A NEW FLASHINESS INDEX: CHARACTERISTICS AND APPLICATIONS TO MIDWESTERN RIVERS AND STREAMS[1]

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ABSTRACT: The term flashiness reflects the frequency and rapidity of short term changes in streamflow, especially during runoff events. Flashiness is an important component of a stream's hydrologic regime. A variety of land use and land management changes may lead to increased or decreased flashiness, often to the detriment of aquatic life. This paper presents a newly developed flashiness index, which is based on mean daily flows. The index is calculated by dividing the pathlength of flow oscillations for a time interval (i.e., the sum of the absolute values of day-to-day changes in mean daily flow) by total discharge during that time interval. This index has low interannual variability, relative to most flow regime indicators, and thus greater power to detect trends. Index values were calculated for 515 Midwestern streams for the 27-year period from 1975 through 2001. Statistically significant increases were present in 22 percent of the streams, primarily in the eastern portion of the study area, while decreases were present in 9 percent, primarily in the western portion. Index values tend to decrease with increasing watershed area and with increasing unit area ground water inputs. Area compensated index values often shift at ecoregion boundaries. Potential index applications include evaluation of programs to restore more natural flow regimes.
(KEY TERMS: stream flashiness; flashiness index; Indicators of Hydrological Alteration; surface water hydrology; watershed management; stormwater management; agricultural hydrology.)

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INTRODUCTION

Streamflows vary in characteristic ways over time frames ranging from hours and days to seasons and years. The pattern of this variation is referred to as the flow regime of a stream (Poff *et al.,* 1997). The flow regime includes such factors as the magnitude and frequency of floods and low flow periods, the seasonal occurrence of various flow rates, the rates of change of flow, and the frequency of flow reversals. The flow regime has multiple impacts on the physical and chemical habitat of a stream and, hence, on the biological communities inhabiting a stream.

The flow regime of a stream reflects the operation of the hydrologic cycle within its watershed. Climate, topography, geology, soils, vegetation, watershed size and shape, stream pattern, land use, water use, and dams all impact the timing and pathways of water movement to and through streams and, hence, the stream's flow regime. Figure 1 illustrates annual hydrographs of two streams with similar drainage areas and precipitation but with distinctly different flow regimes. The Portage River of northwestern Ohio, with its numerous storm runoff peaks having relatively high peak flows and low baseflow, represents a much "flashier" stream than the South Branch of the Au Sable River of northeastern Lower Michigan, with its high baseflow and broader, flatter storm runoff peaks. Land use in the Portage River is dominated by row crop production on soils having high clay content and extensive subsurface drainage. Constructed ditches and channelized tributaries are used to rapidly carry excess water away from cropland. The flow regime of the Portage River is dominated by surface runoff and tile flow. The watershed of the South Branch of the Au Sable River is primarily forested land on sandy soils. Here, the streamflow regime is dominated by ground water inputs, with relatively little surface runoff.

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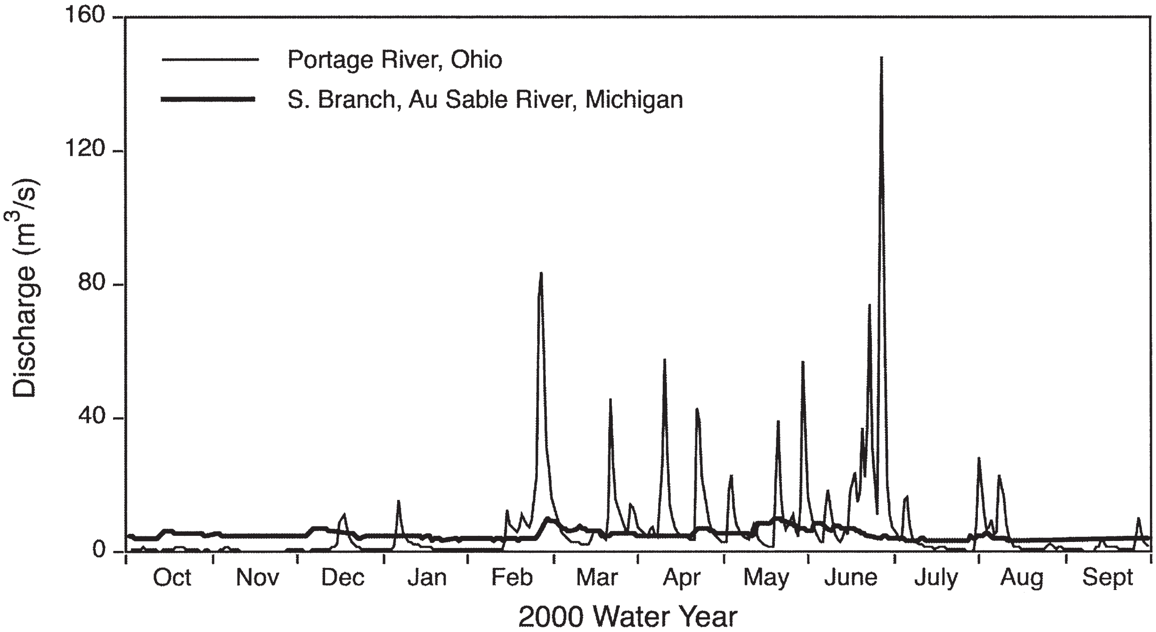

Figure 1. Comparison of Water Year 2000 Annual Hydrographs for a Flashy Stream, the Portage River at Woodville, Ohio, and a Stable Stream of Comparable Size, the South Branch of the Au Sable River near Luzern, Michigan.

There is considerable interest in characterizing the natural flow regimes of streams, that is, their flow regimes prior to significant human alteration of their watersheds (Richter *et al.,* 1996; Poff *et al.,* 1997; Allan *et al.,* 2000). Native flora and fauna in streams and associated riparian zones are adapted to various features of the natural flow regime, and human alteration of flow regimes often impairs these biological communities (Poff *et al.,* 1997). Restoration of more natural streamflow regimes is considered by many to be an essential component of aquatic life restoration efforts in streams (Richter *et al.,* 1996; Graf, 2001).

Human alteration of flow regimes results from two major activities – dam construction and land use change. The onset of operation of a dam generally results in sudden changes in the hydrologic regime of a stream. The most common changes are reductions in the magnitude of high flow events and increases in baseflow (Hirsch *et al.,* 1990; Stanford *et al.,* 1996; Poff *et al.,* 1997; Graf, 2001). Considerable effort is now devoted to learning how to manage water releases from dams so as to restore more natural streamflow regimes downstream and thereby help restore aquatic communities (Stanford *et al.,* 1996; Richter *et al.,* 1998; Magilligan and Nislow, 2001). The hydrologic impacts of both impoundment and restoration of more natural streamflow regimes are relatively easy to detect and to quantify, since the nature of the changes is known, the changes occur at known points in time and the changes are directly managed.

Land use changes, such as conversion of forest and wetlands to cropland and conversion of cropland and forestland to suburban and urban land uses, can also alter streamflow regimes. Likewise, changes in management practices associated with current land uses, such as continuing improvements in agricultural drainage and adoption of conservation tillage, can affect streamflow regimes. Many such changes often occur simultaneously within a watershed. Their cumulative impacts on flow regimes, although possibly substantial and ecologically important, may go unnoticed because they occur gradually. Once the hydrologic impact is noticed, it is typically difficult to determine the relative importance of the different causal factors. The most common effects of changes in land use and land management are increases in stream flashiness and decreases in baseflow (Hirsch *et al.,* 1990; Poff *et al.,* 1997).

Restoration of more natural streamflow regimes is a difficult challenge where the altered regimes are a consequence of altered land use patterns and practices, because the changes are spread across the landscape and involve many stakeholders with diverse interests. However, a variety of land and water management practices are available that could shift flow regimes back toward more natural conditions. These include wetland construction, cropland management to increase infiltration and decrease surface runoff, controlled drainage, use of permeable paving materials in urban and suburban areas, and construction of storm runoff holding basins.

One can expect that restoration of more natural streamflow regimes associated with implementation of such practices will be gradual. However, documenting gradual improvements in streamflow regimes is very difficult (Potter, 1991; Bales and Pope, 2001). Most hydrologic phenomena have high interannual variability. This variability tends to mask trend detection in short time intervals. Furthermore, changes in precipitation amounts, intensity and timing associated with either cyclic weather patterns or climate change could possibly mask effects of improved management practices (Hirsch *et al.,* 1990).

We have developed a new hydrologic index that appears relatively well suited to track gradual changes in stream flashiness. Following a brief review of indices frequently used to characterize flow regimes and flashiness, several characteristics of the new index are described, regional applications of the index are illustrated, and it is compared with some other indices.

SOME FLOW REGIME AND FLASHINESS INDICES

A variety of indices have been developed to describe natural flow regimes, their degree of alteration, and progress in their remediation. These include standard hydrologic analyses such as flood frequency and low flow recurrence analyses (Dunne and Leopold, 1978). Richter *et al.* (1996) developed a set of 33 indices, the Indicators of Hydrological Alteration (IHA) that are deemed to be particularly relevant to aquatic communities. These 33 indices fall into five categories: monthly average magnitudes, magnitude and duration of annual extreme conditions, timing of annual extreme conditions, frequency and duration of high and low pulses, and rate and frequency of change in flow conditions. In their analyses of changes in streamflow regimes in North Carolina, Bales and Pope (2001) included the use of 10-day and 12-month moving range values and separation of baseflow and runoff, with separate analyses of each.

The term "flashy," as applied to streamflow, has no set definition and in general applies to a set of characteristics. In Poff *et al.* (1997), flashiness is equated with the rate of change in flow – flashy streams have rapid rates of change and stable streams have slow rates of change. In a classification of unregulated streams in the United States (Poff, 1996), the class "perennial flashy" included rivers with high flow variability (coefficient of variation in daily flows), high flood frequency, and low seasonality for both floods and low flow events. In Burges *et al.* (1999), increased flashiness was equated with increased magnitude of flood peaks relative to wet season baseflow, increased rate of storm flow recession, and decreased duration of time that the mean discharge rate is exceeded. While Richter *et al.* (1996) do not use the term "flashiness" for any of the IHA parameters, several of them, such as average rate of flow increase or decrease, frequency and duration of high pulses, and number of flow reversals, reflect the general concept of stream flashiness.

Concerns about, and analyses of, stream flashiness extend to programs that measure and model nonpoint source pollutant transport in streams. Richards (1990) developed a flow based classification of Great Lakes tributaries for use in planning monitoring programs for quantification of tributary loading. In that scheme, various ratio and spread measurements of flow duration (exceedency) data were used to characterize the flow responsiveness or flashiness of tributaries. Ratio measurements included the ratios of flows exceeded 10 percent of the time to flows exceeded 90 percent of the time, 20 percent of the time to 80 percent of the time, and 25 percent of the time to 75 percent of the time. Spread measurements included the differences between the 25th and 75th percentile flows, the 20th and the 80th percentile flows and the 10th and 90th percentile flows, each normalized by the median flow. Richards (1989) used these types of measurements to assess sampling frequency needs relative to pollutant load estimation. Robertson and Roerish (1999) used the ratio of the flows exceeded 5 percent of the time to flows exceeded 95 percent of the time as a flashiness index for evaluating sampling strategies for small streams.

The Richards-Baker Flashiness Index

In connection with a recent study to model peak herbicide concentrations during storm events in Midwestern rivers, a new flashiness index was developed and evaluated (Gustafson *et al.,* 2004). That index involved calculation (Equation 1) of the length of the line tracing the annual hydrograph, such as those shown in Figure 1. This pathlength was then normalized by dividing it by the median daily flow during the study period, and by the length of the study period. This index is referred to as the Richards Pathlength (Gustafson *et al.,* 2004):

$$L_R = \frac{\sum_{i=1}^{n} \sqrt{\left(q_i - q_{i-1}\right)^2 + \left(t_i - t_{i-1}\right)^2}}{\left(t_n - t_0\right) * \tilde{q}} \qquad (1)$$

where q is mean daily flow, t is time, and $\tilde{q}$ is the median of the mean daily flows. In typical applications, $(t_i - t_{i-1})$ is always equal to one day.

We have subsequently modified the Richards Pathlength to the form shown in Equation (2). Inclusion of the x-axis (time) in the Richards Pathlength (Equation 1) has the effect of adding to the calculation of each segment of the pathlength a constant (one day) whose impact on the total pathlength varies depending on the magnitude of the y-axis (flow) values. Furthermore, the units of the pathlength in Equation (1) are undefined, since the x-axis and y-axis have different units. Consequently, the x-axis component of the length of the annual hydrograph has been dropped and the index is computed from the magnitude of the oscillations in flow along the y-axis alone. The pathlength is equal to the sum, usually over one year, of the absolute values of day-to-day changes in daily discharge volumes (or mean daily flows). The index is derived by dividing this pathlength by the sum of the daily discharge volumes (or mean daily flows) for the year, as shown in Equation (2). The resulting index is dimensionless and its value is independent of the units chosen to represent flow. In particular, the value of the index is the same whether the values of q are treated as daily discharge volumes (m^3) or as average daily flows (m^3/s).

$$R - B\ Index = \frac{\sum_{i=1}^{n} |q_i - q_{i-1}|}{\sum_{i=1}^{n} q_i} \qquad (2)$$

We refer to the new index as the Richards-Baker Flashiness Index (abbreviated as R-B Index), reflecting its derivation from the Richards Pathlength. It measures oscillations in flow (or discharge) relative to total flow (or discharge), and as such, appears to provide a useful characterization of the way watersheds process hydrologic inputs into their streamflow outputs. Relative to the Richards Pathlength, and many other hydrologic indicators, the R-B Index has much less annual variability, as reflected in its coefficient of variation, and reveals many more trends in discharge data.

METHODS

Flow Data

Mean daily streamflow data were obtained from the U.S. Geological Survey (USGS, 2004) for 515 stream gage sites from six Midwestern states – Illinois, Indiana, Iowa, Michigan, Ohio, and Wisconsin. A listing of all 515 stream gaging stations included in the study is available (Heidelberg College, 2003). Streams used to illustrate specific features of the R-B Index are listed in Table 1, along with their corresponding areas and R-B Index values.

Streams were selected based on the availability of daily records beginning on or before October 1, 1974, and extending through September 30, 2001 (September 30, 2000, for Michigan streams). Thus, the study period consisted of 27 water years beginning with the 1975 Water Year (26 water years for Michigan streams). A starting date of October 1, 1974, was selected because that date coincided with the onset of detailed tributary loading studies for the Lake Erie basin (Baker, 1993). Changes in land use and adoption of agricultural best management practices (BMPs) since that time were recently analyzed in connection with evaluations of the effectiveness of agricultural nonpoint pollution control programs in the Lake Erie basin (Richards *et al.,* 2002a,b). The current work was initiated to determine whether adoption of those same BMPs might have also been accompanied by reductions in the flashiness of area streams.

The study includes stations with watersheds ranging in size from 8.5 km^2 to 28,813 km^2. The stations are not all independent of one another – some of the stations are nested within larger watersheds, and multiple stations are included on single rivers. Streams were excluded if available station descriptions (Indiana, Michigan, and Ohio) indicated extensive flow regulation from upstream impoundments. Continental scale rivers, such as the Mississippi, Missouri, and Ohio, were also excluded. Since most large rivers have some degree of flow regulation, along with water withdrawals and wastewater flows, some index values are impacted by factors other than the combinations of natural watershed factors, associated land use factors, and climate. Because of gaps in some of the records, fewer than 515 rivers were available for some of the analyses.

For selected streams, longer term records were examined using daily data for the entire period of record. In addition, hourly stage and flow data were obtained directly from the state offices of the USGS for selected streams to assess the effects on pathlength values of using hourly rather than average daily flow volumes. To compare R-B Index values and low flow discharges, the 90^{th} percentile flow exceedency values for the period of record were chosen to represent low flow discharges.

TABLE 1. Streams Used for Illustrating Various Features of the R-B Index. Streams are listed alphabetically by state and alphabetically by stream name within each state.

Stream	USGS No.	State	Area (km^2)	R-B Index
McDonald Creek near Mount Prospect	05529500	Illinois	20.5	0.667
Rock River at Rockton	05437500	Illinois	16,480	0.052
Spoon River at London Mills	05569500	Illinois	2,776	0.266
East Fork Whitewater River at Abington	03275600	Indiana	518	0.470
Kankakee River at Dunns Bridge	05517500	Indiana	3,004	0.050
Little Sioux River at Linn Grove	06605850	Iowa	1,548	0.111
Augusta Creek near Augusta	04105700	Michigan	101	0.081
Clinton River near Fraser	04164000	Michigan	1,150	0.273
Paw Paw River at Riverside	04102500	Michigan	1,010	0.054
Pine River near Rudyard	04127918	Michigan	477	0.182
Rifle River near Sterling	04142000	Michigan	829	0.141
South Branch Au Sable River near Luzerne	04135700	Michigan	1,039	0.043
Honey Creek at Melmore	04197100	Ohio	386	0.480
Killbuck Creek at Killbuck	03139000	Ohio	1,202	0.185
Maumee River at Waterville	04193500	Ohio	16,395	0.267
Mill Creek near Bellepoint	03220000	Ohio	461	0.651
Portage River at Woodville	04195500	Ohio	1,109	0.494
Rock Creek at Tiffin	04197170	Ohio	89.6	0.803
Sandusky River near Fremont	04198000	Ohio	3,240	0.374
Unnamed Tributary to Lost Creek near Farmer	04185440	Ohio	11.0	0.966
Whiteoak Creek near Georgetown	03238500	Ohio	565	0.954
White River at West Hartford	01144000	Vermont	1,787	0.260

Land Use and Land Cover in the Study Area

Cropland is the dominant land use in four of the six states of the study area (Table 2). Only in Wisconsin and Michigan does forest land exceed cropland. In these two states, the forest land is most concentrated in the northern regions, while cropland is the dominant land use in the southern portions. For Illinois, Indiana, and Iowa, the forest land that is present is more concentrated in the southern portions of these states. In Ohio, forestland is more concentrated in the eastern and southern portions of the state. In the land cover/use classification used in the National Resource Inventory by the Natural Resources Conservation Service, developed land includes urban, industrial, suburban, transportation, and recreational areas, such as golf courses. Major metropolitan centers in the study area include Chicago, Milwaukee, Detroit, Cleveland, Columbus, Cincinnati, and Indianapolis. For many of the watersheds in the study area, land use is dominated by row crop production, with minimal impacts from urban and other land uses.

TABLE 2. Overview of Land Cover/Use in the Six-State Study Area.

State	Cropland (percent)	Pasture Land (percent)	Forest Land (percent)	Other Rural (percent)	Developed (percent)	Federal (percent)
Illinois	68	7	11	4	9	1
Indiana	58	8	17	5	10	2
Iowa	72	10	6	7	5	0
Michigan	24	6	44	7	10	9
Ohio	45	8	27	5	14	1
Wisconsin	31	9	41	7	7	5

Data from 1997 National Resource Inventory, Natural Resources Conservation Service (USDA-NRCS, 2004).

Calculation of the R-B Index

For most applications, the R-B Index was calculated using Equation (2). To investigate the relationship between daily pathlength and average daily discharge (see below), Equation (3) was used instead since it centers the pathlength over the same time period as the average daily flow. The values of the annual index are the same with either Equation (2) or (3). The index can be calculated for seasonal as well as annual time periods.

$$R-B\ Index = \frac{\sum_{i=1}^{n} 0.5\left(|q_{i+1}-q_i| + |q_i - q_{i-1}|\right)}{\sum_{i=1}^{n} q_i} \qquad (3)$$

Calculation of Other Indices

For 100 streams, the 33 indices included by Richter *et al.* (1996) in their IHA were calculated for comparison with the R-B Index. These streams were randomly selected from among the 446 streams that had no data gaps during the study period. Software for calculating the IHA parameters (Version 5, July 2001) was provided by The Nature Conservancy in cooperation with Smythe Scientific Software. The indices are described in the results section. The general method for calculation of each index is evident from the name of the particular index and is described in more detail in the users manual that accompanies the above software (The Nature Conservancy, 2001). The software includes programs that calculate index values for each year, coefficients of variation among annual values, and trend slopes and probabilities within the time period.

We also calculated annual coefficients of variation for daily discharge (CVD) for each of the above 100 streams. The CVD was used by Poff (1996) in his characterization of unregulated streams in the United States. The CVD and R-B Index use exactly the same data in their calculation. However, the R-B Index incorporates the daily sequence of flows whereas the CVD uses the daily flows without regard to their temporal sequence.

RESULTS AND DISCUSSION

Some General Characteristics of the R-B Index

The Relationship Between Annual Pathlength, R-B Index, and Annual Discharge. The relationship between annual pathlengths and annual discharges is shown in Figure 2 for Portage River (Ohio) over the 27-year study period. Annual discharges ranged from 132.1 to 553.0 million m^3, while annual pathlengths ranged from 50.0 to 283.8 million m^3 during the study period. Annual pathlengths are highly correlated with the annual discharges (r^2 = 0.898). The relationship between the corresponding R-B Index values and annual discharge is also shown in Figure 2. Index values have less variability, ranging from 0.36 to 0.54, and are largely independent of the annual discharge (r^2 = 0.011).

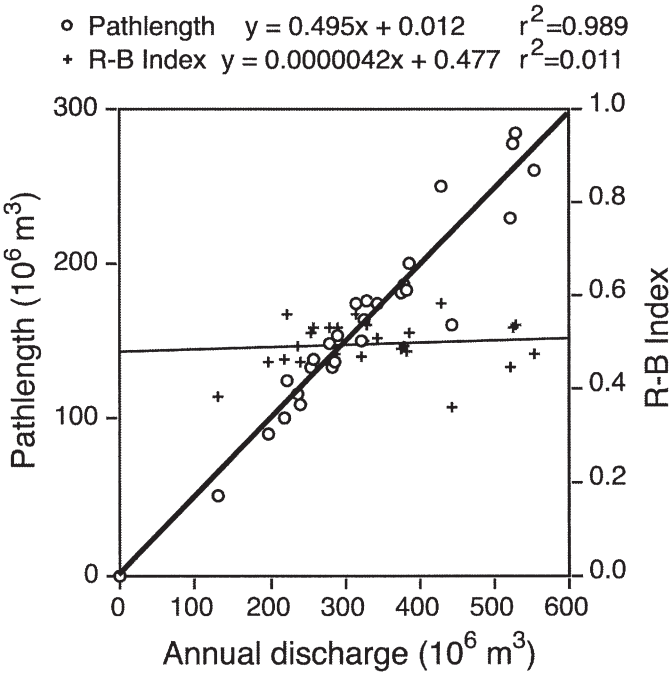

Figure 2. Annual Values of Pathlength and R-B Index in Relation to Annual Discharge for the Portage River at Woodville, Ohio, During Water Years 1975 Through 2001.

R-B Index in Relation to Watershed Area. The relationship between the magnitude of the R-B Index and watershed area is shown in Figure 3. Here, the averages of the annual index values over the study period have been plotted in relation to watershed area for each of 515 stream gaging sites. The graph indicates that R-B Index values tend to decrease with increasing watershed size. These results reflect the common observation that small streams are flashier than large streams. Decreasing flashiness with increasing watershed size is to be expected as a consequence of hydrograph mixing accompanying flood routing through stream networks and other scale dependent runoff factors (Baker and Richards, 2000).

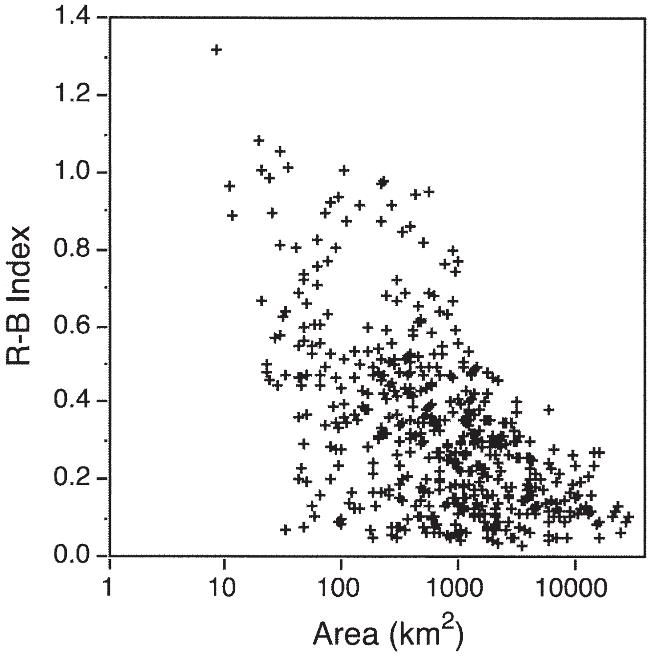

Figure 3. Relationship Between 27-Year Average R-B Index Values and Watershed Area for 515 Streams in the Six-State Area.

The extent of this scale effect is masked, in part, by the use of mean daily flows in the calculation of annual pathlengths. As watersheds become smaller, the use of mean daily flows increasingly underestimates the actual pathlength of flow oscillations associated with storm runoff. The extent of these underestimates was examined for five streams of varying watershed size in northwestern Ohio. For these watersheds, hourly flow data for the 2000 Water Year were used to calculate pathlengths and the resulting values were compared with pathlengths based on mean daily flows (Table 3).

The ratios of hourly to mean daily pathlengths dropped from 3.44 to 1.14 with increasing watershed areas for the first four streams shown in Table 3. Since mean daily flows are based on hourly or more frequent data, total discharges are not affected. Consequently, the R-B Index would increase by the ratio of the pathlengths. The relationship of decreasing ratios with increasing watershed area did not apply to the Maumee River, where the ratio of 1.69 was almost as large as for the much smaller Rock Creek site. Comparisons of hydrographs based on hourly and mean daily flow show that this unexpectedly high ratio was a consequence of diurnal oscillations at low flow, which are pronounced in the Maumee River but absent from the other four streams.

The choice of whether to use hourly or average daily flow values in the calculation of the R-B Index depends on the particular application. Where diurnal fluctuations in flow are present and of importance for the issue at hand, hourly data should be used. Similarly, when making comparisons of the absolute values of the R-B Index among large and small watersheds, the effects of using hourly versus daily flow measurements for small watersheds should be considered.

The Stable to Flashy Continuum. One way to classify streams is to place them on a continuum ranging from superstable ground water based streams at one end to very flashy streams at the other. The R-B Index is one quantitative measure that can be used to establish such a continuum. In Figure 4, 27-year average index values are represented by box plots for each of six ranges of watershed size. For a given size range, stable streams are characterized by low index values and flashy streams by high index values. Note that an index value of 0.25 for a stream with a watershed area greater than 7,770 km^2 would place that stream at the flashy end of the continuum, while the same index value for a stream with an area less than 77.7 km^2 would place it in the stable end. The box plots divide the range of R-B values into quartiles, with the first quartile having the most stable streams and the fourth quartile having the most

TABLE 3. Effects of Using Hourly Rather Than Daily Flows on Magnitude of Annual Path Lengths for Stations of Varying Drainage Areas in Northwestern Ohio. Stations are arranged in order of increasing drainage area.

Stream	Drainage Area (km^2)	Pathlength Based on Daily Average Flows (10^6 m^3)	Pathlength Based on Hourly Flows (10^6 m^3)	Pathlength Ratio (hourly/daily)
Unnamed Tributary to Lost Creek	10.96	3.3	11.4	3.44
Rock Creek	89.6	19.4	34.6	1.78
Honey Creek	386	48.8	68.4	1.40
Sandusky River	3,240	298.2	337.8	1.14
Maumee River	16,480	980.7	1,660.9	1.69

flashy. These quartile groupings are used to reduce the effects of watershed area on index values in subsequent mapping of stream flashiness.

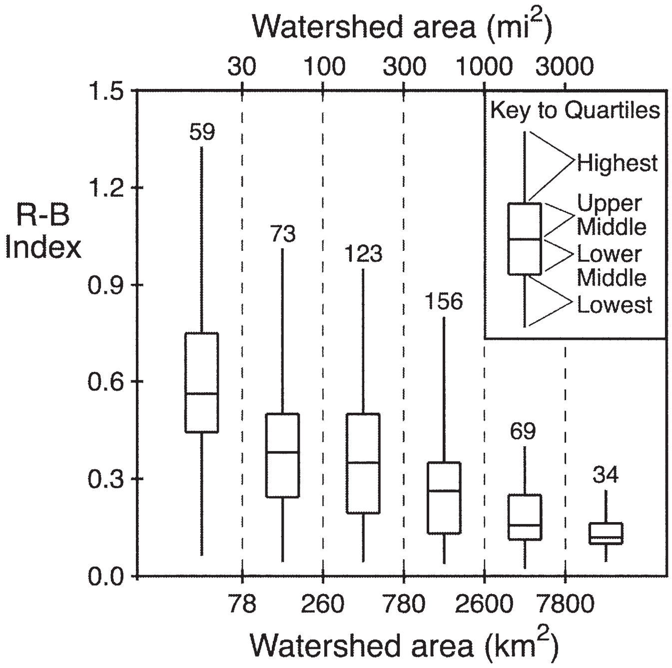

Figure 4. The Distribution of R-B Index Values for Streams in Six Size Classes of Watersheds, Showing Quartiles of Index Values Along the Continuum of Stable to Flashy Streams. The whiskers of the box plots shown here extend to the maximum or minimum values, unlike some forms of box plots that may identify certain values as "outliers."

Contributions of High Flow Periods to Pathlength. The pathlength component of the R-B Index makes the index sensitive to the frequency and magnitude of storm events. To evaluate the role of high flow periods in determining the magnitude of the pathlength, the relationship between the percentage of time flows were exceeded at a gaging station and the percentage of the total pathlength associated with those flows was examined. Specifically, the pathlength was calculated for each day for six consecutive water years (1996 through 2001 or 1995 through 2000) for selected streams. Then the mean daily flows and associated daily pathlengths were sorted by decreasing flow. The percent of time flows were exceeded was calculated. The cumulative pathlength was determined for the ranked flows, and the percentage of the total pathlength determined in relation to the ranked flows.

In Figure 5a, the relationship between the percent of total pathlength and the percent of time flows were exceeded is illustrated for four streams of varying size in northwestern Ohio. All of these streams have high R-B Index values, relative to their areas (Table 1). It is evident from the graph that high flows (low percent exceedencies) are primarily responsible for the magnitude of the pathlength. Figure 5a also illustrates that, as watersheds become smaller, greater proportions of the total pathlength occur at low percent flow exceedencies. For example, flows exceeded 10 percent of the time accounted for 74 percent of the total pathlength for Rock Creek, 62 percent for Honey Creek, 57 percent for the Sandusky River, and 44 percent for the Maumee River.

In Figure 5b, the same relationship is illustrated for four streams with relatively low R-B Index values and with watershed areas paired closely with the northwestern Ohio streams. For the Rock River, USGS station descriptions noted some regulation at low flows, while for the other streams, flow regulation was not mentioned. For three of these streams, the role of high flow periods in determining the pathlength was not as pronounced as for comparably sized streams shown in Figure 5a. Only the Pine River had a curve similar to its size match (Honey Creek) in Northwestern Ohio. Flows exceeded 10 percent of the time accounted for 28 percent of the pathlength for Augusta Creek, 59 percent for the Pine River, 20 percent for the Kankakee River, and 26 percent for the Rock River. Even in these less flashy streams, the high flows affect the pathlength value more than the lower flows. In contrast to the flashy streams described above, where the relationships between percent of total pathlength and percent of flow exceedency shifted systematically in relation to watershed size, watershed scale effects were not evident in this set of streams. The lack of scale effects in these more stable streams may reflect their lack of geographic proximity, in contrast to the flashier Ohio streams.

Relationships Between Low Flow Discharges and R-B Index Values. To evaluate the relationship between R-B Index values and low flow discharges of streams, the 90 percent flow exceedency values were used as representative of low flow discharges. These exceedency values were obtained for the period of record for each station from Indiana, Michigan, and Ohio. Since the absolute values of the 90 percent exceedency flows depend, in part, on watershed size, those values were divided by the watershed area to obtain a unit area 90 percent flow exceedency value in $m^3/s/km^2$. In Figure 6, the average annual R-B Index values are plotted in relation to these unit area low flow discharges. Streams with high unit area low flow tend to have low R-B Index values. High unit area low flows generally occur in locations with high infiltration rates and associated high ground water inputs. These same areas are likely to have low rates of surface runoff. Both of these factors tend to reduce pathlengths relative to total discharge. The data in Figure 6 also indicate that there is considerable variation in R-B Index values for streams with similar unit area low flows, especially in the smaller ranges of low flow values.

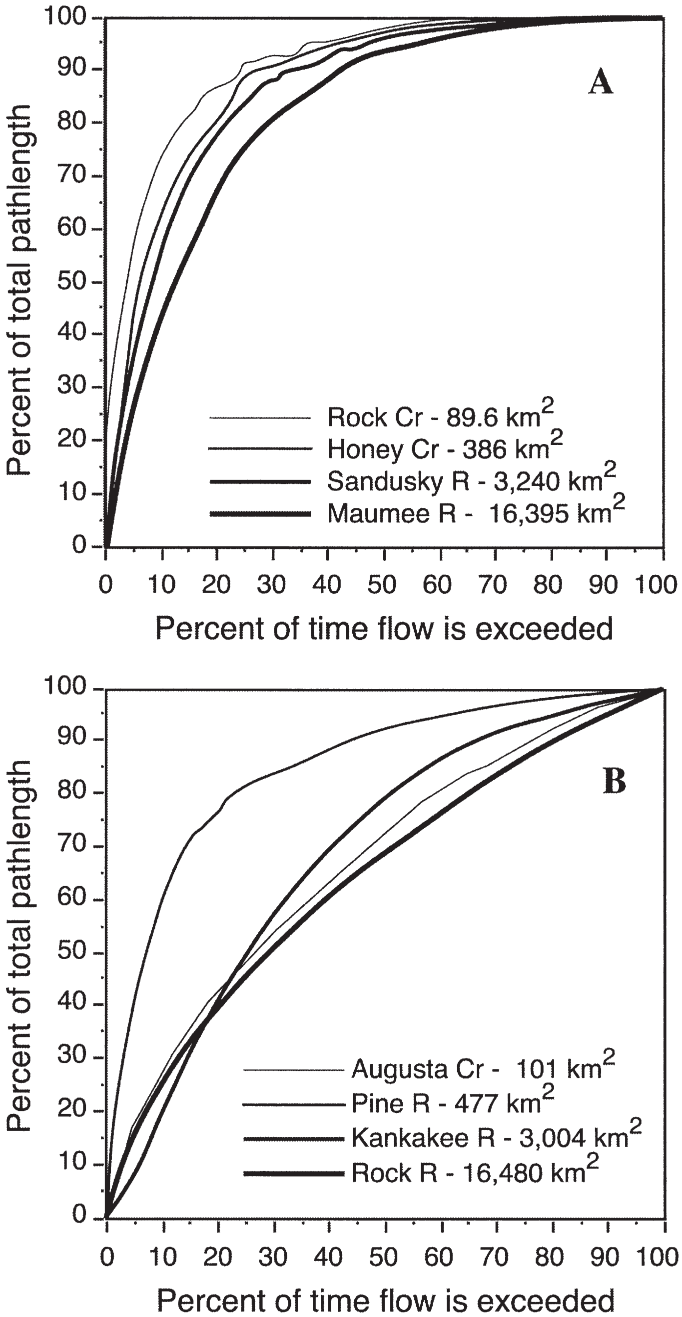

Figure 5. Relationships Between the Percent of Time Flow is Exceeded and the Cumulative Percentage of the Total Pathlength for the Six-Year Period Including Water Years 1996 Through 2001. Figure 5a includes four streams in northwestern Ohio with high R-B Index values, while Figure 5b includes four streams with low R-B Index values.

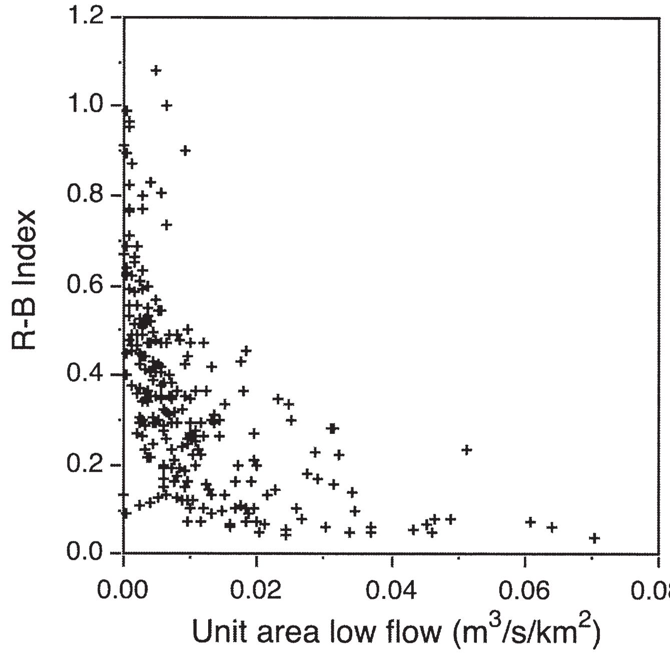

Figure 6. Relationship Between the 27-Year Average R-B Index Values and Low Flow Discharges for Streams in Indiana, Michigan, and Ohio.

Trends in R-B Index Values. An important feature of the R-B Index is that statistically significant trends may be present in the index, while statistically significant trends are absent from the quantities used to calculate the index. This is illustrated in Figure 7 using the same data as presented in Figure 2 for the Portage River. Over the study period, the slope of the regression of annual discharge on time is negative. Due to the large variability in annual discharge, the decrease is not statistically significant ($r^2 = 0.011$, $p = 0.690$). The slope of annual pathlength with time is positive. Again, the annual variability is large, and the increase is not statistically significant ($r^2 = 0.003$, $p = 0.784$). However, the R-B Index values calculated from these same annual pathlengths and annual discharges increase with time, and that increase is statistically significant ($r^2 = 0.194$, $p = 0.022$). R-B Index values calculated from the regression equation indicate that the index value in 2001 was 15.9 percent higher than the value in 1975.

Trend lines for five other streams, along with the Portage River, are shown in Figure 8. All six streams have increasing trends in index values that are significant at the 95 percent confidence level ($p < 0.05$). Three streams with significant decreases ($p < 0.05$) in R-B values during the 1975 through 2001 period are shown in Figure 9. As a group, streams with significant decreases in R-B Index values have larger coefficients of variation and larger magnitudes of decrease.

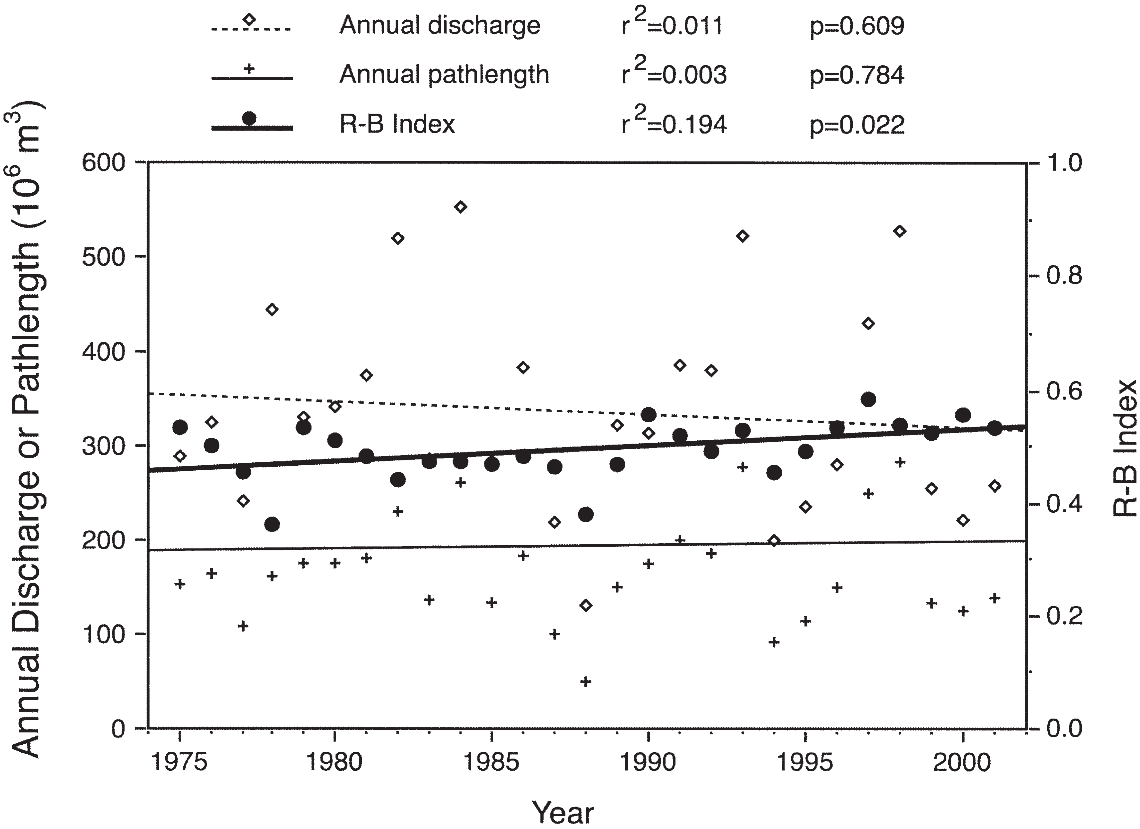

Figure 7. Time Trends for Annual Discharge, Annual Pathlength, and Annual R-B Index Values in the Portage River for the 1975 Through 2001 Water Years.

Trend directions and significance levels for 507 streams in the study area are summarized in Table 4. R-B Index values increased in 303 streams and decreased in 204 streams. The increases were significant at the $p < 0.1$ level in 141 streams and decreases were significant at that level in 59 streams.

Size of Changes in R-B Index Values. The size of the changes in R-B Index values and the statistical significance of the trends are distinct but related characteristics. Equations for the linear regressions of index values versus year were used to calculate an initial (1975) index value and final (2000 or 2001) index value for 484 streams. Changes are expressed using the final value as a percentage of the initial value. A histogram showing the direction and sizes of changes in these streams is shown in Figure 10. Each bar of the histogram indicates the number of stations having either significant changes ($p < 0.1$) or nonsignificant changes ($p > 0.1$) for that particular 10 percent range of change. For samples with statistically significant increases ($p < 0.1$), the median increase was 21.9 percent over the time interval, while for samples with statistically significant decreases, the median decrease was 33.5 percent. The smallest increase that was significant ($p < 0.1$) was 9.9 percent (109.9 percent), while the smallest decrease significant at that level was 13.1 percent (86.9 percent). At the present time, the ecosystem significance of changes in the R-B Index of the magnitudes shown in Figure 10 is unknown.

Some Longer Term Trends for Selected Rivers. Longer term trends in R-B Index values for selected streams have been examined. Examples of five streams are shown in Figure 11. For all of these streams, statistically significant changes in the R-B Index have occurred during the extended period of record. In several cases, significant decreases during the earlier portion of the period of record have been followed by more recent significant increases. LOWESS curves have been used to smooth the data and thereby illustrate the general pattern of any changes.

Long term data for the Maumee River (Figure 11a) indicate slightly decreasing R-B Index values from the 1920s through the mid-1970s, followed by a rather sharp, statistically significant increase through the present time. The causes of these index changes are unknown.

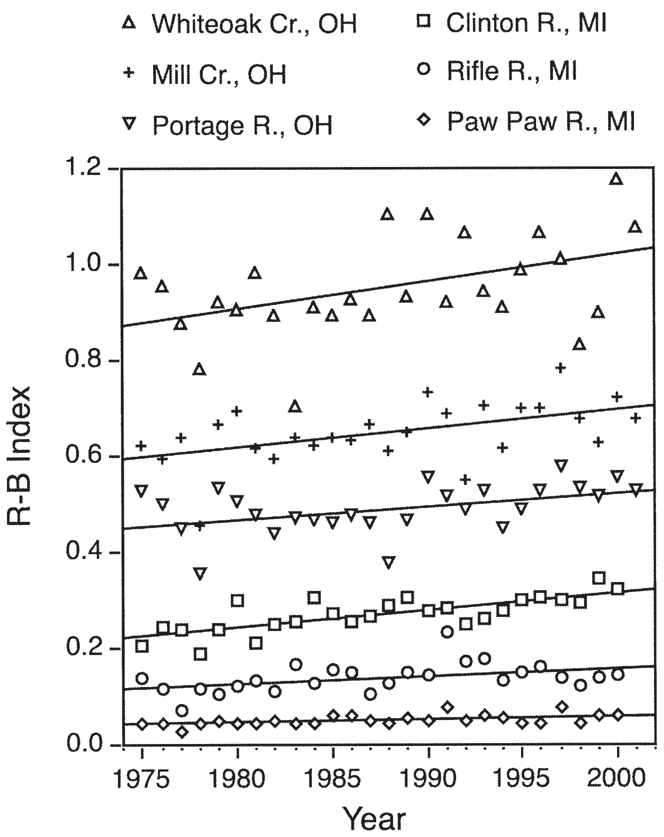

Figure 8. Time Trends in R-B Index Values for Six Streams in Ohio and Michigan for 1975 Through 2001. All streams have increasing trends that are significant at the 95 percent level ($p < 0.05$).

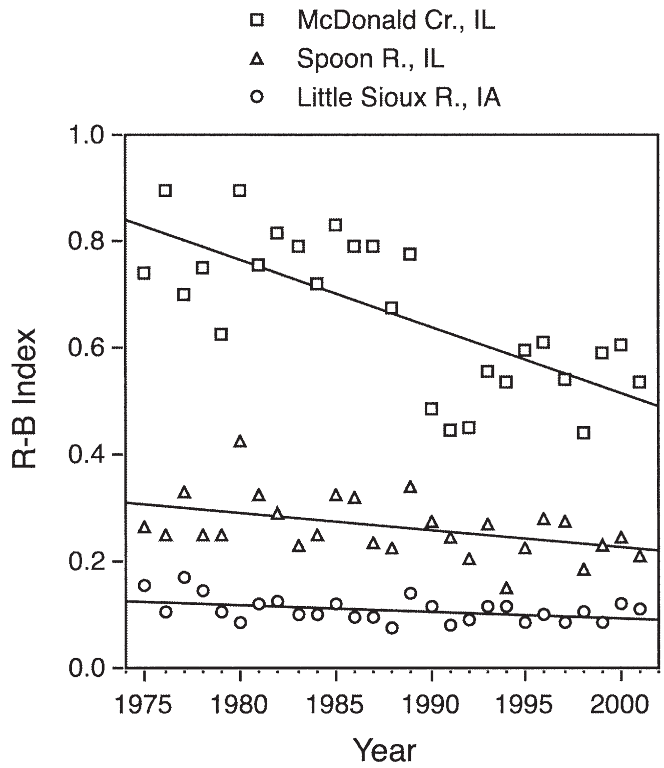

Figure 9. Time Trends in R-B Index Values for Three Streams in Illinois and Iowa for 1975 Through 2001. All streams have decreasing trends that are significant at the 95 percent level ($p < 0.05$).

TABLE 4. Trend Directions and Significance Levels for R-B Index Values for 507 Streams During the 1975 Through 2001 Water Years.

Trend Direction	Significance Level	Number of Streams	Percent of Total
Increase	$p < 0.05$	110	21.7
Increase	$0.05 < p < 0.1$	31	6.1
Increase*	$p > 0.1$	162	32.0
Decrease*	$p > 0.1$	145	28.6
Decrease	$0.05 < p < 0.1$	11	2.2
Decrease	$p < 0.05$	48	9.5

*As indicated by the slope of the regression line. The apparent trend is not statistically significant.

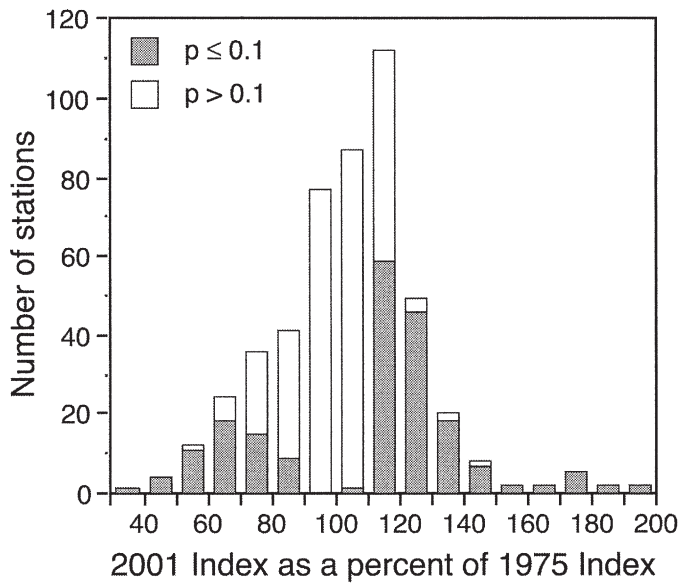

Figure 10. Histogram of Changes in R-B Index Values During the 27-Year Study Period for 484 Stations, Calculated From Linear Regression Equations Using the 2001 Value Expressed as a Percentage of the 1975 Value. The distribution of changes significant at the 90 percent level ($p < 0.10$) is also shown.

For Killbuck Creek (Figure 11b), the R-B Index has been decreasing from the 1930s through the present, with more rapid decreases in the earlier portion of the period of record. This pattern contrasts with that of the Maumee (Figure 11a) and with most other agricultural watersheds in Ohio in showing a downward trend in the last 27 years. The pattern of agricultural

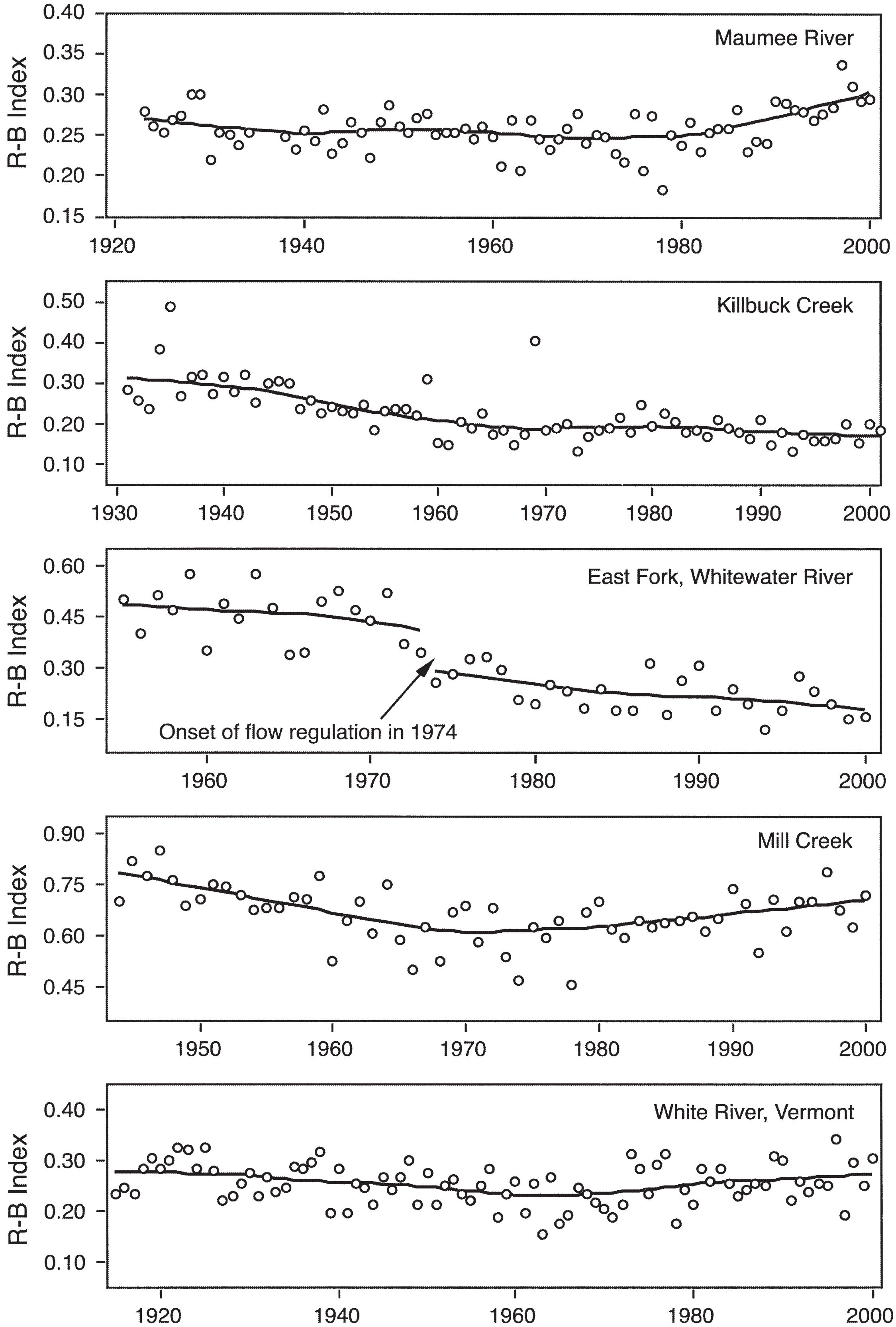

Figure 11. Examples of Period of Record Trends in Annual R-B Index Values for Selected Streams, Using LOWESS Smoothing to Indicate Possible Trends.

land use in the Killbuck Creek watershed differs from that of most other agricultural areas in Ohio in having a higher proportion of hay and pasture acreage and a lower proportion of soybean acreage. Whether the difference in trends results from these differences in crops is unclear at this time.

The R-B Index values of the East Fork of the Whitewater River in Indiana reflect the 1974 onset of flow regulation on that stream, upon completion of dam construction (Figure 11c). Separate LOWESS curves were applied to the data sets prior to and following the onset of dam operation. The sharp drop in R-B Index values with dam construction is the most prominent feature of the long term data for this stream.

Mill Creek (Figure 11d) is located in the Cincinnati metropolitan area. It had a decreasing trend through the mid-1970s and has an increasing trend since that time. The recent increases in index values in Mill Creek may be associated with urbanization, while the causes of the earlier decreases are unknown.

The White River of Vermont (Figure 11e) was examined since it is a free flowing stream and was used as a control to evaluate impacts of dam construction on streams in that area (Magilligan and Nislow, 2001). Decreases significant at the 95 percent level occurred from pre-1920s to the mid-1960s, after which statistically significant increases occurred to the present. The decreases may have been caused by reforestation of the White River watershed during the early 1900s. Magilligan and Nislow (2001) have documented increases in baseflow in the White River, which they attribute to reforestation. The causes of increases from the mid-1960s are, at present, unknown.

Ecoregional Patterns in Sizes and Trends of R-B Index Values

Ecoregional Patterns in Average R-B Index Values. One application of the R-B Index is for analysis of geographical patterns of stream flashiness. In Figure 12, the locations of 510 of the stream gages are plotted against a background of Level 3 Ecoregion (Omernik, 1987) and state boundaries. Each symbol in Figure 12 indicates the terminus of a gaged watershed, but indicates nothing about the size of the watershed or its location relative to the gaging station. To compensate for the effects of watershed area on R-B Index values (Figure 3), quartile values within each of the six watershed size classes shown in Figure 4 have been plotted rather than 27-year average R-B values. The first quartile (Lower Quartile) has the lowest R-B Index values in each size range, while the fourth quartile (Upper Quartile) has the highest R-B Index values in each size range.

The watersheds above some of the gages drain lands from several ecoregions. In some cases, nearly all the watershed lies in a different ecoregion than the gaging station. These geographic realities confound the current analysis. Nevertheless, some ecoregion boundaries coincide with transition zones in R-B Index quartiles for the stations. The boundaries between Ecoregions 56 (Southern Michigan/Northern Indiana Drift Plains) and 55 (Eastern Corn Belt Plains), 53 (Southeastern Wisconsin Till Plains) and 54 (Central Corn Belt Plains), and 54 and 72 (Interior River Valleys and Hills) are examples of relatively clear cut transition zones in quartile rankings of R-B Index values. Not surprisingly, some of the physical and land use factors that produce distinct ecoregions also appear to affect stream flashiness.

While the quartile values plotted in Figure 12 show interesting patterns of regional homogeneity, the patterns are far from perfect. R-B Index values show apparent trends within certain ecoregions. One good example is Ecoregion 47 in Iowa, which has relatively more flashy streams to the south and relatively more stable streams to the north.

In addition, some individual streams have values that appear inconsistent with those of their neighbors. Inspection of a limited number of streams that appeared to be anomalous in comparison to surrounding streams revealed two types of explanations for such inconsistent quartile scores. In southern Indiana, there are four streams from the lower quartile and one from the lower middle quartile. These are surrounded by streams in the upper and upper middle quartiles. The five outliers all had significant flow regulation, while the surrounding flashier streams either had no regulation or limited regulation at low flows. Thus, flow regulation is one explanation for apparent anomalies. In Ecoregion 57 of northwestern Ohio, most of the streams are in the upper quartile of the R-B Index. One stream, the Tiffin River, is in the lower middle quartile. It is near the boundary of a narrow arm of Ecoregion 55 that extends into Michigan. The watershed of the Tiffin River extends northward across Ecoregion 55 and into Ecoregion 56, which is characterized by low R-B Index values. Thus, another source of anomalies is that watershed boundaries often cross ecoregion boundaries. In some cases their hydrologic regimes are determined largely by conditions in one ecoregion, but their hydrology is measured at a gaging station located in a different ecoregion (cf. Omernik and Bailey, 1997).

Within a given ecoregion, streams in urbanized areas tend to have higher quartile rankings than adjacent less developed areas. This is evident along

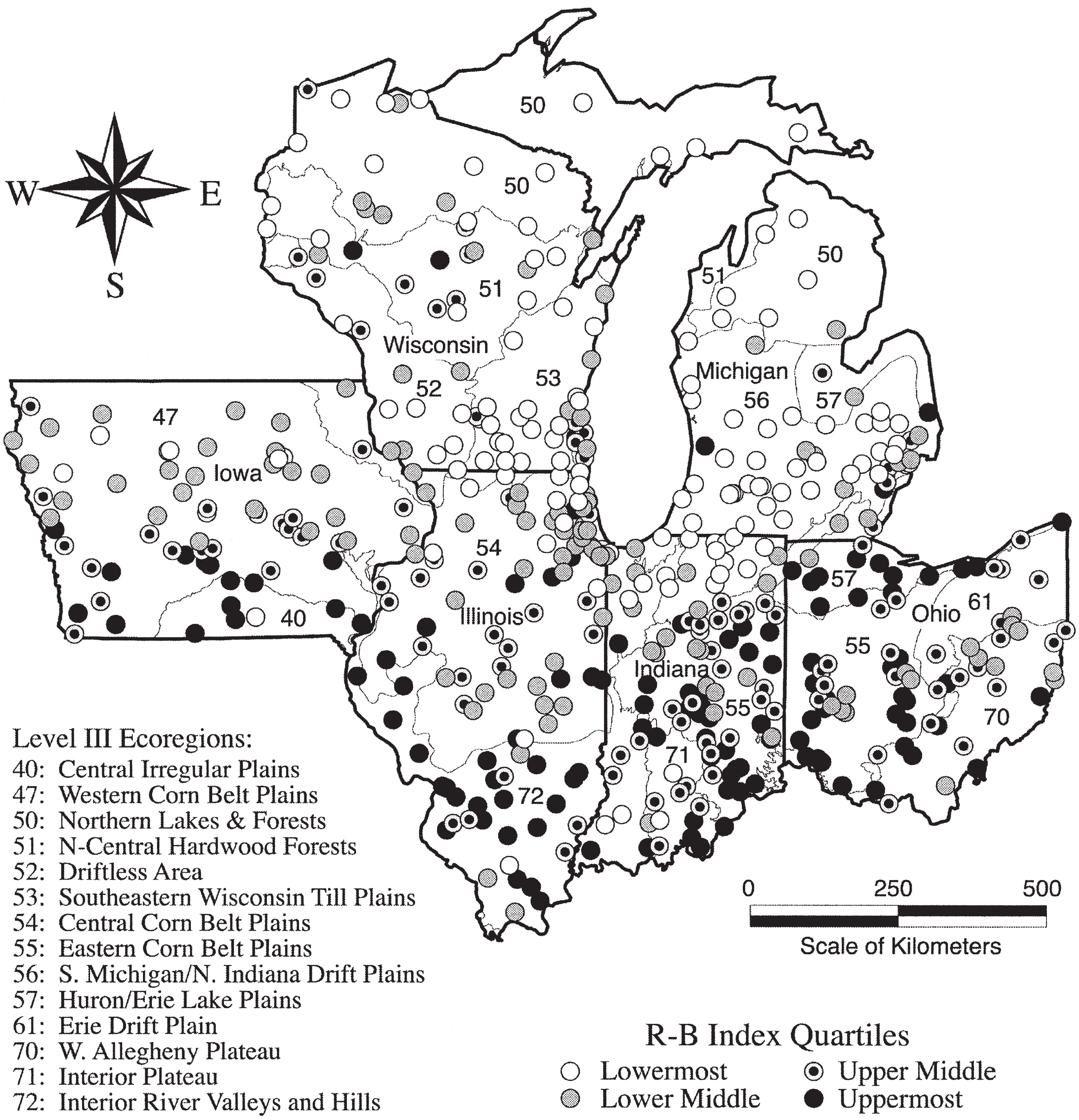

Figure 12. Quartile Rankings of 27-Year Average R-B Index Values Plotted by Location of Stream Gages in Relation to Level III Ecoregions in the Six State Study Area.

the Chicago-Milwaukee corridor on the western shore of Lake Michigan, the Detroit metropolitan area in the eastern section of Ecoregion 56, and the Indianapolis area in central Indiana. However, high flashiness is not confined to urban streams. Many rural areas, such as those in Ecoregion 57 (Huron/Erie Lake Plains) of northwestern Ohio, have higher indices than urban streams in other ecoregions.

To compare ecoregions relative to the flashiness of their streams, a weighted average quartile ranking for each ecoregion was calculated using weighting factors of 1 to 4 from the lowest to the highest quartile (Table 5). For ecoregions with more than 10 stations, Ecoregions 50 (Northern Lakes and Forests), 56 (Southern Michigan/Northern Indiana Drift Plains), and 53 (Southeastern Wisconsin Till Plains) have the lowest weighted index values, even though Ecoregions 53 and 56 contain large metropolitan areas (Milwaukee and Detroit). Ecoregions 72 (Interior River Valleys and Hills), 55 (Eastern Corn Belt Plains), and 57 (Huron/Erie Lake Plains) have the highest weighted average quartile rankings.

Ecoregional Patterns in Trends for R-B Index Values. Another application of the R-B Index is for

TABLE 5. Distribution of R-B Index Quartiles Among Ecoregions in the Six-State Region. Ecoregions are listed in the order of increasing weighted average quartile rankings.

Ecoregion Number	Ecoregion Name	R-B Index Quartile Ranking				Total Stations	Weighted Average*
		Lower	Lower Middle	Upper Middle	Upper		
50	Northern Lakes and Forests	18	7	1	0	26	1.35
56	Southern Michigan/Northern Indiana Drift Plains	47	11	7	3	68	1.50
53	Southeastern Wisconsin Till Plains	20	4	5	2	31	1.65
52	Driftless Area	6	7	3	0	16	1.81
51	North Central Hardwood Forests	8	4	4	2	18	2.00
54	Central Corn Belt Plains	14	36	24	14	88	2.43
47	Western Corn Belt Plains	4	26	23	8	61	2.57
70	Western Allegheny Plateau	0	7	9	5	21	2.90
61	Erie Drift Plain	0	1	6	2	9	3.11
71	Interior Plateau	2	2	5	8	17	3.12
57	Huron/Erie Lake Plains	0	4	3	8	15	3.27
55	Eastern Corn Belt Plains	0	16	29	43	88	3.31
72	Interior River Valleys and Hills	3	3	8	25	39	3.41
40	Central Irregular Plains	1	0	0	7	8	3.63
83	Eastern Great Lakes and Hudson Lowlands	0	0	1	3	4	3.75

*Weighting factors were 1, 2, 3, and 4 for Lower, Lower Middle, Upper Middle, and Upper quartiles, respectively.

geographical analysis of trends in stream flashiness. A map of trend direction and significance for 502 streams within the ecoregions of the six states is shown in Figure 13. These are the same stations summarized in Figure 10 and Table 4. The most obvious feature of the map is the dominance of decreasing trends in the western part of the region and increasing trends in the eastern part. The pattern of trends does not follow ecoregion boundaries as closely as the sizes of R-B Index values.

Ecoregional differences in trends are summarized in Table 6. A weighted average of trend direction and significance was calculated for each ecoregion, using the weighting factors shown in Table 6. With these weighting factors, ecoregions with a weighted average below 3.5 would, on average, have decreasing flashiness, while ecoregions with a weighted average above 3.5 would, on average, have increasing flashiness. The lowest weighted averages (decreasing trends) are in Ecoregions 47 (Western Corn Belt Plains), 52 (Driftless Area), and 40 (Central Irregular Plains). The highest weighted averages (increasing trends) are in Ecoregions 57 (Huron/Erie Lake Plains), 55 (Eastern Corn Belt Plains), and 56 (Southern Michigan/Northern Indiana Drift Plains). Within Ecoregion 54 (Central Corn Belt Plains) decreasing trends are present in the southwestern part, while increasing trends are present in the northeastern part. Many of the stations showing significant ($p < 0.1$) trends are in rural areas. Increases in R-B Index values occurred in areas with both high and low average R-B Indices, such as in Ecoregions 55, 56, and 57 of Ohio, Indiana, and Michigan (Figures 12 and 13).

From Figure 13, it is also evident that many of the streams in urban areas have statistically significant increases in R-B Indices. This is particularly evident in the Milwaukee, Chicago, and Detroit areas. Increases in impervious areas accompanying urbanization are likely causes of increases in stream flashiness in these areas.

While explanations of increasing flashiness in urbanizing watersheds are readily available, explanations of trends in agricultural and forested watersheds largely remain to be determined. There have been many changes in agriculture across the six-state area during the study period. Some of these include increased farm size, increased soybean production, decreased hay production, increased use of no-till and reduced tillage practices, decreased acres of pasture lands, improvements in tile drainage, increases in conservation reserve program acres, and increased use of buffer strips. In Iowa, the decreasing trends in R-B Index are attributable, at least in part, to the increasing baseflow that has been observed in representative streams in that state (Schilling and Libra, 2003). The authors attribute those increases to adoption of a combination of conservation measures that reduce erosion, increase infiltration, and reduce surface runoff. Greater infiltration increases ground water levels and subsequent baseflow in streams.

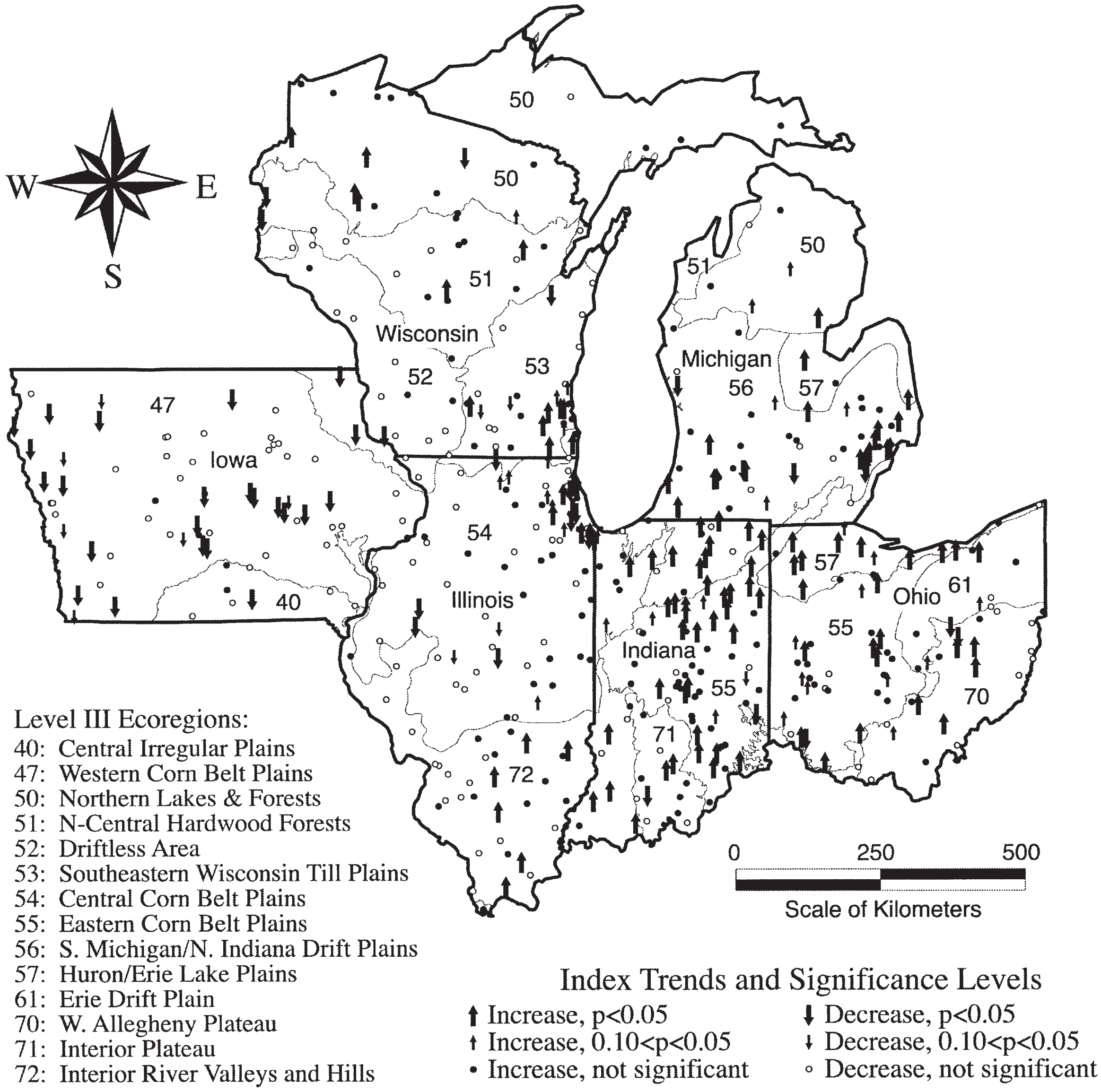

Figure 13. Direction and Significance of Trends in R-B Index Values During the Study Period Plotted by Location of Stream Gages in Relation to Level III Ecoregions in the Six State Area.

Richards *et al.* (2003b) have documented multiple changes in farming practices, including the adoption of many conservation measures, in the northwestern Ohio and northeastern Indiana portions of the Lake Erie drainage. While these measures have significantly reduced sediment and phosphorus loading to Lake Erie (Richards and Baker, 2002), stream flashiness has increased in the rural streams of this area (Figure 13, Table 7). The higher clay content of most soils in the eastern part of the study area relative to the western part could account for differing responses to the adoption of conservation measures in these regions. Increases in infiltration associated with adoption of conservation tillage in Iowa may not be occurring in Indiana and Ohio because of the higher clay content of these soils. Other potential causes of increased flashiness in many Ohio and Indiana streams may include continuing improvements in systematic tile drainage, increases in soil compaction, reductions in depressional storage on no-till soybean fields, and improved conveyance of ditches and small streams. Since hydromodification is a major cause of impaired aquatic life in the rural headwaters streams of northwestern Ohio (Ohio Environmental Protection Agency, 2003) and the second leading source of river and stream impairment for river miles assessed throughout the United States (USEPA, 2002), determination of the specific causes of increasing flashiness in the streams of this area and elsewhere is warranted.

TABLE 6. Distribution Among Ecoregions of Stations Falling Within the Plotting Categories of Figure 13.

		Figure 13 Plotting Category							
Ecoregion Number	Ecoregion Name	- Trend ($p < 0.05$)	- Trend ($0.05 < p < 0.1$)	- Slope ($p > 0.1$)	+ Slope ($p > 0.1$)	+ Trend ($0.05 < p < 0.1$)	+ Trend ($p < 0.05$)	Number of Stations	Weighted Average*
47	Western Corn Belt Plains	20	6	32	3	0	0	61	2.30
52	Driftless Area	3	0	10	3	0	0	16	2.81
40	Central Irregular Plains	1	0	5	2	0	0	8	3.00
51	North Central Hardwood Forests	2	0	5	9	0	2	18	3.61
54	Central Corn Belt Plains	9	2	29	29	9	10	88	3.65
71	Interior Plateau	2	0	5	5	0	4	16	3.81
53	Southeastern Wisconsin Till Plains	2	2	10	8	3	6	31	3.84
70	Western Allegheny Plateau	2	0	8	5	1	5	21	3.86
72	Interior River Valleys and Hills	0	0	16	13	0	10	39	4.10
50	Northern Lakes and Forests	1	0	3	13	3	5	25	4.28
56	Southern Michigan/Northern Indiana Drift Plains	4	0	8	22	4	25	63	4.54
61	Erie Drift Plain	0	0	1	4	2	2	9	4.56
55	Eastern Corn Belt Plains	1	1	7	42	9	28	88	4.60
83	Eastern Great Lakes and Hudson Lowlands	0	0	1	1	0	2	4	4.75
57	Huron/Erie Lake Plains	0	0	1	2	2	8	13	5.31

*Weighting of 1, 2, 3, 4, 5 and 6 for six categories from - trend, $p < 0.05$ to + trend, $p < 0.05$ respectively.

Studies of precipitation records from 1910 to 1999 indicate that both the amounts of rainfall and the frequency of intense rainfalls have increased both nationwide and throughout the study area (Soil and Water Conservation Society, 2003). These studies also indicate that the increases were particularly pronounced during the 1970 to 1999 period. However, the increases in both amounts and intensities of rainfall have been greater in areas of decreasing R-B Index, such as Iowa, than in many of the areas of increasing R-B Index values, such as north-central Indiana and northwestern Ohio. Thus, changes in rainfall amount and intensities cannot solely account for the geographical patterns of changes in stream flashiness observed in this study.

Comparisons of the R-B Index, IHA Indices, and the CVD

The 33 IHA indices and the CVD were calculated for each of 100 randomly selected streams from the 446 streams with complete hydrologic records. The IHA software was used to analyze the 27-year period for each stream as a single series of data, selecting the program outputs that provided results of regression analyses, including the coefficient of variation and the probability of significant time trends within the time period for each parameter. The CVD values were analyzed in a similar fashion. The results of these calculations, along with the corresponding values for the R-B Index, are shown in Table 7.

Hydrologic indices serve a variety of purposes and, consequently, take a variety of forms. The individual IHA parameters characterize particular features of a stream's flow regime that are deemed important to aquatic life. Since interannual variability is an important feature of a stream's hydrologic regime, only one of the 33 IHA parameters, the baseflow parameter, is normalized by mean annual flow. The coefficient of variation in annual values of each parameter is used to characterize this annual variability. The R-B Index and the Coefficient of Variation in Daily Flows (CVD), as used by Poff (1996), attempt to characterize the flashiness of streams in ways that reflect the manner in which watersheds process their hydrological inputs (precipitation and ground water flows) into streamflow outputs. Both normalize a discharge characteristic (pathlength or standard deviation in daily flows) by annual discharge. For these two indices, the coefficient of variation can also be used to characterize interannual variability.

TABLE 7. Coefficients of Variation and Occurrence of Trends in IHA Indices, Coefficient of Variation in Daily flows (CVD) and R-B Index in 100 Randomly Selected Streams.

IHA Parameter Group, CVD, and R-B Index	IHA Individual Parameters	Average Coefficient of Variation for 27 Annual Values	Number of Stations From Set of 100 With Trends Significant at Indicated p Values		
			p < 0.05	0.05 < p < 0.1	Percent With p < 0.1
IHA-Magnitude of Monthly Water Conditions	October, Mean	1.0809	6	4	10
	November, Mean	0.9492	3	2	5
	December, Mean	0.7884	2	2	4
	January, Mean	0.6898	9	7	16
	February, Mean	0.6557	8	5	13
	March, Mean	0.6123	13	26	39
	April, Mean	0.5733	10	4	14
	May, Mean	0.7358	3	6	9
	June, Mean	0.8355	22	10	32
	July, Mean	0.9970	4	4	8
	August, Mean	1.1256	3	8	11
	September, Mean	1.2815	7	5	12
IHA-Magnitude and Duration of Annual Extreme Water Conditions	1-Day Minimum	0.7265	16	6	22
	3-Day Minimum	0.7034	16	9	25
	7-Day Minimum	0.6684	18	12	30
	30-Day Minimum	0.6531	15	11	26
	90-Day Minimum	0.7697	6	9	15
	1-Day Maximum	0.4859	5	5	10
	3-Day Maximum	0.4607	6	2	8
	7-Day Maximum	0.4353	6	5	11
	30-Day Maximum	0.3982	12	3	15
	90-Day Maximum	0.3546	7	8	15
	Number of Zero Days	0.5604	1	4	5
	Baseflow	0.5923	17	16	33
IHA-Timing of Annual Extreme Conditions	Date of Minimum	0.1654	8	13	21
	Date of Maximum	0.2062	1	2	3
IHA-Frequency and Duration of High and Low Pulses	Low Pulse Count	0.5373	14	4	18
	Low Pulse Duration	0.7237	9	6	15
	High Pulse Count	0.7946	0	2	2
	High Pulse Duration	0.7946	0	2	2
IHA-Rate and Frequency of Water Condition Changes	Rise Rate	0.4371	8	4	12
	Fall Rate	-0.3998	8	4	12
	Number of Reversals	0.1099	21	4	25
CVD		0.2499	12	6	18
R-B Index		0.1982	33	9	42

Table 7 shows that interannual variability, as reflected in the average coefficient of variation for 100 streams, is much larger for most IHA parameters than for the R-B Index and the CVD. The only exceptions are for IHA parameters of dates of minimum and maximum flows and number of flow reversals. The coefficient of variation for the R-B Index (0.1982) is lower than the coefficient of variation for the CVD (0.2499).

The IHA parameters most closely related to flashiness would be the average rates of flow increase and decrease. These average rates are directly related to the annual pathlengths of the R-B Index. Except for differences in flow at the beginning and end of the year, the total increase in flow is equal to the total decrease in flow and both are equal to one half of the pathlength used in the calculation of the R-B Index. In the IHA software, the average rate of increase in flow is calculated by dividing the total increase in flow by the number of days flow increased relative to the previous day (The Nature Conservancy, 2001). A similar calculation is done to determine the average rate of flow decrease. In contrast, for the R-B Index, the pathlength is divided by the total discharge. The coefficients of variation for the IHA rise rate and fall rate were 0.437 and -0.400, values two-fold greater than the coefficient of variation for the R-B Index.

Significant trends were present more often in the R-B Index than in any of the IHA parameters or in the CVD (Table 7). In the 100 randomly selected rivers, trends in the R-B Index significant at the 95 percent level were present in 33 streams, with another nine streams having trends significant between the 90 percent and 95 percent level. Among the IHA parameters, monthly mean flows for June and March had the greatest frequency of trends, with 22 and 13 streams having trends significant at the 95 percent level. Significant trends were also present relatively frequently in the set of one-day, three-day, seven-day and 30-day minimum flows and in baseflow. The IHA parameters most closely associated with flashiness, the average rise rate and average fall rate, each had trends significant at the 95 percent level in only eight streams. For the CVD, trends significant at the 95 percent level were present in only 12 streams, compared with 33 streams for the R-B Index. In comparing the frequency of significant trends, trend direction was not considered.

These data indicate that the R-B Index has lower coefficients of variation and, hence, greater power to detect trends than any of the IHA parameters or the CVD. Since the R-B Index reflects a different set of features of a stream's flow regime than individual IHA parameters, similar frequencies of trends would not necessarily be expected, even if IHA parameters and the R-B Index had equal powers of trend detection. In addition to their value in characterizing individual components of the flow regime of a stream, IHA analyses may be useful in determining the causes of trends in flashiness, as revealed by the R-B Index.

CONCLUSIONS

The results of this study support the following conclusions.

- The R-B Index integrates several flow regime characteristics associated with the concept of stream flashiness. The index is positively correlated with increasing frequency and magnitude of storm events, and negatively correlated with baseflow and watershed area.

- The size of the R-B Index varies greatly among ecoregions of the six-state area, suggesting that some of the physical attributes of the landscape that result in distinct ecoregions also impact stream flashiness.

- The R-B Index has lower interannual variability than many other flow regime indicators, making it well suited for detecting gradual changes in flow regimes associated with changes in land use and in land management practices.

- During the period 1975 through 2001, flashiness appears to be significantly increasing in many streams while decreasing in others. The increases in flashiness are occurring primarily in the eastern portion and decreases are occurring in the western portion of the six-state region. Changes in amounts and intensity of rainfall cannot account for the geographical pattern of changes in stream flashiness.

- Increases in flashiness are not limited to urban areas but extend to agricultural and forested landscapes. Increases are occurring in watersheds having both high and low R-B Index values.

- The R-B Index may be useful as a tool for assessing the effectiveness of programs aimed at restoring more natural streamflow regimes, particularly where modified regimes are a consequence of land use/land management practices.

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