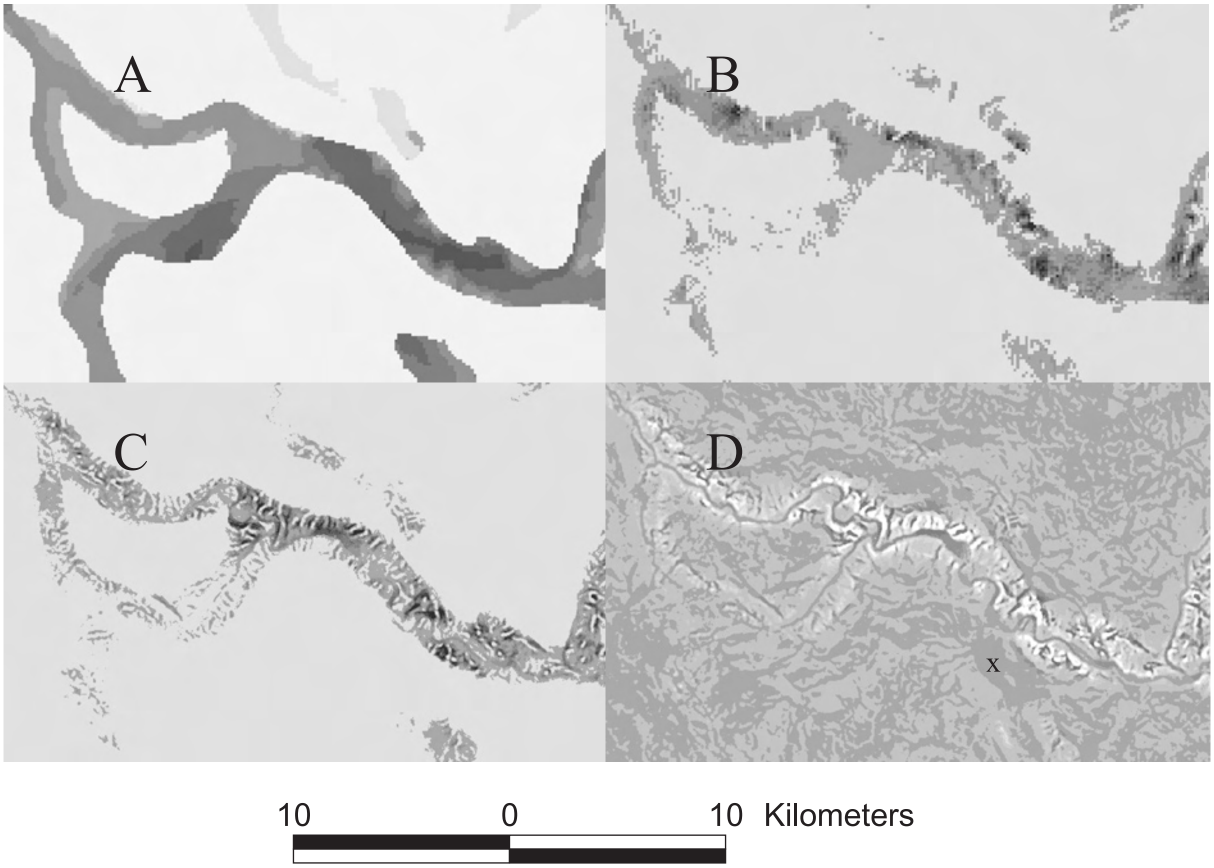

Figure 4.–Comparison of (A) low resolution, buffer model (MRI-DARCYv.2) output with (B) low resolution, transect model output; (C) high resolution, transect model (MRI-DARCYv.3) output; and (D)the mass-balance version of the high resolution, transect model (MRI-DARCYIO). Shades of dark gray correspond to ½ standard deviations above model means in A-C. In D, lighter shades indicate areas of potential net withdrawal and darker shades indicate areas of potential net accumulation relative to the neutral gray marked with an “X.” Area shown is Huron River valley near Ann Arbor, MI (42°17´30″ N 83°43´ W).

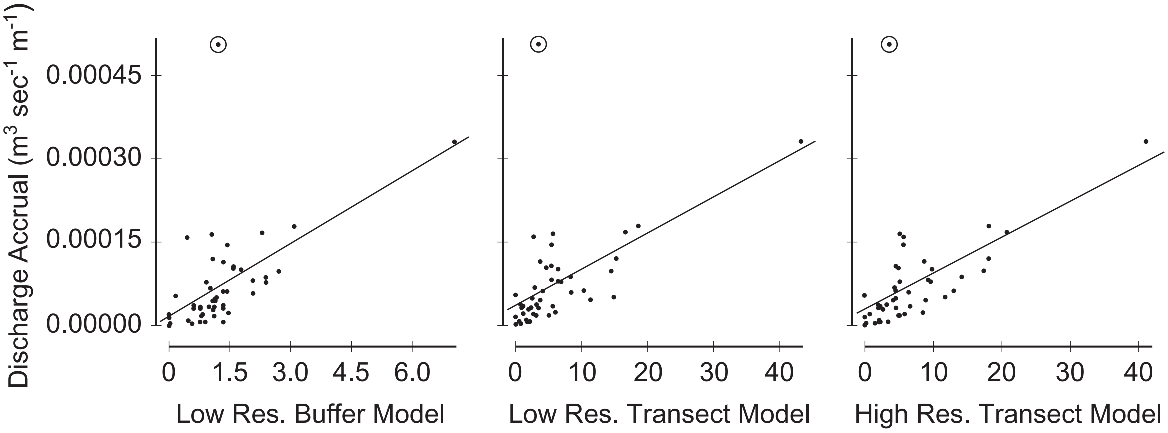

Figure 5.–Comparison of the low resolution buffer model (MRI-DARCYv.2), low resolution transect model, and high resolution transect model (MRI-DARCYv.3) using relationship between observed discharge accrual and model predictions from 48 river segments across Lower Michigan. Both axes are standardized by channel length. A single outlier with massive accrual is circled in the upper portion of each graph.

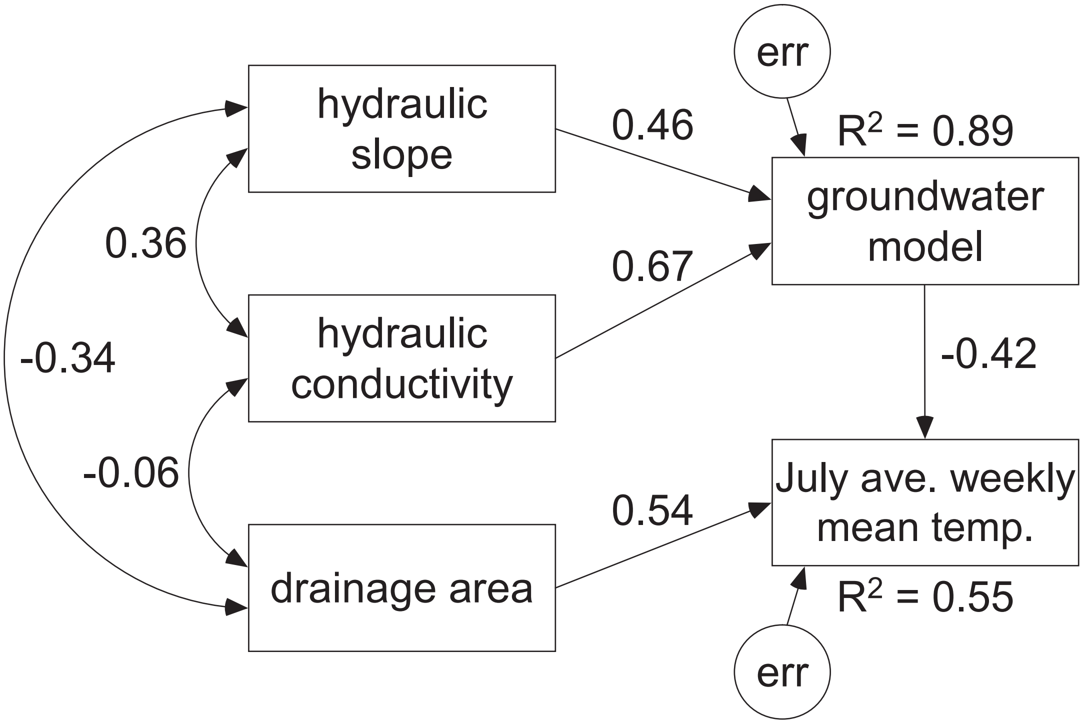

Figure 6.–Path diagram of catchment summaries of MRI-DARCY v.2 model components, model output, stream size, and summer stream temperatures. Values next to arrows are standardized path coefficients. R-square values placed next to each predicted endogenous variable may be interpreted as the proportion of explained variance.

Table 1.–Hydrologic conductivity values used in the groundwater models (m day^{-1}).

Deposit	K
organic deposits	1.000
dunes	20.000
lacustrine clay	0.001
lacustrine sand	10.000
glacial outwash	20.000
ice-contact terrain	100.000
fine textured till	0.005
medium textured till	0.500
coarse textured till	30.000
thin till over bedrock	1.000

Table 2.–Comparison of model performance at catchment and segment scales using adjusted R-squares. $P < 0.01$ for all individual values.

Predictive model	Catchment-level low-flow yield	July monthly mean temperature	Segment-level discharge accrual
Low Resolution Conductivity	0.367	0.089	–
Low Resolution Slope	0.591	0.412	–
Low Resolution Buffer	0.485	0.235	0.598
Low Resolution Transect	0.491	0.329	0.629
High Resolution Transect	0.538	0.394	0.648

Table 3.–Path analysis table showing direct effects, indirect effects, total causal effects, non-causal correlations, implied model correlations, sample correlations, and non-causal correlations as a percent of implied correlations. Variables are catchment summaries of model or model components and drainage area. $P < 0.01$ for all effects.

Variable	Direct	Indirect	Total causal	Non-causal	Implied r	Sample r	% Spurious
Hydraulic slope	--	-0.214	-0.214	-0.265	-0.479	-0.618	55
Hydrologic conductivity	--	-0.268	-0.268	-0.115	-0.383	-0.348	30
Drainage area	0.563	--	0.563	0.057	0.62	0.612	9
Darcy model	-0.422	--	-0.422	-0.103	-0.525	-0.512	20

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