Unusually large loads in 2007 from the Maumee and Sandusky Rivers, tributaries to Lake Erie

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Abstract: During water year 2007 (October 1, 2006, through September 30, 2007), the Maumee River and Sandusky River in northern Ohio transported the largest, or nearly the largest, loads of several water quality constituents that have been observed in 33 years of monitoring. Discharge, total phosphorus, dissolved reactive phosphorus, total Kjeldahl nitrogen, and chloride all recorded 33-year maximum loads, while the loads for nitrate ranked 5th (Sandusky) and 8th (Maumee) out of 33. Loads of particulate phosphorus ranked 2nd (Sandusky) and 4th (Maumee), and those for suspended solids ranked 10th (Sandusky) and 9th (Maumee). This is partly a consequence of total rainfall, which was the largest observed at the Tiffin weather station (Sandusky watershed) and nearly the largest at the Toledo station (Maumee watershed) during this period. It also results from other aspects of the weather in interaction with agricultural practices, notably a warm, wet fall and early winter. Longer-term trends were also significant factors for some parameters. The weather was the major factor responsible for these large loads. Regardless of cause, these loads represent a substantial loss of resources from agricultural fields in the watersheds. This loss could have been reduced by better management. Losses of sediment and phosphorus from these watersheds are higher than average for Midwestern agricultural watersheds, and losses of nitrogen are slightly above average. Based on winter 2008 fertilizer prices from local fertilizer dealers, replacing the nutrients lost from these watersheds in water year 2007 would cost more than \$80,000,000 or \$166 ha⁻¹ (\$67 ac⁻¹) for every field in the watershed receiving fertilizer in a given year.

Key words: hydrology—nonpoint source pollution—nutrients—sediment—weather effects

In the lower Great Lakes watershed, loadings of sediment and nutrients to the lakes are strongly influenced by weather patterns and by the extent of agricultural land use (IJC 1978; Baker 1993). For a number of reasons, Lake Erie is the most vulnerable of the five Great Lakes to negative anthropogenic influences. Lake Erie is the shallowest (mean depth 19 m [62 ft]) and the warmest (Bennett 1978) and has the shortest residence time (2.6 years). Its watershed has the largest population (11.7 million), the highest population density (150 km⁻² [388 mi⁻²]), and the largest ratio of population to lake volume (24,100 km⁻³ [100,700 mi⁻³]) (data from USEPA 2008b). Its watershed has the highest percentage of agricultural land use (67%) and the lowest percentage of forest (21%) (data from USEPA 2008c). It almost certainly receives the highest nutrient loads

from all sources combined, though a paucity of loading data for the other Great Lakes prevents a thorough comparison.

By the late 1960s, Lake Erie was in the throes of cultural eutrophication (ES&T 1967; IJC 1965, 1970). This manifested itself in many ways, including increased extent and severity of hypoxia in the Central Basin hypolimnion in late summer (Carr 1962), the extirpation of mayflies (Krieger et al. 2007), impacts on other benthic fauna, a simplified trophic structure dominated by alewives and other planktivores, and extensive blooms of *Cladophora* sp. (Read 1999) and noxious cyanobacteria such as *Microcystis* sp. Rehabilitation of the lake focused on reducing phosphorus loads to limit algal productivity (ACOE 1982; GLWQA 1972; IJC 1965, 1970, 1978). 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 bound to sediment (IJC 1978). In this context, more detailed and accurate knowledge of tributary loads of sediment, phosphorus, and other nutrients became a matter of concern.

The National Center for Water Quality Research (NCWQR) at Heidelberg University began monitoring sediment and nutrients in the major US tributaries to Lake Erie in 1975, with some records extending back as far as the late 1960s. The past thirty years have seen improvements in some aspects of water quality in these tributaries (reductions in suspended solids [SS] and particulate phosphorus [PP] [Richards et al. 2008, 2009]), as well as some worsening trends (increasing dissolved reactive phosphorus [DRP] [Richards 2006]). Year-to-year changes in loads from these nonpoint source-dominated rivers primarily reflect weather influences, particularly the number, seasonal timing, and intensity of storms and the extent and duration of frozen ground conditions in the winter. Because of this variability, detection of sustained trends requires data series of decadal scale or longer (Richards and Grabow 2003). The importance of weather-related fluctuations is well-illustrated by the loads of water year (WY) 2007 (October 1, 2006, through September 30, 2007).

The goals of this paper are to document the unusually large loads in 2007, to consider why they were so large, and to explore some of the interactions between weather and farming practices that influence constituent loads from agricultural watersheds. Aspects of the weather of particular interest are the amount, timing, and nature of precipitation. Aspects of farming practices of interest include the timing and method of application of chemical fertilizers and manures, crop selection, and the use of reduced tillage and other erosion-reduction measures. This paper is an analysis of the accumulation of these loads throughout the water year, in compari-

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Table 1

Watershed characteristics of the Maumee and Sandusky Rivers.

Name	Watershed area (km ²)†	Area upstream of gage (km ²)‡	Land-use distribution for watershed upstream of gage (%)*				
			Agriculture: row crops	Grassland, pasture	Forest	Urban/residential	Other
Maumee	16,995	16,395	74	6	6	10	3
Sandusky	3,678	3,240	78	4	9	8	1

* Source: Watershed classification by Dan Button, US Geological Survey, Columbus, Ohio, (personal communication 2007) using the 2001 National Land Cover Database (USGS 2010).

† Source: Sanders 2002.

‡ Sources: Maumee (USGS 2008a). Sandusky (USGS 2008b).

son with those from previous years, for the Maumee and Sandusky Rivers in northern Ohio. These rivers were chosen for analysis for several reasons: they have the longest and most complete water quality records of any Great Lakes rivers; the Maumee has the largest watershed and the greatest annual discharges and constituent loads of any Lake Erie tributary, and the Sandusky is among the top five; and they are broadly representative in land-use distribution and crop selection of many agricultural watersheds in the Midwestern United States and southern Ontario.

Materials and Methods

Data Acquisition. Daily precipitation data were obtained from the National Oceanic and Atmospheric Administration National Climate Data Center for the major weather stations in each watershed, located in Toledo (Maumee basin) and Tiffin (Sandusky basin). Their locations are shown as stars in figure 1. Flow data are daily mean flows and are provided by the US Geological Survey (USGS). The locations of the gaging stations are shown as round dots in figure 1.

The NCWQR collects samples for sediment and nutrient analysis at or near USGS gaging stations on five major tributaries to Lake Erie, including the Maumee and Sandusky. The gaging stations are located as close to the lake as feasible but sufficiently far upstream to be free from flow reversals due to seiche activity in the lake. 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.

Samples are taken using Isco autosamplers (Teledyne Isco, Lincoln, Nebraska). Prior to May 1988, samples were taken four times per day, and the autosamplers were not refrigerated. In May 1988, refrigerated autosamplers were installed, and the sampling frequency was reduced to three times per day. During

Figure 1

Map of the study area, showing the locations of the water quality sampling stations (dots) and weather stations (stars).

Table 2

Identification and location of the Maumee and Sandusky flow and sample collection stations.

Name	USGS station number	Location of gage		Location of sampling station		Comment	Date of first sample
		Latitude	Longitude	Latitude	Longitude		
Maumee	04193500	41.500°N	83.713°W	41.478°N	83.738°W	Sampled from water intake at Bowling Green drinking water treatment plant	Jan. 10, 1975
Sandusky	04198000	41.308°N	83.159°W	Same as gage		Sampler in USGS gage station	July 8, 1969

Note: USGS = United States Geological Survey.

periods of high flow or high turbidity, all samples are analyzed; at other times, only one sample per day is analyzed. Typically, this program provides 400 to 450 analyzed samples per year, of which about 270 are low-flow samples and the rest are high-flow samples.

The results in this paper are based on nearly 30,000 water samples taken between 1975 and 2007, 13,933 from the Maumee and 14,754 from the Sandusky. Of these, 544 and 534, respectively, were taken in WY 2007. The NCWQR data area available from Baker (2005).

Sediment and Chemical Analyses. The NCWQR methods for analysis of sediment and chemicals in water closely parallel established US Environmental Protection Agency protocols and are summarized in table 3, which also provides references to the methods. Two of the parameters in table 3 may need explanation. Dissolved reactive phosphorus is measured colorimetrically on a filtered (0.45 μm [0.000018 in] pore size) sample without digestion; it is largely composed of orthophosphate. Total Kjeldahl nitrogen (TKN) is measured colorimetrically on an unfiltered, digested sample; it includes organic nitrogen and ammonia. In typical samples from these rivers, most of the TKN

is organic nitrogen because ammonia concentrations, which we measure separately, are small compared to TKN concentrations. For example, the average concentration of TKN in the Maumee River in WY 2007 was 1.60 mg L^{-1} ($n = 545$), and the average concentration of ammonia was 0.28 mg L^{-1} .

Particulate phosphorus was estimated for this study. Special studies, in which total phosphorus (TP), total dissolved phosphorus (TDP), and DRP were all measured (Baker unpublished), indicate that TDP in these rivers is about 110% of the DRP. The TP, by definition, is the sum of PP and TDP. Since we do not routinely measure TDP, we estimate it as $1.1 \times \text{DRP}$. Consequently, PP was estimated as $\text{PP} = \text{TP} - 1.1 \times \text{DRP}$.

Data Preparation and Analysis. Daily flow-weighted mean concentrations were calculated by dividing the daily load by the daily discharge. The daily load is the sum of sample loads obtained by multiplying the observed concentration by the instantaneous flow at the time of the sample and a sample time window. The 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) plus half the time from the current sample to the next

sample (or the time to the end of the day, for the last sample). The daily discharge is similarly calculated as the sum of the sample discharges, each of which is the product of the flow at the time of each sample and the sample time window. Daily loads were then calculated as the product of daily flow-weighted mean concentration and the official daily mean flow reported by the USGS.

In order to compare cumulative loads, there must be a daily load for each day of the year. Thus, it was necessary to fill gaps in the record that resulted from equipment malfunction or analytical problems. Short gaps in the record (five days or less) were filled by linear interpolation. Longer gaps were filled by estimated daily loads. Daily loads were estimated by multiple regression of log-load as a function of log-flow. Log-flow squared and log-flow cubed were included to allow modeling of simple nonlinearity in the load-flow relationship. Time and time squared terms were included to account for trends. Sine and cosine of $2\pi t$, $4\pi t$, and $6\pi t$, where t is time in years, were included to model seasonality. Terms that were not statistically significant in a particular analysis were removed, least significant first. This approach is similar to an approach often used by the

Table 3

Analytical methods, method citations, and method detection limits for the parameters reported in this paper.

Parameter	Instrumentation	USEPA equivalent method	Method detection limit (mg L^{-1})
Total suspended solids (SS)	Mettler Toledo balance	160.2*	2.86
Total phosphorus (TP)	Technicon Autoanalyzer II	365.4†	0.0023
Particulate phosphorus (PP)	Computed as $\text{TP} - 1.1(\text{DRP})$	na	na
Dissolved reactive phosphorus (DRP)	Braun-Luebbe TrAAcs 800	365.3†	0.001
Nitrate (NO_3)	Dionex Ion Chromatograph	300.0†	0.042
Total Kjeldahl nitrogen (TKN)	Technicon Autoanalyzer II	351.2†	0.055
Chloride (Cl)	Dionex Ion Chromatograph	300.0†	0.27

Notes: USEPA = United States Environmental Protection Agency. na = not applicable.

* USEPA 2008d.

† USEPA 2008a.

US Geological Survey to estimate daily loads (Cohn et al. 1989, 1992)

Because predictions from regression analysis generally have a smaller range than the observed values, the range of the predicted values was expanded by using a multiplier on the residuals from the model. In addition, a multiple of the variance of the residuals (initially 0.5) was added to each predicted value to avoid back-transformation bias (Ferguson 1986; Cohn et al. 1989, 1992). These two "tuning" factors were adjusted to yield predicted values with a median and range comparable to the observed load values, as judged by comparisons of box plots of the log-values and the back-transformed values.

While these statistical models capture the general behavior of the daily load series as influenced by flow and by seasonal and long-term trends, they cannot capture excursions from the average condition, such as might result, for example, from a particularly cold winter or an atypical storm, because there are no variables in the models that reflect these factors. Consequently, the estimated concentrations for some periods of missing data do not fit smoothly with the real data on either end of the gap. For this reason, the estimated daily loads used to fill the gap received a ramped adjustment. An initial ratio was computed by dividing the load estimated for the day before the gap by the observed load for that day. A final ratio was calculated in the same way using the values for the day following the gap. Ratios for each day of the gap were calculated by linear interpolation between these two ratios. Each estimated value was then multiplied by the corresponding ratio to produce the ramped values used to fill the gap.

This procedure was used only to estimate values to fill gaps, which generally amount to well less than 10% of the data. In 2007, there was one gap six days long due to sampler failure, one gap three days long for SS and TP due to analytical problems for the Maumee (1.6% or 2.5% of the days, depending on the parameter), and four gaps involving a total of 23 days (6.3%) due to sampler failure for the Sandusky. The modeled load procedure allows these gaps to be filled by values that are reasonable and realistic both in comparison to the overall data and in comparison to the data that immediately surround the gaps.

Cumulative loads for each water year were computed by adding the load for a given day to the sum of the loads from the pre-

vious days of the water year. Graphs of the cumulative loads of most parameters were prepared (figures 2 to 8) using a heavy line for the cumulative load for 2007 and light lines for loads for each of the other 32 water years. (Graphs for parameters not presented in this paper are available upon request from the author.) Average cumulative loads as of February 1 (the approximate end of the rapid accumulation period for many parameters) and April 1 (the midpoint of the water year) were computed for the 33-year period of study and compared with those for 2007 (table 4).

Loads from Other Watersheds. To provide a larger context for these loads, loads reported in the literature were assembled for comparison. Such comparisons are interesting but involve many confounding factors. These include influences of static natural factors such as watershed size, land use, climate, topography, soil types, and the presence of impoundments in the basin (Robertson et al. 2006); water quality trends and stochastic factors such as year to year variations in the weather, in interaction with the period of study; and technical factors such as differences in chemical analysis methods, sampling frequency and pattern, and load calculation methodology. To reduce the influence of some of these factors, our search for other studies was limited to watersheds with more than 50% cropland and with land areas between 50 to 100,000 km² (19.3 to 38,600 mi²). Selected watersheds were confined to a geographic region defined by the western borders of Iowa and Missouri and the northern border of Iowa and the southern border of Missouri projected eastward to the Atlantic coast, a region of reasonably similar climate. To facilitate comparison of results from watersheds of different sizes, the data were expressed as yields, or unit area loads, computed by dividing the load by the watershed area.

An extensive database of average annual yields of suspended solids, total nitrogen, and TP was provided by the USGS (Dale Robertson, research hydrologist, US Geological Survey, Middleton, Wisconsin, personal communication, 2009), covering more than 900 mostly Midwestern sites and updating and extending data from Robertson (2006). This dataset was analyzed separately from the dataset described in the previous paragraph because some data were present in both datasets. In addition, this dataset included

multiple sites on some rivers, unlike the first dataset, and only average annual yields are available. After filtering using the geographic and land-use criteria described above, average annual yields for approximately 300 sites remained. The exact number differed from parameter to parameter. These were compared with average annual yields and WY 2007 yields for the Lake Erie tributaries.

Results and Discussion

Cumulative Loads. Precipitation and storm runoff events produce rapid, step-like increases in the cumulatives; dry periods with low flow and small daily loads produce plateaus. Precipitation (figure 2) shows less variation from year to year than does discharge and the loads of the various constituents. Although late summer and early fall are often thought of as times of little precipitation, the graphs do not support this perception. The general pattern is one of nearly uniform accumulation of precipitation throughout the year, though there are some years with prolonged dry periods. In WY 2007, fall/winter precipitation was above average through early January 2007: 149% of the 33-year average at the Toledo weather station and 135% at the Tiffin station. At Tiffin, May, June, and most of July were drier than usual, but 42.2 cm (16.6 in) of rain fell between July 15 and August 31, 2007, 36% of the annual total. Heavy rains on August 20 and 21 accounted for 10.7 cm (4.2 in) of this total and raised the annual precipitation to a record level. The Maumee did not have as pronounced a dry spell but also received less rainfall in late July and August, 2007: 28.3 cm (11.1 in) between July 15 and August 31 (28% of the annual total), with 9.9 cm (3.9 in) on August 19 and 20.

Discharge was above average for both watersheds, notably during the fall and early winter (figure 3). Between October 1, 2006, and February 1, 2007, the discharge for the Maumee was 3,949 million cubic meters (Mm³) (139 billion cubic feet [Bft³]) and that for the Sandusky was 936 Mm³ (33 Bft³). These are more than 2.5 times the 33-year averages of 1,504 Mm³ (53 Bft³) and 336 Mm³ (12 Bft³), respectively. Dry conditions during May through July were reflected in little accumulation of discharge during these months and most of August. Between July 15 and August 17, 2007, discharge as a percent of rainfall was only 2.18% in the Maumee basin and 2.13% in the Sandusky, compared with 48.0% and 54.7%, respectively, for the year as

Table 4

Accumulation of precipitation, flow, and loads during 2007 compared to the 33-year average.

Parameter	River or location	October 1, 2006, to February 1, 2007	October 1 to February 1, 33-year average	Percent of full year load, 2007	Percent of full year load, 33-year average	October 1, 2006, to April 2, 2007	October 1 to April 2, 33-year average	Percent of full year load, 2007	Percent of full year load, 33-year average	Full year, 2007	Full year, 33-year average
Precipitation (cm)	Toledo	39.0	25.6	38.1%	29.7%	47.1	36.6	46.0%	42.5%	102.4	86.1
	Tiffin	42.5	27.9	36.1%	29.2%	55.0	39.2	46.7%	41.0%	117.7	95.7
Discharge (Mm ³)	Maumee	3,949	1,504	49.0%	29.4%	5,605	2,952	69.5%	57.7%	8,066	5,115
	Sandusky	936	336	44.8%	31.0%	1,643	661	78.6%	61.0%	2,090	1,084
Suspended solids (KMg)	Maumee	727	268	53.4%	24.8%	976	60	71.7%	55.6%	1,362	1,080
	Sandusky	165	54	47.3%	23.0%	287	118	82.2%	50.2%	349	235
Total phosphorus (Mg)	Maumee	2,063	683	56.9%	30.8%	2,730	1,317	75.3%	59.3%	3,626	2,221
	Sandusky	524	133	55.7%	29.0%	800	265	85.0%	57.9%	941	458
Particulate phosphorus (Mg)	Maumee	1,487	527	57.0%	29.8%	1,955	1,038	74.9%	58.7%	2,611	1,769
	Sandusky	371	100	54.9%	26.7%	575	207	85.1%	55.2%	676	375
Dissolved reactive phosphorus (Mg)	Maumee	523	143	56.7%	34.7%	704	255	76.3%	61.9%	923	412
	Sandusky	139	29	57.7%	38.2%	204	51	84.6%	67.1%	241	76
Nitrate (KMg)	Maumee	13.8	8.82	41.7%	30.1%	25.51	16.40	77.0%	100.4%	33.11	29.33
	Sandusky	3.05	1.78	44.1%	29.3%	5.22	3.38	75.4%	55.7%	6.92	6.07
Total Kjeldahl nitrogen (KMg)	Maumee	6.76	2.67	40.4%	29.2%	9.21	5.24	55.0%	57.3%	16.74	9.14
	Sandusky	1.46	0.51	47.2%	27.1%	2.48	1.06	80.3%	56.4%	3.09	1.88
Chloride (KMg)	Maumee	78.6	47.5	42.5%	33.1%	126.6	87.2	68.5%	60.7%	184.8	143.6
	Sandusky	16.2	9.7	35.8%	33.8%	36.9	18.6	81.5%	64.8%	45.3	28.7

Notes: Mm³ = million cubic meters. KMg = thousand megagrams (thousand metric tons). Mg = megagrams or metric tons.

a whole and 48.2% and 55.7%, respectively, for August 18 to 30, 2007. The extreme rainfall in late August, which led to widely reported flooding in Findlay, Ohio, (within the Maumee basin) was not uniformly distributed throughout these watersheds. The combination of uneven rainfall distribution and dry soil conditions kept the jump in cumulative discharge in late July and August from being larger than it was, but this discharge increment completed the accumulation of record-setting discharges for both watersheds (figure 3).

Suspended solids loads accumulated at a record-setting pace for the first half of water year 2007 (figure 4), especially for the Sandusky, but little additional accumulation occurred during the dry period in late spring and early summer. The large storm event in late August did not generate particularly high sediment concentrations, perhaps in part because crop cover was well developed and

protected the land from erosion. As a result, the increase in sediment loads did not match that in discharge.

The TP loads set records for the period of record for both the Maumee and the Sandusky (figure 5). Most of the loading occurred during the fall and winter, with major loading events in December and particularly in January. The cumulative load curves for TP reflect the patterns of movement of both PP and DRP, which were quite different from each other.

Loads of PP accumulated rapidly in the fall and winter, especially in the Sandusky, and then did not change much during the dry period in the spring. The cumulative curves are very similar to those for SS. The loads for both watersheds were less than the highest ever observed, but only slightly. The highest load for the Maumee occurred in 1991 and was mostly due to a major storm at the end of December with very high flows,

up to 2,450 m³ s⁻¹ (86,700 ft³ sec⁻¹) and very high PP concentrations up to 2.07 mg L⁻¹, both above the 99.9th percentile of all values in the 33-year period. With the exception of the Maumee load for 1991, the WY 2007 PP loads for both rivers are within 3% of the highest observed loads.

Loads of DRP were easily the most extreme of the record-setting parameters and were two to three times as high as average (figure 6). Fall and winter months were periods of high loading. By April 2, half way through the water year, 76% of the Maumee load and 85% of the Sandusky load had already passed downstream. Years with large loads often have major loading events in January, February, or March and relatively little additional load during the second half of the year. Water year 2007 had some significant loading during this time, but what sets it apart is the very high loading from October to January. On average, TP loads are about

Figure 2

Cumulative precipitation for weather stations in (a) Toledo (Maumee watershed) and (b) Tiffin (Sandusky watershed), Ohio. The heavy line is the precipitation for water year 2007. Lighter lines show precipitation for the other 32 water years.

Figure 3

Cumulative discharges for the (a) Maumee River and (b) Sandusky River. The heavy line is the discharge for water year 2007. Lighter lines show discharge for the other 32 water years.

Figure 4

Cumulative suspended solids loads for the (a) Maumee River and (b) Sandusky River. The heavy line is the load for water year 2007. Lighter lines show suspended solids for the other 32 water years.

Figure 5

Cumulative total phosphorus loads for the (a) Maumee River and (b) Sandusky River. The heavy line is the load for water year 2007. Lighter lines show total phosphorus for the other 32 water years.

Figure 6

Cumulative dissolved reactive phosphorus loads for the (a) Maumee River and (b) Sandusky River. The heavy line is the load for water year 2007. Lighter lines show dissolved reactive phosphorus for the other 32 water years.

Figure 8

Cumulative chloride loads for the (a) Maumee River and (b) Sandusky River. The heavy line is the load for water year 2007. Lighter lines show chloride for the other 32 water years.

Figure 7

Cumulative nitrate loads for the (a) Maumee River and (b) Sandusky River. The heavy line is the load for water year 2007. Lighter lines show nitrate nitrogen for the other 32 water years.

80% PP, but in 2007, they were only 72% PP, reflecting the especially rapid loss of DRP in the fall and early winter.

Nitrate loads typically accumulate fairly steadily during most of the first three quarters of the year (on average about $0.07 \text{ kg ha}^{-1} \text{ day}^{-1}$ (or $0.06 \text{ lb ac}^{-1} \text{ day}^{-1}$) for both rivers between November 15 and June 30) but increase minimally during the last quarter of the water year (average $0.01 \text{ kg ha}^{-1} \text{ day}^{-1}$ [$0.009 \text{ lb ac}^{-1} \text{ day}^{-1}$]), as shown by the prevalence of flat curves at the right side of figure 7. This general pattern is consistent with a temperate Midwest cropland nitrogen cycle, in which July, August, and September (the end of the water year) are times of relatively dry soil conditions that promote mineralization of organic nitrogen to nitrate, which is then flushed out of the soil during the fall, winter, and early spring (part of the following water year) (e.g., David et al. 1997; Randall and Goss 2001). Nitrate loads in WY 2007 accumulated at near-record rates during the fall and winter and were comparable to the largest previously observed as late as May. The dry conditions of May through most of August led to very little load accumulation during this period, and the increase resulting from the late August storm was modest. As a result, the annual loads were above average but nowhere near record setting.

Total Kjeldahl nitrogen loads (not graphed) in WY 2007 followed a trajectory very similar to that for TP, with sustained accumulation through early May and major periods of accumulation in January and March, the latter particularly for the Sandusky. A major loading pulse for the Maumee at the end of August is noteworthy. It resulted from much higher than usual concentrations associated with the late August storm and led to an annual load that was substantially greater than any previously measured. The load during that one event, nearly 5,000 t (5,510 tn), was greater than the load for all of WY 1988.

Table 5

Descriptions of watersheds from which yield data were obtained. The National Center for Water Quality Research (NCWQR) watersheds are listed first, followed by others in west-to-east order by state.

River	State	Area (km ²)	Percent cropland	Years*	Average runoff (cm)	Remarks	Source
Maumee River at Waterville	OH	16,395	74	1974 to 2007	31.2		NCWQR, Heidelberg University
Sandusky River at Fremont	OH	3,240	78	1974 to 2007	33.2		NCWQR, Heidelberg University
River Raisin at Monroe	MI	2,699	50	1982 to 2007	27.4		NCWQR, Heidelberg University
Honey Creek at Melmore	OH	386	81	1976 to 2007	31.1		NCWQR, Heidelberg University
Rock Creek at Tiffin	OH	90	72	1983 to 2007	30.7		NCWQR, Heidelberg University
Vermilion River near Vermilion	OH	679	54	2001 to 2007	40.7		NCWQR, Heidelberg University
Great Miami below Miamisburg	OH	7,032	65	1996 to 2007	42.0	Impacted by point sources	NCWQR, Heidelberg University
Scioto River at Chillicothe	OH	9,970	62	1996 to 2007	38.7	Impacted by point sources	NCWQR, Heidelberg University
Cedar River at Cedar Falls	IA	12,260	70	16	29.0		Goolsby et al. 1999
Skunk River at Augusta	IA	11,100	57	17	26.6		Goolsby et al. 1999
Raccoon River at Des Moines	IA	8,900	74	14	24.0		Goolsby et al. 1999
Des Moines River at St. Francisville	IA	37,040	62	14	23.8		Goolsby et al. 1999
Iowa River at Wapello	IA	32,400	65	1978 to 2005	27.3		Aulenbach et al. 2007
Walnut Creek	IA	52	69	1996 to 2005	22.2		Schilling 2002; Schilling and Spooner 2006; Schilling et al. 2006
Kaskaskia River near Venedy Station	IL	11,400	57	13	28.0		Goolsby et al. 1999
Illinois River at Valley City	IL	69,267	61	1975 to 2005	31.6		Aulenbach et al. 2007
Embarrass River	IL	481	91	1994 to 2005	32.0		Gentry et al. 2007; David personal communication 2009
Lake Fork, Kaskaskia River	IL	365	91	1998 to 2005	29.8		Gentry et al. 2007; David personal communication 2009
Big Ditch, Sangamon River	IL	101	86	1994 to 2003	25.8		Gentry et al. 2007
Bark River at Delafield	WI	93	54	3			Corsi et al. 1997; personal communication 2009
Delavan Lake Inlet at Lake Lawn	WI	56	75	4			Corsi et al. 1997; personal communication 2009
Rattlesnake Creek near North Andover	WI	110	99	3			Corsi et al. 1997; personal communication 2009
Yellowstone River near Blanchardville	WI	74	99	2			Corsi et al. 1997; personal communication 2009
Turtle Creek near Clinton	WI	515	88	2			Corsi et al. 1997; personal communication 2009
Yahara River at Windsor	WI	191	96	6			Corsi et al. 1997; personal communication 2009
Little Menomonee River at Milwaukee	WI	51	69	2			Corsi et al. 1997; personal communication 2009
Wabash River at New Harmony	IN	75,716	54	1975 to 1982, 1997 to 2005	36.8		Aulenbach et al. 2007
Four Mile Creek	OH/IN	129	94	1994 to 2006	41.0		Renwick et al. 2008
Little Four Mile Creek	OH	80	91	1994 to 2006	42.0		Renwick et al. 2008
Choptank River near Greensboro	MD	293	50	1981 to 2006	43.2		USGS 2009a

Notes: OH = Ohio. MI = Michigan. IA = Iowa. IL = Illinois. WI = Wisconsin. IN = Indiana. MD = Maryland.

* A range of years is given if that information was provided by the source. Some sources only provided the number of years for which data were available.

Chloride loads typically accumulate gradually throughout the year, with the rate of accumulation tapering off during the summer. Chloride cumulative loads have more subdued jumps during storm events because chloride concentrations typically decrease with increasing flow. Chloride loads accumulate rapidly in the winter in some years due to contributions from road salt. In WY 2007, the loads accumulated rapidly from the beginning (figure 8), well before the season of road salt application. These early loads prob-

ably came from potassium chloride applied as fertilizer. The surge in the Sandusky load in late February may reflect inputs from road salt. Figure 3 shows that there was a bigger runoff event at that time in the Sandusky than in the Maumee, which explains why there is not a jump in the Maumee chloride load corresponding to the jump in the Sandusky chloride load at that time.

The high loads of these parameters observed in WY 2007 were a consequence of a warm fall and early winter, which allowed

crops to be harvested and tillage and fertilization to be completed in the fall, activities that in other years are not completed as early and are often partly postponed until spring. Frequent rain during this time washed sediment and nutrients from the fields and led to high fall and winter loads, which were largely responsible for the greater-than-usual annual loads for these rivers.

Concentration and Flow as Determinants of Load. As stated earlier, discharge for WY 2007 was substantially higher than

Table 6

Yields of sediment and nutrients from Midwestern watersheds. Average yields are means of annual yields in most cases; averages that are medians are indicated by bold text. River numbers correspond to those in figure 9.

River number	River	Suspended solids		Total phosphorus		Dissolved reactive phosphorus		Particulate phosphorus		Total nitrogen		Nitrate nitrogen		Total Kjeldahl nitrogen	
		Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range	Average	Range
1	Maumee River	635	206 to 1,410	1.32	0.51 to 2.14	0.221	0.060 to 0.501	1.08	0.40 to 1.83	23.6	13.6 to 33.7	18.1	26.3	5.53	9.52
2	Sandusky River	678	164 to 1,780	1.38	0.42 to 2.82	0.219	0.034 to 0.673	1.14	0.34 to 2.11	23.4	10.5 to 36.7	18.0	8.6 to 28.5	5.37	1.88 to 9.60
3	River Raisin	213	87 to 345	0.51	0.24 to 0.77	0.086	0.024 to 0.222	0.42	0.18 to 0.70	15.2	9.1 to 21.2	12.1	7.3 to 17.8	3.10	1.61 to 4.15
4	Honey Creek	501	62 to 1,580	1.25	0.32 to 2.62	0.228	0.041 to 0.772	1.00	0.22 to 1.98	22.2	9.7 to 32.3	17.0	6.7 to 26.9	5.23	1.87 to 8.29
5	Rock Creek	749	121 to 2,020	1.34	0.35 to 3.24	0.151	0.025 to 0.569	1.18	0.29 to 2.65	16.9	7.2 to 28.3	11.5	5.5 to 17.4	5.37	1.77 to 10.87
6	Vermilion River	861	190 to 1,650	1.24	0.34 to 1.99	0.197	0.065 to 0.339	1.02	0.27 to 1.65	16.2	7.7 to 23.8	10.3	5.7 to 14.0	5.90	2.02 to 9.79
7	Great Miami River	597	101 to 1,708	1.66	0.75 to 2.96	0.609	0.368 to 0.990	0.99	0.35 to 2.16	22.6	12.7 to 30.1	17.5	10.5 to 23.3	5.13	2.15 to 8.35
8	Scioto River	488	188 to 997	1.31	0.74 to 1.99	0.455	0.278 to 0.776	0.81	0.41 to 1.58	18.9	12.6 to 25.4	14.4	10.0 to 19.8	4.50	2.53 to 7.13
9	Cedar River			0.85		0.870				27.5		25.0			
10	Skunk River			1.21		0.417				20.2		15.6			
11	Raccoon River			0.85		0.445				30.9		26.1			
12	Des Moines River			0.64		0.371				18.5		16.9			
13	Iowa River			0.94	0.18 to 1.14	0.475	0.090 to 1.466			25.2	2.3 to 69.3	20.6	1.4 to 61.4	4.64	1.00 to 10.03
14	Walnut Creek	650	135 to 1,440	0.66	0.32 to 0.81							30.3	17.4 to 58.9		
15	Kaskaskia River			0.81		0.493				7.3		3.9			
16	Illinois River			1.14	0.51 to 1.54	0.519	0.335 to 0.628			19.6	8.6 to 34.6	15.2	5.9 to 28.9	4.36	2.06 to 7.06
17	Embarrass River			0.82	0.16 to 2.13	0.452	0.089 to 0.902			30.5	9.3 to 64.5	29.3	8.9 to 56.7		
18	Lake Fork			0.65	0.10 to 1.23	0.313	0.049 to 0.603			35.7	8.6 to 60.4	33.6	7.6 to 57.6		
19	Big Ditch			0.58	0.31 to 0.76	0.287	0.139 to 0.406					26.8	9.0 to 46.8		
20	Bark River	137		0.14											
21	Delavan Lake Inlet	104		0.49											
22	Rattlesnake Creek	701	487 to 2,930	1.44	1.26 to 6.43										
23	Yellowstone River	480	189 to 771	1.2											
24	Turtle Creek	389	158 to 620	1.26											
25	Yahara River	77	28 to 406	0.27	0.15 to 0.92										
26	Little Menomonee River	375	263 to 490	0.97											
27	Wabash River			0.98	0.38 to 1.48	0.446	0.128 to 0.651			16.9	6.1 to 27.3	13.1	4.1 to 22.2	3.77	1.98 to 5.48
28	Four Mile Creek	881	222 to 3,220	1.19	0.27 to 3.24	0.369	0.014 to 0.729	0.72	0.23 to 2.32	34.4	3.8 to 80.3	28.1	1.4 to 64.7		
29	Little Four Mile Creek	425	2 to 1,238	3.10	0.58 to 7.97	0.249	0.006 to 0.627	2.78	0.56 to 7.17	52.6	2.9 to 122.6	37.0	0.8 to 82.8		
30	Choptank River	81	7.9 to 214	0.44	0.12 to 1.29	0.130	0.024 to 0.305			7.4	2.4 to 16.5	4.6	1.8 to 10.1		

average, especially in the fall and winter. Concentrations of all parameters except chloride are positively correlated with flow in these datasets, and thus one might expect WY 2007 concentrations to be higher than normal. However, with two exceptions, the annual average concentrations of most parameters in WY 2007 were lower than or about the same as the averages for the entire period of record. The WY 2007 TP concentrations were slightly higher than the long-term average, and the DRP concentrations were 150% to 200% of the long-term average. Thus for most parameters, the high loads for WY 2007 were due mainly to high discharge, but for DRP, both higher discharge and higher concentration were important.

Part of the reason for lower than average concentrations is seasonality. More of the discharge in WY 2007 occurred in the fall and winter, when concentrations of most parameters are typically lower than at other times of year. Dissolved reactive phosphorus concentrations, by contrast, are higher at this time than at other times of year, especially in the last decade.

Over the last decade, DRP concentrations have shown an increasing trend in these watersheds (Richards 2006). The effects of the weather in WY 2007 were superimposed on this long-term trend and seasonal influences, leading to especially large DRP loads. Similarly, a long-term trend toward lower SS and PP concentrations in these watersheds (Richards et al. 2008, 2009) is probably part

of the reason that these WY 2007 loads were not more extreme than they were.

Loads Compared to Those from Other Studies. In general, the comparison of Midwestern agricultural watersheds indicates that average yields are broadly comparable for most parameters and that annual yields vary greatly from year to year (tables 5 and 6 and figure 9). The rivers studied by the NCWQR (river numbers 1 through 8, defined in table 6) tend to have slightly higher TP yields than most of the other rivers, partly as a consequence of the fine-grained soils that characterize these watersheds. The Lake Erie tributaries (rivers 1 through 6) have lower DRP yields, reflecting a 30-year effort to reduce phosphorus inputs to Lake Erie from all sources. Comparisons of PP and TKN

yields are precluded because most authors do not report values for these parameters.

Many of these other watersheds display the wide range of annual yields that are the main focus of this paper, and the complete yield data for some of them show that they have also had extreme years. As one example, the Embarrass River in Illinois had TP yields ranging from 0.16 to 2.13 kg ha⁻¹ (0.14 to 1.90 lb ac⁻¹) in the years 1997 to 2003 (Gentry et al. 2007). The highest yield, in 2002, was more than two times the second highest yield and more than ten times the lowest yield. This great variation from year to year (and over shorter time frames) is the main cause of uncertainty in water quality studies in rivers. It necessitates studies of considerable detail over decadal time periods to document systematic changes in water quality or provide an adequate context within which to understand an extreme year, such as 2007 was for the Lake Erie tributaries.

Results from analysis of the USGS dataset (figure 10) provide a useful complement to those described above. Also shown in figure 10 are the average annual yields and the 2007 yields for the Lake Erie tributaries. For the USGS dataset, the median of the average annual yields for SS is 332 kg ha⁻¹ (296 lb ac⁻¹), that for TP is 0.78 kg ha⁻¹ (0.69 lb ac⁻¹), and that for total nitrogen is 23.5 kg ha⁻¹ (20.9 lb ac⁻¹). For the Maumee and Sandusky Rivers, the average annual yields are 625 and 687 kg ha⁻¹ (557 and 612 lb ac⁻¹), respectively, for SS, 1.33 and 1.41 kg ha⁻¹ (1.18 and 1.26 lb ac⁻¹) for TP, and 24.1 and 23.7 kg ha⁻¹ (21.5 and 21.1 lb ac⁻¹) for total nitrogen. The 2007 annual yields are 825 and 1012 kg ha⁻¹ (735 and 901 lb ac⁻¹) for SS, 2.13 and 2.82 kg ha⁻¹ (1.90 and 2.51 lb ac⁻¹) for TP, and 27.6 and 27.2 kg ha⁻¹ (24.6 and 24.2 lb ac⁻¹) for total nitrogen.

Implications. Water year 2007 was characterized by large loads of nutrients, particularly DRP, and most of the loading occurred in fall and winter. During these times, biological activity in streams and rivers is less intense than in the summer (USGS 2009b). The combination of large loads and associated large flows, cool temperatures, and low biological activity would lead to more of the nutrient loads being delivered into Lake Erie without delay and assimilation than would have happened under other circumstances. Events of this sort may be particularly important in fueling algal growth, leading to more severe hypoxia in the Central Basin in the summer.

Figure 9

Average and range of annual yields (unit area loads) for selected Midwestern rivers:

(a) suspended solids, (b) total phosphorus, (c) dissolved reactive phosphorus, (d) total nitrogen, and (e) nitrate nitrogen. Rivers numbers are defined in table 6. The average annual yield is indicated by the diamond, and the range is indicated by the length of the vertical line. For the rivers monitored by Heidelberg University, an open circle indicates the yield for Water year 2007.

Figure 10

Histograms showing the distribution of average annual yields of (a) suspended solids, (b) total phosphorus, and (c) total nitrogen for approximately 300 watersheds in which agriculture is the main land use. Note that U is the median of the US Geological Survey average yields, M is the mean of Maumee annual yields, S is the mean of Sandusky annual yields, Mo7 is the Maumee water year 2007 yield, and So7 is the Sandusky water year 2007 yield.

Note: n = sample size.

While weather is the main reason for these high loads, agricultural practices, such as incorporation of fertilizer and manure into the soil as opposed to surface application, use of cover crops, and spring rather than fall tillage and fertilization, would have reduced the losses. Excessive loads of nutrients and sediment are stressors to the aquatic ecosystems of our rivers and lakes. But they also represent lost resources, mostly in the form of topsoil and nutrients from agricultural fields. Based on winter 2008 fertilizer prices at local fertilizer dealers, we estimate that the value of the nitrogen and phosphorus lost from the Maumee and Sandusky watersheds in WY 2007 is about \$80,000,000, or \$41.30 ha⁻¹ (\$16.70 ac⁻¹) for every hectare in the watersheds. Seventy-five percent of the two watersheds is in row crop agriculture, and fertilizer is commonly applied only before corn in sufficient amounts to cover the three-year rotation (corn, soybeans, wheat) (Steve Davis, Watershed Program Coordinator, USDA Natural Resources Conservation Service Ohio office, personal communication). If every hectare of cropland only received fertilizer once every three years, the value of nutrients lost would be nearly \$166 ha⁻¹ (\$67 ac⁻¹) of cropland receiving fertilizer.

Conservation practices implemented in the 1980s and 1990s in these watersheds were designed primarily to reduce erosion, and they were successful at doing so (Richards et al. 2008, 2009). The worst of the current problems are the loads of DRP. In addition, nitrate and chloride are thought to be important in influencing the species of algae that grow in the lake. These are all transported in the dissolved phase so they are not reduced by conservation practices aimed at erosion. Other practices, such as those mentioned earlier, will be needed to reduce these loads.

Summary and Conclusions

Loads of sediment and nutrients from agricultural watersheds vary greatly from year to year because of weather differences, but those from the Maumee River and the Sandusky River are higher than average for Midwestern agricultural rivers. For WY 2007, loads from the Maumee River and the Sandusky River were the largest observed in 33 years of monitoring for the following parameters: discharge, TP, DRP, TKN, and chloride. The PP load was the second highest

Table 7

Annual precipitation, discharge, and loads for water year 2007, compared with those for water years 1975 through 2006.

Parameter	River or location	Unit area load, WY 2007	Rank of WY 2007 load	Percent of average annual amount	Percent of next highest amount*	Percent of maximum annual amount
Precipitation (cm)	Toledo	102	4	119		93
	Tiffin	118	1	123	100	100
Discharge (cm)	Maumee	49.2	1	158	105	100
	Sandusky	64.5	1	193	108	100
Suspended solids (kg ha ⁻¹)	Maumee	831	8	126		65
	Sandusky	1,080	5	149		60
Total phosphorus (kg ha ⁻¹)	Maumee	2.21	1	163	106	100
	Sandusky	2.91	1	206	133	100
Particulate phosphorus (kg ha ⁻¹)	Maumee	1.59	4	148		87
	Sandusky	2.09	2	180		98
Dissolved reactive phosphorus (kg ha ⁻¹)	Maumee	0.56	1	224	108	100
	Sandusky	0.74	1	319	119	100
Nitrate (kg ha ⁻¹)	Maumee	20.2	9	113		77
	Sandusky	21.4	10	114		73
Total Kjeldahl nitrogen (kg ha ⁻¹)	Maumee	10.2	1	183	128	100
	Sandusky	9.6	1	165	101	100
Chloride (kg ha ⁻¹)	Maumee	113	1	129	104	100
	Sandusky	140	1	158	110	100

Note: WY = water year.

* Only reported if the 2007 load was the highest observed.

in the Sandusky and the fourth highest in the Maumee, the SS load was the fifth highest in the Sandusky and the eighth highest in the Maumee, and the nitrate load ranked ninth (Maumee) and tenth (Sandusky). Precipitation at Tiffin in the Sandusky watershed was the largest in 33 years, by a small margin, and was the fourth largest at Toledo in the Maumee watershed. These excessive loads stress aquatic ecosystems, including those of Lake Erie, and at the same time, represent a loss of valuable resources from the landscape. While the weather patterns of 2007 are largely responsible for the magnitude of these loads, agricultural practices also play an important role. Losses of valuable nutrients and sediment could be reduced by straightforward changes in agricultural practices, including incorporation of fertilizer and manure rather than surface application, spring fertilization rather than fall or winter,

and the use of cover crops to reduce erosion and to scavenge nutrients leached from the soil and from decaying crop residue.

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