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Use of Multiple Linear Regression to Estimate Flow Regimes for All Rivers Across Illinois, Michigan, and Wisconsin

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Abstract.–We estimated flow regimes for all river reaches in Illinois, Michigan, and Wisconsin, as a step in developing consistent ecological river mapping and assessment frameworks across this diverse climatic and physiographic region. Our objectives were to: 1) build and evaluate, for each state, multiple linear regression models that predict attributes of stream flow regimes, using catchment summaries of climate and landscape attributes as independent variables; 2) compare the performance of the state models with alternative 'full region' and 'ecoregion' models; and 3) predict stream flow regimes for all ungaged stream reaches. Recent stream discharge regimes were characterized using data from a set of 206 U.S. Geological Survey stream gages scattered across the three states. As independent variables we used data summarizing climate and landscape attributes for catchments of selected gage sites and also for every stream reach within the three states. We successfully built multiple linear regression models for a range of exceedance discharges representing several seasons, using gage data stratified by either state, ecoregion, or entire three-state region Significant independent variables consistently included catchment area, precipitation, slope, surficial geology variables that index hydrologic conductivity, and amount of land in urban and agricultural uses. Models explained a very high degree of observed variation in exceedance discharges; however model predictions often showed fair deviation from observed values in the initial data and even larger deviation from observed values using independent data. Performance of single-state models was similar to that of ecoregional models and both sets performed better than the three-state model. We used the single-state models to populate all river reaches across the three states, providing a data system containing exceedance discharges and flow duration curves for any reach of interest, and that can also be used to display the regional hydrologic landscape (or riverscape) in terms of any selected exceedance discharge. Despite the relative ease of model development, the excellent statistical fit of the models, and the appeal of generating comprehensive stream flow metrics for all ungaged reaches; the regression modeling approach has some important limitations that translate into substantial prediction error in some instances. Targeted flow sampling strategies and use of hybrid statistical—spatial accounting modeling approaches should reduce prediction error rates in future iterations. The statewide hydrologic attributes described herein are currently used in combination with other sets of ecological attributes as a powerful riverscape framework for a number of statewide river management applications in Illinois, Michigan, and Wisconsin.

Introduction

Instream and floodplain habitat conditions of a specific river reach result from the interaction of hydrologic process (deliveries of water, and related sediments and nutrients from uphill landscapes) with the geomorphic setting of its valley (slope, valley character, and geologic material)(Montgomery 1999; Trush et al. 2000; Thorp et al. 2005; Seelbach et al. 2006; Baker and Wiley 2009). River ecologists therefore need to understand and characterize aspects of local stream hydrologic regimes and their specific influences on habitat formation, and on biological and ecosystem processes (Poff and Ward 1989; Poff et al. 1997; Montgomery 1999; Bunn and Arthington 2002; Naiman et al. 2002; Richter et al. 2003; Wehrly et al. 2003). Natural hydrologic regimes vary greatly among streams and rivers, sometimes even within a fairly localized region or even one river network. Streams can differ in terms of both water budgets and water delivery mechanisms (surface vs. underground paths; Winter et al. 1998). Flow variation among streams is related to differences in the processes of precipitation, evapotranspiration, infiltration, aquifer storage, aquifer loss, and aquifer transmissivity among catchments. Here we define ‘catchment’ as the land surface area that drains to the outlet of a specific river reach. A ‘reach’ is defined as beginning as either a headwater or at a water body confluence, and ending at a water body confluence. Thus flows vary according to the regional and local geographies of climate and landscape physiography.

The emergence of landscape ecology approaches and GIS technologies has stimulated interest in comprehensive regional mapping of riverine habitats for management assessment and planning (Anonymous 2003; Moore et al. 2004; Higgins et al. 2005; Arthington et al. 2006; Seelbach et al. 2006; Wang et al. 2006; Sowa et al. 2007; Anonymous 2008). Information on flow regimes is highly desired in such mapping frameworks, however long-term flow data are only available from a limited number of river reaches where gages are operated. For example, a typical Midwestern state has gages at perhaps 150-200 reaches, while it likely contains ~30,000 total reaches. Hydrologists have addressed the need for understanding flows at ungaged reaches by various methods of extrapolation from gaged reaches. One common method is to model flow attributes within a region (often a state) using multiple linear regression (Dunne and Leopold 1978; Smakhtin 2001), with map-derived catchment attributes as the independent variables. Regression models have been developed for many areas of the world and for many states (Holtschlag and Croskey 1984; Ries et al. 2004; Hamilton et al. 2008). Often model fits are excellent (r^2 ~.95), but prediction errors are substantial (~ 20-50% or higher) and not rigorously evaluated. Typically regression estimates have been used by hydrologists as tools for local reach evaluations but until very recently (e.g., Ries et al. 2004) have not been applied comprehensively across regional river networks.

As a fundamental step in a larger project to develop ecological river data frameworks, classifications, and management assessments for several states in the upper Midwest, we needed to estimate flow regimes for all reaches across these states. Our overall goals in this study were: 1) to expand the traditional state scope of modeling to the multi-state region that includes Illinois, Michigan, and Wisconsin in hopes of capturing an array of climatic and physiographic diversity representative of that seen across the upper Midwest; and 2) to update modeling for these states using current GIS technologies. We felt that characterizing and modeling this set of states would both illustrate the applicability of the modeling approach across diverse climatic and physiographic settings, and also allow examination of the utility of modeling at several different regional scales: all three states together; each state separately; and each ecoregion (Omernik 1988) separately. The recent development of the National Hydrography Dataset (NHD; Anonymous 2002) and GIS tools for automated catchment delineations provided the opportunity for consistent and efficient model development and application.

Accordingly, our specific objectives were to:

1. Build and evaluate, for each state, best-fit multiple linear regression models that predict attributes of stream flow regimes. The dependent variables would be existing stream flow gage summaries, and the independent variables would be catchment summaries of climate and landscape attributes.
2. Compare the performance of the single-state models with alternative ‘full region’ and ‘ecoregion’ models.
3. Use the single-state models, along with a new comprehensive landscape database, to extrapolate stream flow regimes for all ungaged stream reaches across the three states, thus providing the first comprehensive and consistent hydrologic ‘riverscape’ (Winter 2001; Fausch et al. 2002) tool for ecological assessment, planning, and management across this region.

Methods

Characterizing Hydrologic Variability within the Study Region

Review of descriptive hydrologic data from the Illinois-Michigan-Wisconsin region showed considerable variation in reach water budgets, influenced by both regional and local variables. This region is influenced by arctic, prairie, Gulf of Mexico, and (moderating) Great Lakes weather patterns; is underlain by a rich mosaic of both glaciated and unglaciated landforms; and displays the full suite of human land uses. Mean annual precipitation varied among catchments across the region; with most receiving 750-1100 mm/yr (Figure 1A). Precipitation is highest in Illinois and the Corn Belt ecoregions, located on the northernmost edge of moist Gulf of Mexico air masses. Precipitation is intermediate windward of lakes Michigan and Superior. Mean annual stream discharge yield varied within a range of 150-500 mm/yr (Figure 1B) but strong geographic patterns were not evident by states or ecoregions. (Discharge yield is defined as discharge [m^3s^{-1}] / catchment area [km^2]; the resulting units can be simplified to depth / time period, which are identical to units for precipitation).

Base flow yield is a key ecological determinant of summer habitat conditions and biotic composition in rivers (Petts et al. 1999; Power et al. 1999; Zorn et al. 2002; Wehrly et al. 2006). Base flow yield is a strong indicator of the degree of groundwater inputs to a stream; streams with high base flow yields have high summer discharge per channel width, cold and stable summer temperatures, some thermal refuge during winter, and sustain coldwater fish assemblages. In the Illinois-Michigan-Wisconsin region, base flow yields varied from near zero to 0.01 m^3s^{-1}/km^{-2} (among the highest in North America). A strong geographic pattern exists for base flow yield (Figure 1C) with very low yields in Illinois and the Corn Belt ecoregions, as compared with higher, though quite variable, yields across the northern states.

A simple descriptor of flow regime is the ‘flow duration curve’, created by sequentially plotting a reach’s series of exceedance discharges. The smaller percentage exceedance discharges, e.g., 5%, describe infrequent high flow conditions for the data series, while the larger ones, e.g., 95%, describe persistent or base flow conditions; plotting the series of discharges for 5%, 10%, 25%, 50%, 75%, 90%, and 95% exceedances creates an informative curve. Steep curve slopes indicate a flashy flow regime for the period of study (this could be a year, a season, or a particular month), while gentle slopes indicate a stable flow regime for the period. Examination of flow duration curves from upper Midwestern river reaches reveals considerable variation in water budgets and flow responsiveness. Some groups of curves form a series of decreasing slopes that suggest a similar annual water allotment among reaches, but clear tradeoffs between groundwater and overland water routing paths (Figure 2A). In this set, streams with low base flows had high peak flows and visa versa. Other curves have similar slopes but are shifted up or down on the y-axis, indicating a similar routing path but differences in total water allotments among reaches (Figure 2B).

Data Sets

Stream discharge regimes were characterized using data from a set of 206 U.S. Geological Survey stream gages scattered across Illinois (N=76), Michigan (N=76), and Wisconsin (N=54). Gage data were from the database assembled by Piggott and Neff (2005). Gages were selected where stream flows were not directly altered by either major diversions or seasonal regulation at dams. We summarized data from 1981-2000, a period chosen to be long enough to characterize natural inter-annual discharge variation and to also match temporally with recent (1991-2000) land cover/ land use map themes.

We used data summarizing landscape attributes for catchments both of the selected gage sites and of every stream reach within the three states (total N~110,000 reaches). This extensive database was compiled through a cooperative effort between U.S. Environmental Protection Agency, Science to Achieve Results Grant R-83059601-0 and the U.S. Geological Survey, Great Lakes Regional Aquatic GAP Analysis program (Anonymous 2003; Brenden et al. 2006). Stream reaches were defined as origin-to-confluence or confluence-to-confluence units, according to the NHD (1:100,000 scale). Catchment attributes were summarized across the three states from the following digital map themes: elevation, mean annual precipitation, mean annual growing degree days, land cover/land use, and surficial geology (Brenden et al. 2006).

Multiple Linear Regression Analyses

Multiple linear regression models were developed for a series of exceedance discharges (5%, 10%, 25%, 50%, 75%, 90%, and 95%) for each of three time periods (annual, April, and August) for each state. We also modeled an index of surface runoff, defined as 10% exceedance discharge (total peak discharge) minus 90% exceedance discharge (base flow portion of discharge),for the April and August time periods for each state. We selected independent variables for inclusion in the modeling exercise based on previous experiences in Michigan (Wiley et al. 1997) and across the Great Lakes basin (Allan and Hinz 2004). Some variables were combinations of theme attributes; for example percent lakes and percent emergent wetlands were combined into one ‘open water’ variable. All dependent and independent variables were checked for normality assumptions using scatter plots, normal probability plots, and correlation between the variable and its normal score; and then transformed using either the natural logarithm or the exponential function to reduce skewness in the plots and improve the correlation between the variable and its normal score. All models predict the natural logarithm of the exceedance discharge to maximize linearity within the modeled relationships. We also calculated discharge yields by dividing estimated discharges by catchment area (units for yield were $m^3s^{-1}km^{-2}$).

We used a manual, stepwise regression approach. Independent variables were entered in the following order that we felt best fit hydrologic theory: 1) catchment area, 2) precipitation, 3) slope, 4) surficial geology variables, and 5) land cover/land use variables. If an entering variable was highly correlated with one already in the model, we used the variable that most improved model fit. We used values of T greater than 2 and P less than 0.05, as well as improved r^2, as guides for selecting variables. For each state, we first developed the model for the 50% exceedance discharge and then used this set of variables across the remaining range of exceedance discharges to create a standard family of models. All data points were retained in the models.

We evaluated performance of the single-state models in several ways: 1) first we examined the proportion of variance in the dependent variable explained by each model (r^2); 2) for each model we compared predicted to observed exceedance discharge yields based on the initial set of gage data; 3) we then compared predicted to observed exceedance discharge yields using 30 gages per state that were independent of the set used to build the models; 4) we visually compared frequency distributions of both independent and dependent variables between the gaged reaches and the total set of reaches for each state, to see how well the gage set represented the true landscape; and 5) we examined the sign and strength of the coefficients for variables that were summarized as proportions (0-1.0), such as surficial geology and land use/land cover. We pooled all annual, April, and August coefficients and then split the coefficients into two groups: positive signs (N=208) and negative signs (N=289). Each group was then divided into three quantiles, and each coefficient was assigned a symbol based on its quantile (positive, weak influence quantile 1 = ‘+’; positive, moderate influence quantile 2 = ‘++’; and positive, strong influence quantile 3 = ‘+++’).

Comparison of Models Built at Regional vs. State Scales

We used the above procedure to also build models for the annual exceedance discharge data at the major ecoregion and entire three-state region scales. Some ecoregions were minimally represented within the three states, so we combined these into the major ecoregion groups of ‘Forested’, ‘Till Plains’, and ‘Corn Belt’; each of which contained an adequate sample size of stream gages (N = 50, 75, and 63, respectively). We compared models built at respective state, ecoregion, and three-state region scales by examining the sign and behavior of variable coefficients, and also by comparing predicted to observed exceedance discharge yields using the initial gage set.

Prediction for All Reaches

Discharges at exceedance frequencies were estimated seasonally for each reach in each of the three states (total N ~110,000 reaches) using the multiple linear regression equations generated for that state. Independent variables were catchment summaries of climate and landscape attributes for each reach (Brenden et al. 2006). We also calculated exceedance yields (discharge / catchment area) to facilitate comparisons and ecological interpretations among reaches. These estimates of current (1981-2000) flow regime were stored in a data table and linked to the reaches mapped in GIS, providing a comprehensive hydrologic coverage for river systems across the three states.

We checked for poor reach estimates by comparing each exceedance discharge with those just preceding and just following. Any value that was not lower than that preceding or higher than that following was considered poor (i.e., $Q_{50}>Q_{75}>Q_{90}$). We did not include Q_{05} or Q_{10} in this check, as these metrics are based on few data and are known to sometimes be unstable. Large river reaches consistently had unreasonably high estimated values and we eliminated all reaches with catchment area >20,000 km^2 from further analysis. For smaller reaches with poor estimates we estimated exceedance discharges based on the average exceedance yield (discharge / catchment area) from several gages with similar catchment attributes and the estimate reach’s catchment area. For river systems that straddle state boundaries, we estimated exceedance discharges based on the state multiple linear regression models where each reach lay.

Results

Evaluation of State Multiple Linear Regression Models

Model structure and fit.–Multiple linear regression models were successfully built for each exceedance discharge, season, and state (N=72 permutations). Independent variables consistently included catchment area, precipitation, slope, several surficial geology variables that index hydrologic conductivity, and the primary land use/land cover variables of urban and agricultural coverage. An example of the model output is shown in Table 1. Models explained a very high degree of the observed variation in exceedance discharges, with average r squares of 0.95, 0.97, and 0.92 for annual, April, and August seasons, respectively (Table 2). Lower discharges (e.g., August) had somewhat lower fits, and models for 90% and 95% exceedance discharges (annual and August) in Illinois were clearly poorer, with an average r2 of 0.74.

Comparison of predicted and observed discharge yields.–Despite the tight fit of the regression models, predictions often showed fair deviation from observations, using both the initial data set and the independent test data set. Examining the 10%, 50%, and 90% exceedance models (per three seasons) for the initial data set (the best case scenario), the average percent deviations were 19%, 21%, and 49%, respectively (Table 3). Thus, the ecologically interesting low flows proved most difficult to predict. Most deviations were within 50-75% of observed values for the annual 90% and August 50% exceedance models. However, some cases showed very large deviations of 100-600%; many of these occurred in Illinois, where the lowest flows occurred (Figure 3). Most of the very large (>100%) percent deviations coincided with very low actual discharges (Figure 4). Models correctly predicted relatively low discharges, but small prediction errors were portrayed as unusually large percent deviations. In every case, models overpredicted at lower discharge yields and underpredicted at higher discharge yields (Figure 5).

Performance of the models was much poorer based on an independent test data set. For the annual 90% exceedance discharge models, many estimates were again within 50-75% of observed values but cases of large deviations were much more frequent, and deviations averaged 200-300% for Illinois and Wisconsin gages (Figure 3; Table 4).

How well do the gaged reaches represent the overall reach network?–We compared frequency distributions between gages and all reaches in each state for both independent and dependent variables, to see whether the gage sites provide a representative foundation for a state stream discharge template. Some independent variables showed considerable bias; gages appear to be preferentially placed on streams draining larger, coarse-textured catchments (likely those with more permanent summer base flows; Figure 6A). Other variables were well represented by the gage sets, including precipitation, catchment slope, and most land use/land cover variables (Figure 6B).

Median discharge yields for the gaged reaches were fairly representative of yields estimated at all reaches (Figure 7). However the gage site yields were somewhat high for both peak and base discharges.

Model coefficients.–Model coefficients were examined according to the logical model series developed for each state and season (Tables 5a-5d). The coefficient for ln(catchment area) should theoretically be slightly higher than 1.0, as discharge increases with area and is slightly higher in downstream reaches. In our models the coefficient was generally slightly greater than 1.0 and the increasing effect was most pronounced for base flows. The coefficient rose quite sharply for base flows in Illinois streams. This odd behavior matched the difficulty in fitting the models for Illinois low flows. For other variables, the coefficients generally had signs appropriate to our theoretical expectations, and decreased or increased smoothly across the series of exceedance percentages. For example in the Michigan annual models, percent agriculture had a negative sign at all exceedances, indicating it was competing for stream flow; and it became an increasingly negative value as the exceedances approached base flows—indeed, the base flow coefficient was tenfold the peak flow coefficient.

Examining the relative sign and strength of coefficients provides insight into key variables influencing high vs. base flows across the three states (Table 6). Michigan appeared as a ‘glaciated’ state, with low flows most influenced by coarse deposits of outwash sands and ice contact gravels. Wisconsin and Illinois appeared more similar, perhaps representing ‘prairie’ states, where base flows were strongly and positively associated with the presence of open wetlands and negatively associated with fine-textured sediments and bedrock; peak flows were positively associated with these latter geologies as well as occurrence of forested wetlands. Coefficients of land use/land cover variables were likewise interesting.

Agriculture land use had a modest negative effect through most of the models (it was so widespread across Illinois that it did not appear in those models). Urban land use had a consistently strong positive influence on base flows, especially in Illinois. Urban land use had a strong positive influence on peak flows across all states during August when soils are unsaturated.

Comparison of State with Alternative Regional Models

Full regional (three-state) models showed the highest percent deviations from observed (Table 3) and also showed unreasonable behavior of coefficients. For example precipitation had an erroneous negative coefficient for low flows; i.e., more precipitation was associated with less stream base flow. This was due to the interesting geographic patterns (Figure 1), where Illinois exhibits higher average annual precipitation yet experiences extremely low base flows. Ecoregion models were essentially equivalent to state models in terms of deviations from observed (Table 3).

Creation of a Spatially Comprehensive Information System

We used the state regression models to populate all reaches across each of the three states (N~110,000 reaches), respectively, with estimates for the range of exceedance discharges for each of the annual, April, and August time periods. For any reach, these data can be used to form a flow duration curve for any of these seasons. Viewing any selected exceedance discharge or discharge yield effectively creates a regional hydrologic riverscape. Overall mapped patterns of peak flows and base flows fit our knowledge of the hydrology and ecology of these states (compare for example, Figure 1c with figures 7 and 8). There were, of course, errors associated with these thousands of predictions. First, we know from the above analyses that the inherent prediction error was mostly <50% but sometimes perhaps 500%. The most obvious errors (e.g., $Q_{50}<Q_{75}$) amounted to ~1-2% of all predicted values. Additionally, because individual states served as our model frame, we did create discontinuities in flow predictions where rivers cross state boundaries.

Discussion

Development of multiple linear regression models relating (spatially lumped) catchment attributes to stream flow summary metrics at the scale of one state is feasible (Holtschlag and Croskey 1984; Ries et al. 2004). Often the spatial scale of one state contains a broad enough spectrum of climatic and physiographic conditions for building such simple models. But working at a state scale also has limitations: some states are small or homogenous in some regards; some catchment types might be rare or not gaged; and rivers often cross state boundaries, potentially resulting in discontinuous flow estimates. We found that, modeling at a scale of three midwestern states, regional climatic patterns overwhelmed local catchment information and caused nonsensical results. For example, both climate and physiography of southern-middle Illinois are distinct from the remainder of this three-state region, setting up a very strong, negative correlation between annual precipitation and summer stream flow for the region. This nonsensical correlation prevented these models from describing a more useful precipitation-streamflow relationship at the catchment scale of interest.

The observation of distinct intra-regional climate and landscape breaks suggests the use of ecoregions (Omernik 1988) as ideal spatial strata for developing streamflow models. Ecoregions are defined by major breaks in climate, physiography, and land cover/land use and thus would serve to control for the macro-scale variation in these variables, allowing the statistical models to describe variation and pattern at smaller scales such as the catchment. However, our analysis did not show a performance edge for ecoregions over states. We conclude that a state scale is probably similar to ecoregions in model performance and superior in terms of practical application and model administration (a state scale is also used in the USGS StreamStats application; Ries et al. 2004). However to address some operational weaknesses of the state approach: 1) gage and catchment data could be borrowed from neighboring states to increase sample size for rare catchment types; and 2) where smaller rivers and streams cross state lines, sub-watershed boundaries could be honored over state boundaries, to decrease the discontinuity problem.

While these correlative statistical models do not truly describe the causal or mechanistic relationships at work, crafting them in concert with fundamental hydrologic theory does provide some insight into the most important natural and human-induced controls on river stormflows and base flows across these states and the region. Our modeling supports the observation of previous analysts (Hendrickson and Doonan 1972; Holtschlag and Croskey 1984) that while precipitation inputs are certainly important, spatial patterns in surfical geologic texture are what primarily drives variation in water source (stormflows and groundwater) among midwestern rivers; especially in the glaciated region. Examining human influences, we did not capture the complexities of agricultural or urban drainage; however three major patterns were consistently observed: 1) agricultural land use tends to compete for stream base flows; 2) urban land use creates stronger peak flows during the summer period of unsaturated soils; while 3) urban land use often supplements stream base flows. This latter, somewhat surprising, observation has been documented in several cases (L. W. Stanfield, personal communication, Ontario Ministry of Natural Resources, Picton; M. J. Wiley, University of Michigan, personal communication) It is particularly apparent in the Illinois models, where naturally very low base flows are strongly enhanced by percent urban land use. Urbanization appears capable of reducing natural stream base flows by either reducing infiltration and groundwater recharge (Simmons and Reynolds 1982; Winter et al. 1998) or increasing observed summer stream flows through point source discharges or leaky plumbing (Allan and Hinz 2004). A pattern of increasing base flows downstream of urban landscapes was apparent in these three upper Midwestern states.

Despite the relative ease of model development, the close statistical fit of the models, and the appeal of generating comprehensive stream flow metrics for all ungaged reaches; this approach has some important limitations that translate into substantial prediction error in some instances. Regression models predict well the central tendency of the data; however, they have inherent difficulties predicting extremes of the data distribution. In this case, higher prediction errors are found for very high flows, very low flows, very small catchments, and very homogeneous catchments. Very high and very low flows are infrequent and thus are represented by small sample sizes within gage data records. Very low flows are inherently difficult to predict, in terms of percent accuracy. Compounding this are two problems: 1) some independent variables have large (positive or negative) coefficients that, coupled with high percent catchment attributes, can produce erroneous predictions; and 2) catchment attributes at ungaged reaches can fall outside ranges of modeled gage data, again resulting in erroneous predictions. Very small catchments are very abundant within river networks and are most likely to suffer prediction errors as they often have homogeneous (high percent) landscape attributes and are not well-represented by gaged data.

Another limitation of this approach is that estimates for a given reach are made only in reference to the model structure and the catchment attributes for that reach, and not in reference to any nearby, actual gage or field flow measurements. So there is no mechanism for incorporating local, accurate measures into the model estimates.

Management and Research Implications

We have demonstrated that comprehensive regional hydrologic information systems can be created relatively easily. While not perfect, such mapping systems provide an excellent ‘coarse level’ tool for regional-, state-, or even watershed-scale river management practices such as: visualizing extent and spatial patterns of habitat or ecological resources; or developing management or regulatory standards. One important step in developing a mapping system for riverscapes is the choice of riverine spatial units for extrapolation of information (in this case, discharge predictions; Wang et al. 2006). We used the NHD

(Anonymous 2002) as the national standard set of river reaches. As an extension to our project, scientists in Michigan have aggregated neighboring reaches into a smaller set (from ~30,000 to ~7,000) of ecologically meaningful river segments to be used as spatial units for riverine management programs (Seelbach et al. 2006). With either reaches or segments, we were using a fixed array of stream units with a similarly fixed set of catchments related to the downstream node of each river unit. Thus conditions at any point within the unit were explicitly considered to be homogenous. The U.S. Geological Survey, StreamStats application offers an alternative approach, where for any specific point on the river network, the catchment character and resulting stream discharge statistics can be predicted (Ries et al. 2004). This offers the advantage of maximum spatial accuracy. Our choice of fixed units offers the advantage of portraying the entire watershed or regional riverscape at once, while retaining meaningful representation of system character and spatial variation.

Our models intentionally contained independent variables representing degree of urban and agricultural land use. This information is needed to describe the current state of hydrologic conditions (e.g., imperviousness or artificial drainage; Leopold 1968) and when using the regression models to set assessment reference values (sensu Wiley et al. 2003; Baker et al. 2005; Kilgour and Stanfield 2006) and to explore the relative effects of human vs. natural landscape attributes (sensu Steen 2008).

The regression models in this study represent one traditional approach to predicting flow statistics. They are simple and provide excellent fits to gage data. However, the models' predictive accuracy can be less than desired and they have several obvious weaknesses: 1) state gage sets are typically limited in number and geographical coverage; 2) they do not incorporate actual local gage or field data into the prediction process (i.e., the Baysian "prior"), so predictions may be unnecessarily inaccurate; 3) they do not account for known major withdrawals or return flows to particular river reaches; and 4) as they are not mechanistic, they cannot reliably be used to examine alternative future scenarios relating to climate or land use changes. In response to weakness 1, states need to implement sampling strategies for deployment of gages and other field measures that better represent the full range of hydrologic variability. In response to weakness 2, it is now possible to develop regression models that operate within the constraints of both site field measures and the river's spatial network structure. Weaknesses 2 and 3 will be addressed in development of a new hybrid statistical--flow accounting model for Michigan rivers (D. Holtschlag, USGS Michigan Water Science Center, personal communication). Weakness 4 is traditionally addressed by developing detailed, mechanistic models at the scale of small catchments or portions of catchments. Exploring ways to scale up this type of modeling power is an important challenge for hydrologists.

The statewide hydrologic attributes described herein are used in combination with other sets of ecological attributes as a powerful riverscape framework for a number of statewide river management applications in Illinois, Michigan, and Wisconsin. For example, the framework is being used: to design biological and environmental sampling programs; to classify river segment types for fisheries management, and for water quality and quantity protection; and to organize aquatic community conservation strategies. This is the first time these state agencies have examined their entire riverine resource in a fairly detailed manner. As data sources and modeling approaches improve through time, these riverscape tools will only become more and more accurate.

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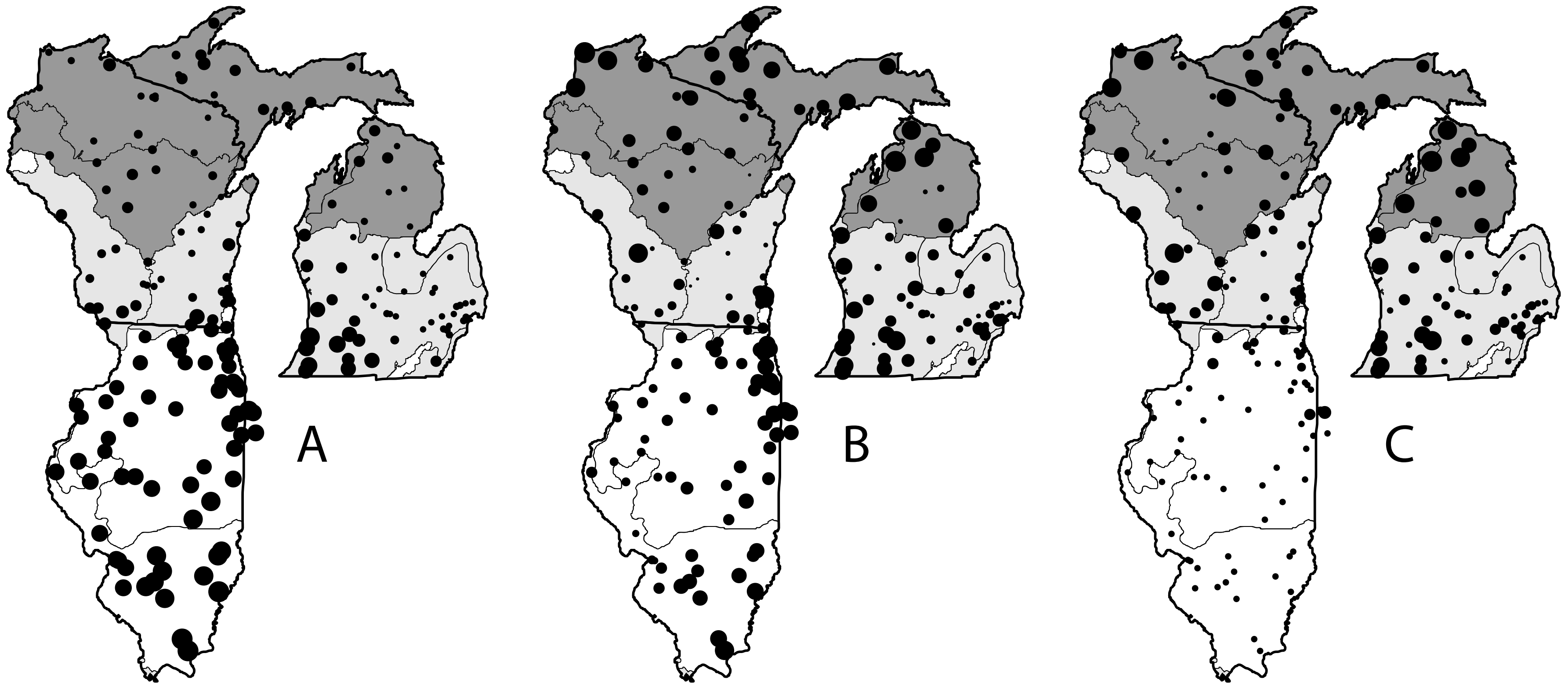

Figure 1.–Regional variation in water budget attributes of gaged stream catchments across Illinois, Michigan, and Wisconsin. Attributes shown are: A) mean annual precipitation; B) mean annual discharge; and C) annual 90% exceedance discharge yield. Dot size indicates ‘amount relative to this 3-state region’ for each attribute. Also shown are state and ecoregion boundaries, as well as shaded ‘lumped’ ecoregions.

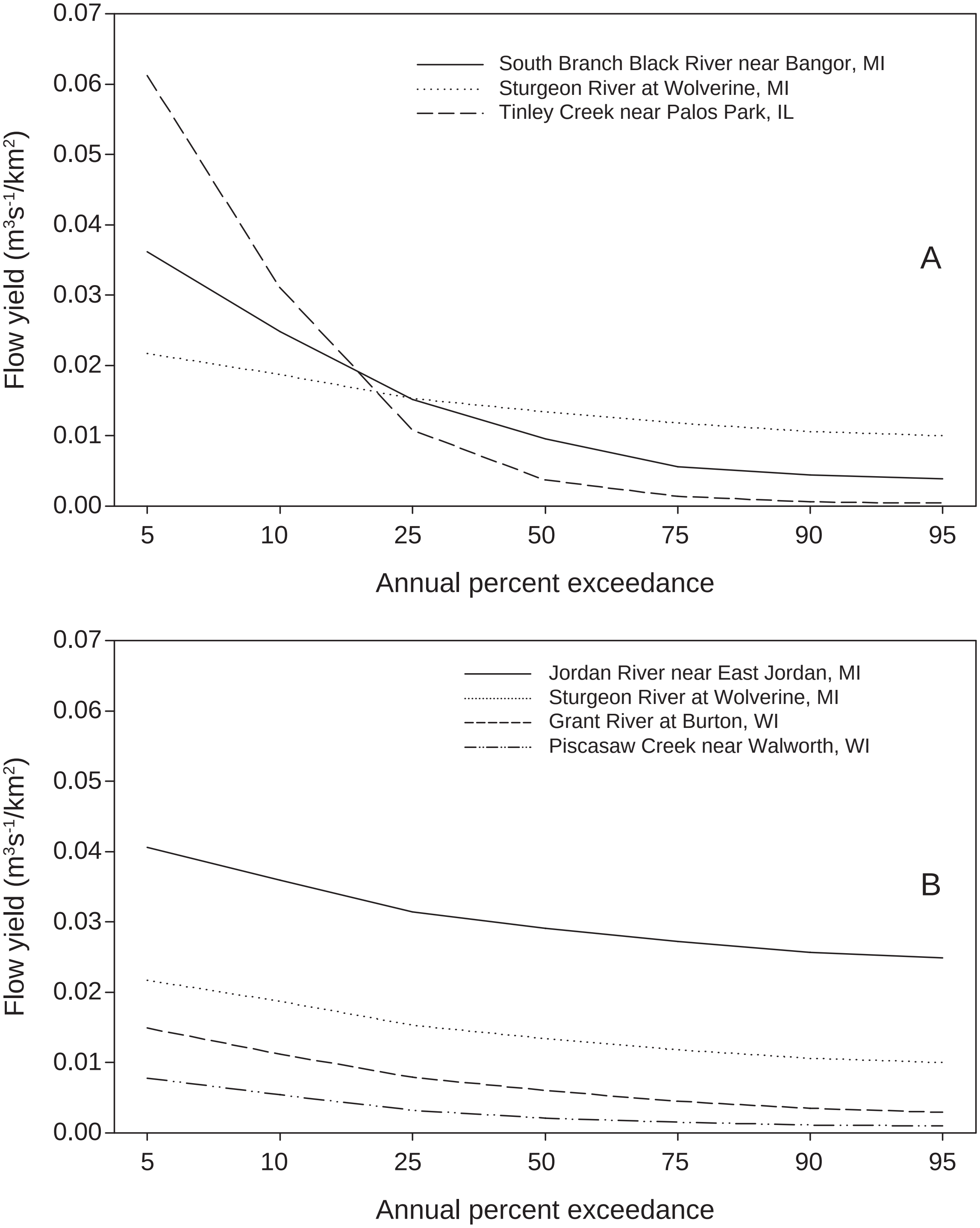

Figure 2.–Comparison of selected flow duration curves from gaged streams in Illinois, Michigan, and Wisconsin illustrating: A) differences in water routing to the stream reach. For rivers with similar annual water budgets, curves with steeper slopes indicate routing of water to the river channel through rapid surface pathways, resulting in higher, brief peak flows and lower sustained base flows. Curves with gentle slopes indicate routing of water to the river channel more slowly through groundwater pathway, resulting in muted peak flows and high, stable base flows; and B) Differences in annual water budgets. For rivers with similar water routing paths (similar curve slopes), curves with larger y-intercepts indicate catchments that are processing more water.

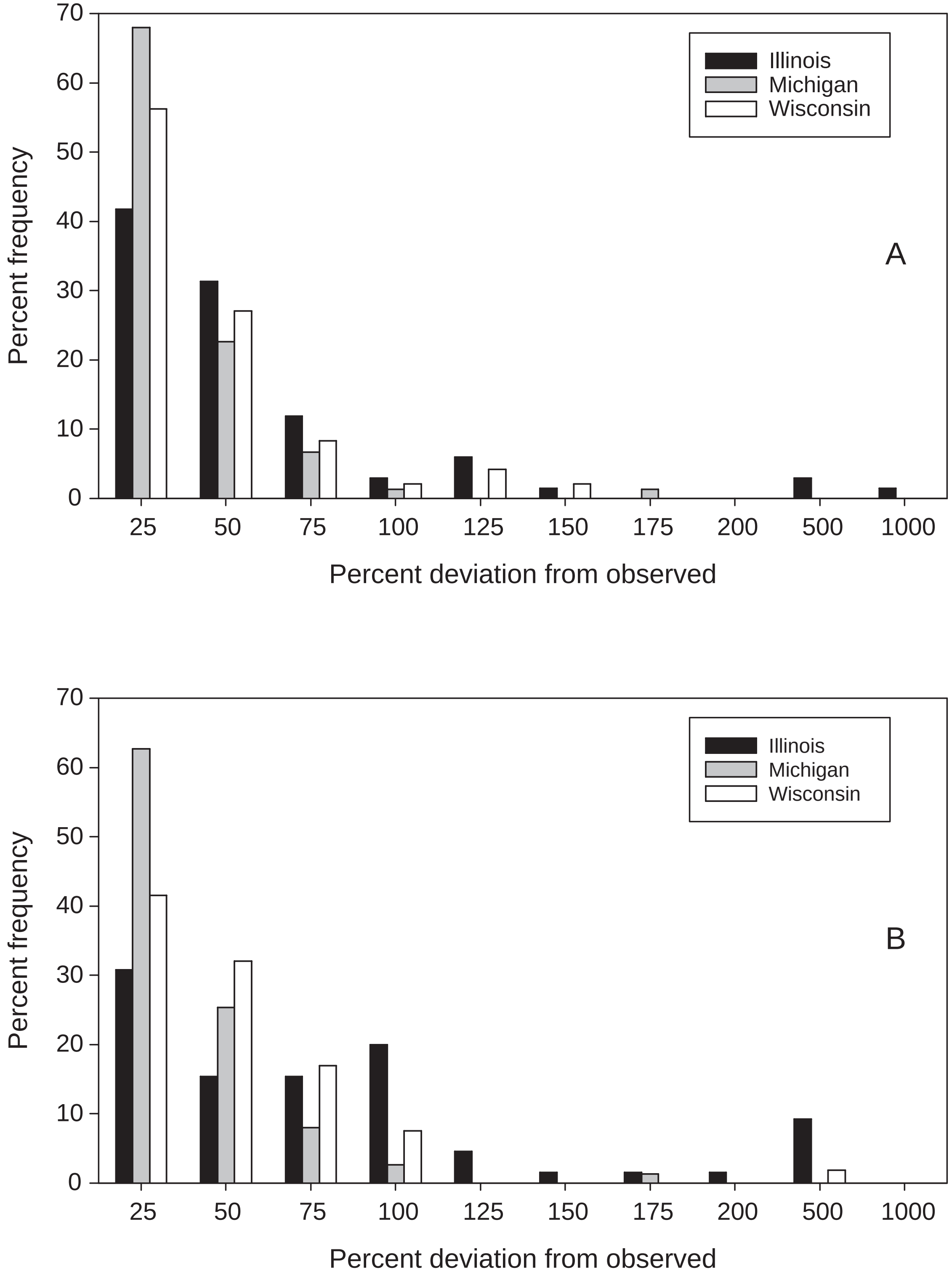

Figure 3.–Histograms describing frequencies of percent deviation of predicted from observed annual 90% exceedance discharges at gaged streams across Illinois, Michigan, and Wisconsin. Panel A shows deviation where observed data are from the same gage sites used in developing the prediction models. Panel B shows deviation for observed data from a set of gage sites independent of those used to develop the prediction models.

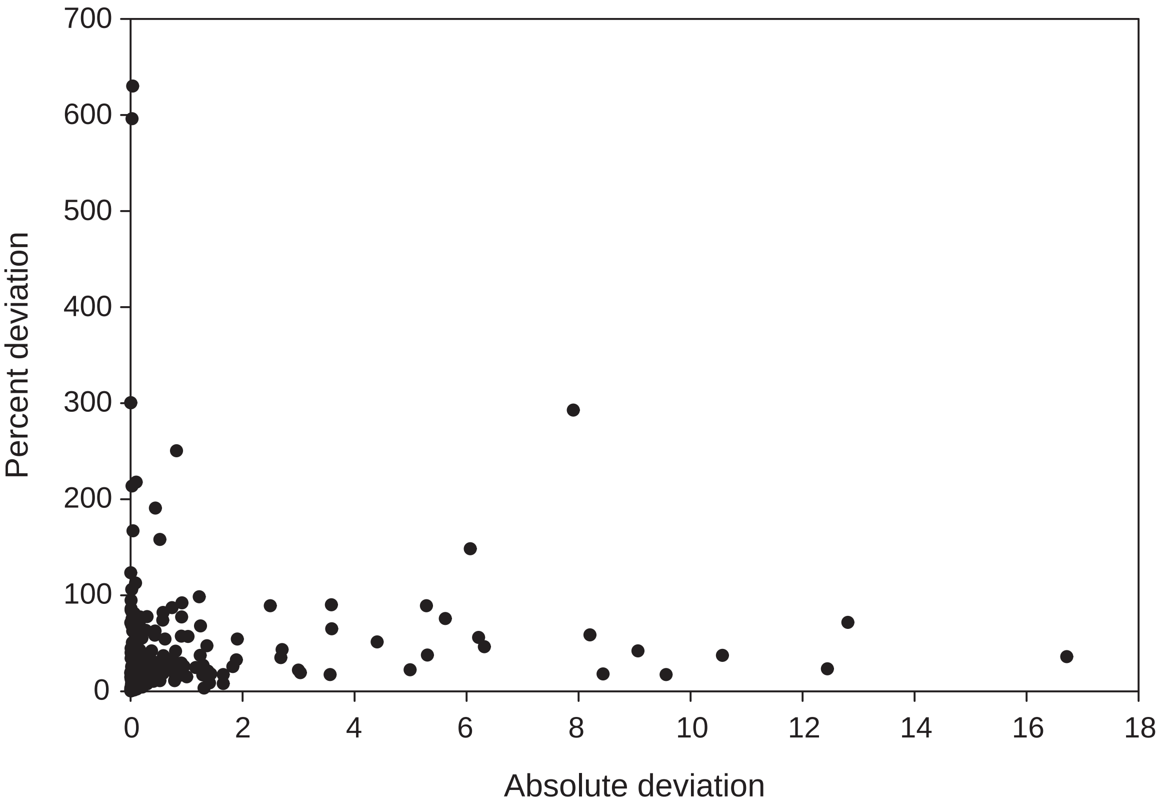

Figure 4.–Negative hyperbolic relationship between percent deviation and absolute deviation, for predicted vs observed annual 90% exceedance discharge yields across Illinois, Michigan, and Wisconsin stream gages. The highest percent deviations are seen for the smallest absolute deviations. In this comparison, observed data were from the same gage sites used in developing the prediction models.

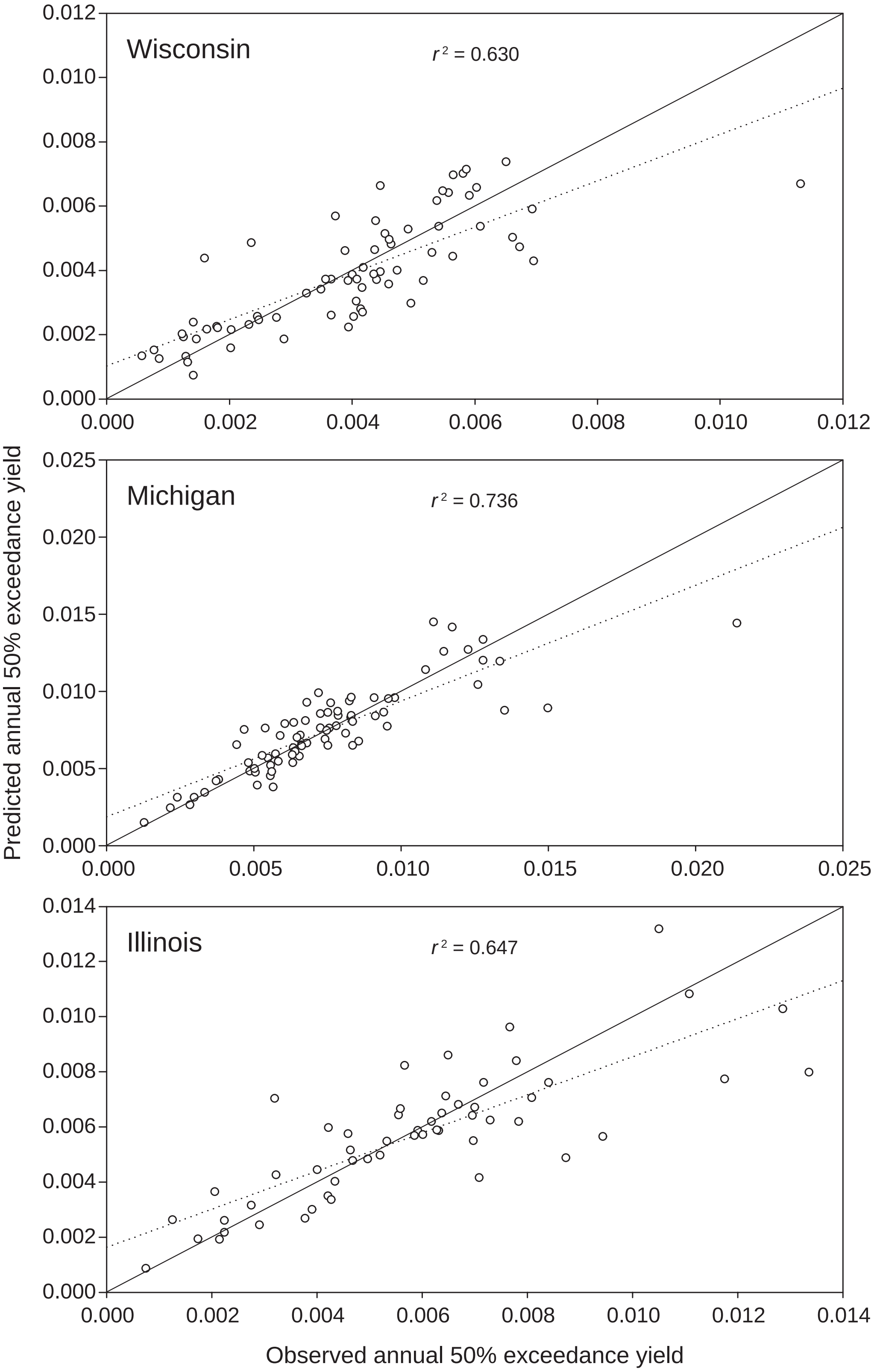

Figure 5.–Relationship between predicted and observed (dashed line) annual 50% exceedance discharge yields for gaged streams in: Wisconsin; Michigan; and Illinois. The ideal 1:1 relationship is shown as a solid line. Predictions were consistently high for low flows and low for high flows. In this comparison, observed data were from the same gage sites used in developing the prediction models.

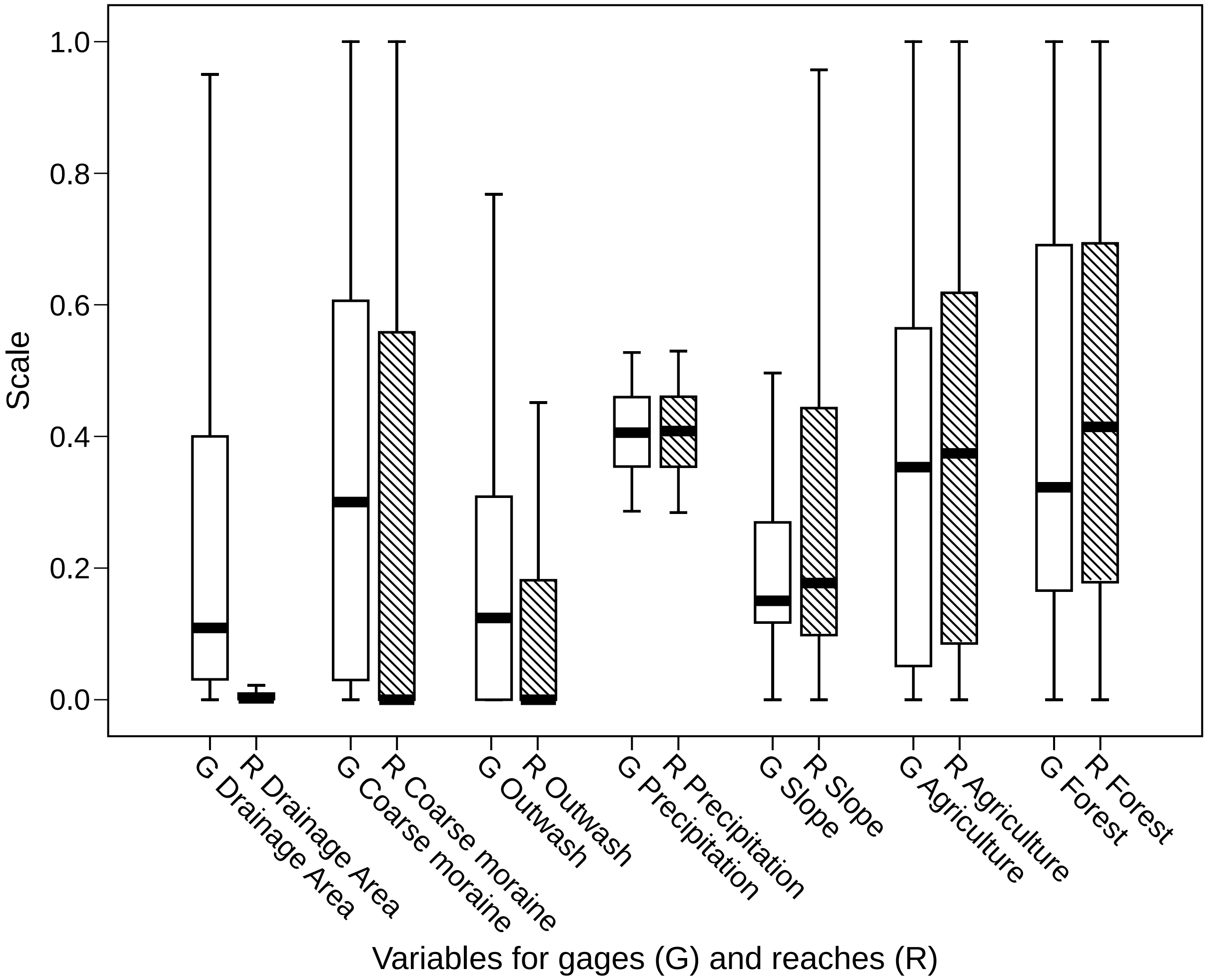

Figure 6.–Comparison of distributions of selected catchment attributes (independent variables) between gaged (G) and total statewide reach (R) populations in Wisconsin. Each comparison is shown as a pair of box and whisker plots. For some attributes, gage means are clearly biased higher than those representing the entire state population, while for other variables gaged reaches appear representive of the statewide reach population.

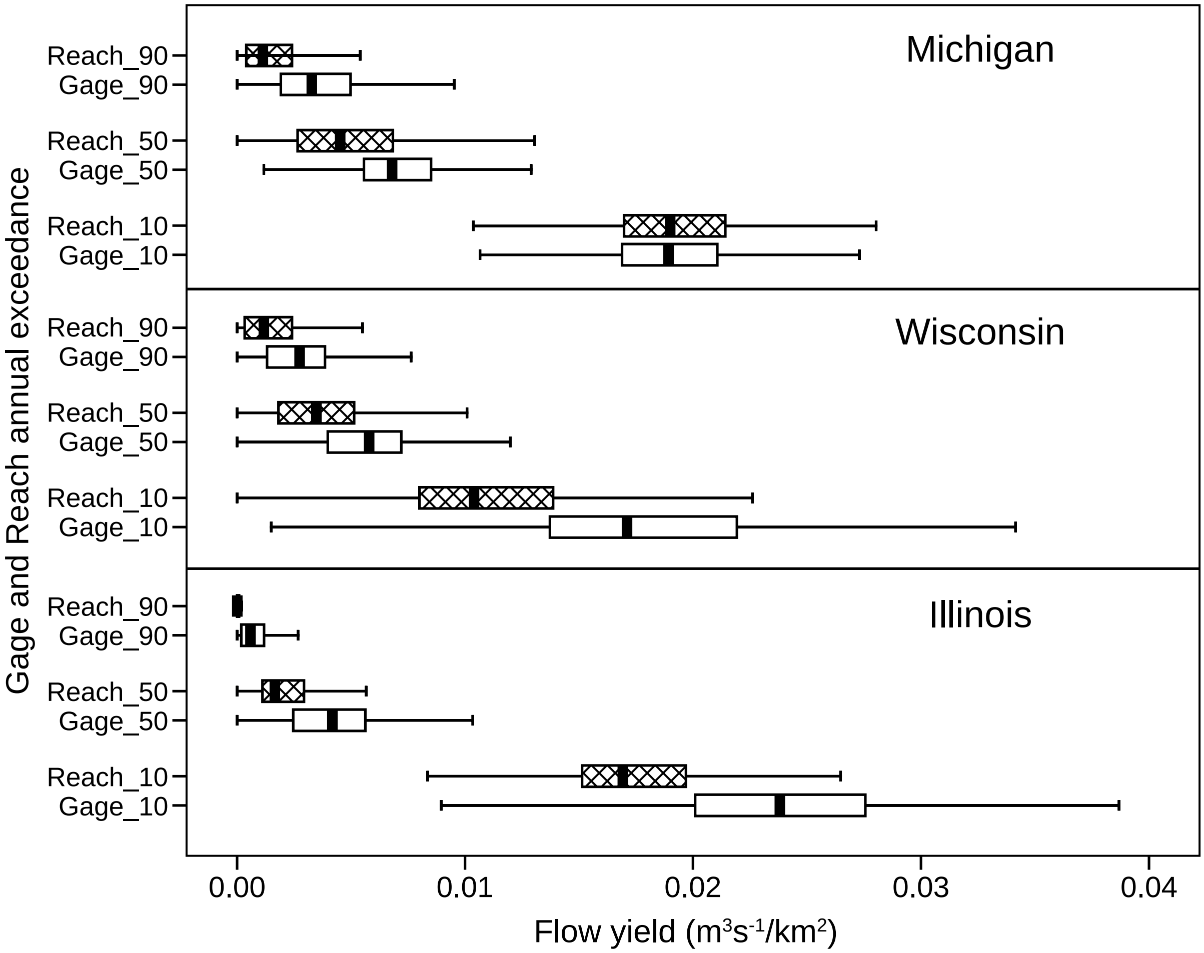

Figure 7.–Comparison of distributions of selected flow exceedance yields (dependent variables) between gaged and total statewide reach populations in Michigan, Illinois, and Wisconsin. The gage sample had consistently higher values than those projected for statewide reach populations.

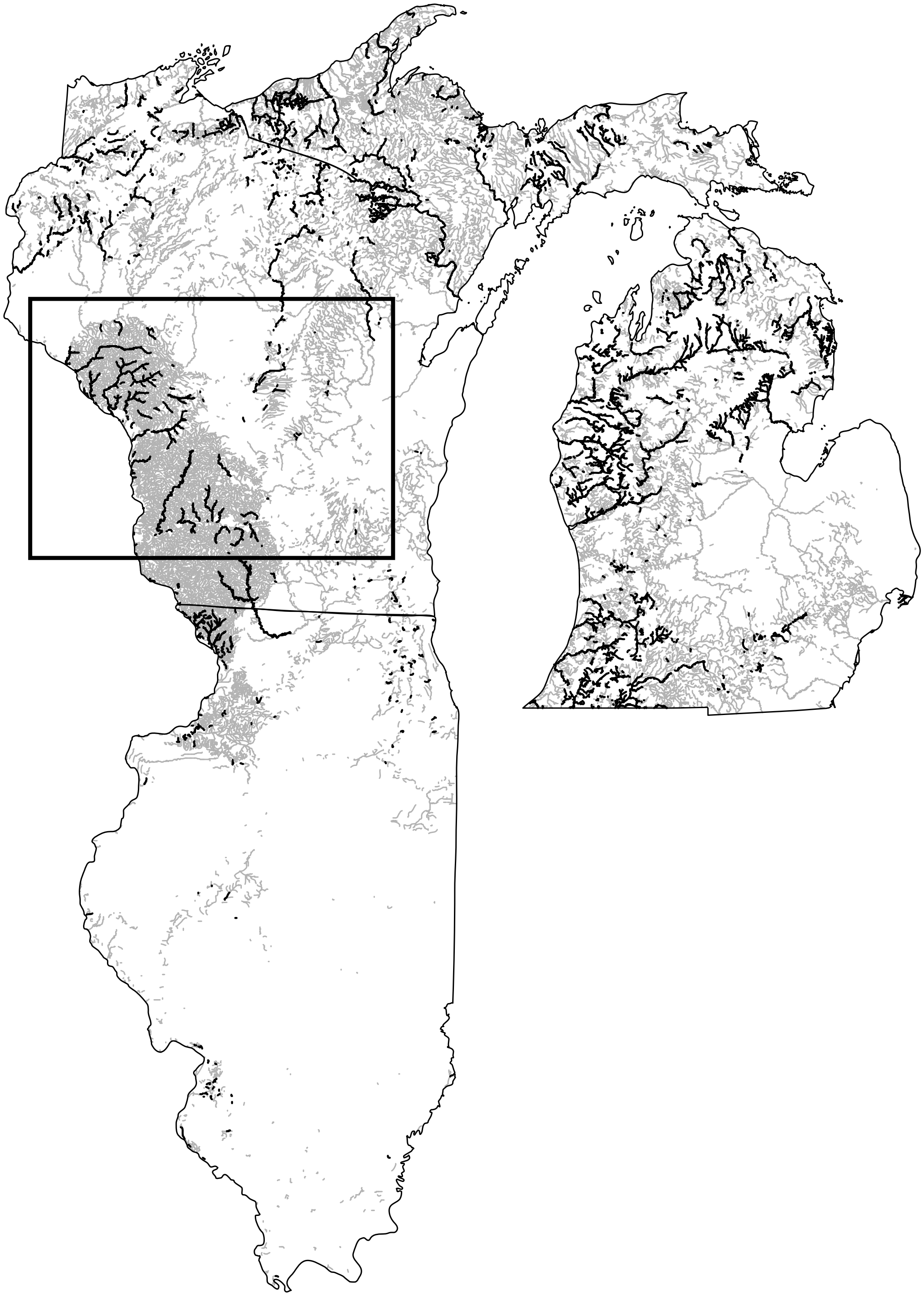

Figure 8.–Map of the base flow riverscape of Illinois, Michigan, and Wisconsin. Shown is predicted annual 90% exceedance discharge yield estimated for all stream reaches (N>100,000) across the three states. The shading scheme is relative to this three-state region and is: black = high yield; and grey = medium yield. Low yield streams are not shown. The boxed area is shown in more detail in Figure 9.

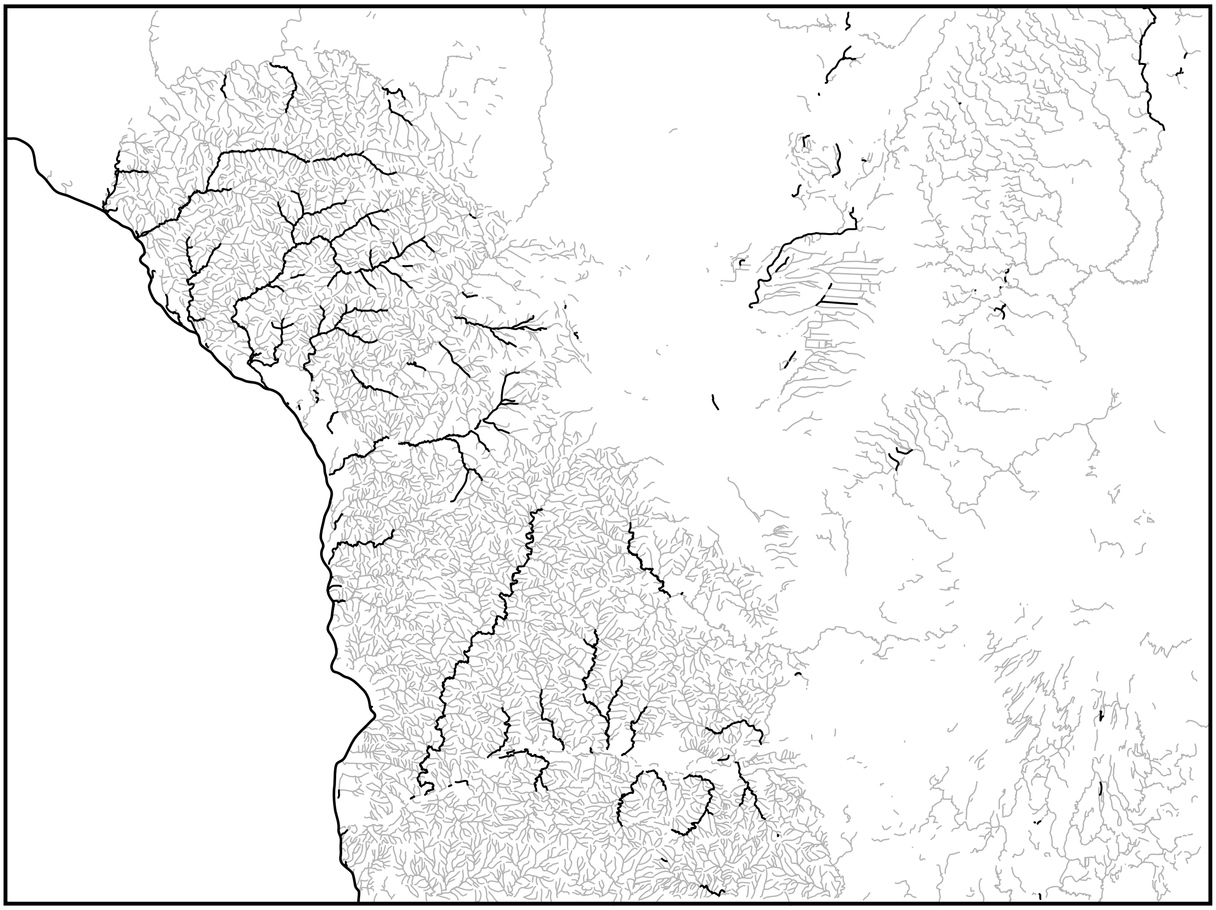

Figure 9.–Map of predicted annual 90% exceedance discharge yield estimated for stream reaches in southwest Wisconsin. The shading scheme is relative to this three-state region and is: black = high yield; and dark grey = medium yield. Low yield streams are not shown.

Table 1.–Multiple linear regression coefficients and statistical metrics for the model run: Michigan, annual 50% exceedance discharge. This is representative of other models.

Dependent variable is: lnQann50.
Cases selected according to MI; 209 total cases of which 133 are missing.
Statistics: r^2 = 97.9%; r^2 (adjusted) = 97.6%; s = 0.248 with 76 – 11 = 65 degrees of freedom.

Source	**Sum of squares**	**df**	**Mean square**	**F-ratio**
regression	184.452	10	18.4452	300
residual	3.99867	65	0.0615179	

Variable	**Coefficient**	**s.e. of Coeff**	**t-ratio**	**prob**
constant	-38.5828	4.567	-8.45	<0.0001
ln(catchment area)	1.08047	0.02212	48.8	<0.0001
ln(mean catchment slope)	0.119119	0.06416	1.86	0.0679
exp(catchment percent outwash sand %)	6.52352	1.333	4.89	<0.0001
ln(mean annual catchment precipitation)	3.28633	0.5598	5.87	<0.0001
exp(catchment percent all coarse textured geology categories)	0.452029	0.1365	3.31	0.0015
exp(catchment percent outwash sand + ice contact gravel)	-5.72608	1.303	-4.39	<0.0001
exp(catchment percent ice contact gravel)	9.26903	2.348	3.95	0.0002
exp(catchment percent agriculture)	-0.402201	0.1364	-2.95	0.0044
exp(catchment percent all medium-textured moraines)	0.372773	0.1134	3.29	0.0016
exp(catchment percent urban)	0.112336	0.3028	0.371	0.7118

Table 2.–R^2 values for all multiple linear regression models run for exceedance discharges across Illinois, Michigan, and Wisconsin. “RD” represents runoff discharge defined as 10–90% exceedance discharges, similar to a flow separation. Lower values for Illinois low flows are shown in boxes. Overall mean = 0.95.

	Annual			April			August		
	IL	MI	WI	IL	MI	WI	IL	MI	WI
RD	NA	NA	NA	0.99	0.96	0.96	0.96	0.97	0.97
5	0.99	0.96	0.96	0.97	0.96	0.95	0.94	0.97	0.94
10	0.98	0.97	0.97	0.98	0.97	0.96	0.95	0.97	0.97
25	0.98	0.97	0.98	0.98	0.97	0.98	0.94	0.97	0.97
50	0.97	0.98	0.98	0.98	0.98	0.98	0.92	0.96	0.96
75	0.93	0.97	0.96	0.97	0.97	0.97	0.78	0.95	0.93
90	0.74	0.96	0.94	0.96	0.96	0.96	0.74	0.94	0.89
95	0.73	0.95	0.91	0.94	0.96	0.95	0.71	0.93	0.88
Mean	0.91	0.97	0.96	0.97	0.97	0.96	0.87	0.96	0.94

Table 3.–Comparison of percent deviation between predicted and observed annual discharges across Illinois, Michigan, and Wisconsin stream gages (same data); based on: 1) full regional model; 2) 3 individual state models; 3) combined ‘macro’ ecoregions; and 4) 3 largest true ecoregions.

	Discharge exceedance			
Geographic scope	10%	50%	90%	Average
Full region	21	33	88	47
Individual states	19	21	49	30
Combined ecoregions	20	23	54	32
Ecoregions	19	20	46	28

Table 4.–Comparison of percent deviation between predicted and observed annual 90% exceedance discharges across Illinois, Michigan, and Wisconsin stream gages using same modeling data vs independent gage set.

State	Same data	Independent data
Michigan	25	52
Illinois	83	303
Wisconsin	39	238
Average	49	198

Table 5a.–Independent variables and their coefficients for multiple linear regression models of annual exceedance discharges across Illinois, Michigan, and Wisconsin. Units of "%" are percent of catchment.

	Annual exceedance discharges						
Variable	lnQann05	lnQann10	lnQann25	lnQann50	lnQann75	lnQann90	lnQann95
Michigan							
constant	-18.8862	-21.8051	-29.1494	-38.5828	-46.0099	-54.2726	-58.2333
ln(drainage area); mi^2	0.9887	1.0082	1.0426	1.0805	1.1362	1.1939	1.2203
ln(slope); degrees	-0.0903	-0.0391	0.0455	0.1191	0.2042	0.2372	0.2157
exp(outwash); %	2.7270	3.5193	5.0473	6.5235	7.4365	8.3623	9.2527
ln(precipitation); in	1.8854	1.9947	2.4601	3.2863	4.0459	4.9669	5.3298
exp(total coarse); %	-0.3185	-0.1632	0.1396	0.4520	0.5719	0.6427	0.6745
exp(outwash/ice contact); %	-3.3512	-3.7759	-4.7141	-5.7261	-6.3868	-7.1676	-7.9570
exp(ice contact); %	4.6625	5.5114	7.3227	9.2690	10.6229	12.0836	13.4301
exp(agriculture); %	-0.1140	-0.1412	-0.2116	-0.4022	-0.6932	-0.9851	-1.1507
exp(medium moraine); %	-0.2509	-0.1000	0.1889	0.3728	0.3873	0.4091	0.4521
exp(urban); %	-0.1570	-0.1619	-0.0168	0.1123	0.1176	0.0713	-0.1092
Wisconsin							
constant	-23.2602	-24.3778	-19.4078	-18.1380	-22.7648	-26.5687	-31.5373
ln(drainage area); mi^2	1.0676	1.0885	1.0923	1.0898	1.1017	1.1674	1.3052
ln(slope); degrees	-0.1330	-0.1121	-0.0424	0.0810	0.1735	0.1564	0.1447
exp(agriculture); %	-0.6063	-0.6063	-0.4916	-0.4576	-0.5186	-0.5914	-0.6694
exp(total open water); %	-1.0441	0.1814	1.8487	2.9623	3.6284	4.3448	5.8213
ln(precipitation); in	3.0699	3.2622	2.6473	2.5702	3.3685	4.5324	6.3409
exp(medium moraine); %	0.2387	-0.0469	-0.7824	-1.2304	-1.4004	-1.7664	-2.0294
exp(peat/muck); %	-0.7611	-1.8168	-3.3480	-4.4379	-5.3407	-8.3368	-13.6839
exp(coarse moraine); %	0.1780	0.0466	-0.2071	-0.4344	-0.6605	-0.8666	-0.9240
exp(lacustrine); %	0.3650	0.1303	-0.3800	-1.0557	-1.6285	-3.3499	-7.4262
exp(fine moraine); %	0.3683	0.2228	-0.1066	-0.4453	-0.7837	-0.9561	-1.0232
exp(urban); %	-0.0034	-0.0153	0.1656	0.5778	1.0519	1.3182	1.6460
Illinois							
constant	-2.8432	-8.1071	-12.3829	-13.9436	-17.5671	-31.7504	-43.2928
ln(drainage area); mi^2	1.0101	1.0586	1.0812	1.1077	1.2185	1.6929	1.9537
ln(slope); degrees	-0.1972	-0.1532	-0.0422	0.0851	0.3596	1.1114	1.0581
exp(coarse moraine); %	0.1853	-0.0523	-0.5132	-0.8811	-1.2744	-1.0542	-1.9459
exp(total open water); %	-5.9037	-1.9040	7.3050	13.9319	24.6835	49.8736	52.3465
exp(total wetland); %	5.7818	4.6152	-2.4996	-8.2953	-17.0256	-40.7260	-34.4817
exp(fine moraine); %	0.1748	0.0321	-0.1733	-0.4102	-0.7707	-0.6469	-1.1990
exp(urban); %	-0.3264	0.1336	0.4258	0.8252	1.7878	4.2820	5.5361
exp(bedrock); %	0.5753	0.5059	0.1654	-0.3713	-1.3182	-1.8877	-2.0536
exp(peat/muck); %	-0.1203	0.6946	2.2125	2.1617	2.6008	7.1110	7.9695
exp(outwash); %	-0.4725	-0.2318	0.0940	0.5621	1.1802	2.2425	2.0970
exp(agriculture); %	-0.3046	0.0001	0.1498	0.2587	0.1063	0.3485	0.4868

Table 5b.–Independent variables and their coefficients for multiple linear regression models of April exceedance discharges across Illinois, Michigan, and Wisconsin. Units of “%” are percent of catchment.

	April exceedance discharges						
Variable	lnQann05	lnQann10	lnQann25	lnQann50	lnQann75	lnQann90	lnQann95
Michigan							
constant	12.9099	10.3545	2.7489	-3.7200	-10.0020	-15.5756	-17.5628
ln(drainage area); mit^2	0.9988	1.0133	1.0314	1.0465	1.0570	1.0687	1.0797
ln(slope); degrees	-0.1859	-0.1131	-0.0119	0.0440	0.0718	0.0651	0.0336
exp(total wetland); %	1.3122	1.2572	1.2649	1.0502	0.8611	0.5983	0.3196
exp(total open water); %	-6.6869	-5.9609	-4.4885	-3.1624	-2.3764	-2.4070	-2.5543
exp(fine moraine); %	0.6651	0.3030	-0.2106	-0.5037	-0.6734	-0.7302	-0.6544
exp(total rocky); %	0.9301	0.8798	0.7628	0.5153	0.2262	0.0022	-0.1919
ln(precipitation); in	0.6302	0.9002	1.5172	2.1850	2.8765	3.6454	4.0868
exp(total coarse); %	1.8365	1.8324	1.6225	1.6330	1.5271	1.5295	1.6062
exp(ice contact); %	-3.9454	-3.7333	-3.2360	-2.9450	-2.7698	-2.7576	-2.8363
exp(coarse moraine); %	-1.5311	-1.5899	-1.5085	-1.6529	-1.7446	-1.7596	-1.8161
exp(dunes); %	-11.6290	-11.4814	-9.8041	-8.8017	-7.3374	-6.4453	-6.5949
exp(lacustrine); %	0.0938	-0.0007	-0.1242	-0.3997	-0.6168	-0.7689	-0.8405
exp(agriculture); %	-0.4937	-0.4327	-0.3767	-0.3559	-0.3982	-0.4564	-0.5874
exp(urban); %	-0.8081	-0.8954	-0.7570	-0.6836	-0.6509	-0.6124	-0.7680
Wisconsin							
constant	-6.6680	-6.5124	-6.2265	-5.5750	-4.9918	-3.3254	-3.3189
ln(drainage area); mi^2	0.9656	0.9783	1.0012	1.0336	1.0606	1.0755	1.0564
ln(slope); degrees	-0.5796	-0.5507	-0.4191	-0.2596	-0.0900	-0.1115	-0.0066
exp(agriculture); %	-0.6894	-0.7339	-0.8466	-0.8820	-0.9658	-1.2405	-1.3015
exp(total wetland); %	6.0617	6.6867	7.3015	6.4110	6.0470	7.1542	7.9572
exp(outwash); %	-1.5111	-1.3141	-0.9998	-0.6760	-0.3153	-0.0315	-0.0467
exp(broken rocky); %	0.6490	0.6503	0.6115	0.4907	0.3901	0.4629	0.4080
exp(forest wetland); %	-1.1453	-2.1521	-3.4067	-3.7827	-4.8470	-7.8970	-8.7721
exp(urban); %	0.3858	0.0831	-0.3458	-0.5398	-0.4362	-0.4916	-0.4146
Illinois							
constant	1.1952	-4.6877	-15.2457	-15.3898	-17.2219	-18.2038	-18.5301
ln(drainage area); mi^2	0.9636	1.0060	1.0559	1.0651	1.0813	1.1148	1.1205
ln(slope); degrees	-0.2213	-0.1966	-0.1202	-0.0985	-0.0507	-0.0366	-0.0803
exp(coarse moraine); %	1.0056	1.6876	3.7280	2.4609	1.7376	1.1817	0.1304
exp(total open water); %	-6.8671	-3.8585	5.0927	13.8218	18.1704	21.6300	28.5014
exp(total wetland); %	4.9785	4.9302	-0.1841	-8.3784	-11.0019	-13.0194	-18.4148
exp(peat/muck); %	0.0345	0.2456	1.4885	2.1774	2.2765	2.2729	2.4794
exp(dunes); %	-0.2502	1.3604	5.0578	3.9413	3.1927	2.0572	0.7983
exp(total coarse); %	-0.6683	-1.5532	-3.8805	-2.9315	-2.3499	-1.9088	-0.9846
exp(fine moraine); %	0.1893	0.0957	-0.0438	-0.1675	-0.3407	-0.4245	-0.5248
exp(agriculture); %	-0.9078	-0.6493	-0.2133	-0.2552	-0.1220	-0.1162	-0.2204
exp(urban); %	-0.7793	-0.5199	-0.0516	-0.0654	0.1572	0.3563	0.3869

Table 5c.–Independent variables and their coefficients for multiple linear regression models of August exceedance discharges across Illinois, Michigan, and Wisconsin. Units of “%” are percent of catchment.

	August exceedance discharges						
Variable	lnQann05	lnQann10	lnQann25	lnQann50	lnQann75	lnQann90	lnQann95
				Michigan			
constant	-30.2939	-37.3397	-45.8002	-52.2497	-57.2783	-59.9669	-60.8190
ln(drainage area); mi^2	1.0308	1.0719	1.1120	1.1633	1.2056	1.2469	1.2708
ln(slope); degrees	0.2042	0.2501	0.3443	0.3500	0.3096	0.2702	0.2607
exp(outwash); %	4.9235	6.0228	7.3469	8.0374	8.9942	10.1253	11.1814
exp(total coarse); %	0.1043	0.2519	0.4353	0.6198	0.7352	0.7781	0.7995
ln(precipitation); in	2.1892	2.8999	3.7380	4.4557	4.9261	5.0977	4.9705
exp(agriculture); %	-0.1692	-0.3490	-0.5352	-0.6814	-0.8915	-1.1191	-1.1969
exp(medium moraine); %	-0.0098	0.1501	0.3188	0.3990	0.4908	0.5278	0.5049
exp(outwash/ice contact); %	-4.6119	-5.4233	-6.3935	-6.8747	-7.6377	-8.6589	-9.5970
exp(ice contact); %	7.2630	8.7494	10.7197	11.7267	13.1206	14.7390	16.1546
exp(peat/muck); %	1.2131	1.1820	1.2889	1.1986	1.1159	0.8679	0.8336
exp(urban); %	1.9025	1.6159	1.0114	0.6203	0.3805	0.1230	0.0939
				Wisconsin			
constant	-2.2793	-2.5238	-1.4222	-1.1840	0.8819	11.3271	14.2363
ln(drainage area); mi^2	1.0363	1.0623	1.0814	1.1117	1.1758	1.3350	1.3603
ln(slope); degrees	0.0600	0.0501	0.0929	0.1834	0.2099	0.0934	0.0194
exp(agriculture); %	-0.6053	-0.4855	-0.3141	-0.2486	-0.2454	-0.3726	-0.5105
exp(lacustrine); %	-0.7868	-1.0824	-1.5953	-2.1997	-4.0163	-8.5318	-9.1399
exp(lakes/ponds); %	-0.6850	0.9660	2.7293	4.0316	5.1251	6.0415	5.1597
exp(coarse moraine); %	-0.0099	-0.1863	-0.3829	-0.5706	-0.7275	-1.0154	-1.3264
exp(peat/muck); %	-1.6012	-2.4809	-4.0596	-5.0846	-6.7524	-13.7946	-14.7285
exp(medium moraine); %	0.0963	-0.2356	-0.7953	-1.2006	-1.5055	-1.9873	-2.0572
exp(fine moraine); %	-0.1661	-0.3612	-0.4683	-0.7190	-0.8967	-1.0854	-1.2115
exp(urban); %	1.7970	1.6696	1.0310	1.3177	1.6469	2.0471	2.1538
				Illinois			
constant	-10.7345	-11.4443	-10.2932	-9.6222	-23.2898	-29.8018	-24.7365
ln(drainage area); mi^2	1.1184	1.1828	1.2202	1.2959	1.6387	1.8821	2.0643
ln(slope); degrees	0.1667	0.1923	0.2113	0.2956	0.5098	0.5769	0.4503
exp(urban); %	2.1025	2.4167	2.3771	2.4253	5.1409	6.6760	7.1087
exp(coarse moraine); %	-0.2884	-0.7876	-1.5034	-2.2362	-2.9796	-3.9305	-4.6347
exp(total forest); %	-0.7383	-1.0722	-2.0544	-3.1762	-2.7554	-3.0637	-3.2561
exp(fine moraine); %	-0.2103	-0.5009	-0.9929	-1.5394	-2.4339	-3.3925	-3.8596
exp(total open water); %	3.3387	5.1929	7.9912	11.3836	20.4906	25.8737	23.9331
exp(medium moraine); %	-0.2501	-0.4012	-0.7661	-1.3201	-2.4305	-3.7276	-3.7294
exp(lacustrine); %	0.5038	-0.3495	-1.4575	-2.4539	-3.2178	-2.2331	-4.4341
exp(agriculture); %	0.7342	0.6836	0.2516	-0.1933	0.9841	1.1986	0.5153

Table 5d.–Independent variables and their coefficients for multiple linear regression models of August and April runoff discharges across Illinois, Michigan, and Wisconsin. Monthly runoff discharges were calculated as the monthly 10% exceedance discharge minus the 90% exceedance discharge. Units of “%” are percent of catchment.

	Monthly runoff discharges					
	August			April		
Variable	IL	WI	MI	IL	WI	MI
constant	-24.923	-3.43151	2.45963	-11.8881	-2.18177	-13.1399
ln(drainage area); mi^2	1.15463	1.00455	1.01848	1.02758	0.971614	0.985054
ln(precipitation); in			1.67256	1.76163		
ln(slope); degrees	0.147713	-0.34596	0.354519	-0.10718	-0.73606	0.041892
exp(total coarse); %	-0.21164	0.225227				
exp(outwash ice contact); %	1.29997			-0.75811	-1.27021	-0.61476
exp(ice contact); %	-8.93718					
exp(fine moraine); %					0.354244	
exp(lacustrine); %	1.06571					0.443346
exp(alluvial/fluvial); %	2.30416			-1.18733		
exp(colluvium); %				-0.64824		
exp(loess); %	1.18715			0.770685		
exp(broken rocky); %		0.765618			0.656681	
exp(attenuated drift); %						0.787112
exp(peat/muck); %	4.02074					-2.28719
exp(total forest); %				-0.65523		1.68325
exp(urban); %	2.55583	0.899805	3.38219	-0.97174	-1.0629	2.64779
exp(forested wetland);%		-8.98881	2.7218	4.113		
exp(total wetland); %		7.06391			3.87881	2.65712
exp(barren); %			-26.2547			
exp(agricultural); %	1.15122	-1.18826	0.342852	-1.08499	-1.07304	1.77811
exp(grassland); %				-1.82527		
exp(lakes/ponds); %	12.8828				-2.26309	

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