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Improved water quality in Ohio tributaries to Lake Erie: A consequence of conservation practices

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Abstract: Sediment is an important pollutant for Lake Erie and its tributaries, both as a carrier of other substances, particularly phosphorus, and as a pollutant in its own right. Environmental managers have called for major reductions in sediment and phosphorus loadings from Lake Erie tributaries. In this study, thirty-year datasets (Water Years 1975–2004) with daily resolution are analyzed to identify and interpret trends in suspended sediment and particulate phosphorus concentrations and loads in two major US tributaries to Lake Erie. The Maumee and Sandusky Rivers in agricultural northwest Ohio show continual decreases in concentrations and loads throughout this period. The greatest decreases are observed in summer and fall and under low flow conditions, whereas the smallest decreases are observed in the spring and under high flow conditions. Analysis of concentration-flow relationships indicates that these changes are not due to weather but reflect the successful use of agricultural practices to reduce erosion and prevent sediment loss. Opportunities for further reductions in suspended sediment and particulate phosphorus loads and concentrations lie in better management of sediment losses during winter and spring.

Key words: ANCOVA—conservation practices—Lake Erie—particulate phosphorus—suspended solids—trend analysis

Of the five Lauretian Great Lakes, Lake Erie is the shallowest and the warmest (Bennett 1978) and has the shortest residence time. It has the largest population, the highest percentage of its watershed in agricultural land use, and the lowest percentage in forest. These and other factors cause Lake Erie to be particularly sensitive to anthropogenic influences, a major one of which is non-point pollution from agricultural sources.

By the late 1960s, Lake Erie was suffering from a bad case of cultural eutrophication (ES&T 1967; IJC 1965, 1969). The infamous burning of the Cuyahoga River in 1969 was the emotional tipping point that precipitated efforts to rescue the nearly "dead" lake. The major problem with the open lake, however, was not burning tributaries but excessive nutrient inputs, which led to hypoxia in the summer months and all the ecological problems that accompany such conditions (Vallentyne 1974). Actions to rehabilitate the open lake focused on reducing phosphorus to limit algal productivity (ACOE 1982; GLWQA 1972; IJC 1965, 1969, 1978). A target load of 11,000 t (12,125 tn) from all sources was established by the International Joint Commission; this represented a more than 60% decrease from the estimated load in 1968 (Fraser 1987) of 28,000 t (30,865 tn). As remediation efforts moved beyond point sources to include non-point sources of pollution, the control of erosion and sediment transport to Lake Erie became important because much of the non-point phosphorus was carried attached to sediment (IJC 1978). In this context, improved knowledge of tributary sediment concentrations and loads became a matter of ongoing concern.

Sediment was and remains important as a carrier of phosphorus and many other pollutants. But sediment is also important in its own right. Sedimentation in harbors and shipping channels necessitates expensive dredging and creates problems disposing of the dredge spoils (Myers and Metzker 2000). The need to remove sediment from source waters increases the costs of drinking water treatment. Sediment deposited in rivers and streams can clog spawning beds and degrade other benthic habitats (Hynes 1974). Turbidity from suspended solids may limit light penetration and thereby photosynthesis, favoring planktonic algae over aquatic macrophytes in river mouths and bays (Chow-Fraser 1999).

The Ohio Lake Erie Commission has identified sediment loading as one of its water quality metrics for Lake Erie, rated it as poor, and called for a 67% reduction from baseline conditions measured in 1991 through 1996 (OLEC 1998). The Lake Erie watershed in northwestern Ohio has been the site of many demonstration programs and other efforts to stimulate adoption of agricultural best management practices to reduce sediment and phosphorus losses (see Forster and Rausch 2002 for a review). Currently, the Ohio Lake Erie Conservation Reserve Enhancement Program represents a major effort to promote sediment reduction measures in the western Ohio Lake Erie watershed (ODNR 2008).

The National Center for Water Quality Research (NCWQR) at Heidelberg College has been monitoring sediment and nutrients in the major US tributaries to Lake Erie for many years, with some records extending back as far as the late 1960s. This study is an analysis of NCWQR sediment and phosphorus data for the thirty-year period beginning with the 1975 Water Year (which began October 1, 1974), and continuing through the 2004 Water Year (ending September 30, 2004). The goals of this study were to identify and quantify trends in sediment and particulate phosphorus loads and concentrations and to interpret them in the context of efforts to manage Lake Erie and its watershed. This paper is focused around a new form of analysis of covariance (ANCOVA), which we believe advances the argument that the observed trends are due to changes in management. It serves to update and expand an earlier study of sediment and nutrient trends in these same rivers (Richards 2002a)

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Figure 1

Map of the study area, showing the locations of the five National Center for Water Quality Research Lake Erie tributary sampling locations.

Materials and Methods

Sampling. The NCWQR collects samples for sediment and nutrient analysis at or near US Geological Survey gaging stations on five major tributaries to Lake Erie, at locations as close to the lake as feasible but sufficiently far upstream to be free from flow reversals due to seiche activity in the lake (figure 1). As such, each station integrates the runoff and associated materials from the majority of its watershed. Tables 1 and 2 provide information about the stations and the watersheds that drain to them. This paper is concerned with the Maumee and Sandusky Rivers, which are dominated by agricultural land use.

The Maumee and Sandusky Rivers drain mostly fine-grained soils that are developed on glacial and lake-bottom deposits and overlie sedimentary rock, primarily Silurian and Devonian limestones and dolostones. The watersheds are characterized by low gradients except where steeper relief is provided by end moraines. The watersheds are primarily located in the Eastern Corn Belt Plain and Huron/Erie Lake Plain Ecosystems (Level IV). Monthly average temperatures range from −4.5°C (24°F) in January to 22.5°C (72.5°F) in July. Annual precipitation averages about 90 cm (35.4 in). A more detailed description of these watersheds is provided in Richards et al. (2000a).

At these sampling locations, samples of approximately 500 mL (16.9 oz) in volume are taken using autosamplers. All samples are discrete; samples are never composited. Prior to May 1988, samples were taken four times per day at even intervals, and the autosamplers were not refrigerated. In May 1988, refrigerated autosamplers were installed, and the sampling frequency was reduced to three times per day, every eight hours. All samples taken during periods of storm runoff are analyzed; at other times, only one sample per day is analyzed, and the others are discarded. Typically, this program provides 400 to 450 analyzed samples per year. The results in this paper are based on analyses of approximately 12,000 samples at each location. The NCWQR sample collection and analysis at these stations continue. Data can be accessed at http://wql-data.heidelberg.edu.

Analytical Methods. Total suspended solids concentrations are measured using US Environmental Protection Agency Method 160, Residue (Gravimetric) (USEPA 1971). The total suspended solids concentration is determined by filtering a sample aliquot of known volume, approximately 100 mL (3.4 oz), through a pre-dried and pre-weighed glass fiber filter and then redrying and reweighing the filter.

Total phosphorus (TP) and dissolved reactive phosphorus (DRP) concentrations are measured using the ammonium molybdate/ascorbic acid method (USEPA 1978). Total phosphorus is determined from a whole water sample digested with sulfuric acid and ammonium persulfate, which is then filtered through a 0.45 µm (0.000018 in) filter; DRP is determined from a sample that is filtered but not digested.

Particulate phosphorus was estimated as the difference between TP and DRP. Since some components of dissolved phosphorus, such as polyphosphates and phosphorus in dissolved organic compounds, are not measured by the DRP method, our approach overestimates particulate phosphorus slightly. Analysis of a more complete suite of phosphorus forms using a subset of samples from these rivers (David Baker unpublished) indicates that DRP is typically 85% or more of the total dissolved phosphorus concentration. Since DRP is generally in the range of 15% to 20% of TP, the overestimate involved in our particulate phosphorus calculation is in the range of 3.5% of TP or less. Concentration results for all parameters are reported as mg L^{-1}.

Data Preparation. Loads associated with each sample were obtained by multiplying the observed concentration by the instantaneous flow at the time of the sample and a sample time window; these sample loads were then summed to obtain daily loads. The sample time window is equal to half the time from the previous sample to the current sample (or the time from the beginning of the day, for the first sample of the day) plus half the time from the current sample to the

Table 1
Watershed characteristics of the five National Center for Water Quality Research Lake Erie watershed stations. Watersheds are listed in order from west to east.

Name	Watershed area (km²)*	Area upstream of gage (km²)†	Land use distribution (%)‡ Agriculture: row crops	Grassland, pasture	Forest	Urban/ residential	Other
Raisin	2,764	2,699	49.74	19.26	10.24	10.62	10.14
Maumee	16,995	16,395	73.57	6.40	6.39	10.38	3.26
Sandusky	3,678	3,240	77.72	4.33	8.83	7.99	1.13
Cuyahoga	2,095	1,831	9.27	12.38	34.58	37.74	6.03
Grand	1,826	1,774	25.14	13.24	43.28	8.68	9.66

* Source: Ohio rivers and streams, Sanders, (2002); River Raisin: Fongers (2006).

† Source: US Geological Survey web-based station descriptions.

‡ Source: 2001 National Land Cover Database, summarized on a watershed basis by Dan Button, US Geological Survey, Columbus.

Table 2
Station characteristics of the seven Lake Erie watershed stations. Watersheds are listed in order from west to east.

Name	US Geological Survey station number	Location of gage		Location of sampling station		Comment	Date of first sample
		Latitude	Longitude	Latitude	Longitude		
Raisin	04176500	41.9642	−83.5443	41.9639	−83.5465	Manual grab samples from Ida-Maybee Bridge	March 6, 1982
Maumee	04193500	41.5002	−83.7128	41.4777	−83.7375	Sampled from water intake at Bowling Green drinking water treatment plant	Jan. 10, 1975
Sandusky	04198000	41.3078	−83.1589	41.3078	−83.1589	Sampler in US Geological Survey gage station	July 8, 1969
Cuyahoga	04208000	41.3953	−81.6300	41.3953	−81.6300	Sampler in US Geological Survey gage station	Nov. 4, 1981
Grand	04212100	41.7189	−81.2281	41.7189	−81.2281	Sampler in US Geological Survey gage station	Feb. 16, 1988

next sample (or the time to the end of the day, for the last sample). The daily discharge (of water) is similarly calculated as the sum of the sample discharges, which are the product of the flow at the time of each sample and the sample time window. Daily flow-weighted mean concentrations were then calculated by dividing the daily load by the daily discharge. For subsequent statistical analysis, the official daily mean flows reported by US Geological Survey were used rather than the daily discharges calculated as just described. For statistical analyses that were based on loads, these loads were recalculated as the product of the daily flow-weighted mean concentration and the US Geological Survey daily mean flow.

Trend Analysis. The detection and interpretation of trends in water quality constituents in rivers is a complicated undertaking. The importance of a trend is often related to changes in the total quantity of a constituent reaching a receiving water such as Lake Erie; consequently when the focus is on what is happening in the receiving water, the load is the appropriate quantity to use for the trend analysis. In trying to understand causes for a trend, however, it is often more useful to examine the trend in concentrations. This is because a trend in load may be due simply to changes in weather, which lead to changes in flow and consequently in load (the product of concentration and flow). Furthermore, concentrations of some parameters are influenced by flow, so trends in flow can lead to trends in concentration that have no other cause. Thus it is useful to adjust concentrations to remove the influence of flow. It is also important to look for trends in flow itself and to investigate whether any such trends are related to human activity in the watershed. The interpretation of trends may be facilitated by looking for seasonal differences in the trend or differences in trends under ambient conditions and during storm runoff.

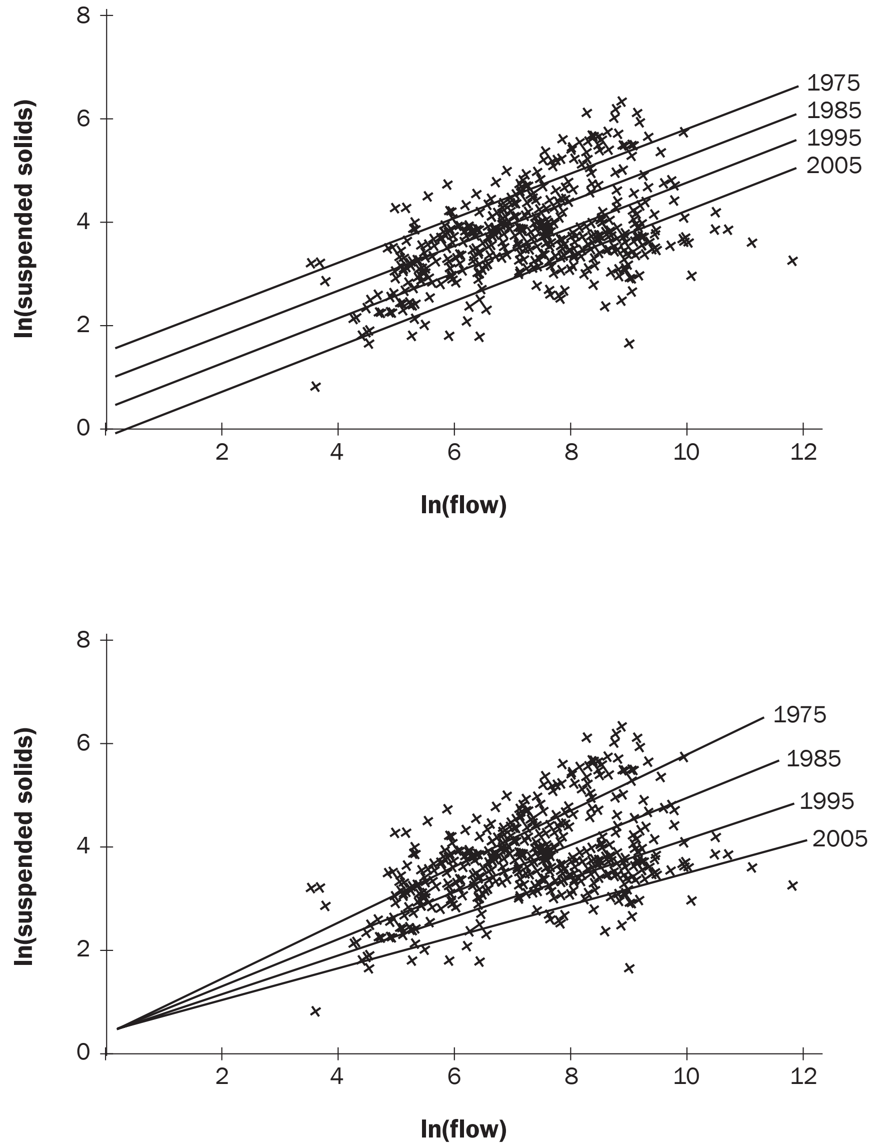
Trend analysis often uses regression approaches, which fit a straight line through the data. However, in data that span three decades, there may be important shifts in the rate of change or even reversals in the trend direction. Thus, some type of smoothing or filtering procedure that can detect trends of a more complicated nature should be used to determine if a single linear trend is appropriate or not.

For this paper, trends in flow, load, and concentration were evaluated. Locally weighted scatterplot smoothing (LOWESS) (Cleveland 1979) was used for visualization of trends and to evaluate their complexity, and the significances of trends were determined using linear regression applied to natural log (ln) transformed data, after accounting for the effects of autocorrelation on statistical significance. This approach is similar to that employed for trend analysis in our previous work (Richards and Baker 2002), by Hirsch (1991), and by Helsel and Hirsch (1992). A more detailed treatment of the statistical approaches can be found in Richards et al. (2008).

Analysis of Covariance for Changes in Concentration-Flow Relationships. Trends may be identified that have no causes other than changes in weather. Such trends are not of particular interest for this paper because they don't reflect success or failure of environmental management efforts. Changes in weather are reflected primarily in changes in flow, among the parameters available for study. Changes in weather are not expected to change the relationship between concentration and flow, the "rating curve." (The rating curve is usually a linear relationship established by regression of ln[concentration] against ln[flow]). Rather, the data should migrate upward along the rating curve during wet years and downward in dry years. Changes in land use and environmental management, on the other hand, are intended to reduce the amount of suspended sediment or particulate phosphorus associated with a given flow, leading to a change in the rating curve itself. Increases in practices like conservation tillage should decrease erosion and cause the regression line to shift downward (lower slopes and/or lower intercepts) over time (figure 2). Analysis of covariance (ANCOVA) was used to evaluate this, with ln(concentration) a function of ln(flow) and YEAR, which is simply the year in which the sample was taken. YEAR was treated as a categorical variable. The ANCOVA allows an "interaction" term, which explores how the explanatory variables interact: in this case how the relationship between ln(concentration) and ln(flow) changes from year to year. If an interaction term is included, each year may have a different slope for the relationship between ln(concentration) and ln(flow); if it is excluded, the slopes for all years are the same, but the intercepts or annual mean concentrations can vary from year to year.

Examination of preliminary results with and without interaction between ln(flow) and YEAR demonstrated that the major mode of change over time was a downward shift in the line (a decrease in the intercept or the annual mean concentration) rather than a change in the slope, so the final analysis was done without interaction. When this statistical model is used, the slope is held constant, but an annual average concentration (through which the line for the year passes) is calculated for each year of the period of record. Because YEAR is treated as a categorical variable, these values are not constrained to change in a systematic way over time. The annual average values for YEAR were then regressed against time (as a continuous variable) to determine if there was a systematic shift in the rating curve over time or just random "skipping around." Analyses of this form were done for both rivers and both parameters for the data as a whole; for the data divided into high and low flow classes corresponding to storm runoff and baseflow conditions; and for the data divided into four seasons of three months each, with winter being defined as November through January, and the other months defined accordingly. This seasonal division, among those based on three months per season, maximized the difference between the seasons in terms of concentrations and trends in concentration.

Figure 2
Illustration of hypothetical changes in a rating curve over time. Each line represents the rating curve based on data from that particular year: (a) change in the intercept over time, keeping the slope constant; (b) change in the slope over time, keeping the intercept constant.



Results and Discussion

Trend Displays for Each River. Trends in flow, suspended solids, and particulate phosphorus are displayed in figures 3 to 6. Each figure contains four plots: one each for ln-transformed flow, load, and concentration, and one for ln-transformed concentration divided into "summer" and "winter" seasons, with summer defined as May through October and winter defined as November through April. In each plot, the data from which the trend was computed are also shown. A few extreme values are excluded from each plot to avoid compressing the majority of the data into a narrow range in the middle of the graph.

The trends are also plotted alone in figure 7. In this figure, each plot is limited to

Figure 3

Suspended solids trends for the Maumee River. In the lower right panel, the heavy trend line (marked S) is for summer concentrations, and the lighter trend line (W) is for winter concentrations. All quantities are expressed as natural logs of the original units: cubic feet per second for flow, metric tons for load, and mg L^{-1} for concentration.

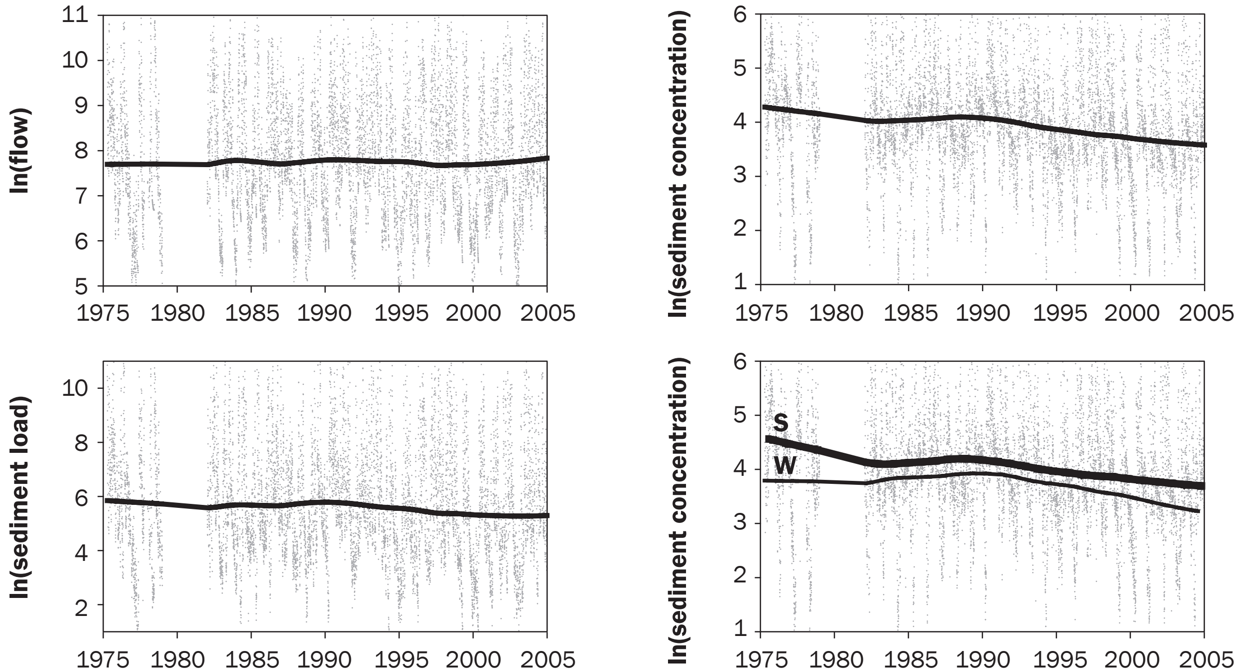


Figure 4

Particulate phosphorus trends for the Maumee River. In the lower right panel, the heavy trend line (marked S) is for summer concentrations, and the lighter trend line (W) is for winter concentrations. All quantities are expressed as natural logs of the original units: cubic feet per second for flow, metric tons for load, and mg L^{-1} for concentration.

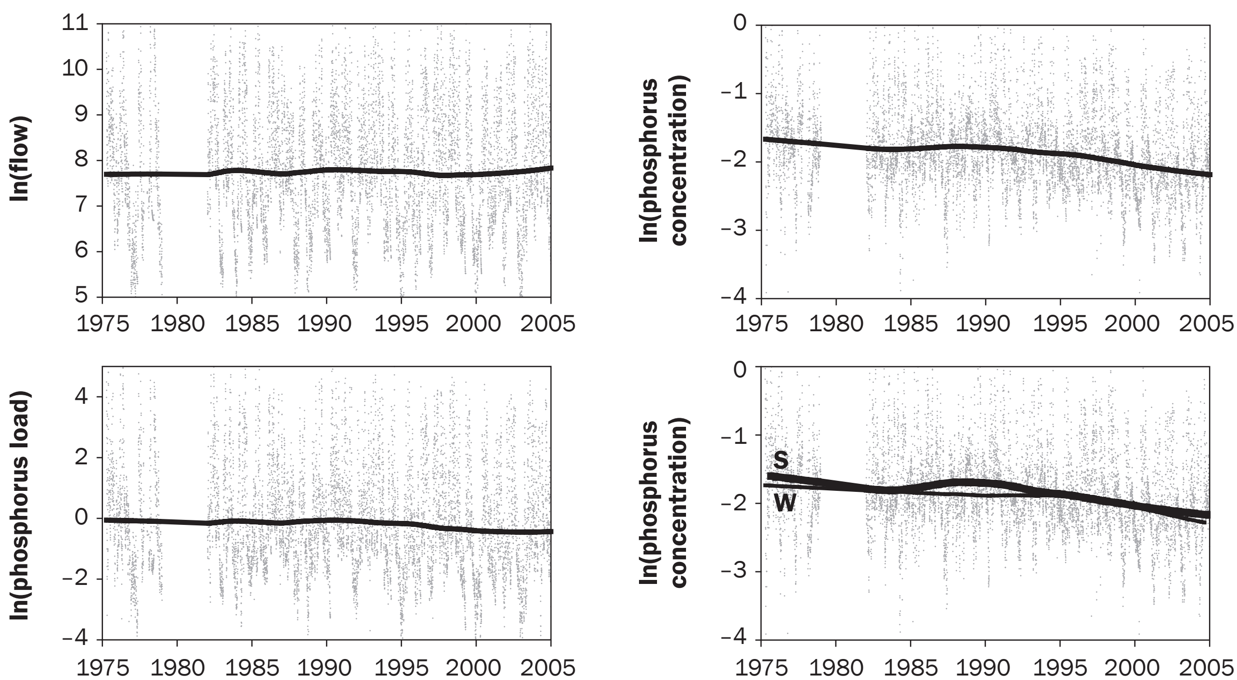


Figure 5

Suspended solids trends for the Sandusky River. In the lower right panel, the heavy trend line (marked S) is for summer concentrations, and the lighter trend line (W) is for winter concentrations. All quantities are expressed as natural logs of the original units: cubic feet per second for flow, metric tons for load, and mg L^{-1} for concentration.

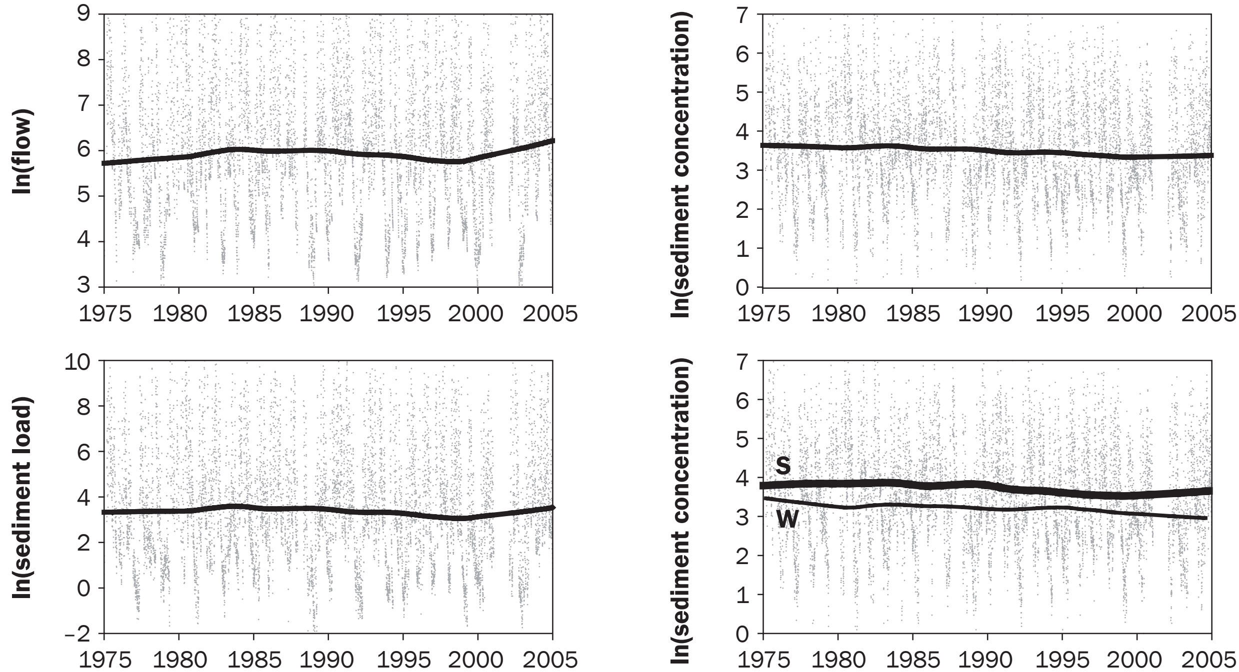


Figure 6

Particulate phosphorus trends for the Sandusky River. In the lower right panel, the heavy trend line (marked S) is for summer concentrations, and the lighter trend line (W) is for winter concentrations. All quantities are expressed as natural logs of the original units: cubic feet per second for flow, metric tons for load, and mg L^{-1} for concentration.

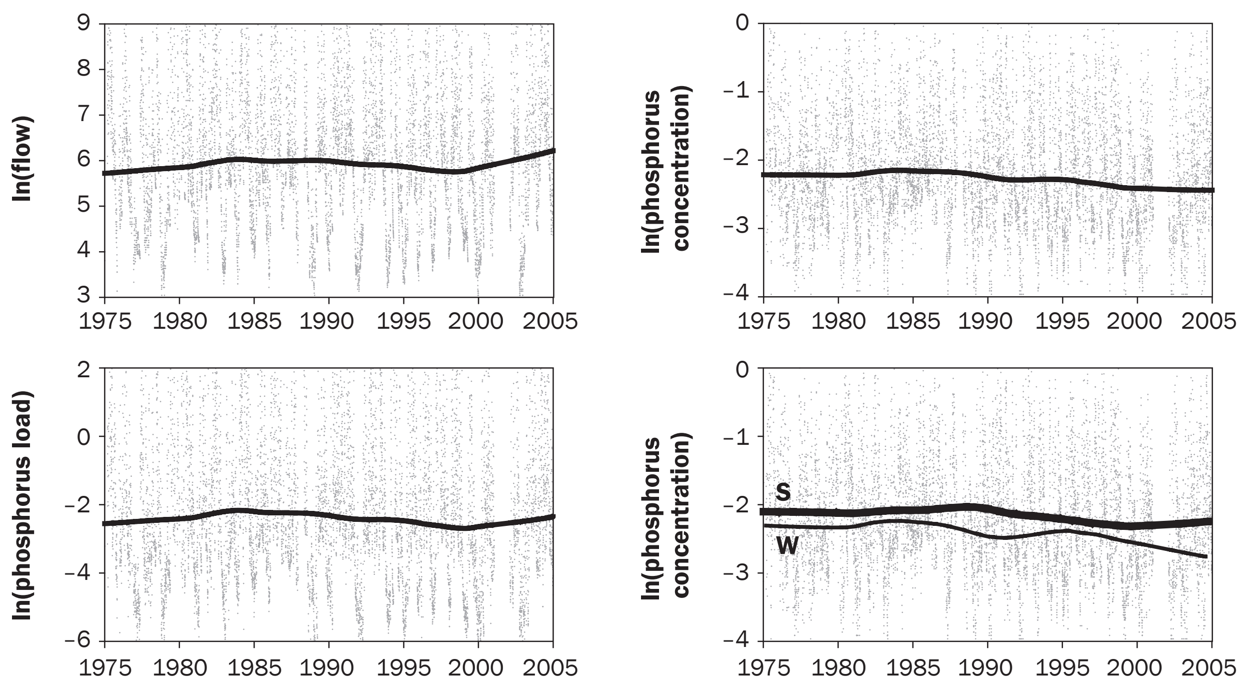
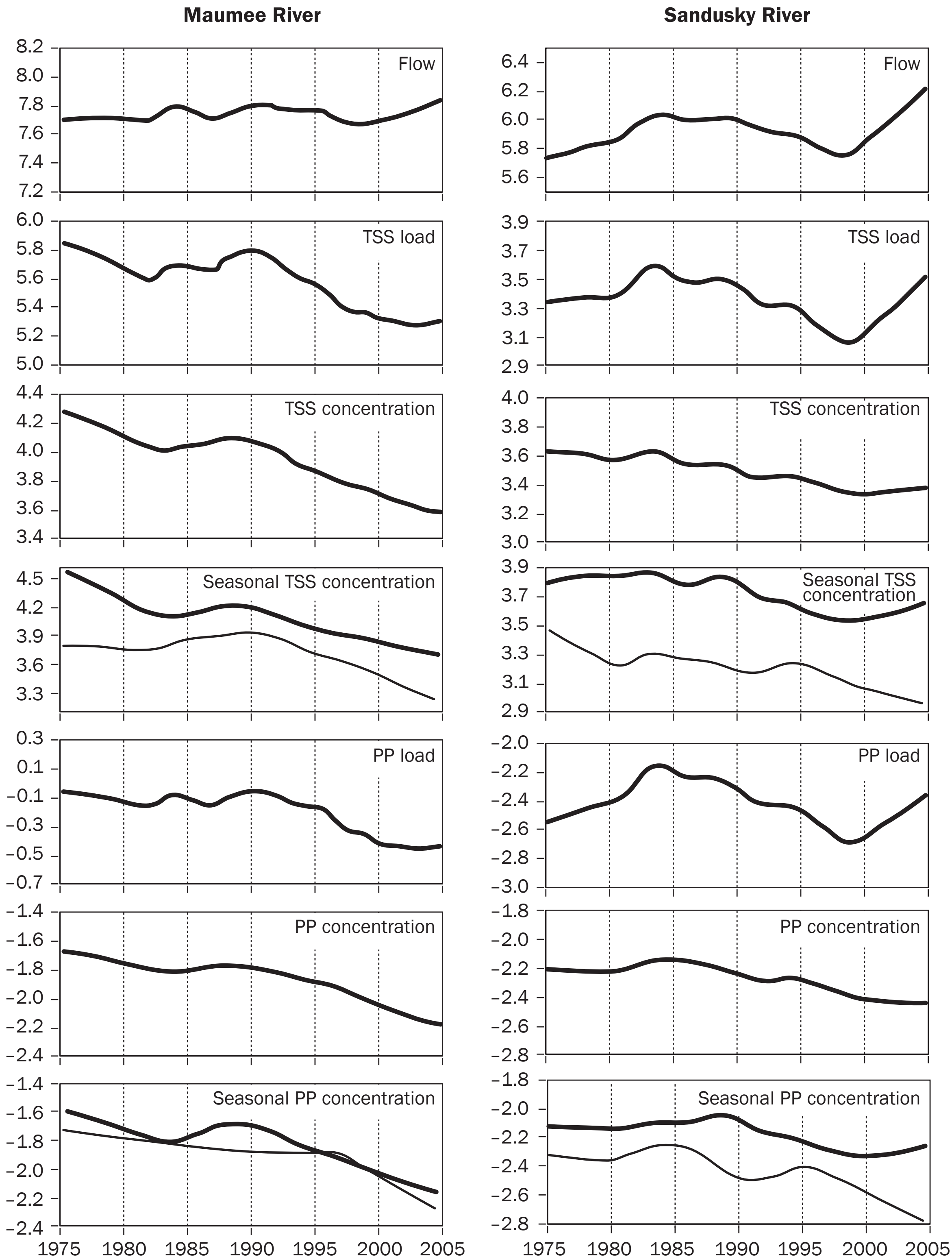


Figure 7

Trends plotted without the data. All graphs use the same vertical range, one natural-log unit, except the Maumee seasonal sediment concentration graph, which spans 1.5 log units.



Notes: TSS = total suspended solids. PP = particulate phosporus.

Table 3
Results of linear regression analysis for trend over the entire period of record. Statistically significant results are highlighted by bolding of the p-value.

River	Parameter	Trend coefficient	Percent change per decade	Student's t value	Multiple r^2 (%)	AR1 auto-correlation	Adjustment factor for t	Adjusted t-value	p value
Maumee River	ln flow	0.0045	4.6	3.086	28.2	0.949	0.192	0.059	0.554
	ln TSS load	−0.0127	−11.9	−5.160	18.1	0.936	0.182	−0.939	0.348
	ln TSS conc	−0.0195	−17.7	−26.139	41.8	0.778	0.353	−9.227	**<0.001**
	ln PP load	−0.0133	−12.5	−5.624	19.8	0.897	0.233	−1.310	0.190
	ln PP conc	−0.0153	−14.2	−29.582	24.6	0.806	0.328	−9.703	**<0.001**
Sandusky River	ln flow	0.0048	4.9	3.079	31.1	0.931	0.190	0.585	0.559
	ln TSS load	−0.0066	−6.4	−2.322	20.0	0.909	0.219	−0.509	0.611
	ln TSS conc	−0.0113	−10.7	−7.836	21.5	0.859	0.276	−2.163	**0.031**
	ln PP load	−0.0064	−6.2	−2.37	19.4	0.912	0.216	−0.570	0.569
	ln PP conc	−0.0105	−10.0	−10.204	12.2	0.851	0.285	−2.908	**0.004**

Notes: ln = natural log. TSS = total suspended solids. PP = particulate phosphorus.

a range of one natural log cycle, to facilitate comparison of the shapes of the trend lines.

In general, the trends in flow are increasing, while the trends in concentration are decreasing. Loads are products of flow and concentration, and the load trends are consequently intermediate between the flow trends and the concentration trends. The Sandusky has a marked increase in flow over the last five years of the study period, and the impact of this increase in flow can be seen in the load trends as well. Since flow affects concentration, even the concentration trends show some influence from this change in flow in the form of a transition from a period of declining concentrations to one of essentially unchanged concentrations. Summer concentrations of both sediment and phosphorus are higher than winter concentrations, but the trends for the two seasons generally parallel each other.

Regression-based Linear Trends for Entire Period of Record. Representing data for these rivers as a single linear trend, in many cases, ignores some important details, as can be seen from figures 3 to 7. Nonetheless, such analyses indicate the net change over the entire period of record, which is useful to provide context for the analysis of covariance (ANCOVA) analyses that follow. Table 3 presents the results of analyses of flow and sediment and phosphorus concentrations for each tributary. In each analysis, sine and cosine terms in 2 × π × time and 4 × π × time were included to reduce the variance due to seasonality. In analyses of concentration, concentrations were adjusted for flow using the locally weighted scatterplot smoothing relationship between ln(flow) and ln(concentration) (Richards et al. 2008).

The trends in flow for the two rivers are increasing, but neither is statistically significant at $p \leq 0.05$, after adjustment for autocorrelation. All of the trends for concentrations are downward, and all are statistically significant ($p \leq 0.05$), with those for the Maumee achieving a higher level of significance than those for the Sandusky. All of the trends for loads are downward, but none is statistically significant. The trends in concentration involve greater rates of decrease than the apparent trends for loads, consistent with the loads being the product of increasing flows and decreasing concentrations. The difference in significance levels between concentration and load trends reflects the slower rate of change in loads, the greater variance of loads as compared with concentrations, and the success of flow-adjustment in decreasing the variance (and autocorrelation) of concentration data.

The apparent trends in suspended sediment loads amount to a 32% decrease for the Maumee and 18% for the Sandusky during the period of record. The Ohio Lake Erie Commission's goal of a 67% reduction is in reference to a base period of 1991 through 1996. Between 1996 and 2005, the apparent decreases in Maumee and Sandusky loads were 12% and 6%, respectively. Relative to this ambitious goal, more progress is clearly needed.

The apparent decrease in particulate phosphorus load is 33% for the Maumee and 18% for the Sandusky during the period of record. These decreases are important contributions to reductions in total phosphorus loads entering Lake Erie. The management goal of 11,000 t (12,125 tn) of total phosphorus per year from all sources was first met in the mid-1980s and has been met since then in more years than not. Variability from year to year is driven by non-point source loads, which are strongly influenced by the weather.

If one assumes that progress in reducing these parameters is better measured by concentration than by load, the results are better. The suspended sediment concentration decreased 44% during the period of record in the Maumee and 29% in the Sandusky. Between 1996 and 2005, the decreases in Maumee and Sandusky suspended sediment concentrations were 18% and 11%. The particulate phosphorus concentration decreased 37% during the period of record in the Maumee and 27% in the Sandusky.

Analysis of Covariance for Change in Concentration-Flow Relationships. Results of the analysis of covariance (ANCOVA) described in the methods section are reported in table 4. Analyses were done for each river and for suspended solids and particulate phosphorus. The graphs in figures 8 and 9 are plots of the mean value of ln(concentration) for each year as a function of time. All four graphs show decreases that are highly significant statistically. These graphs indicate that the amount of suspended solids or particulate phosphorus expected for a given flow is decreasing over time.

It is difficult to imagine these results being a consequence of weather effects. Monthly precipitation shows non-significant trends with slopes less than 0.013 cm y^{-1} (0.005 in yr^{-1}) and p-values of 0.60 and 0.99, in the two climate regions in which these watersheds are located. Discharge shows non-significant increases, which if anything should lead to increasing concentrations. Moreover, the concentrations have been adjusted to remove

Table 4

Results of analysis of covariance (ANCOVAs) of ln-transformed suspended solids and particulate phosphorus concentrations as a function of ln-transformed flow and YEAR, which is simply the year in which the sample was taken. YEAR was treated as a categorical variable. Results are reported for each river for the entire data sets, and for data broken down into four seasons or high flow and low flow periods. Statistically significant results are highlighted by bolding of the *p*-value.

River	Analysis	Trend coefficient for YEAR	r^2 (%)	*p* value
Suspended solids				
Maumee River	Overall	−0.0207	45.9	**0.0001**
	High flow	−0.0126	16.5	**0.0357**
	Low flow	−0.0268	41.6	**0.0003**
	Spring	−0.0009	0.1	0.8964
	Summer	−0.0272	50.0	**≤0.0001**
	Fall	−0.0289	81.7	**≤0.0001**
	Winter	−0.0129	13.6	0.0586
Sandusky River	Overall	−0.0157	33.4	**0.0008**
	High flow	−0.0104	9.5	0.0971
	Low flow	−0.0179	24.7	**0.0052**
	Spring	−0.0105	8.6	0.1229
	Summer	−0.0199	23.2	**0.0081**
	Fall	−0.0236	36.4	**0.0004**
	Winter	−0.0015	0.1	0.8512
Particulate phosphorus				
Maumee River	Overall	−0.0154	52.8	**≤0.0001**
	High flow	−0.0111	26.0	**0.0066**
	Low flow	−0.0170	56.6	**≤0.0001**
	Spring	−0.0070	9.2	0.1249
	Summer	−0.0171	45.4	**0.0001**
	Fall	−0.0195	78.1	**≤0.0001**
	Winter	−0.0114	10.7	0.0959
Sandusky River	Overall	−0.0121	36.9	**0.0004**
	High flow	−0.0057	6.7	0.1663
	Low flow	−0.0151	31.0	**0.0014**
	Spring	−0.0105	17.7	**0.0232**
	Summer	−0.0116	21.5	**0.0113**
	Fall	−0.0177	38.6	**0.0002**
	Winter	−0.0057	2.1	0.4662

flow effects. Temperature shows an increase of a bit less than 1°C (1.8°F) during the period of study. This increase is statistically significant but small compared to the range of monthly average temperatures of about 25°C (45°F). It is not clear what impact increasing temperature should have on concentrations, but it would seem more likely to increase them than to decrease them. The only other weather change that might affect the relationship between concentration and flow is a change in the intensity of storms. While such a change has been reported for the Midwest (e.g., Kunkel et al. 1999), the change is toward increasing storm intensity, which again should lead to increasing sediment or particulate phosphorus for a given flow, not the decrease observed for these data.

Upstream point sources are a minor contributor to loads and concentrations in these watersheds. During the period of this study, upstream point sources contributed, on average, 8.6% of the observed Maumee tributary load of total phosphorus and 5.9% of the observed Sandusky load. Point source loading has decreased during the period of record, but these point source reductions account for less than 30% of the decreases in total phosphorus loads observed at the sampling stations. Since much of the point source phosphorus is dissolved, decreases in point source loads of particulate phosphorus (which are unknown) would be an even smaller percentage of the overall decreases in particulate phosphorus loads.

On the other hand, these results are consistent with the expected benefits of erosion-control practices, such as reduced tillage and the use of filter strips. They are also consistent with increases in tile drainage in these watersheds, at least according to modeling studies (Bingner et al. 2004). Tile drainage reduces soil moisture and allows infiltration of more rainfall, especially early in the storm period when erosion and soil loss tend to be greatest. Model scenarios that incorporate tile drainage generate more total discharge but less surface discharge and sediment yield than scenarios that differ only in lacking tile drainage.

Trends in a number of agricultural variables through 1995 were described for these watersheds by Richards et al. (2002b). They reported minor shifts in crop preferences, with soybeans increasing and wheat and hay decreasing. The number of farms decreased, but farm size increased, and overall there was a less than 10% decrease in total farm acreage. Crop yields increased by 15% to 30% (depending on the crop), reflecting better varieties, increased soil fertility, and better farming techniques. Important for this paper are increases in conservation tillage from minimal to about 50% by 1995, and increases in Conservation Reserve Program (CRP) acres from 0% to about 5% of the total farmland, including most highly-erodable land. Fertilizer sales decreased after about 1980, and manure production decreased throughout 1975 to 1995. In spite of reduced fertilizer and manure, Baker and Richards (2002) calculated that nutrient imports exceeded exports in every year, and Calhoun et al. (2002) reported that soil phosphorus levels increased throughout the period.

From 1995 to 2005, many of these trends continued, including changes in farm size and number, crop choices and yields, and animal populations. However, dairy cows increased in the Maumee from 2000 to 2005, and hogs and pigs increased in the Sandusky between 1995 and 2005. Phosphorus budgets indicate continuing net imports of phosphorus into the watersheds, with some indications of larger surplusses recently. Soil concentrations of phosphorus have remained at 1995 levels or have declined slightly, and soil organic carbon content has declined. Conservation tillage has increased to about 60% since 1995.

The Ohio Lake Erie Conservation Reserve Enhancement Program has enrolled nearly 13,350 ha (33,000 ac) in CRP since 2000, an increase of 17.5%. However, some "traditional" CRP land is being brought back into production. In these watersheds, overall CRP enrollment peaked in the mid 1990s and has declined about 20% since then. We know of no source of data on trends in tile drainage but observe that contractors continue to install tile in previously untiled fields and to improve drainage in previously tiled fields.

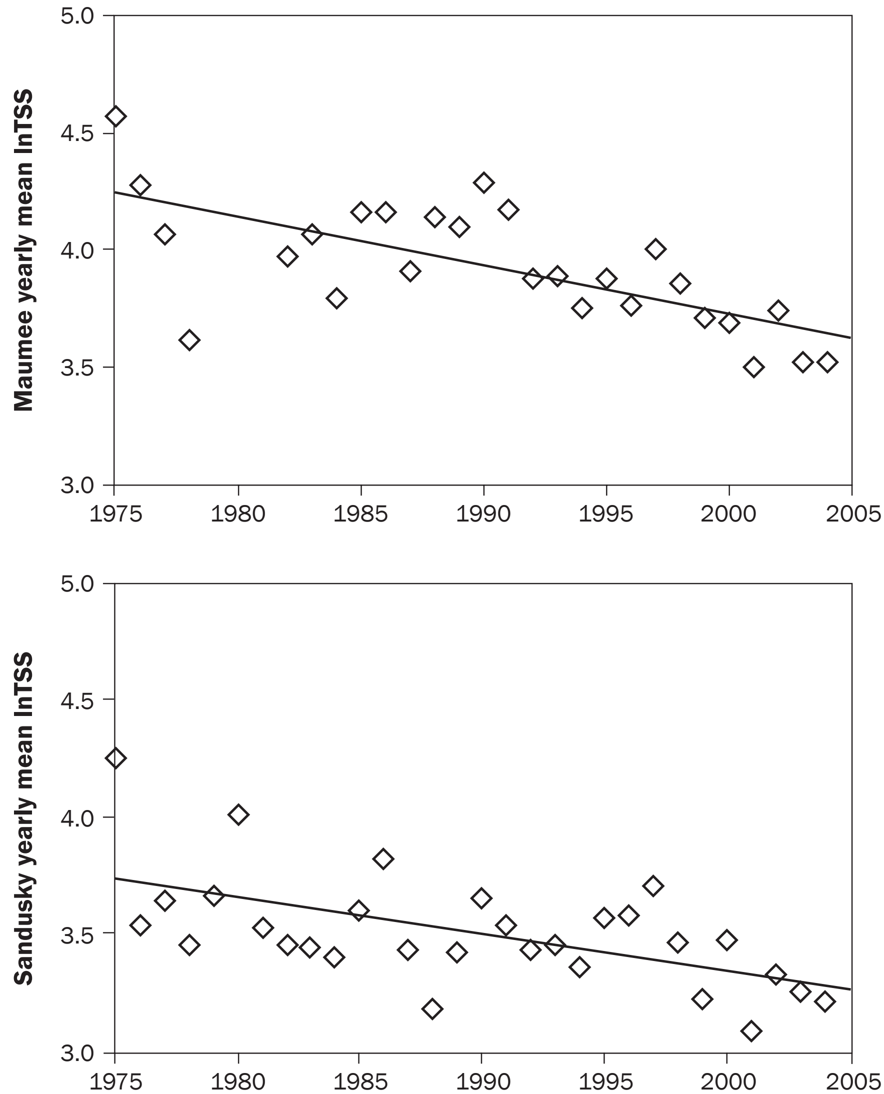
The observed changes in the relationship between suspended sediment or particulate phosphorus and flow appear to reflect beneficial effects of erosion control practices, including conservation tillage and conservation reserve programs and possibly tile drainage. The observed changes are contrary to what would be expected from recent increases in animal numbers in the watersheds and decreases in CRP acreage. Nor are they consistent with observed changes in the weather and in discharge. Presumably, if these factors had not changed in the ways they have, the decreases in suspended sediment and particulate phosphorus would have been even larger than those we observed.

High and Low Flow Conditions. The same analyses were performed separately on high- and low-flow data. Results are reported in table 4. High flows correspond to flows above the 60th percentile of flow; low flows were below the 60th percentile flow. This cutoff corresponds approximately to the boundary between flows associated with storm runoff and medium to low flows for which overland storm runoff is not a major component. It was also chosen for consistency with a related but more complex analysis of sediment trends as a function of flow (Richards et al. 2008).

For both the Maumee and the Sandusky, and for both suspended solids and particulate phosphorus, downward trends in the relationship between concentration and flow are stronger for the low-flow compartment than for the high-flow compartment. For the Maumee, all trends are statistically significant, but the low-flow trends have higher levels of statistical significance and explain more of the variability in the data. For the Sandusky, only the low-flow trends are statistically significant, though the high-flow trends are nearly significant when compared to the standard $\alpha = 0.05$ criterion. The larger negative slopes indicate that the relationships between concentration and flow are changing (improving) faster at low flow than at high flow. The lower r^2 and p-values associated with high flows probably reflect the fact that storm runoff is the major source of variability in concentrations from year to year, and consequently the high-flow annual averages are subject to more weather-imposed variability than the low-flow averages. Changes in low-flow sediment concentrations may reflect changes in nutrient status of the river as well as changes related to land management because during low flow conditions, sediment and particulate phosphorus are not being carried off the land, and under sustained low-flow conditions, a significant portion of the "sediment" may in fact be algae, not sediment from the land. Sediment concentrations are generally much lower under low flow conditions than under high flow.

Seasonal Analysis. Results for ANCOVAs with the data divided into four seasons are also reported in table 4. The strongest

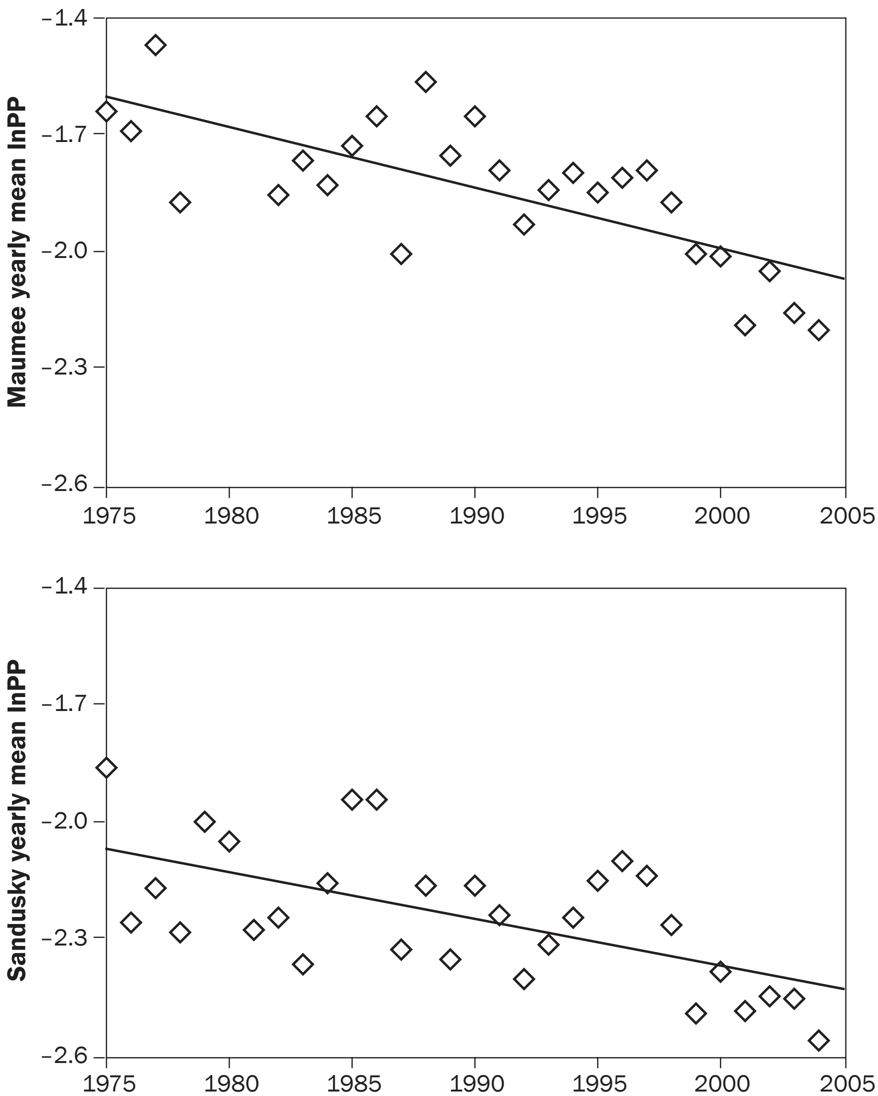
Figure 8
Trends in the yearly mean value returned from analysis of covariance (ANCOVAs) of the natural log of suspended solids concentration as a function of the natural log of flow and YEAR, where YEAR was treated as a categorical variable. The downward trends in this figure document a change in the sediment rating curve over time, leading to lower suspended solids concentrations for a given flow.



Note: TSS = total suspended solids.

Figure 9

Trends in the yearly mean value returned from analysis of covariance (ANCOVAs) of the natural log of particulate phosphorus concentration as a function of the natural log of flow and YEAR, where YEAR was treated as a categorical variable. The downward trends in this figure document a change in the phosphorus rating curve over time, leading to lower particulate phosphorus concentrations for a given flow.



Note: PP = particulate phosphorus.

decreases in the concentration-flow relationship are associated with the fall season, followed by summer. Trends in the spring and winter seasons are generally weak. Only one of the eight (particulate phosphorus in the spring in the Sandusky) achieves statistical significance.

These results are not completely independent from those for high and low flows because summer and fall months have more frequent low flows than winter and spring. For both rivers, the season of maximum average daily flow is spring, followed by winter, then summer, then fall. Of the average annual discharge for each river, about 44% occurs in the spring, 25% in the winter, 23% in the summer, and only 8% in the fall.

One change in agricultural practices that is consistent with the observed patterns is the adoption of conservation tillage in general, which has major benefits in early summer (May to June) before crop cover is well established and continued benefits in the fall and winter. Another is the increase in winter wheat, now planted without tillage, which provides major benefits in the fall when it is planted and additional benefits in the winter. The minimal change in concentration-flow relationships in the spring may reflect the difficulty of controlling erosion under spring thaw conditions, when the ground is partly frozen, but the upper soil layer is thawed, saturated with water, and highly mobile.

Summary of Analysis of Covariance Results Relating Concentration and Flow. The direction of change in the concentration-flow relationship is downward for all (28) analyses, though in nine analyses the trend is not statistically significant. Decreases in the concentration-flow relationship over time are primarily concentrated in the summer and fall seasons, when flows are moderate to minor. Changes in the winter and spring relationships are generally less favorable, when evaluated against the goal of reducing the concentration of sediment associated with a given flow. These results point to opportunities to improve winter and spring losses of sediment through increases in best management practices such as the use of cover crops and the avoidance of fall tillage.

The Maumee and Sandusky Rivers show similar patterns in all aspects of their trends. Shifts in concentration-flow relationships of the sort reported here would not be expected as a consequence of long-term shifts in climate. The consistent decreases in concentration-flow relationships for these Ohio agricultural tributaries appear to signal the success of agricultural management practices in lowering the export of sediment and its associated particulate phosphorus from these watersheds.

Summary and Conclusions

Over a thirty-year period of record from Water Year 1975 through Water Year 2004, flows in the Maumee and Sandusky Rivers increased, but this increasing trend is not statistically significant. Trends in concentrations and loads of suspended solids and particulate phosphorus were all decreasing. Because of increases in flow, decreases in load were smaller than decreases in concentration. Decreases in concentration were statistically significant, even after adjusting for autocorrelation, but decreases in loads were not significant. Apparent rates of decrease for loads were in the range of 6% to 12% per decade. Rates of decrease for concentrations were in the range of 10% to 18% per decade.

Analysis of the relationship between ln(flow) and ln(concentration) (the rating curve) shows that this relationship has changed systematically over time in the direction of lower concentrations for a given flow. This systematic change in the rating curve would not be expected as a result of changes in weather but is consistent with changes in land use.

Changes in the concentration-flow relationship are greater under low-flow conditions than under high-flow conditions and are greater in the summer and fall months than in the winter and spring months. Seasonal trends and trends by flow class are not totally independent of each other because some seasons have higher flows than others. The season with the highest flows shows the least improvement in the concentration-flow relationship, and the season with the lowest flows shows the greatest improvement.

Sustained decreases in concentrations and loads of suspended solids and particulate phosphorus, and in the rating curves for these parameters, appear to reflect the success of agricultural management programs in these watersheds in reducing erosion and delivery of sediment and associated phosphorus to the tributary system. The fact that the smallest changes are associated with the winter and spring, periods of above-average discharge, indicates that significant opportunities exist to further reduce sediment and phosphorus loads and concentrations in these seasons. An increased focus on best management practices such as winter cover crops and avoidance of fall tillage might pay large dividends here.

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