Nutrient and Sediment Concentrations and Corresponding Loads during the Historic June 2008 Flooding in Eastern Iowa

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A combination of above-normal precipitation during the winter and spring of 2007–2008 and extensive rainfall during June 2008 led to severe flooding in many parts of the midwestern United States. This resulted in transport of substantial amounts of nutrients and sediment from Iowa basins into the Mississippi River. Water samples were collected from 31 sites on six large Iowa tributaries to the Mississippi River to characterize water quality and to quantify nutrient and sediment loads during this extreme discharge event. Each sample was analyzed for total nitrogen, dissolved nitrate plus nitrite nitrogen, dissolved ammonia as nitrogen, total phosphorus, orthophosphate, and suspended sediment. Concentrations measured near peak flow in June 2008 were compared with the corresponding mean concentrations from June 1979 to 2007 using a paired *t* test. While there was no consistent pattern in concentrations between historical samples and those from the 2008 flood, increased flow during the flood resulted in near-peak June 2008 flood daily loads that were statistically greater ($p < 0.05$) than the median June 1979 to 2007 daily loads for all constituents. Estimates of loads for the 16-d period during the flood were calculated for four major tributaries and totaled 4.95×10^7 kg of nitrogen (N) and 2.9×10^6 kg of phosphorus (P) leaving Iowa, which accounted for about 22 and 46% of the total average annual nutrient yield, respectively. This study demonstrates the importance of large flood events to the total annual nutrient load in both small streams and large rivers.

According to the National Climatic Data Center (2008), from December 2007 to May 2008 eastern Iowa was characterized by "extremely wet conditions that normally occur less than 2.5% of the time" (Standardized Precipitation Index values greater than +2) (Buchmiller and Eash, 2010). This was the second wettest six-month period and the second wettest June since records were started in 1895 (National Climatic Data Center, 2008), and it led to severe flooding over much of eastern Iowa. Sixty-two sites out of 219 monitored sites in Iowa experienced a 1% flood probability or smaller (100-yr flooding or greater) or experienced record peak discharge, with 9 sites experiencing a 0.2% flood probability or smaller (500-yr flooding or greater) calculated from peak-flow records (Buchmiller and Eash, 2010). Such flooding can lead to substantial amounts of nutrient and sediment transport by streams (Goolsby et al., 1993). This may have been enhanced further by the timing of flooding, which occurred shortly after fertilizer application associated with crop planting and during a time when crop growth was limited (e.g., early growing season) and delayed during the wet conditions (USDA National Agricultural Statistics Service, 2008a).

Past studies have shown that nutrients are generally transported during high flow events (Vanni et al., 2001; Tomer et al., 2003; Royer et al., 2006). Nutrients exported from the midwestern United States have been linked to the development of the hypoxic zone in the Gulf of Mexico (Goolsby et al., 2000; Royer et al., 2006; Bianchi et al., 2010). Royer et al. (2006) simulated how load reductions during different flow regimes would affect nitrate and total phosphorus (TP) export to the Mississippi River from Illinois basins. They found that very high discharges (>90th percentile) were responsible for more than 50% of the nitrate export and more than 80% of the TP export annually. Therefore, reducing loads during high flow from the Midwest would aid reducing the load of nutrients to the Gulf of Mexico (Royer et al., 2006; Mississippi River/Gulf of Mexico Watershed Nutrient Task Force, 2008).

Nutrient transport from the Midwest during extreme hydrologic events was first investigated during the flood of 1993. Goolsby et al. (1993) estimated that 7.5×10^8 kg of nitrate was exported to the Gulf of Mexico during April to August 1993,

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Abbreviations: ammonia, dissolved ammonia as nitrogen; nitrate, dissolved nitrate plus nitrite as nitrogen; EWI, equal-width increment; ortho-P, orthophosphate; RL, reporting limit; SS, suspended sediment; TN, total nitrogen; TP, total phosphorus.

approximately 37% more than in all of 1991 and 112% more than in all of 1992 (Goolsby et al., 1993; Goolsby, 1994). Although flow increased, nitrate concentrations in the lower Mississippi River (portion of the Mississippi River downstream from Cairo, IL) during the 1993 flood were similar to those for the same time period during relatively low flows in 1991 and 1992; therefore, the differences in loads were caused by the increase in flow in 1993.

One of the effects of the 1993 flood was a change in the size and shape of the hypoxic zone (Rabalais et al., 1998). The areal extent of hypoxia during 1993 was approximately twice that of the previous eight summers. These effects of the high loads of 1993 were still seen in the Gulf in 1994, when the nutrient fluxes were back to normal, but the hypoxic zone remained nearly equal to the hypoxic zone of the previous year (Rabalais et al., 1998). The 1993 and 1994 hypoxic zone data illustrate the lasting effects of flooding to ecosystem health.

Iowa has been shown to be one of the major contributors of nutrients and sediment to the Mississippi River and eventually to the Gulf of Mexico because of its intense row crop agriculture (Goolsby et al., 1999; Royer et al., 2006; Alexander et al., 2008). Approximately 59.7% of Iowa is used for corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] production (Fig. 1A; USDA National Agricultural Statistics Service, 2008b). In 2008, Iowa had the highest harvested corn acreage and was second in soybean production (USDA National Agricultural Statistics Service, 2009). Nitrogen fertilizers are used extensively to increase yields. Between 1985 and 2003, Iowa had an average annual fertilizer use of 8.64×10^8 kg N (Iowa State University Extension, 2003). Other sources of nutrients include livestock manure, domestic sewage, domestic fertilizers (David and Gentry, 2000), and natural fixation (Russelle and Birr, 2004).

To characterize nutrient (N and P), sediment, and other contaminant concentrations and loads during the extreme discharge event in June 2008, water samples were collected near peak flow at 31 locations across Iowa (median of 8.75 h of peak flow; Supplemental Fig. S1). Many sites were large rivers with long, broad peak discharges during the June 2008 flood event. Results are used to describe the concentrations, loads, and yields in six major Mississippi River tributaries and sites on the main stem of the Mississippi River. In addition, nutrient and sediment yields during 16 d of the flood were calculated for four major Mississippi River tributaries. The percentages of the total annual flux for three tributaries were calculated to determine how important the short-term loading during the extreme events is to the total annual loading.

Materials and Methods

The USGS collected water samples at 31 sites throughout Iowa during the 2008 flood, beginning 10 June and continuing through 25 June 2008 to capture the progression downstream of the concentrations and loads during peak flows. Samples were collected within 24 h of peak flow at all but one of the 31 sites (that sample was collected within 52 h of peak flow) (Supplemental Fig. S1), including 28 sites in the Cedar, Des Moines, Iowa, Maquoketa, Skunk, Turkey, and Wapsipinicon River basins (accounting for 65% of the total area of Iowa) and three sites on the Mississippi River (Fig. 1B). With a few exceptions, flow and water samples were collected at an existing USGS gaging station. Due to bridge safety and/or bridge access problems, a few samples were collected upstream or downstream of the gaging station (maximum distance was 13 km). In addition, multiple samples (from three to four) were collected at several sites. When possible at these sites, samples were collected on the rising limb, at peak flow, and on the receding limb of the flood hydrographs.

Grab samples from the centroid of flow were collected at most sites using a weighted bottle sampler and a 1-L baked amber glass bottle. This simplified sampling technique was necessary to collect the maximum number of samples across Iowa during this extreme hydrologic event. Four samples associated with another USGS project (Fig. 1B, map #1, 2, 8, 9) were collected using the equal-width increment (EWI) depth integrated technique (USGS, 2006).

Water samples were filtered using a 0.45-μm capsule filter for the analysis of ammonia (dissolved ammonia as nitrogen), nitrate (dissolved nitrate plus nitrite as nitrogen), and orthophosphate (ortho-P). Unfiltered water samples, preserved with 1 mL of 2.25 M sulfuric acid, were used to analyze for total nitrogen (TN) and TP. Nutrient samples were chilled and shipped with ice to maintain 4°C. All nutrients samples were analyzed at the USGS National Water Quality Laboratory. Total N was analyzed using an alkaline persulfate digestion (with a reporting limit [RL] = 0.1 mg L^{-1}; Patton and Kryskalla, 2003). Total P was analyzed using semi-automated colorimetry (RL = 0.008 mg L^{-1}; USEPA method 365.1 [Clesceri et al., 1998]). Ammonia (RL = 0.02 mg L^{-1}), ortho-P (RL = 0.008 mg L^{-1}), and nitrate (RL = 0.04 mg L^{-1}) were analyzed using colorimetry (Fishman, 1993). Suspended sediment (SS) was analyzed in unfiltered water samples at the USGS Iowa Sediment laboratory (Guy, 1969).

Stream discharge was measured at the sites using an Acoustic Doppler Current Profiler (Mueller and Wagner, 2009). Many of the measurements were discharge maxima and were critical in extending the discharge rating curve at these sites to new historical highs (Rantz et al., 1982). The mean daily discharge, determined from the rating curve, was used to calculate the corresponding daily constituent load. Discharges for large rivers do not increase or decrease rapidly as small streams; therefore, the use of grab samples from one point in time and a mean daily discharge were appropriate to calculate the daily loads for the large streams. In addition, 16-d transport yields were estimated for four Mississippi River tributaries (Fig. 1B; map #6, 17, 22, 31) by linearly interpolating between measured concentrations (three to four samples per site) over the hydrograph for all 16 d. These four sites were selected because of their proximity to the confluence with the Mississippi River. Interpolated concentrations were multiplied by the daily mean discharge and summed to estimate the 16-d transport mass for select constituents at each site.

Grab samples were assumed to produce a representative sample of dissolved constituents because major rivers are usually well mixed during high flow. Grab samples, however, may have resulted in concentrations of TP, TN, and SS being biased low. It is well known that the grab sample method introduces a negative bias when sampling SS and constituents that are

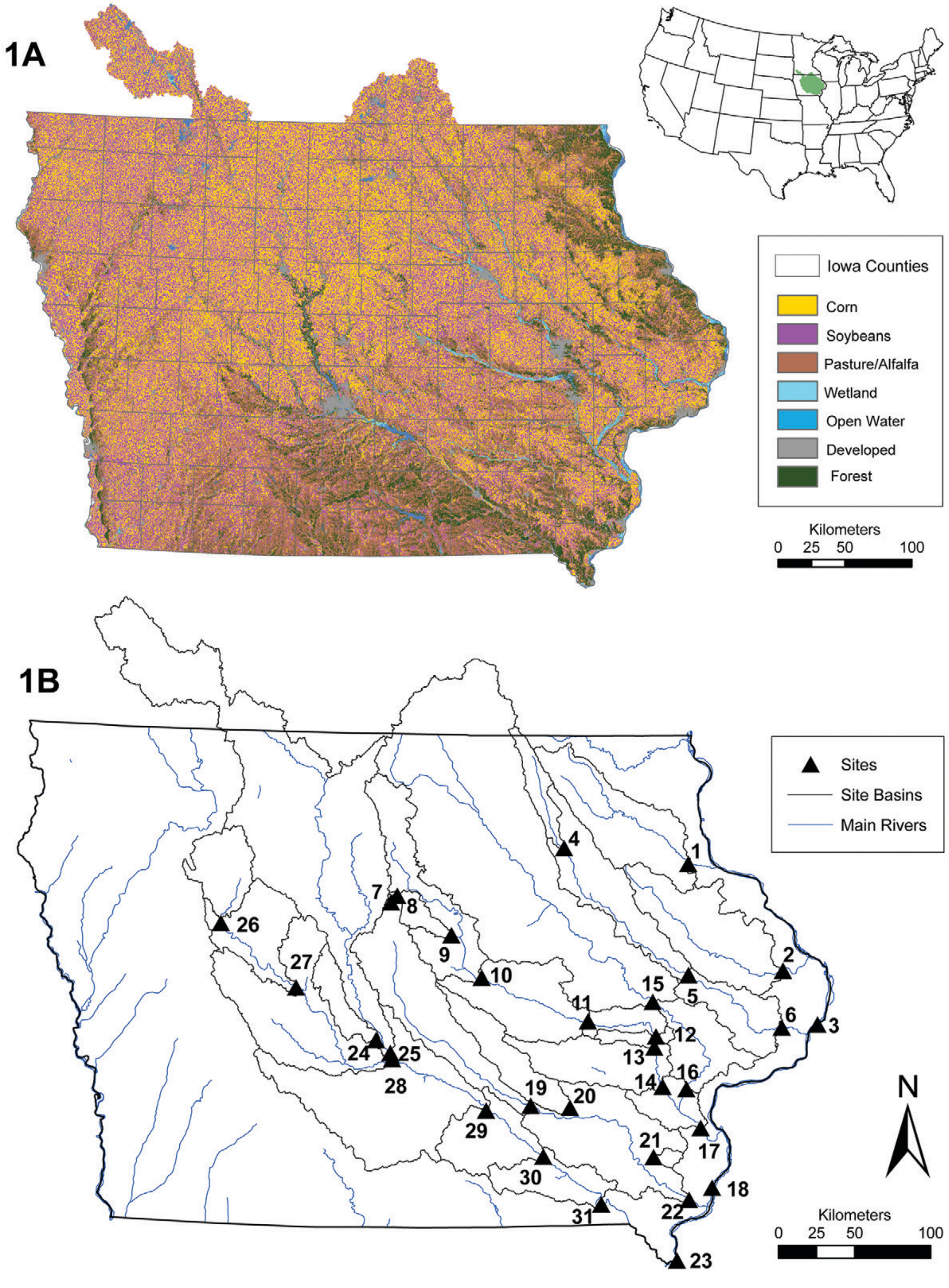

Fig. 1. (A) Land use (USDA National Agricultural Statistics Service, 2008b) and (B) location of USGS gaging stations (31 sampling locations) in eastern Iowa. Sites where water samples were collected for analysis in 2008 are designated with black triangles. The number adjacent to this map symbol denotes the corresponding map number that is cross-referenced in Table 4.

sorbed onto suspended material (USGS, 2006). To determine the appropriateness of the grab samples representing the entire water column, concurrent grab and EWI samples were collected at two sites (Fig. 1B; map #13, 14) during different parts of the hydrograph. The two methods produced ammonia concentrations that differed by 0.01 mg L^{-1} (Table 1). Nitrate, ortho-P, and TN were within 6% (Table 1). Grab samples, however, generally provided SS and possibly TP concentrations that were biased low (Table 1).

The accuracy of discharge data depends primarily on the stage-discharge relation or the frequency of discharge measurements, and the accuracy of observations of stage,

Table 1. Water quality replicate sample results, June 2008.

Replicate no./ Flow condition	Site name	Date	Type	Ammonia	Nitrate	TN†	Ortho-P	TP	SS
						mg L^{-1}			
1 Receding limb	Iowa River at Iowa City, IA 05454500	06/20/2008 11:20	EWI	0.04	3.77	4.30	0.18	0.34	488
	Iowa River at Iowa City, IA 05454500	06/20/2008 11:25	GRAB	0.05	3.74	4.33	0.18	0.28	38
2 Receding limb (later)	Iowa River near Lone Tree, IA 05455700	06/26/2008 10:45	EWI	0.02	3.80	4.37	0.19	0.28	67
	Iowa River near Lone Tree, IA 05455700	06/26/2008 11:10	GRAB	<0.01	3.82	4.45	0.20	0.28	44

† TN, total nitrogen; Ortho-P, orthophosphate; TP, total phosphorus; SS, suspended sediment.

measurements of discharge, and interpretations of records. The degree of accuracy of the records can be found in the USGS annual data report (USGS, 2009). Records for the 31 sites were considered “fair” or better, meaning that at least 85% of the daily discharges are within 15% of the true value (USGS, 2009). In computing daily loadings, it was assumed that the instantaneous concentration for these rivers represented the daily average concentration. This was a good assumption for large rivers but may have introduced errors for the smaller streams.

Results

Concentrations

The spatial distribution of TN and TP concentrations are shown in Fig. 2A and 3A. Total N and TP both exhibited larger peak flow concentrations (TN ≥ 100; TP ≥ 1 mg L^{-1}) in smaller streams (map #7, 8) headwaters (map #4), and at sites with both higher relief and samples collected with the EWI method (map #1, 2). Total N peak flow concentrations were also higher in the Des Moines River basin (map #25, 26, 27). Total P peak flow concentrations were high in additional smaller streams (map #9, 21). Suspended sediment peak flow concentrations had a similar spatial distribution to TP (Supplemental Fig. S5), and ammonia was similar to TN (Supplemental Fig. S3). Nitrate and ortho-P peak flow concentrations did not vary as much spatially as the other constituents; however, concentrations were higher in the Des Moines River basin and the Iowa River basin (Supplemental Fig. S2, S4).

Water-quality concentrations for six major Iowa Mississippi River tributaries and main channel Mississippi River samples are given in Table 2. Each basin had a value (one sample) or a median value calculated from multiple samples collected near peak flow, depending on constituent. A median value was used to demonstrate the typical concentration in

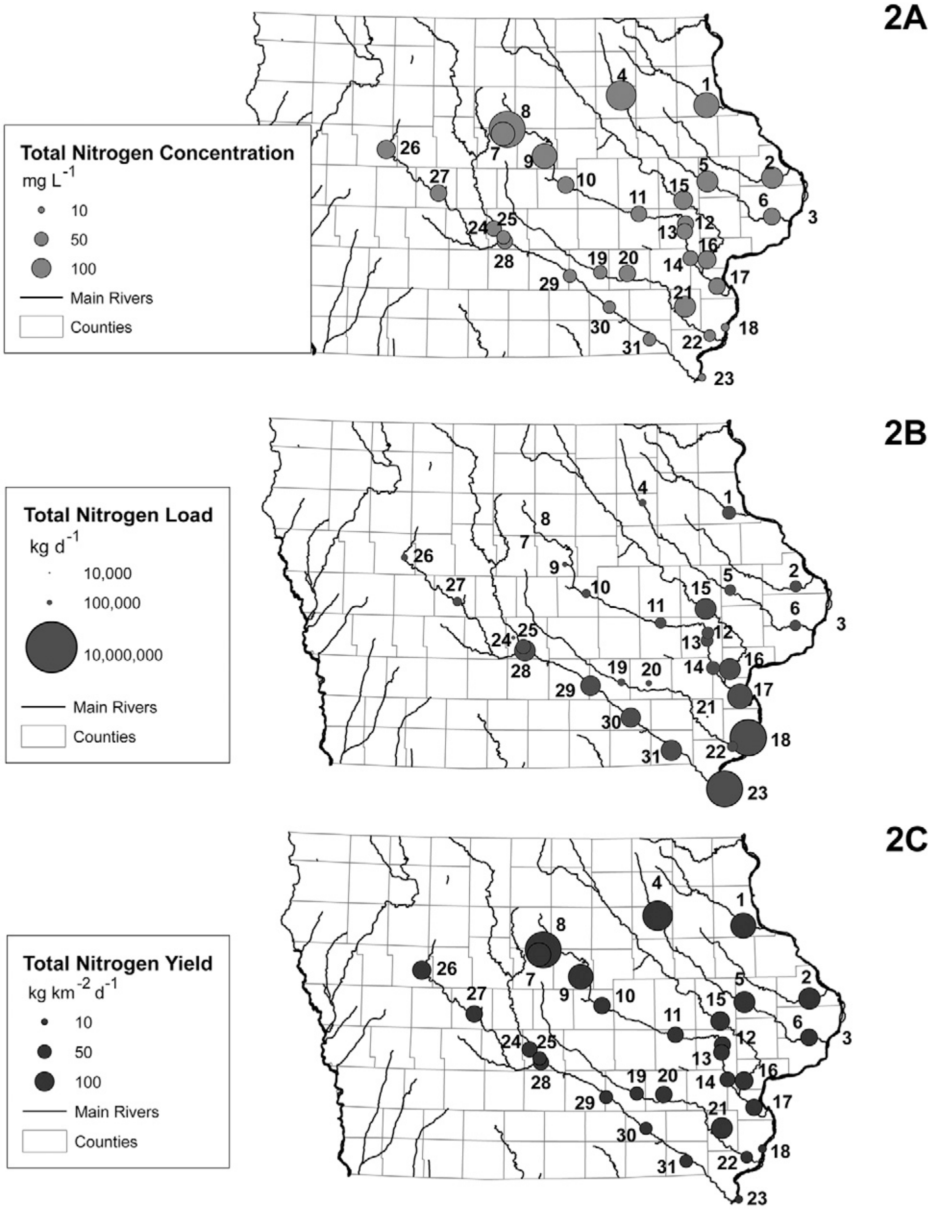

Fig. 2. Maps demonstrating the spatial distribution of near peak flow total nitrogen (A) concentration (B) load and (C) yield spatial distributions of the 31 sites during the June 2008 flood. Note: total nitrogen data not available for map #3.

each basin. The highest concentrations of all constituents were not observed in the same basins. The Maquoketa River basin (Fig. 1B; map #2) had the highest TP, SS, and ammonia concentrations (Table 2). The Des Moines River basin had the highest nitrate concentration, whereas the Turkey River basin had the highest TN concentration (Table 2). The Iowa River basin had the highest ortho-P concentration. The lowest ammonia and TN concentrations were observed in the Skunk River basin, whereas the lowest ortho-P and SS concentrations were observed in the Wapsipinicon River basin (Table 2). The Mississippi River had the lowest TP concentration, whereas the Maquoketa River basin had the lowest nitrate concentration. The median peak flood concentrations of the Mississippi River main stem were at or below the median of the peak flood concentrations of the 31 samples (Table 2).

To determine how concentrations changed from mean conditions to flood conditions, concentrations measured near peak flow in June 2008 were compared with the corresponding mean concentrations from June 1979 to 2007 (USGS, 2008). Statistical significance of these differences was examined using a paired *t* test (10 to 19 paired values depending on constituent; Table 3). There was no statistical difference between the 2008 peak flow samples and the means from June 1979 to 2007 for ammonia and SS ($p > 0.05$). Concentrations of nitrate and TN during peak flow were significantly lower ($p < 0.05$) than the corresponding mean June concentrations. Concentrations of ortho-P and TP during peak flow were significantly higher ($p < 0.05$) concentrations than the mean June concentrations (Table 3).

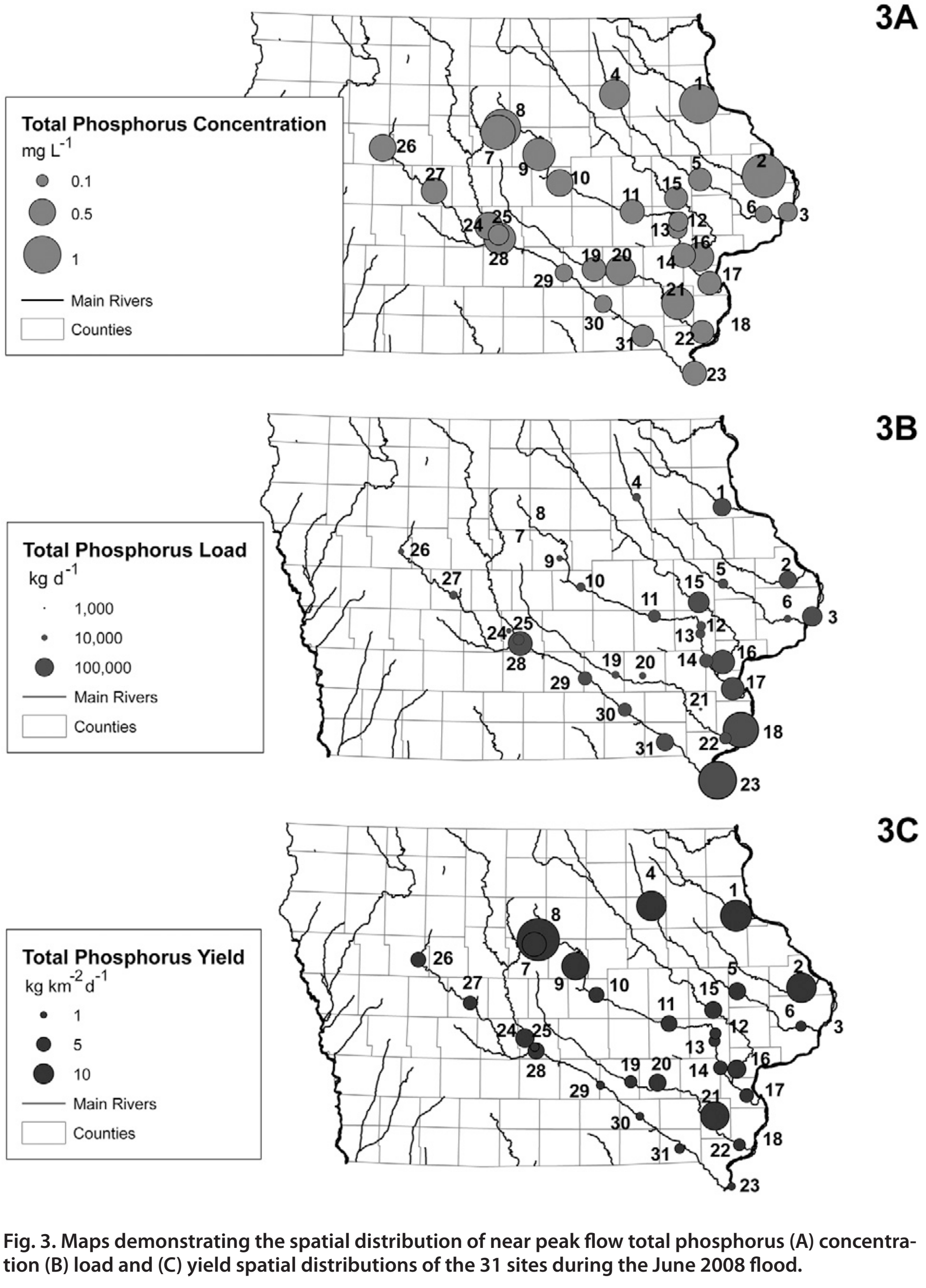

Fig. 3. Maps demonstrating the spatial distribution of near peak flow total phosphorus (A) concentration (B) load and (C) yield spatial distributions of the 31 sites during the June 2008 flood.

Daily Discharges and Loads

The spatial distribution of TN and TP peak flow loads is shown in Fig. 2B and 3B. Total N and TP peak flow loads were smaller (TN ≤ 100,000; TP ≤ 10,000 kg d^{-1}) at the headwaters of the large rivers (map #4) and smaller streams (map #7, 8, 9) and larger (TN ≥ 1000,000; TP ≥ 100,000 kg d^{-1}) on the Mississippi River (Fig. 2B, 3B; map #3, 18, 23). In general, TN and TP loads were larger in the Des Moines River basin (map #25, 28, 29, 30, and 31) and the Iowa River basin (Fig. 2B, 3B; map #15, 16, and 17). Similar patterns for the other constituents (Supplemental Fig. S2–S5) exhibit larger peak flow loads on the Mississippi River and Des Moines and Iowa River basins.

Peak June 2008 flood flows were generally higher in the Mississippi River and Iowa and Des Moines River basins (ranging from 1.39 to 11,700 $m^3 s^{-1}$) and were significantly higher ($P < 0.05$) than median June 1979 to 2007 flows (ranging from 0.103 to 2890 $m^3 s^{-1}$) for the same sites (n = 19). Nineteen of the 31 sites had both near-peak loads during this flood and mean daily loads estimated from June 1979 to 2007 that could be compared. Statistical significance of these differences were examined using a paired *t* test (Table 3). Instantaneous loads during near peak flow in June 2008 were statistically higher ($p < 0.05$) than the median June 1979 to 2007 daily loads (n = 10–19) for all constituents (Table 3). Peak flow loads for the 31 sites can be found in Supplemental Table S1.

Daily Yields

When peak flow loads (Fig. 2B, 3B) are normalized by basin size, the spatial distribution changes (Fig. 2C, Fig. 3C). Larger peak flow yields (TN ≥ 100; TP ≥ 10 kg km^{-2} d^{-1}) were exhibited in smaller streams (map #7, 8, 9, 21), headwaters (map #4), and at sites with both higher relief and samples collected with the EWI method (map #1,2) and smaller (TN ≤ 10; TP ≤ 1 kg km^{-2} d^{-1}) in the Mississippi River samples. Similar patterns for the other constituents (Supplemental Fig. S2–S5) exhibit larger peak flow yields in the smaller streams, headwaters, and at sites with both higher relief and the EWI method of sample collection.

The highest six TN daily yields ranged from 123 to 353 kg km^{-2} d^{-1}, TP daily yields ranged from 18.6 to 44.2 kg km^{-2} d^{-1}, and SS daily yields ranged from 9070 to 41,300 kg km^{-2} d^{-1}

Table 2. Summary statistics for concentrations of selected constituents near peak flow in major rivers during extreme high-flow conditions, June 2008.

Major river basin	No. of sites	Statistic	Ammonia	Nitrate	TN†	Ortho-P	TP	SS
			mg L^{-1}					
Turkey River‡	1	Value	0.081	5.06	7.86	0.171	1.10	1880
		§	–	–	–	–	–	–
Maquoketa River‡	1	Value	0.123	3.68	7.67	0.170	1.35	2570
		§	–	–	–	–	–	–
Wapsipinicon River	2–3	Median	0.043	5.18	6.38	0.102	0.387	102
		Standard deviation	0.067	0.12	0.62	0.011	0.224	57
Iowa River	11	Median	0.032	4.79	6.14	0.183	0.423	239
		Standard deviation	0.025	0.65	1.24	0.028	0.242	258
Skunk River	4	Median	0.022	3.78	4.89	0.146	0.520	250
		Standard deviation	0.010	0.88	1.07	0.072	0.175	228
Des Moines River	6–8	Median	0.052	5.50	6.70	0.166	0.415	260
		Standard deviation	0.024	1.34	1.11	0.069	0.173	260
Mississippi River	2–3	Median	0.042	3.91	4.90	0.117	0.350	152
		Standard deviation	0.035	0.53	0.04	0.021	0.080	80
Median of all samples			0.042	4.79	6.14	0.166	0.423	237

† TN, total nitrogen; Ortho-P, orthophosphate; TP, total phosphorus; SS, suspended sediment.

‡ indicates equal-width increment samples.

§ indicates single samples with no corresponding summary statistics.

Table 3. Comparison of concentrations and daily loads near peak flow in June 2008 and June 1979 to 2007.

Constituent†	Statistic	Concentration		Daily load	
		1979–2007	2008	1979–2007	2008
		mg L^{-1}		kg d^{-1}	
Ammonia	No. of sites	19		19	
	mean	0.060	0.054	4,300	8,400
	median	0.030	0.033	200	5,600
	p-value (paired *t* test)	$p = 0.70$		$p = 0.001$	
Nitrate	No. of sites	19		19	
	mean	9.86	4.70	184,000	745,000
	median	8.40	4.79	38,400	395,000
	p-value (paired *t* test)	$p = 0.001$		$p = 0.001$	
Ortho-P	No. of sites	19		19	
	mean	0.091	0.161	3,200	23,700
	median	0.090	0.170	400	13,300
	p-value (paired *t* test)	$p < 0.001$		$p < 0.001$	
TP	No. of sites	17		17	
	mean	0.296	0.586	11,800	80,600
	median	0.335	0.423	1,000	48,200
	p-value (paired *t* test)	$p = 0.01$		$p = 0.002$	
TN	No. of sites	10		10	
	mean	14.8	6.87	122,000	642,000
	median	11.4	6.93	56,000	416,000
	p-value (paired *t* test)	$p = 0.001$		$p = 0.01$	
SS	No. of sites	16		16	
	mean	332	523	14,600,000	59,900,000
	median	196	250	2,650,000	19,800,000
	p-value (paired *t* test)	$p = 0.44$		$p = 0.004$	

† Ortho-P, orthophosphate; TP, total phosphorus; TN, total nitrogen; SS, suspended sediment.

(Table 4). The highest TN, TP, and SS daily yields were often calculated in the same seven basins (Turkey River at Garber [Fig. 1B, map #1], Maquoketa River near Spragueville [Fig. 1B, map #2], Wapsipinicon River near Tripoli [Fig. 1B, map #4], South Fork Iowa River headwaters near Blairsburg [Fig. 1B, map #7], South Fork Iowa River near Blairsburg [Fig. 1B, map #8], South Fork Iowa River NE of New Providence [Fig. 1B, map #9], and Big Creek north of Mount Pleasant [Fig. 1B, map #21]).

Complete 2008 Flood Loads

Samples were collected on the rising limb, peak, and recession limb of the hydrograph to capture variability in constituent concentrations during the flood. Inconsistent changes in concentration with flow were shown between sites and constituents. Concentrations either increased or decreased with flow or increased or decreased throughout the flood. Concentrations for four Mississippi River tributaries (Wapsipinicon River, Iowa River, Skunk River, and Des Moines River; Fig. 1B, map #6, 17, 22, 31, respectively) were used to calculate the 16-d transport TN, TP, and SS loads (Table 5). Total N loads ranged from 4.86×10^6 to 2.2×10^7 kg, TP loads ranged from 1.63×10^5 to 1.3×10^6 kg, and SS loads ranged from 7.48×10^7 to 1.04×10^9 kg (Table 5). The Iowa River at Wapello (Fig. 1B, map #17) and the Des Moines River at Keosauqua (Fig. 1B, map #31) had the highest discharge and the highest TN, TP, and SS loads (Table 5). All four tributary loads were summed to estimate a cumulative load discharged to the Mississippi River. Total N transport load during the 16-d period was 4.95×10^7 kg, TP was 2.9×10^6 kg, and SS was 1.95×10^9 kg (Table 5).

Discussion

Importance of Floods to Annual Fluxes

Total fluxes for the 16-d period of the 2008 flood were computed for the Iowa River at Wapello, the Des Moines River at Keosauqua, and the Skunk River at Augusta (Table 6) and then compared to typical annual estimates from previous studies (Goolsby et al., 1999; Robertson et al., 2009) to determine how important the 2008 flood was to the typical transport of nutrients and sediment from watersheds in

Table 4. Daily yields for 29 eastern Iowa sites near peak flow in 2008. Italics indicate the six largest loads for each constituent.

Map #	STAID†	Name	Drainage Area	Daily Peak Flow	TN	TP	SS
			km^2	m^3 s^{-1}	——— kg km^{-2} d^{-1} ———		
1	05412500	Turkey River at Garber, IA‡	4,002	1,010	*172*	*24.1*	*41,100*
2	05418600	Maquoketa River near Spragueville, IA‡	4,227	787	*123*	*21.7*	*41,300*
3	05420500	Mississippi River at Clinton, IA	22,1703	5,180	–	0.525	214
4	05420680	Wapsipinicon River near Tripoli, IA	896	351	*239*	*22.0*	–
5	05421740	Wapsipinicon River near Amamosa, IA	4,079	878	119	7.19	2,660
6	05422000	Wapsipinicon River near De Witt, IA	6,050	923	76.8	2.70	817
7	05451070	South Fork Iowa River Headwaters near Blairsburg, IA	7	1.39	*152*	14.7	*9,070*
8	05451080	South Fork Iowa River near Blairsburg, IA‡	31	15.7	*353*	*44.2*	*40,700*
9	05451210	South Fork Iowa River NE of New Providence, IA‡	580	166	*168*	*18.6*	*10,800*
10	05451500	Iowa River at Marshalltown, IA	3,968	151	73.7	5.73	3,150
11	05453100	Iowa River at Marengo, IA	7,236	1,240	66.8	6.29	2,110
12	05453520	Iowa River below Coralville Dam near Coralville, IA	8,068	1,100	72.4	3.20	625
13	05454500	Iowa River at Iowa City, IA	8,472	1,160	69.2	3.22	626
14	05455700	Iowa River at Lone Tree, IA	11,119	1,470	62.0	4.83	1,370
15	05464765	Cedar River at Highway 30 near Bertram, IA	18,026	3,910	97.2	7.30	6,310
16	05465000	Cedar River near Conesville, IA	20,168	3,370	87.7	8.46	3,450
17	05465500	Iowa River at Wapello, IA	32,375	4,500	73.8	4.80	2,150
18	05469720	Mississippi River at Burlington, IA	295,259	12,200	17.4	1.25	544
19	05472010	South Skunk River below Lake Keomah near Oskaloosa, IA	4,369	481	51.6	3.90	1,710
20	05472500	North Skunk River near Sigourney, IA	1,891	255	74.2	7.35	3,090
21	05473450	Big Creek north of Mt. Pleasant, IA	150	47.3	119	*20.4*	*18,400*
22	05474000	Skunk River at Augusta, IA	11,168	1,220	37.6	3.67	2,210
23	05474500	Mississippi River at Keokuk, IA	308,209	11,700	16.2	1.38	859
24	05481950	Beaver Creek near Grimes, IA	927	174	66.2	8.75	5,510
25	05482000	Des Moines River at second Avenue at Des Moines, IA	16,174	1,320	51.1	2.13	720
26	05482300	North Raccoon River near Sac City, IA	1,813	7,890	94.0	5.54	–
27	05482500	North Raccoon River near Jefferson, IA	4,193	17,300	76.1	4.84	–
28	05485500	Des Moines River below Raccoon River at Des Moines,IA	25,586	2,800	65.7	6.71	7,210
29	05488500	Des Moines River near Tracy, IA	32,320	2,920	46.9	1.73	343
30	05489500	Des Moines River at Ottumwa, IA	34,638	2,860	43.0	1.56	1,280
31	05490500	Des Moines River at Keosauqua, IA	36,358	2,970	45.5	2.47	2,470

† STAID, station ID number.

‡ Indicates equal-width increment samples.

Iowa. Goolsby et al. (1999) used a regression approach to estimate the annual fluxes with continuous flow and routinely collected water samples from the National Stream Quality Accounting Network (NASQAN) program. Robertson et al. (2009) used the SPAtially Referenced Regressions On Watershed attributes (SPARROW) model to estimate annual loads at these sites. The SPARROW models were calibrated by Alexander et al. (2008) using detrended average annual loads from 1975 to 1995 computed from the program Fluxmaster (a regression approach similar to that used by Goolsby et al., 1999).

The total flux during the 16-d flood for the Des Moines River, Iowa River, and Skunk River accounted for 22 to 45% of the average total annual flux estimated by Goolsby et al. (1999) for these sites, depending on the constituent (Table 6). Total N and TP fluxes during the 16-d period accounted for 22 to 46% of the yearly delivered flux estimated by Robertson et al. (2009) for these sites (Table 6). According to both study estimates, TN 16-d flood fluxes accounted for 22 to 31% of the average annual flux, and TP ranged from 30 to 46% of the total annual flux. Compared to the Goolsby et al. (1999) estimates, the 16-d flux of nitrate ranged from 25 to 31% of the total annual flux, and the 16-d flux of ortho-P ranged from 28 to 34% of the total annual flux. In addition, the 16-d flood event accounted for 37 to 46% of the annual mean discharge.

A significant portion of the total yearly nutrient flux can be exported during one extreme event (22–46%); therefore, best management practices need to consider the effects of large precipitation events, and especially large-scale events such as floods. Royer et al. (2006) found that extremely high discharges (>90th percentile) were responsible for >50% of the nitrate export and >80% of the P export annually. Many studies have concluded that most nutrient exports in the Midwest occur during periods of high discharge (Tomer et al., 2003, Vanni et al., 2001), and relatively short-term storm events are having large impacts on these agricultural areas. Mitigation will require wide-scale management actions to reducing these loads from the Midwest.

Relating Nutrient Loss and Fertilizer Use

The fluxes during the 2008 flood and annual fertilizer application rates were used to determine how this loss of nutrients compares with what is applied to agricultural fields. At the listed 2007 N fertilizer application rate for Iowa fields of

Table 5. Nitrogen and phosphorus transported to the Mississippi River from eastern Iowa during the 16-d (10–25 June 2008) storm in June 2008.

Site name/ Station ID no.	Discharge	TN†	TP	SS
	m^3 s^{-1}		kg	
Wapsipinicon River near De Witt, IA 05422000	8,871	4,860,000	163,000	74,800,000
Iowa River at Wapello, IA 05465500	42,577	22,000,000	1,300,000	564,000,000
Skunk River at Augusta, IA 05474000	12,632	4,990,000	408,000	272,000,000
Des Moines River at Keosauqua, IA 05490500	33,932	17,700,000	1,040,000	1,040,000,000
Total	98,000	49,500,000	2,900,000	1,950,000,000

† TN, total nitrogen; TP, total phosphorus; SS, suspended sediment.

Table 6. Comparison of yields from the 16-d flood event in 2008 with annual yields estimate by Goolsby et al. (1999) and Robertson et al. (2009) calculated for three basins in eastern Iowa. Note that the Des Moines River site used in Goolsby et al. (1999) is Des Moines River at Francisville, MO (05490600), approximately 50 km downstream from Keosauqua, IA.

Site name/ Station ID no.	2008 WY Q†	WY annual mean Q	Flood % of annual mean Q	Constituent‡	Flood 16-d yield	Annual yield: Goolsby et al. (1999) Yield	Annual yield: Goolsby et al. (1999) Flood % of avg. annual yield	Annual yield: Robertson et al. (2009) Yield	Annual yield: Robertson et al. (2009) Flood % of avg. annual yield
	m^3 s^{-1}	m^3 s^{-1}			kg km^{-2}	kg km^{-2}		kg km^{-2}	
Des Moines River at Keosauqua, IA 05470500	529	244	46	TN	486	1850	26	1910	26
				TP	28.7	64.1	45	73.7	39
				Nitrate	421	1690	25	–	–
				Ortho-P	11.3	37.1	30	–	–
Iowa River at Wapello, IA 05465500	616	267	43	TN	679	2290	30	2210	31
				TP	40.1	94.9	42	87.2	46
				Nitrate	546	1770	31	–	–
				Ortho-P	17.6	62.3	28	–	–
Skunk River at Augusta, IA 05474000	198	74	37	TN	447	2020	22	2060	22
				TP	36.5	120.5	30	111.7	33
				Nitrate	400	1560	26	–	–
				Ortho-P	14.0	41.7	34	–	–

† WY, water year; Q, discharge.

‡TN, total nitrogen; TP, total phosphorus; Ortho-P, orthophosphate.

145 kg N ha^{-1} (USDA, 2007; IDALS, 2007), the mass of N transported during the flood (4.95×10^7 kg) would fertilize 3410 km^2 of cropland (∼6% of tillable acreage in Iowa). With an average P fertilizer application rate for Iowa fields of 47 kg P ha^{-1} (USDA, 2007; IDALS, 2007), 2.9×10^6 kg of P could fertilize 617 km^2 of cropland (∼1% of tillable acreage in Iowa).

Flood of 2008 Implications for the Mississippi River and Gulf of Mexico

Results show that while most nitrate and TN concentrations during the 2008 flood were significantly lower than the mean concentrations in the same basins from June 1979 to 2007, the loadings were all significantly higher in 2008 (Table 3). Goolsby (1994) noted that while nitrate concentrations between 1992 and 1993 were similar in the lower Mississippi River, the load was substantially higher in 1993 than in 1992 because of the increased discharge. Some water-quality constituents, such as nitrate and TN, can be diluted during high/extreme discharge (concentrations that remain similar or decrease relative to "normal" conditions); however, other constituents, such as SS or constituents that are associated with erosion like TP (and ortho-P), increase during high discharges (Novak et al., 2003). Therefore, changes in loading during flood events are not only a function of changes in flow but also a function of the changes in concentration that occur during these events. Typically, the changes in discharge far exceed the decreases in concentrations, such as seen here for nitrate and TN, and loads greatly increase during flood events.

After the 1993 Midwest flood, the areal extent of hypoxia in the Gulf of Mexico was approximately twice as large as the average area of the previous eight summers (Rabalais et al., 1998). Despite the mixing effects of Hurricane Dolly in July 2008, the size of the hypoxic zone after the June 2008 historic flooding still ranked second largest in size (LUMCON, 2008). The nutrient loading from the June 2008 flooding exacerbated the already-low oxygen conditions in the Gulf of Mexico resulting from the high Mississippi River spring loading due to above-normal precipitation in the Midwest (LUMCON, 2008).

Conclusions

Historically, the primary effort during extreme hydrologic events has been focused on documenting water levels and water quantity of flooding. This study, however, clearly demonstrates how important flood events can be to the annual nutrient and sediment load of both small streams and large rivers. Because the timing and magnitude of floods can vary substantially, further research is needed to characterize nutrient and sediment transport during these events and to incorporate their effects into numerical models. Research has shown that while these extreme events are relatively short in duration, they can have large impacts at the local scale and up to the regional scale (e.g., Gulf of Mexico). Mitigation will require wide-scale management actions to reduce nutrient and sediment transport to the Mississippi River and the Gulf of Mexico. Heavy rainfall is twice as frequent as a century ago, and precipitation is projected to increase (in winter and spring) with more intense downpours, leading to more frequent flooding (Karl et al., 2009) and likely an increase in nutrient export in the Midwest. Thus, more research on the water quality of flood events should continue to help us fully understand their water-quality aspects.

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